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MULTI-AGENCY RADIATION SURVEY AND SITE INVESTIGATION MANUAL (MARSSIM)

Final Report



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ABSTRACT

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides information on planning, conducting, evaluating, and documenting building surface and surface soil radiological surveys for demonstrating compliance with requirements, often as part of a dose- or risk-based regulation or standard.¹ MARSSIM is a multiagency consensus document that was developed collaboratively by four Federal agencies having authority and control over radioactive materials: U.S. Department of Defense (DoD), U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), and U.S. Nuclear Regulatory Commission (NRC). MARSSIM's objective is to describe a consistent approach for planning, performing, and assessing building surface and surface soil radiological surveys to meet established criteria, while concurrently encouraging an effective use of resources.

¹ MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

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The four Federal agencies that originally published MARSSIM agreed that MARSSIM needed a comprehensive revision due to changes in the science of radiation measurement and lessons learned over the 30 years that had passed since its original issuance. The MARSSIM Workgroup began by soliciting comments from the Government agencies and members of the public on revisions to MARSSIM. In addition, the workgroup held a consultation with the EPA Science Advisory Board's Radiation Advisory Committee to solicit additional comments on the document.

Subject matter experts from all four Federal agencies contributed their time and expertise to updating portions of the original document based on the comments and suggestions received, in some cases writing new sections and appendices in order to provide the most comprehensive update possible. The document underwent both internal agency and public review and comment periods, and the workgroup responded to comments by making extensive changes to the document based on feedback received. Finally, the EPA Science Advisory Board's Radiation Advisory Committee completed a full technical peer review of the document. The adjudication of those comments resulted in the version of MARSSIM, Revision 2, that follows. Many experts contributed to the development of MARSSIM, Revision 2; however, the document would not be the same without the key efforts of several individuals.

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DEDICATION

The MARSSIM Workgroup dedicates this document to the memory of Dr. George Edward Powers of the NRC staff. Dr. Powers passed away in late 2011, as the effort to revise the MARSSIM manual was getting underway. As a member of the MARSSIM Workgroup, he made significant contributions to MARSSIM, including on the original document, on its revision in 2001, and on this latest revision. Dr. Powers also contributed in an important way to the development of the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) and Multi-Agency Radiation Laboratory Analytical Protocols (MARLAP) manuals; his participation in the development of all three documents (MARSSIM, MARSAME, and MARLAP) is well recognized. The MARSSIM Workgroup members also are aware of the many contributions he made as an NRC employee, including his involvement in several NRC NUREG publications over the years. Dr. Powers was truly a visionary in encouraging the development of multiagency documents in this collaborative and collegial manner for use by many people. Dr. Powers' sense of humor enhanced his ability to work so well in a positive manner with many of his colleagues in multiagency settings. He was a technically accomplished, kind, and courteous man who contributed much to the workgroup's efforts.

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ABBREVIATIONS

α S	alpha scintillation survey meter
γ S	gamma scintillation (gross)
AARST	American Association of Radon Scientists and Technologists
AEA	Atomic Energy Act of 1954, as amended
AEC	Atomic Energy Commission
AES	atomic emission spectrometer
AFI	Air Force instruction
AGL	above ground level
AGS	above ground surface
AL	action level
AMS	accelerator mass spectrometry
ANOVA	analysis of variance
ANSI	American National Standards Institute
APHA	American Public Health Association
AR	Army regulations
ASQ	American Society for Quality
ASTM	ASTM International
ATSDR	Agency for Toxic Substances and Disease Registry
CAA	Clean Air Act as amended in 1990
Capt.	Captain (Air Force)
CAPT	Captain (Navy)
CCD	continuously collected data
CDR	Commander
CED	committed effective dose
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
CFR	<i>Code of Federal Regulations</i>
CHP	Certified Health Physicist
CLP	(Superfund) Contract Laboratory Program
COC	chain of custody
CSU	combined standard uncertainty
CV	coefficient of variation
CZT	cadmium-zinc telluride
D&D	decontamination and decommissioning
DAF	Department of the Air Force
DCGL	derived concentration guideline level
DCGL _{EMC}	DCGL for small areas of elevated activity, used with the EMC
DCGL _w	DCGL for average concentrations over a wide area, used with statistical tests
DEFT	Decision Error Feasibility Trials (software)
DHA	Defense Health Agency
DL	discrimination limit
DoD	U.S. Department of Defense

DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	Department of Transportation
DQA	Data Quality Assessment
DQI	data quality indicator
DQO	Data Quality Objective
DRP	discrete radioactive particle
ED	electronic dosimeter
EEC	equilibrium equivalent concentration
EIC	electret ion chamber
EMC	elevated measurement comparison
EML	Environmental Measurements Laboratory
EPA	U.S. Environmental Protection Agency
EPIC	Environmental Photographic Interpretation Center
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
ESDA	exploratory spatial data analysis
FA-MS	flowing-afterglow mass spectrometry
FIDLER	Field Instrument for the Detection of Low-Energy Radiation
FS	feasibility study
FSS	final status survey
GCS	geographic coordinate system
GIS	geographic information system
GM	Geiger-Mueller
GPR	ground-penetrating radar
GPS	Global Positioning System
GP α	gas-flow proportional counter (alpha mode)
GP β	gas-flow proportional counter (beta mode)
GUM	Guide to the Expression of Uncertainty in Measurements
H ₂ O	water
HASP	health and safety plan
HPGe	high-purity germanium
HPS	Health Physics Society
HSA	Historical Site Assessment
HVAC	heating, ventilation, and air conditioning
IAEA	International Atomic Energy Agency
ICP	inductively coupled plasma
ICP-AES/MS	inductively coupled plasma-atomic emission spectrometry/mass spectrometry
ICP-MS	inductively coupled plasma-mass spectrometry
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IL _{pp}	a posteriori investigation level for postprocessed data
INAA	instrumental neutron activation analysis
IS	International System
IS γ	in situ gamma spectrometry
ISGS	in situ gamma spectroscopy

ISM	Incremental Sampling Methodology
ISO	International Organization for Standardization
ISy	in situ gamma spectrometry
IV	independent verification
JSA	job safety analysis
KPA	kinetic phosphorescence analysis by laser
LA-ICP-AES	laser ablation-inductively coupled plasma-atomic emission spectrometry
LA-ICP-MS	laser ablation-inductively coupled plasma-mass spectrometry
LANL	Los Alamos National Laboratory
LBGR	lower bound of the gray region
LCD	liquid crystal display
LCDR	Lieutenant Commander
LiDAR	light detection and ranging; laser imaging, detection, and ranging
LLD	lower limit of detection
LSC	liquid scintillation counter
Lt.	Lieutenant (Air Force)
LT	Lieutenant (Navy)
Lt. Col.	Lieutenant Colonel
MARLAP	Multi-Agency Radiation Laboratory Analytical Protocols (Manual)
MARSAME	Multi-Agency Radiation Survey and Assessment of Materials and Equipment (Manual)
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
MAV	manned aerial vehicle
MCA	multichannel analyzer
MDA	minimum detectable activity
MDC	minimum detectable concentration
MDCR	minimum detectable count rate
MDER	minimum detectable exposure rate
MDLEST	Mobile Demonstration Laboratory for Environmental Screening Technologies
MQC	minimal quantifiable concentration
MQO	Measurement Quality Objective
MS	mass spectrometry
NA	not applicable
NARM	naturally occurring or accelerator-produced radioactive material
NCRP	National Council on Radiation Protection and Measurements
ND	nondetectable
NIST	National Institute of Standards and Technology
NORM	naturally occurring radioactive material
NPL	National Priorities List
NRC	U.S. Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act of 1982, as amended
OSHA	Occupational Safety and Health Administration
OSL	optically stimulated luminescence
OSLN	optically stimulated luminescence device sensitive to neutrons

PAEC	potential alpha energy concentration
PIC	pressurized ionization chamber
PMT	photomultiplier tube
PNNL	Pacific Northwest National Laboratory
PPE	personal protective equipment
PRG	preliminary remediation goal
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
Q-Q	quantile-quantile
RAS	remedial action support
RASP	Radiological Affairs Support Program
RCRA	Resource Conservation and Recovery Act
RESRAD	residual radiation (computer code)
RFI	RCRA Facility Investigation
RFP	request for proposal
RI	remedial investigation
RODS	Records of Decision System
RSSI	Radiation Survey and Site Investigation
SADA	Spatial Analysis and Decision Assistance
SDWA	Safe Drinking Water Act
SEMS	Superfund Enterprise Management System
SOP	standard operating procedure
SOR	sum of the ratios
SOW	statement of work
SSG	soil screening guidance
SSL	soil screening level
STAR	Standard Test Atmosphere for Radon
TED	total effective dose
TEDE	total effective dose equivalent
TENORM	technologically enhanced naturally occurring radioactive material
TIGER	Topologically Integrated Geographic Encoding and Referencing (System)
TIMS	thermal ionizing mass spectrometry
TLD	thermoluminescent dosimeter
TOF-MS	time-of-flight mass spectrometry
TSCA	Toxic Substances Control Act of 1976
TVA	Tennessee Valley Authority
UAV	unmanned aerial vehicle
UBGR	upper bound of the gray region
UCL	upper confidence limit
UFP-QAPP	Uniform Federal Policy for Quality Assurance Project Plans
UFP-QS	Uniform Federal Policy for Implementing Environmental Quality Systems
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978, as amended
U.S.C.	United States Code
USGS	United States Geological Survey
USL	upper simultaneous limit

UTL	upper tolerance limit
VSP	Visual Sample Plan
WIPP	Waste Isolation Pilot Plant
WQP	Water Quality Portal
WRS	Wilcoxon Rank Sum

SYMBOLS, NOMENCLATURE, AND NOTATIONS

$<$	less than
$>$	greater than
$\leq$	less than or equal to
$\geq$	greater than or equal to
$^{\circ}$	degrees (angle or temperature)
%	percent
$1-\beta$	statistical power of a hypothesis test
1σ	standard uncertainty
2π	radiation detection in half a sphere
4π	radiation detection in all directions
α	alpha radiation
α	Type I (alpha) decision-error rate, false positive
α_Q	alpha used for the Quantile test
α_W	alpha used for the WRS test
a	upper bound for the magnitude of the error of x_i
A	area
A	activity
Ac	actinium
A_{EA}	area of elevated activity
$A_{\min}$	smallest size of an area of elevated activity that it is important to detect
Al	aluminum
$\text{Al}_2\text{O}_3\text{:C}$	carbon-doped aluminum oxide
A_m	area factor
Am	americium
Ar	argon
A_s	surface activity
$\bar{A}_S$	average surface activity concentration in the survey unit
A_{Total}	total activity of the n radionuclides
β	beta radiation
β	Type II decision-error rate, false negative
B	number of background counts expected to occur while performing an actual measurement
B	background count rate
Ba	barium
Be	beryllium
b_i	total number of background counts in the observation interval (scanning)
Bi	bismuth
Bq	becquerel
$^{\circ}\text{C}$	degrees Celsius
C	carbon
C	derived concentration guideline level
C	radionuclide concentration or activity
C	factor used to convert from counts to concentration

C	constant
$\bar{C}$	average activity concentration
C'	conservative estimate of total detection efficiency and other constants or factors represented by C
Ca	calcium
CaF ₂ :Mn	manganese-doped calcium fluoride
CaSO ₄ :Dy	dysprosium-doped calcium sulfate
C_b	number of background counts
C_i	concentration value for an individual radionuclide ($i = 1, 2, \dots, n$)
c_i	sensitivity coefficient
Ci	curie
cm	centimeter
cm ²	square centimeter
cm ³	cubic centimeter
CdWO ₄	cadmium tungstate
Cl	chlorine
Co	cobalt
cpm	counts per minute
cps	counts per second
CR	count rate
CR _w	net count rate corresponding to the DCGL _w
Cs	cesium
C_s	concentration for the surrogate radionuclide
C_s	integrated net counts recorded by the instrument
C_{s+b}	number of gross counts
CsI(Tl)	thallium-activated cesium iodide
δ	estimate of the mean concentration of residual radioactive material in the survey unit (amount that the distribution of measurements for a survey unit is increased compared to the distribution of measurements of the reference area)
Δ	shift (width of the gray region, UBGR–LBGR)
Δ/σ	relative shift
Δt_i	the observation interval
d	width of the detector in the direction of the scan
d'	index of sensitivity (distance between the means of the background and background plus signal)
d	day
D	the true, but unknown, value of the difference between the true mean concentration of residual radioactive material in the survey unit and the reference area
DCGL _{EMC,S-unmod}	unmodified derived concentration guideline level for the elevated measurement comparison for the first radionuclide
DCGL _{gross}	derived concentration guideline level for a gross measurement
DCGL _{min}	lowest of the derived concentration guideline levels
DCGL _{S-mod}	modified derived concentration guideline level for the surrogate radionuclide
DCGL _{S-unmod}	derived concentration guideline level for the surrogate radionuclide before modification

D_i	difference between the derived concentration guideline level for a wide area (or action level) and a survey unit measurement
dpm	disintegrations per minute
dps	disintegrations per second
ε_i	instrument efficiency
ε_s	source efficiency
ε_t or ε	total efficiency of the instrument
E	mean
E	detection efficiency
Eu	europium
Fe	iron
F_{eq}	equilibrium factor
f_i	relative fraction of activity contributed by radionuclide i to the total
ft	foot
γ	gamma radiation
λ	average number of events per unit time
λt	average value expected
g	gram
g	number of groups of tied measurements
g	fractional part of v_i (Equation L-3)
G	distance between grid points
G	activity in disintegrations per minute
Gy	gray
h	hour
H	hydrogen
H_0	null hypothesis
H_1	alternative hypothesis
He	helium
i	i th sample or measurement in a set
i	observation time interval length (scanning)
I	iodine
in.	inch
in. ²	square inch
j	integer part of v_i (Equation J-3)
j	rank
k	k-statistic for the Quantile test
k	time factor in the lag- k method for a priori calculation of critical levels and detection limits that can be converted to scan minimum detectable concentration
k	coverage factor to obtain the expanded uncertainty, U

k	value of the standard normal deviate corresponding to a one-tailed probability of $(1-\alpha)$ and $(1-\beta)$ (assuming α and β are equal)
k	critical value of the Sign test
K	Kruskal-Wallis statistic
K_d	distribution coefficient
keV	kiloelectron volt (1×10^3 electron-volts)
kg	kilogram
kg^2	square kilogram
L	Bayesian test statistic
L	length (of long axis for an elliptical area of elevated activity)
L	liter
L	grid size spacing
La	lanthanum
LaBr_3	lanthanum bromide
LaBr:Ce	cerium-activated lanthanum bromide
L_C	critical level
L_D	detection limit
L_{EA}	revised spacing of the systematic pattern
LiBO_4	lithium borate
LiF:Mg,Cu,P	magnesium, copper, and phosphorous-doped lithium fluoride
$^6\text{LiF:Mn}$	manganese-doped lithium-6 fluoride
$^7\text{LiF:Mn}$	manganese-doped lithium-7 fluoride
μ	theoretical mean of a population distribution
μ	true mean
μ	micro (10^{-6})
μBq	microbecquerel
μCi	microcurie
μg	microgram
μm	micrometer
μR	microroentgen
μSv	microsievert
m	number of samples in the reference area (for Scenario A), number of samples in the survey unit (for Scenario B)
m	mass of soil sample
m	average number of counts expected
m	adjusted reference sample measurements
m	meter
m^2	square meter
m^3	cubic meter
mBq	millibecquerel
$\text{MDCR}_{\text{surveyor}}$	required number of net source counts
m/e	mass-to-charge ratio
MeV	megaelectron volt (1×10^6 electron-volt)
mg	milligram
mGy	milligray
M_i	total amount of [dose counts, activity, etc.]
min	minute

mL	milliliter
mm	millimeter
mm ²	square millimeter
Mn	manganese
mR	milliroentgen
mrad	millirad
mrem	millirem (1×10^{-3} rem)
mSv	milliseivert (1×10^{-3} Sv)
m/z	mass-to-charge ratio
n	number of samples in the survey unit (for Scenario A), number of samples in the reference area (for Scenario B)
n	number of calculated survey locations
n	n th sample or measurement in a set
n	number of counts actually detected
N	sample size (i.e., number of data points [or samples]); required number of measurements
N	number of increments in the composite
N	actual number of concentration measurements obtained
N	nitrogen
n_0	number of measurements per reference area when the number of measurements in each reference area is the same
Na	sodium
NaI	sodium iodide
NaI(Tl)	sodium iodide (thallium activated)
n_b	number of background counts
$\bar{n}_B$	number of counts observed
nBq	nanobecquerel
n_{EA}	required number of data points for assessing small areas of elevated activity
ng	nanogram
Ni	nickel
Np	neptunium
n_r	number of reference area measurements
n_s	number of survey unit measurements
n_{s+b}	number of counts from the source and background
O	oxygen
oz	ounce
P	probability of observing one or more counts
p	coverage probability for expanded uncertainty
p	surveyor efficiency (scanning)
p	probability that a random measurement from the survey unit is less than Δ
p_2	probability that two random measurements from the survey unit will each exceed a single random measurement from the reference area by less than the DCGL _w
pC	picocoulomb
pCi	picocurie (1×10^{-12} curies)
pg	picogram
PIC	pressurized ionization chamber

ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
P_r	Scenario A: the probability that a random measurement from the survey unit exceeds a random measurement from the background reference area by less than the $DCGL_W$ when the survey unit median is equal to the LBGR above background Scenario B: the estimated probability that the difference between a random measurement from the survey unit and a random measurement from the reference area will be greater than the LBGR (the action level) when the survey unit median is actually at the UBGR or discrimination limit above the background median
P_s	Scenario A: the estimated probability that a random measurement from the survey unit will be less than the UBGR or $DCGL_W$ when the survey unit median is actually at the LBGR and is used only when the radionuclide is not present in background Scenario B: the estimated probability that a random measurement will be greater than the LBGR when the median is near the discrimination limit or UBGR
Pu	plutonium
q^*	critical value for statistical tests
r	number of samples from the combined reference and survey unit that defines the quantile of interest
r	random number from a dataset
r	r-statistic for the Quantile test
R	net count rate
R	rate of missing or unusable measurements
R	roentgen (exposure rate)
Ra	radium
R_A	acceptable level of risk
$\bar{R}_B$	count rate for the background measurement made in the reference area
R_i	established ratio of the concentration of the i th radionuclide to the concentration of the surrogate radionuclide for $i = 2, \dots, n$
R_i	sum of the ranks of the measurements in a given reference area
Rn	radon
R_{net}	net count rate
$r(X_i, X_j)$	correlation coefficient for two input estimates, X_i and X_j
σ	theoretical total standard deviation of the population distribution being sampled
$\sigma(C_i)$	estimate of uncertainty in the concentration in the sample of the i th radionuclide for $i = 1, \dots, n$
σ_M	true measurement method standard deviation
σ_{MR}	required measurement method uncertainty
σ_n	standard deviation of the net count rate result
σ_r	estimate of the measurement variability in the reference area
σ_s	estimate of the measurement variability in the survey unit
$\sigma(T)$	standard deviation of the weighted sum of the ratios

σ^2	theoretical total variance of the population distribution being sampled
$\sigma_{measurement}^2$	standard deviation due to individual measurement uncertainty
σ_s^2	estimate of the standard deviation for the measurements performed in a survey unit including the spatial and temporal variations captured by the survey design
$\sigma_{spatial}^2$	standard deviation due to spatial and temporal variations
s	second
s	arithmetic standard deviation of the survey unit's mean residual radioactive material concentration, assuming a normal distribution
s	surrogate ratio
s	test statistic
S	length of the short axis of the ellipse
S^+	Sign test statistic
s_b^2	mean square between reference areas
s_i	minimum detectable number of net source counts in the observation interval (scanning)
Si	silicon
s_r	standard deviation of reference area
Sr	strontium
s_s	standard deviation for survey unit
Sv	sievert
s_w^2	mean square within reference areas
t	t-test statistic
t	time interval
t	number of "less than" values
T	count time
T	weighted sum
$\bar{T}$	average sum of fractions for soil samples
$t_{1/2}$	half-life
$t_{\alpha, \nu}$	critical value from the t-distribution for a confidence limit of $(1-\alpha)$ and ν degrees of freedom
t_b	time period over which the background counts were recorded
Tc	technetium
Th	thorium
Th _{nat}	natural thorium
Tl	thallium
t_i	time interval
T_i	sum of fractions for the i th soil sample
t_j	number of tied measurements in the j th group
Torr	unit of pressure, about 133.32 pascals
t_s	time period over which counts were recorded in the survey area
t_{s+b}	gross count time
U	expanded uncertainty
U	uranium
u	absolute uncertainty
U _{nat}	natural uranium
UO ₂	uraninite

$\text{U(PO}_3)_4$	uranium metaphosphate
$u(x_i)$	standard uncertainty of the input estimate, x_i
$u(x_i, x_j)$	covariance of two input estimates, x_i and x_j
$u_c(y)$	combined standard uncertainty of y
$u_c^2(y)$	combined variance of y
u_M	measurement method uncertainty
u_{MR}	required measurement method uncertainty
φ	standard uncertainty
φ_{MR}	relative required measurement method uncertainty
$\Phi(z)$	standard normal cumulative distribution function
V	volt
v	scan speed
ν	number of degrees of freedom
Var	variance
V_i	factor for interpolating data to make the number of points in two datasets match
$\hat{\omega}^2$	variance
W	physical probe area
W_C	critical value for the WRS test
W_{MW}	Mann-Whitney form of the WRS test statistic
W_r	sum of the ranks of the (adjusted) reference measurements (WRS test)
W_s	sum of the ranks of the (adjusted) sample measurements (WRS test)
W_T	weighting factors
x	true value of the parameter of interest
X	Poisson random variable representing the number of events occurring during a given time interval or in a specified region in space
$\bar{x}$	sample mean
X	length of the survey unit
X	random concentration in the survey unit when the radionuclide does not appear in background, or the difference between the survey unit and reference area concentration distributions
x_i	reference area measurement
x_i	results of the individual samples
x_i	estimate of the input quantity
X_i	an input quantity for the mathematical model
$X_{[k]l}$	reference area measurements (unless the reference area data set was the larger of the two, in which case this would be the survey unit area data)
$\bar{x}_r$	arithmetic mean of the data for the reference area
$\bar{x}_s$	arithmetic mean of the data for the survey unit
$x_{s,i}$	result of the i th measurement in the survey unit
$x_{r,i}$	result of the i th measurement in the reference area
y	year
y	estimate of the output quantity for a particular measurement, Y
Y	maximum width

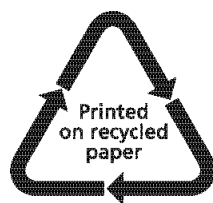
Y	yttrium
Y	output quantity, measurand
Y_j	survey unit data (unless the reference area data set was the larger of the two, in which case this would be the reference area data)
$Z_{1-\alpha}$	$(1-\alpha)$ percentile of a standard normal deviation
$Z_{1-\beta}$	$(1-\beta)$ percentile of a standard normal deviation
Z_{eff}	effective atomic number
Z_i	adjusted reference area measurement
Z_i	interpolated value for use in creating a quantile plot
ZnS(Ag)	silver-activated zinc sulfide

CONVERSION FACTORS

To Convert From	To	Multiply By	To Convert From	To	Multiply By
acre	hectare	0.405	meter (m)	inch	39.4
	m ²	4,050		mile	0.000621
	ft ²	43,600		acre	0.000247
Bq	Ci	2.7×10^{-11}	m ²	hectare	0.0001
	dps	1		ft ²	10.8
	pCi	27		square mile	3.86×10^{-7}
Bq/kg	pCi/g	0.027	m ³	liter	1,000
Bq/m ²	dpm/100 cm ²	0.60	mrem	mSv	0.01
Bq/m ³	Bq/L	0.001	mrem/y	mSv/y	0.01
	pCi/L	0.027	mSv	mrem	100
centimeter (cm)	inch	0.394	mSv/y	mrem/y	100
Ci	Bq	3.70×10^{10}	ounce (oz)	L	0.0296
	pCi	1×10^{12}	pCi	Bq	0.037
dps	dpm	60	dpm	Bq/kg	2.22
	pCi	27	pCi/g	Bq/m ³	37
dpm	dps	0.0167	pCi/L	Gy	0.01
	pCi	0.451	rad	rem	1,000
gray (Gy)	rad	100	rem	mrem	10
hectare	acre	2.47		mSv	0.01
liter (L)	cm ³	1000		Sv	100,000
	m ³	0.001	sievert (Sv)	mrem	1,000
	ounce oz (fluid)	33.8		mSv	100
				rem	

Abbreviations: m = meter; ft = foot; Bq = becquerel; Ci = curie; dps = disintegrations per second; pCi = picocurie; kg = kilogram; g = gram; L = liter; cm = centimeter; in. = inch; dpm = disintegrations per minute; oz = ounce; mrem = millirem; mSv = millisievert; y = year; Gy = gray; Sv = sievert.

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11. ABSTRACT (200 words or less) The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides information on planning, conducting, evaluating, and documenting building surface and surface soil radiological surveys for demonstrating compliance with requirements, often as part of a dose- or risk-based regulation or standard. MARSSIM is a multiagency consensus document that was developed collaboratively by four Federal agencies having authority and control over radioactive materials: U.S. Department of Defense (DoD), U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), and U.S. Nuclear Regulatory Commission (NRC). MARSSIM's objective is to describe a consistent approach for planning, performing, and assessing building surface and surface soil radiological surveys to meet established criteria, while concurrently encouraging an effective use of resources.					
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Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)

July 2026

ROADMAP

Introduction to MARSSIM

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides guidance for planning, implementing, and evaluating radiological surveys to demonstrate compliance with a dose- or risk-based regulation. The MARSSIM guidance demonstrates compliance for the final status survey (FSS) following scoping, characterization, and any remedial actions for a potentially contaminated facility or environment.

The MARSSIM describes the process of planning the survey, implementing the survey data, and assessing the survey results to make decisions. This process is called the Data Life Cycle. Chapter 1 explains the purpose and scope of MARSSIM and gives the missions of the four federal agencies that contribute to it. Chapter 2 provides an overview of the MARSSIM process and describes the different types of surveys that need to be performed before decision-making. Chapter 3 defines historical site assessments and how they can help shape the design of these surveys.

When planning a survey of a facility or environment, investigators must consider factors such as Data Quality Objectives (DQOs), area classification, measurement methods, and number of data points. These considerations and more are described in Chapters 4 and 5. Chapter 6 describes the field instrumentation and measurement methods used in these surveys, while Chapter 7 covers sampling and preparation for laboratory measurements. The interpretation of survey data for making decisions is explained in Chapter 8.

MARSSIM does not provide guidance for determining action levels (ALs) or derived concentration guideline levels (DCGLs).¹ DCGLs must be determined based on guidance from the appropriate regulator. MARSSIM discusses residual radioactive materials in surface soil and building surfaces only; other potentially contaminated media such as groundwater, surface water, subsurface soil, and materials and equipment would require additional guidance outside the MARSSIM.

The Goal of the Roadmap

The goal of the roadmap is to summarize the major steps in designing a survey, implementing that design, and assessing the data for decision-making. This roadmap will reference the sections in MARSSIM that provide more specific guidance.

This roadmap is not a stand-alone document for designing a survey or making decisions; it is a quick reference that points to where to find more information on specific topics. This roadmap contains basic guidance, tables, and “rules of thumb” but should only be used as a quick reference for users who are already familiar with planning and performing surveys. This roadmap also contains flowcharts that summarize the major steps in this process, as well as a reference to the sections where further guidance can be found on each step.

¹ Throughout this chapter, if the scenario is not explicitly stated, the default terms “derived guideline concentration level” or “DCGL” and “lower bound of the gray region” or “LBGR” will be used. If using Scenario B, please substitute “action level” or “AL” and “upper bound of the gray region” or “UBGR” (i.e., “discrimination limit” or “DL”) for these terms, respectively.

This roadmap assumes the user has a working knowledge of MARSSIM terminology. Section 2.2.1 and the glossary at the end of the MARSSIM review this terminology.

Major Changes from MARSSIM, Revision 1 (August 2000)

Several changes and revisions have been made from the MARSSIM, Revision 1, issued in August 2000.

Chapter 4 has been retitled “Considerations for Planning Surveys” and has been expanded and reorganized. Chapter 4 now includes more information about DQOs, which should be considered during every part of the planning process and survey. Chapter 4 also now includes examples to illustrate how to apply the concepts covered in the chapter.

Chapter 5 has been reorganized to cover two broad types of surveys: preliminary surveys and FSSs. Scoping, characterization, and remedial action support surveys are preliminary surveys, and this chapter explains when these surveys are necessary and what data need to be collected from them before planning an FSS.

Chapter 6, on field measurement methods and instrumentation, has been reorganized to make information easier to find, as will be discussed later in the roadmap. Chapter 6 has also added information on measurement quality objectives (MQOs), measurement uncertainty, and newer survey tools, including continuously collected data surveys, and expanded information on aerial radiological surveys.

Revision 2 expands on methodology and statistics related to Scenario B, which is introduced below. New information regarding Scenario B is added throughout the entire document, particularly Chapters 4 and 8.

This revision introduces the concept of site-specific scanning surveys, as described in Sections 4.8.3.1 and 5.3.6.1, with additional information in Sections 6.6.1.1 and 8.5.

Chapter 9 of Revision 1 was titled “Quality Assurance and Quality Control.” Revision 2 places an emphasis on quality throughout the document, so the topic is no longer addressed in a separate chapter.

While many of the appendices are similar to their Revision 1 versions, others have been removed or replaced. MARSSIM Revision 2 contains several new appendices:

- Appendix E, “Effect of Precision on Planning and Performing Surveys”
- Appendix K, “Unity Rule Example for Multiple Radionuclides”
- Appendix L, “Stem and Leaf Displays and Quantile Plots”
- Appendix M, “Calculation of Power Curves”
- Appendix N, “Calculating the Number of Samples Needed for the Wilcoxon Rank Sum and Sign Tests”
- Appendix O, “Upper Confidence Limit Simulation for Site-Specific Scanning Surveys Where the Radionuclide Is Present in Background”

Data Life Cycle

Compliance demonstration is a decision as to whether a survey unit meets the criteria for release. This decision is usually supported by statistical tests based on data from one or more surveys. First, a hypothesis is made about whether the concentration of radioactive material in the survey unit exceeds the release criteria, and then surveys are designed to provide the information needed to reject this hypothesis. MARSSIM uses the Data Life Cycle as a framework for planning, implementing, and evaluating survey results before making a decision.

Figure 1 shows the major activities associated with each phase of the Data Life Cycle.

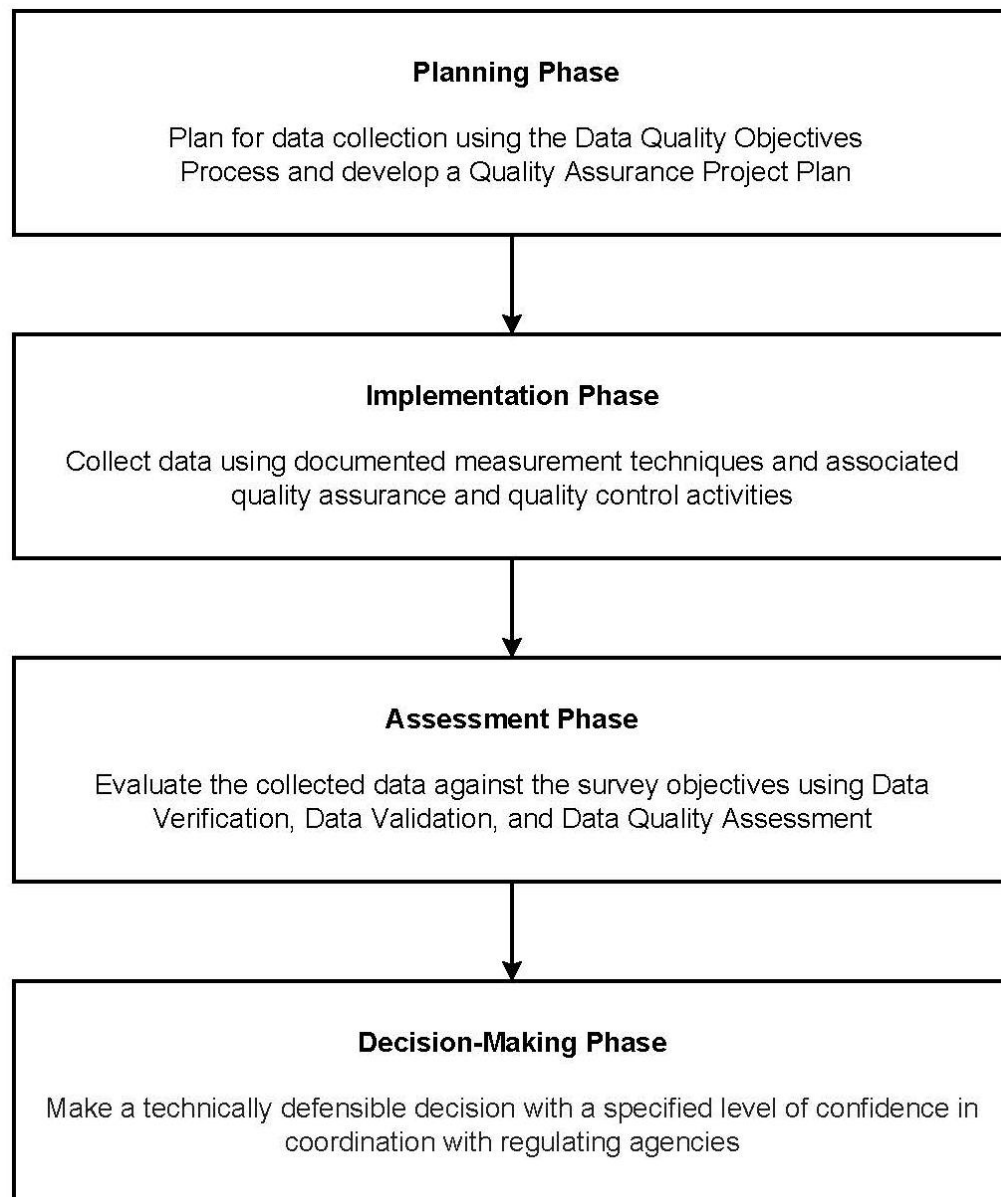


Figure 1 The Data Life Cycle

Planning Stage

The survey is designed using the DQO process (Section 3.2 and Appendix D). After the DQOs are established, preliminary surveys (such as scoping, characterization, and remedial action support surveys) are performed to provide information necessary to design the FSS for compliance demonstration. The DQOs are reevaluated after each preliminary survey.

The preliminary surveys may provide information for purposes other than compliance demonstration that are not discussed in MARSSIM. For example, a characterization survey may provide information to support the evaluation of remediation alternatives.

As part of this process, the objective of the survey and the null and alternative hypotheses should be clearly stated (Section 5.3.1). The objective of FSSs is typically to demonstrate that levels of residual radioactive material meet the release criteria. One of two approaches is used to demonstrate that this objective is met; the two approaches differ in the selection of the null hypothesis (i.e., what is assumed to be the true state of nature), as summarized in **Table 1**.

Table 1 Null and Alternative Hypothesis for Scenarios A and B

Scenario	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)
A	The concentration of residual radioactive material is equal to or exceeds the release criteria.	The concentration of residual radioactive material is less than the release criteria.
B	The concentration of residual radioactive material is equal to or less than the release criteria.	The concentration of residual radioactive material exceeds the release criteria.

Any of the preliminary surveys may be designed to demonstrate compliance with the release criteria as one of the survey objectives. These alternate survey designs are developed based on site-specific considerations (Section 2.6.1). The planning phase of the Data Life Cycle produces an FSS design that is used for demonstrating compliance with the release criteria. Appendix D provides more information about quality assurance/quality control of these data and the development of a Quality Assurance Project Plan (QAPP).

A minimum amount of information is needed from the preliminary surveys to develop an effective FSS design. This includes the following:

- The survey must provide sufficient information to justify classification and specification of boundaries for survey units. The default is Class 1, which results in the highest level of survey effort.
- The survey must provide an estimate of the variability of the contaminant concentration in the survey unit (σ_s) and the reference area (σ_r), if necessary.

After the preliminary surveys are completed, the FSS design can be developed.

Figure 2 presents the major steps in the development of a survey design that may include scanning surveys, direct measurements, and sampling. This figure can also apply to

site-specific scanning surveys. Most of the steps are easy to understand, and references to appropriate sections of MARSSIM are included in the flowchart (**Figure 2**).

Several activities involved in these steps are important enough to justify additional discussion in this guide. The following are discussed in more detail below:

- Classify areas by potential for residual radioactive material.
- Group/separate areas into survey units.
- Determine the number of data points.
- Select instrumentation.
- Develop an integrated survey design.

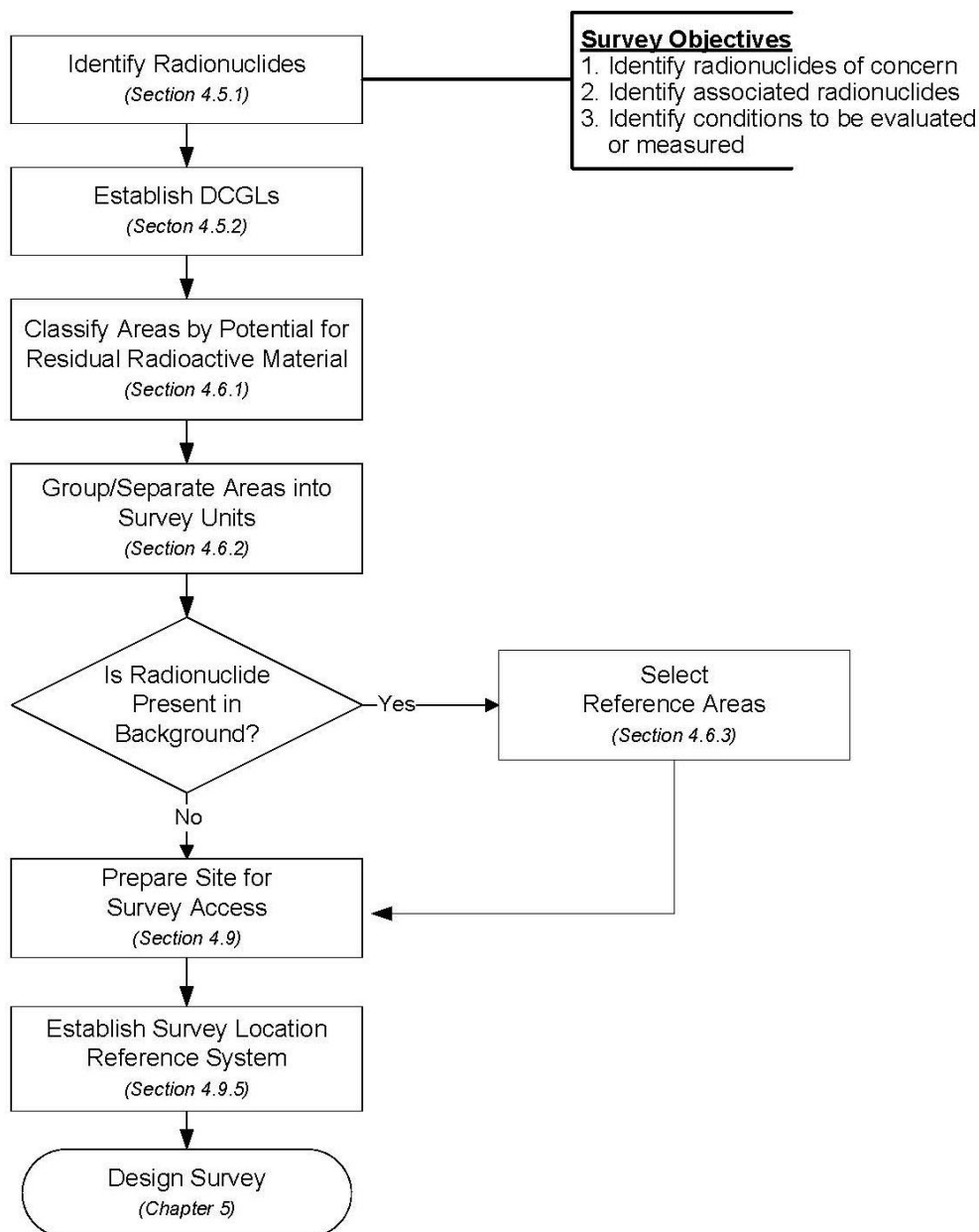


Figure 2 Major Steps in MARSSIM Field Survey Design

Classify Areas by Potential for Residual Radioactive Material (Section 4.6)

Classification is a critical step in survey design because it determines the level of survey effort needed based on the potential for residual radioactive material to exceed the release criteria. Overestimating the amount of residual radioactive material results in an unnecessary increase in the level of survey effort. Underestimating the potential for residual radioactive material increases the probability of failing to demonstrate compliance based on survey results.

Two key decisions are made when classifying areas:

- (1) Is the average activity in the area likely to exceed the DCGL for average concentrations over a wide area (DCGL_W)?
- (2) Is the residual radioactive material present in small areas of elevated activity or is the residual radioactive material distributed relatively homogeneously across the areas?

Each of these decisions is considered separately when designing the survey, then combined into an integrated survey design.

Information from the preliminary surveys is crucial for classifying areas as Class 1, 2, or 3. Briefly, the classes may be summarized as follows:²

- Class 1 areas are impacted with concentrations of residual radioactive material that exceed the DCGL_W.
- Class 2 areas are impacted, but concentrations of residual radioactive material that exceed the DCGL_W are not expected.
- Class 3 areas are impacted areas that have a low probability of containing residual radiative material.

RULE OF THUMB: Area classification considers both the concentration of residual radioactive material relative to the DCGL_W and the distribution of the residual radioactive material, which may be uniformly distributed or grouped into small areas of elevated activity.

Group/Separate Areas into Survey Units (Section 4.6.2)

The limit on the size of a survey unit is based on classification, exposure pathway modeling assumptions, and site-specific conditions. **Table 2** provides the suggested survey unit size based on area classification. The rationale for selecting a larger survey unit area should be developed using the DQO process, which should be fully documented.

² The glossary contains the full definitions of Class 1, Class 2, and Class 3 areas.

Table 2 Suggested Area for Survey Units

Classification	Structures (Floors, Walls, and Ceilings)	Land Areas
Class 1	Up to 100 m ²	Up to 2,000 m ²
Class 2	Up to 1,000 m ²	Up to 10,000 m ²
Class 3	No Limit	No Limit

m² = square meters

RULE OF THUMB: Survey unit areas should be consistent with the same exposure pathway modeling assumptions used to develop the DCGLs.

Determine the Number of Data Points (Section 5.3)

The number of data points is determined based on the selection of a statistical test, which depends on whether or not the radionuclides of concern are present in the background.

The first step in determining the number of data points is to specify the acceptable decision error rates (α and β). These decision error rates are site specific and selected using the DQO process. If remediation or new survey data require a reevaluation of survey areas, the DQO process should also be reevaluated, which may result in changes in the values of α and β .

RULE OF THUMB: Values for α and β are site specific and selected using the DQO process.

Next, it must be determined whether the radionuclide of concern is present in the background. Then the variability of that radionuclide concentration (σ) must be estimated. The standard deviation of the radionuclide concentration determined from preliminary survey results provides the appropriate estimate of σ .

If the radionuclide is present in the background, the second step is to estimate the variability in the survey unit (σ_s) and the variability in the reference area (σ_r), if needed. The larger of these two values should be selected to determine the number of data points. Underestimating σ can underestimate the number of measurements needed to demonstrate compliance with the release criteria, which increases the probability that the survey unit will fail the statistical test. Overestimating σ can result in collecting more data than is necessary to demonstrate compliance.

RULE OF THUMB: It is better to overestimate values of σ_s and σ_r , although doing so will result in more sampling.

RULE OF THUMB: When σ_s and σ_r are different, select the larger of the two values.

The third step is to calculate the relative shift, Δ/σ . The variability of the radionuclide of concern, σ , was determined in the previous step. The shift, Δ , is equal to the width of the gray region. The upper bound of the gray region (UBGR) and the lower bound of the gray region (LBGR) will depend upon the scenario chosen. For Scenario A, the UBGR is defined as the DCGL_w. The LBGR is a concentration less than the DCGL_w and is chosen by the survey designer at or above an estimate of the residual radioactivity concentration in the survey unit. For Scenario B, the UBGR is equal to the discrimination limit (DL), and the LBGR is equal to the AL. The gray region is defined as the interval between the AL and the DL.

The final step in determining the number of data points is to obtain the appropriate value from either Table 5-2 or Table 5-3 using the relative shift and the acceptable decision error rates. Table 5-2 provides the number of data points for each survey unit and each reference area when contamination is present in the background ($N/2$). Table 5-3 provides the number of data points for each survey unit when contamination is not present in the background (N).

As an alternative to the traditional approach of sampling and scanning, site-specific scanning surveys may be completed. A site-specific scanning survey is an approach for evaluating residual levels of radioactive material in which scanning measurements may be used to limit the number of required direct measurements or samples; in some cases, it may even be used to replace the need for direct measurements or samples.

Select Instrumentation (Chapter 6 and Appendix H)

Instrumentation and measurement techniques should be selected based on MQOs, such as minimum detectable concentration (MDC) and measurement method uncertainty, to provide technically defensible results that meet the objectives of the survey. Because of the uncertainty associated with interpreting scanning results, the MDC of the selected instruments should be as far below the DCGL as possible. For direct measurements and sample analyses, MDCs less than 10 percent of the DCGL are preferable, while MDCs up to 50 percent of the DCGL are acceptable. In addition, measurement method uncertainty should be calculated for all results and compared to a required measurement method uncertainty to ensure data are acceptable.

RULE OF THUMB: Find a measurement method that meets the requirements for MDC, measurement method uncertainty, and other relevant MQOs.

Develop an Integrated Survey Design (Section 5.3.9)

The integrated survey design combines scanning surveys, direct measurements, and sampling and analysis. **Figure 3** shows the process for designing an integrated survey plan for an FSS.

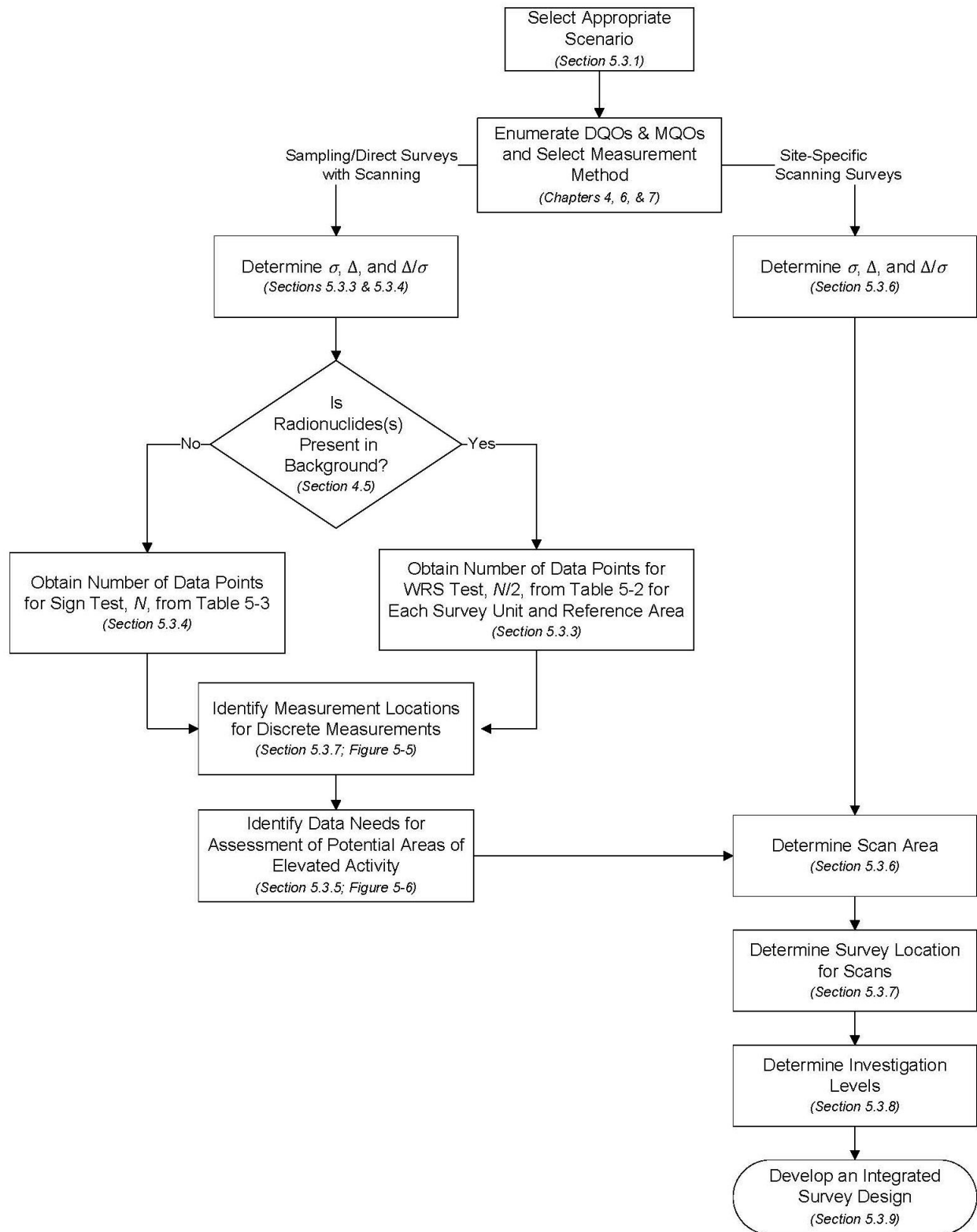


Figure 3 Process for Designing an Integrated Survey Plan for an FSS

The level of survey effort is determined by the potential for residual radioactive material as indicated by the survey unit area classification, illustrated in **Figure 4**. Class 3 survey units receive judgmental scanning and randomly located measurements, if needed. Class 2 survey units receive scanning over a portion of the survey unit based on the potential for residual radioactive material combined with direct measurements and sampling performed on a systematic grid, if needed. Class 1 survey units receive scanning over 100 percent of the survey unit, combined with direct measurements and sampling performed on a systematic grid, if needed. The grid spacing may need to be adjusted depending on the scan MDC.

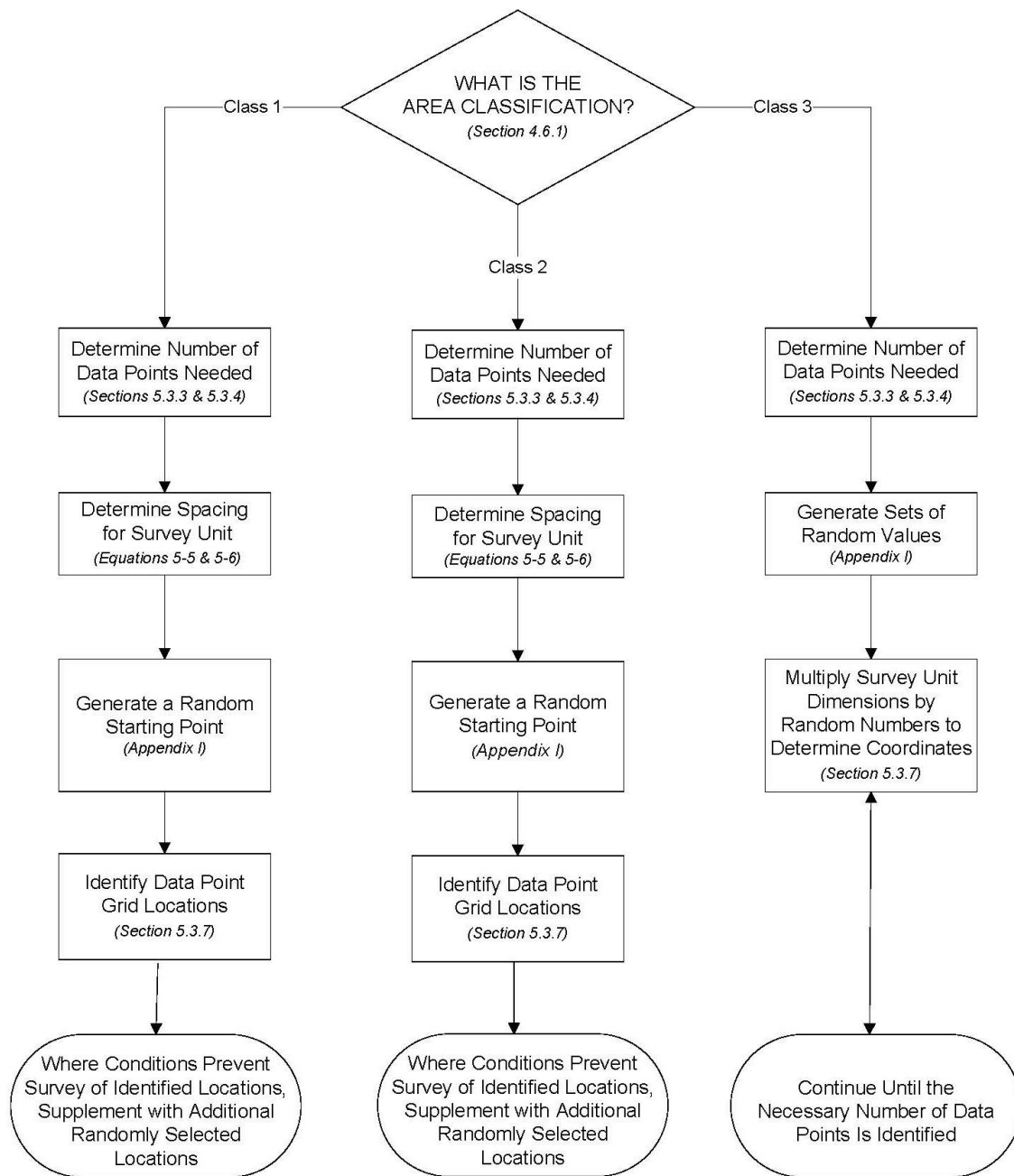


Figure 4 Process for Identifying Discrete Measurement Locations Based on Area Classification

Table 3 summarizes the recommended survey coverage for structures and land areas. Other media, such as groundwater and subsurface soil, are outside of the scope of MARSSIM.

Table 3 Recommended Survey Coverage for Structures and Land Areas

Area Classification	Scanning and Direct Measurements and/or Sampling Survey		Site-Specific Scanning Survey
	Scanning	Direct Measurements or Samples	Scanning
Class 1	100%	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4); additional measurements may be necessary for small areas of elevated activity (Section 5.3.5)	100%
Class 2	10–100% Systematic and Judgment “Scan Area”= $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4)	10–100% Systematic and Judgment “Scan Area” = 10% or $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$ whichever is larger
Class 3	Judgment “Scan Area” = $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4)	10–100% ^a Judgment “Scan Area” = 10% or $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$ whichever is larger

Note: Δ/σ represents the relative shift.

^a For surveys using sampling or direct measurements (or both), this percentage can be lower than 10 percent judgmental.

Implementation Phase

The FSS design is carried out in accordance with applicable standard operating procedures and the QAPP, resulting in the generation of raw data. Chapter 6, Chapter 7, and Appendix H contain information on measurement techniques.

Assessment Phase

The assessment phase of the Data Life Cycle includes verification and validation of the survey results combined with an assessment of the quantity and quality of the data. As previously stated, both the average level of contamination in the survey unit and the spatial distribution of the residual radioactive material within the survey unit are considered during area classification. For this reason, the assessment phase includes (1) a graphical review of the data to provide a

visual representation of the radionuclide distribution, (2) an appropriate statistical test to demonstrate compliance for the average concentration of a uniformly distributed radionuclide, and (3) the elevated measurement comparison (EMC) to demonstrate compliance for small areas of elevated activity.

The survey data are verified to ensure that applicable standard operating procedures were followed and that the measurement systems were performed in accordance with the criteria specified in the QAPP (refer to Appendix D). The data are validated to ensure that the results support the objectives of the survey, as documented in the QAPP, or permit a determination that these objectives should be modified. The Data Quality Assessment (DQA) process is then applied using the verified and validated data to determine whether the quality of the data satisfies the data user's needs. Appendix D and Section 8.2 further describe the DQA process.

The first step in DQA is to review the DQOs, MQOs, and survey design to ensure that they are still applicable. For example, if the data suggest that a survey unit is misclassified, the DQOs, MQOs, and survey design would be modified for the new classification.

The next step is to conduct a preliminary data review to learn about the structure of the data and to identify patterns, relationships, or potential anomalies. This review should include calculating basic statistical quantities (i.e., mean,³ standard deviation, median) and graphically presenting the data using at least a histogram and a posting plot. The results of the preliminary data review are also used to verify the assumptions of the tests. **Table 4** summarizes some of the assumptions and possible methods for assessing them. Information on diagnostic tests is provided in Section 8.2.2 and Appendices I and N.

Table 4 Methods for Checking the Assumptions of Statistical Tests

Assumption	Diagnostic
Spatial Independence	Posting Plot
Symmetry	Histogram, Quantile Plot
Data Variance	Sample Standard Deviation
Adequate Power	Retrospective Power Test

The next steps are to select a statistical test (Section 8.2.3) and to verify the assumptions of the statistical test (Section 8.2.4).

The final step in interpreting the data is to draw conclusions from the data. **Table 5** and **Table 6** summarize the statistical tests recommended in MARSSIM. Section 8.3 provides guidance on performing the Sign test when the radionuclide of concern is not present in background. Section 8.4 discusses performing the Wilcoxon Rank Sum (WRS) test when the radionuclide of concern is present in background.

³ In MARSSIM, "average" and "mean" both refer to the arithmetic mean.

Table 5 Summary of Statistical Tests for Radionuclide Not in Background and Radionuclide-Specific Measurement

Scenario A Survey Result	Scenario A Conclusion
All measurements are less than $DCGL_W$.	Survey unit meets release criteria.
Sample mean is greater than $DCGL_W$.	Survey unit does not meet release criteria.
Any measurement is greater than $DCGL_W$, and the sample mean is less than $DCGL_W$.	Conduct Sign test and EMC.
Scenario B Survey Result	Scenario B Conclusion
Sample mean is less than the AL.	Survey unit meets release criteria.
All measurements are greater than AL.	Survey unit does not meet release criteria.
Any measurement is greater than the AL, and the sample mean is greater than AL.	Conduct Sign test and EMC.

Table 6 Summary of Statistical Tests for Radionuclide in Background or Radionuclide Non-Specific (Gross) Measurements

Scenario A Survey Result	Scenario A Conclusion
Difference between largest survey unit measurement and smallest reference area measurement is less than the $DCGL_W$.	Survey unit meets release criteria.
Difference between survey unit sample mean and reference area sample mean is greater than the $DCGL_W$.	Survey unit does not meet release criteria.
Difference between any survey unit measurement and any reference area measurement is greater than $DCGL_W$, and the difference between survey unit sample mean and reference area sample mean is less than the $DCGL_W$.	Conduct WRS test and EMC.
Scenario B Survey Result	Scenario B Conclusion
Difference between smallest survey unit measurement and largest reference area measurement is greater than the AL.	Survey unit does not meet release criteria.
Difference between any survey unit measurement and any reference area measurement is less than the AL.	Conduct WRS test, Quantile test, EMC, and retrospective power analysis.

Section 8.2.5 contains more information on drawing conclusions from the data.

Table 7 provides examples of FSS investigation levels for each survey unit classification and type of measurement. For a Class 1 survey unit, measurements above the $DCGL_W$ may be expected. However, a measurement above the $DCGL_W$ at one of the discrete measurement locations might be considered unusual if it were much higher than all the other discrete measurements. Thus, any discrete measurement that is above both the $DCGL_W$ or the $DCGL_{EMC}$ should be investigated further. Any measurement, either at a discrete location or from a scan,

that is above the values of the DCGL for the EMC ($DCGL_{EMC}$) should be flagged for further investigation.

Table 7 Example FSS Investigation Levels

Survey Unit Classification	Flag Direct Measurement or Sample Result When...	Flag Scanning Measurement Result When...
Class 1	> $DCGL_{EMC}$ or > $DCGL_W$ and > a statistical parameter-based value	> $DCGL_{EMC}$ for the area bounded by four adjacent systematic grid measurement points to determine the $DCGL_{EMC}$ (when a traditional MARSSIM approach is used), or for the area bounded by an acceptable elevated area size (when a site-specific scanning approach is used)
Class 2	> $DCGL_W$	> $DCGL_W$ or > scan MDC
Class 3	> fraction of $DCGL_W$	> $DCGL_W$ or > scan MDC

Section 5.3.8 contains more information on determining investigation levels.

In Class 2 or Class 3 areas, neither measurements above the $DCGL_W$ nor areas of elevated activity are expected. Any measurement at a discrete location exceeding the $DCGL_W$ in these areas should be flagged for further investigation. Because the EMC does not drive survey design for Class 2 and Class 3 survey units, the scanning MDC might exceed the $DCGL_W$. In this case, any indication of residual radioactivity during the scan would warrant further investigation.

Because there is a low expectation for residual radioactivity in a Class 3 area, it may be prudent to investigate any measurement exceeding a predetermined fraction of the $DCGL_W$. The predetermined fraction one chooses here depends on the site, the radionuclides of concern, and the measurement and scanning methods chosen. This fraction of the $DCGL_W$ should be set using the DQO process during the survey design phase of the Data Life Cycle. In some cases, the user may also decide to follow this procedure for Class 2 and even Class 1 survey units.

Both the measurements at discrete locations and the scans are subject to the EMC. The result of the EMC does not in itself lead to a conclusion as to whether the survey unit meets or exceeds the release criteria but is a flag or trigger for further investigation. The investigation may involve taking further measurements to determine whether the area and level of the elevated residual radioactivity are such that the resulting dose or risk meets the release criteria. In addition to taking further measurements, the investigator may need to reassess how the DCGLs were obtained, how consistent these results are with the Historical Site Assessment, and the adequacy of any preliminary surveys.

This investigation should also provide adequate assurance that there are no other undiscovered areas of elevated residual radioactivity in the survey unit that might result in a dose exceeding the release criteria. This could lead to a reclassification of all or part of a survey unit, unless the results of the investigation indicate that reclassification is not necessary.

Decision-Making Phase

A decision is made—in coordination with the responsible regulatory agency—based on the conclusions drawn from the assessment phase. The results of the EMC are used to demonstrate compliance with any applicable criteria for small areas of elevated activity, while the statistical tests are used to demonstrate that the average radionuclide concentration in the survey unit complies with the release criteria. The objective is to make technically defensible decisions with a specified level of confidence.

The EMC consists of comparing each measurement from the survey unit with the investigation levels as shown in **Table 7**. The EMC is performed for measurements obtained from the systematic or random sample locations as well as locations flagged by scanning surveys. Any measurement from the survey unit that is equal to or greater than the investigation level indicates an area of relatively higher concentration and is investigated, regardless of the outcome of the statistical tests.

RULE OF THUMB: Any measurement from the survey unit that is equal to or greater than the investigation level indicates an area of relatively higher concentration and is investigated, regardless of the outcome of the statistical tests.

The result of the statistical tests is the decision to reject or not to reject the null hypothesis that the survey unit contains residual radioactive material above the $DCGL_w$. Provided that the results of any investigations have been resolved, a rejection of the null hypothesis leads to the decision that the survey unit meets the release criteria (if you are using Scenario A) or that the survey unit does not meet the release criteria (if using Scenario B). If necessary, the amount of residual radioactive material in the survey unit can be estimated so that dose or risk calculations can be made. In most cases, the average concentration is the best estimate for the amount of residual radioactive material in the survey unit.

Summary

This roadmap summarizes the planning, implementation, assessment, and decision-making phases for an FSS. Each step in the process is described briefly, and flowcharts are provided to summarize the major steps in these phases. In addition to providing the user with basic guidance, the roadmap also includes “rules of thumb” that help with performance of compliance demonstration surveys. It refers users to the sections of MARSSIM that contain more detailed guidance on a particular topic.

1 INTRODUCTION

1.1 Purpose and Scope of MARSSIM

Radioactive materials have been produced, processed, used, and stored at thousands of sites throughout the United States. Many of them at one time had or now have residual radioactive material in excess of natural background. The sites range in size from Federal weapons-production facilities covering hundreds of square kilometers to the nuclear medicine departments of small hospitals. Owners and managers would like to find and remove any excess residual radioactive material and release these sites for restricted use or for unrestricted public use.

The U.S. Environmental Protection Agency (EPA), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DoD) are responsible for the release of federally controlled sites. Such sites include DOE and DoD sites, sites licensed by the NRC and its Agreement States, and former unlicensed industrial facilities that handled ores containing radioactive materials that are addressed under Federal or State regulatory programs.

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides a nationally consistent consensus approach to conducting radiation surveys and investigations at sites with the potential for residual radioactive material. This approach is both scientifically rigorous and flexible enough to be applied to a diversity of site cleanup conditions.

To release a site, it is normally necessary to demonstrate to the responsible Federal or State agency that any needed remediation was successful and that the release criteria (specific regulatory limits) were met. In MARSSIM, the “Final Status Survey” (FSS) provides this demonstration. This manual assists site personnel or others in performing or assessing such a demonstration.

As illustrated in **Figure 1-1**, the demonstration of compliance with respect to conducting surveys most often comprises three interrelated parts:

- (1) Translate: Translating the cleanup/release criteria (e.g., millisieverts per year, millirem per year, specific risk) into corresponding derived concentration guideline levels (DCGLs) (e.g., becquerels per kilogram or picocuries per gram in soil) through the use of environmental pathway modeling.
- (2) Measure: Acquiring scientifically sound and defensible site-specific data on the levels and distribution of residual radioactive material, as well as the levels and distribution of radionuclides present in the background, by employing suitable field or laboratory measurement techniques, or both.¹

¹ Measurements include field and laboratory analyses; however, MARSSIM leaves detailed discussions of laboratory sample analyses to another manual (i.e., a companion document, the Multi-Agency Radiation Laboratory Analytical Protocols manual [MARLAP] [NRC 2004]).

- (3) **Decide:** Determining that the data obtained from sampling support the conclusion that the site meets the release criteria, with an acceptable level of uncertainty, through application of a statistically based decision rule.

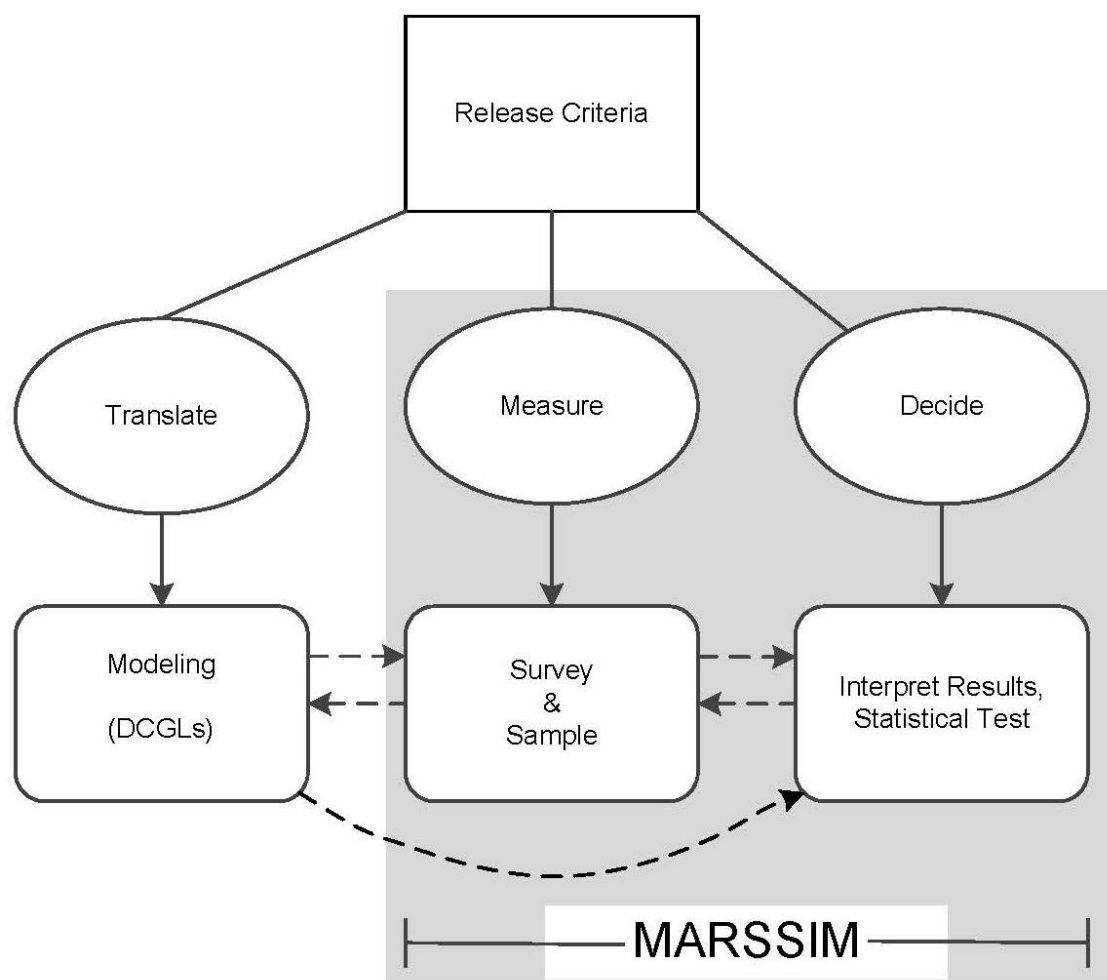


Figure 1-1 Compliance Demonstration

MARSSIM provides standardized and consistent approaches for planning, conducting, evaluating, and documenting environmental radiological surveys, with a specific focus on the FSSs that are carried out to demonstrate compliance with release requirements. The MARSSIM process gathers comprehensive technical information—specifically for items (1) and (2) above—on residual radioactive material in surface soils and on building surfaces. This information is used in a performance-based approach for demonstrating compliance with dose- or risk-based release criteria. This approach includes processes that identify data quality needs and may reveal limitations on the data that can be collected from a survey. MARSSIM's approach supports decision-making at sites with residual radioactive material in surface soil and on building surfaces (as defined in the **glossary**). In particular, MARSSIM describes generally acceptable approaches for the following:

- planning and designing scoping, characterization, remediation-support, and final status surveys for sites with the potential for residual radioactive material in surface soil and on building surfaces
- Historical Site Assessment (HSA)
- quality assurance/quality control in data acquisition and analysis
- conducting surveys
- field and laboratory methods and instrumentation, and interfacing with radiation laboratories
- statistical hypothesis testing, and the interpretation of statistical data
- documentation

Table 1-1 summarizes the scope of MARSSIM. Several issues related to releasing sites are beyond the scope of MARSSIM. These include the translation of dose or risk standards into radionuclide-specific concentrations or demonstrating compliance with groundwater or surface water regulations. MARSSIM can be applied to surveys performed at vicinity properties—those not under Government or licensee control—but the decision to apply MARSSIM at vicinity properties is a decision outside the scope of MARSSIM. Information on designing, implementing, and assessing radiological surveys of materials and equipment is presented in the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) supplement (NRC 2009) to MARSSIM. MARSSIM does not address the potential presence of residual radioactive material in other media (e.g., subsurface soil, groundwater). Information on the survey of subsurface residual radioactive material is found in other agency documents (e.g., the NRC’s NUREG-1757, Volume 2, Revision 2 [NRC 2022a]; NUREG/CR-7021 [in revision] [NRC 2012b]; and DUWP-ISG-02 [NRC 2024a]). MARSSIM’s main focus is on FSSs, so the processes in this manual may follow remediation activities that remove below-surface residual radioactive material. Therefore, the following are some reasons for limiting the scope of the document to surface soils and building surfaces:

- Residual radioactive material is limited to these media for many sites following remediation.
- Because many sites have surface soil and building surface residual radioactive material as the leading source of exposure to radiation, existing computer models used for calculating the concentrations based on dose or risk generally consider only surface soils or building surfaces as a source term.

MARSSIM also recognizes that there may be other factors that have an impact on designing surveys, such as cost or stakeholder concerns. Guidance on how to address these specific concerns is outside the scope of MARSSIM. Unique site-specific cases may arise that require a modified approach beyond what is presently described in MARSSIM. However, the process of planning, implementing, assessing, and making decisions about a site described in MARSSIM is applicable to all sites, even if the recommendations in this manual do not meet a site’s specific objectives.

Of MARSSIM’s many topics, the Data Quality Objectives (DQO) approach to data acquisition and analysis and the Data Quality Assessment (DQA) for determining that data meet stated

objectives are a consistent theme throughout the manual. The DQO process and DQA approach, described in **Chapter 2**, present a scientific, common-sense method for designing and conducting surveys and making best use of the obtainable information. A formal framework for systematizing the planning of data acquisition surveys can ensure that the information can support important decisions, such as whether to release a particular site following remediation.

DQOs must be developed on a site-specific basis. The approaches presented in MARSSIM may not meet the DQOs at every site, so other methods may be used to meet site-specific DQOs, as long as an equivalent level of performance can be demonstrated.

Table 1-1 Scope of MARSSIM

Within the Scope of MARSSIM	Beyond the Scope of MARSSIM
<i>Technical Information</i> MARSSIM provides technical, performance-based guidance on conducting radiation surveys and site investigations, remediation and restoration activities, and demonstration of compliance with dose- or risk-based release criteria. MARSSIM includes a framework for developing a phased approach to site investigations that includes stakeholder involvement and emphasizes development of the FSS for site release.	<i>Regulation</i> MARSSIM does not set new regulations or requirements, or address nontechnical issues (e.g., legal or policy) for site cleanup. Release criteria will be provided rather than calculated using MARSSIM.
<i>Tool Box</i> MARSSIM can be thought of as an extensive tool box with many components—some within the text of MARSSIM, others by reference.	<i>Tool Box</i> Many topics are beyond the scope of MARSSIM. For example— • a public participation program • staging, classification, packaging, and transportation of wastes for disposal • remediation and stabilization techniques • training
<i>Stakeholder Involvement</i> MARSSIM encourages stakeholder involvement but does not provide specific guidance.	<i>Stakeholder Involvement</i> Specific guidance is determined by the individual Federal and State agencies.
<i>Measurement</i> The information given in MARSSIM is performance based and directed toward acquiring site-specific data and goals.	<i>Procedure</i> The approaches suggested in MARSSIM vary depending on the various site data needs—there are no set procedures for sample collection, measurement techniques, storage, or disposal established in MARSSIM.

Within the Scope of MARSSIM	Beyond the Scope of MARSSIM
<i>Modeling</i> The interface between environmental pathway modeling and MARSSIM is an important survey design consideration addressed in MARSSIM.	<i>Modeling</i> Environmental pathway modeling and ecological endpoints in modeling are beyond the scope of MARSSIM.
<i>Soil and Buildings</i> The two main media of interest in MARSSIM are surface soil and building surfaces affected by residual radioactive material.	<i>Other Media</i> MARSSIM does not cover other media, including construction materials, equipment, subsurface soil, surface or subsurface water, biota, air, or sewers.
<i>Final Status Survey</i> The focus of MARSSIM is on the FSS, as this is the deciding factor in judging whether the site meets the release criteria.	<i>Instruments and Radiation Detection Equipment</i> MARSSIM does not recommend the use of any specific radiation detection equipment—there is too much variability in the types of sites.
<i>Radiation</i> MARSSIM considers only radiation-derived hazards.	<i>Chemicals</i> MARSSIM does not consider any hazards posed by chemicals.
<i>Remediation Method</i> MARSSIM assists users in determining when sites are ready for an FSS and provides information on how to determine whether a site meets the release criteria.	<i>Remediation Method</i> MARSSIM does not discuss selection and evaluation of remediation alternatives, public involvement, legal considerations, and policy decisions related to planning.
<i>DQO Process</i> MARSSIM presents a systemized approach for designing surveys to collect data needed for making decisions, such as whether to release a site.	<i>DQO Process</i> MARSSIM does not provide prescriptive or default DQOs.
<i>DQA</i> MARSSIM provides a set of statistical tests for evaluating data and lists alternate tests that may be applicable at specific sites.	<i>DQA</i> MARSSIM does not prescribe a statistical test for use at all sites.
<i>Radon Assessment</i> MARSSIM does address measurements of radon (concentration or flux) at sites with the immediate radon parents present because of previous site operations.	<i>Radon Assessment</i> MARSSIM does not include measurements of radon in ambient air, air emissions, effluents, water, or indoor air at sites with none of the immediate radon parents present because of previous site operations.

1.2 Structure of the Manual

Chapter 2 provides an overview of the Radiation Survey and Site Investigation process. **Figures 2-4** through **2-8** are flowcharts that summarize the steps taken and decisions made in the process. **Chapter 3** provides instructions for performing an HSA—a detailed investigation to collect existing information on the site or facility and to develop a conceptual site model. The results of the HSA are used to plan surveys, perform measurements, and collect additional information at the site. **Chapter 4** covers issues that arise in all types of surveys. Detailed information on performing specific types of surveys is included in **Chapter 5**. Information on selecting the appropriate measurement method combining instruments and measurement techniques is included in **Chapters 6** and **7**. **Chapter 6** discusses direct measurements and scanning surveys, and **Chapter 7** discusses sampling and sample preparation for laboratory measurements. The interpretation of survey results is described in **Chapter 8**.

MARSSIM also contains several appendices to provide additional information on specific topics. **Appendix A** presents an example of how to apply the MARSSIM process to a specific site through an FSS. **Appendix B** describes a simplified procedure for compliance demonstration that may be applicable at certain types of sites. **Appendix C** summarizes the regulations and requirements associated with radiation surveys and site investigations for each of the agencies involved in the development of MARSSIM. Detailed information on the EPA Quality System is in **Appendix D**. **Appendix E** includes three illustrative examples demonstrating the potential consequences of using methods with different levels of precision for planning and designing an FSS and for actually performing the FSS. **Appendix F** describes the relationships among MARSSIM; the Comprehensive Environmental Response, Compensation, and Liability Act; and the Resource Conservation and Recovery Act. Sources of information used during site assessment are listed in **Appendix G**. **Appendix H** describes field survey and laboratory analysis equipment that may be used for radiation surveys and site investigations. **Appendix I** offers tables of statistical data and supporting information for interpreting survey results described in **Chapter 8**. The derivation of the alpha scanning detection limit calculations used in **Chapter 6** is described in **Appendix J**. **Appendix K** gives a unity rule example for multiple radionuclides. **Appendix L** includes guidance for the use of stem and leaf displays and quantile plots. Instructions for the calculation of power curves are included in **Appendix M**. **Appendix N** provides additional information about the Wilcoxon Rank Sum test and Sign test and illustrates examples of the DCGL determinations. Finally, **Appendix O** contains an upper confidence limit for site-specific scanning surveys where the radionuclide is present in background.

MARSSIM is presented in a modular format, with each module containing information on conducting specific aspects of, or activities related to, the survey process. Followed in order, each module leads to the generation and implementation of a complete survey plan. Although this approach may involve some overlap and redundancy in information, it also allows many users to concentrate only on those portions of the manual that apply to their own particular needs or responsibilities. The procedures within each module are listed in order, and options are provided to let the user skip portions of the manual that may not be applicable to a specific site. Where appropriate, checklists condense and summarize major points in the process. The checklists may be used to verify that every suggested step is followed or explain why a step was unneeded.

MARSSIM contains a simplified procedure (refer to **Appendix B**) that many users of radioactive materials may be able to employ to demonstrate compliance with the release criteria—with the approval of the responsible regulatory agency. Sites that may qualify for simplified release procedures are those in which the radioactive materials used were—

- of relatively short half-life (e.g., $t_{1/2} \leq 120$ days) and have since decayed to insignificant quantities
- kept only in small enough quantities so as to be exempted or not requiring a specific license from a regulatory authority
- used or stored only in the form of nonleaking sealed sources
- combinations of the above

1.3 Use of the Manual

Potential users of this manual are Federal, State, and local government agencies with regulatory authority and control of residual radioactive material in the environment; their contractors; and other parties, such as organizations with licensed authority to possess and use radioactive materials. The manual is intended for a technical audience having knowledge of radiation health physics and statistics, as well as experience with the practical applications of radiation protection. An understanding of instrumentation and methodologies and expertise in planning, approving, and implementing surveys of environmental levels of radioactive material is assumed. This manual has been written so that individuals responsible for planning, approving, and implementing radiological surveys will be able to understand and apply the information provided here. Certain situations and sites may require consultation with personnel with specific types of expertise and experience.

MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

As previously stated, MARSSIM supports compliance with dose- or risk-based release criteria. MARSSIM does not address the translation of the regulatory dose or risk limit to a corresponding concentration level, so the information in this manual is applicable to a broad range of regulations, including concentration-based regulations. The terms dose, risk, and dose-based and risk-based regulation are used throughout the manual, but these terms are not intended to limit the use of the manual.

Note that Federal or State agencies that can approve a demonstration of compliance may support requirements that differ from the guidance presented in this version of MARSSIM. It is essential, therefore, that the persons carrying out the surveys remain in close communication with the proper Federal or State regulatory authorities throughout the compliance demonstration process.

1.4 Missions of the Federal Agencies Producing MARSSIM

MARSSIM is the product of a multi-agency workgroup with representatives from the EPA, NRC, DOE, and DoD. This section briefly describes the missions of the participating agencies. Regulations and requirements governing site investigations for each of the agencies associated with radiation surveys and site investigations are presented in **Appendix C**.

1.4.1 U.S. Environmental Protection Agency

The mission of the EPA is to protect human health and the environment. The EPA's scope of responsibility includes implementing and enforcing environmental laws, setting guidelines, monitoring pollution, performing research, and promoting pollution prevention. EPA Headquarters maintains overall planning, coordination, and control of EPA programs, and the EPA's 10 regional offices are responsible for executing the EPA's programs within the boundaries of each region. The EPA also coordinates with State and local governments' pollution control activities and supports further research and development.

1.4.2 U.S. Nuclear Regulatory Commission

The mission of the NRC is to protect public health and safety and advance the Nation's common defense and security by enabling the safe and secure use and deployment of civilian nuclear energy technologies and radioactive materials through efficient and reliable licensing, oversight, and regulation for the benefit of society and the environment. The NRC's scope of responsibility includes the regulation of commercial nuclear power reactors; nonpower research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste. The Energy Reorganization Act of 1974 and the Atomic Energy Act of 1954, as amended, provide the foundation for regulation of the Nation's commercial use of radioactive materials.

1.4.3 U.S. Department of Energy

The mission of the DOE is to develop and implement a coordinated national energy policy to ensure the availability of adequate energy supplies and to develop new energy sources for domestic and commercial use. In addition, the DOE is responsible for the development, construction, and testing of nuclear weapons for the U.S. military. The DOE is also responsible for managing the low- and high-level radioactive wastes generated by past nuclear weapons and research programs and for constructing and maintaining a repository for civilian radioactive wastes generated by commercial nuclear reactors. The DOE has the lead in remediating facilities and sites previously used in atomic energy programs.

1.4.4 U.S. Department of Defense

The global mission of the DoD is to provide for the defense of the United States. In doing this, the DoD is committed to protecting the environment. Each military service has specific regulations addressing the use of radioactive sources and the development of occupational health programs and radiation protection programs. The documents describing these regulations are used as guidance in developing environmental radiological surveys within the DoD and are discussed in **Appendix C**.

In accordance with Section 91b of the Atomic Energy Act of 1954, as amended, the DoD (including separate military services) has authority to acquire nuclear reactor systems and special nuclear materials. Additionally, the DoD (including separate military services) is the lead Federal agency for environmental remediation under several Federal regulatory programs.

2 OVERVIEW OF THE RADIATION SURVEY AND SITE INVESTIGATION PROCESS

2.1 Introduction

The purpose of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) is to provide a standardized approach to demonstrating that release criteria are met. This chapter provides a brief overview of the Radiation Survey and Site Investigation (RSSI) process, several important aspects of this process, and its underlying principles. The purpose of this chapter is to provide the overview information required to understand the rest of this manual. The concepts introduced here are discussed in detail throughout the manual.

This chapter covers the following topics:

- **Section 2.2** introduces and defines key terms used throughout the manual. Some of these terms may be familiar to the MARSSIM user, while others are new terms developed specifically for this manual.
- **Section 2.3** describes the flow of information used to decide whether a site or facility complies with release criteria. The section describes the framework that is used to demonstrate compliance with the release criteria and is the basis for all information presented in this manual. The decision-making process is broken down into four phases: (1) planning, (2) implementation, (3) assessment, and (4) decision-making.
- **Section 2.4** introduces the RSSI process, which can be used for compliance demonstration at many sites. The section describes a series of surveys that form the core of this process. Each survey has specified goals and objectives to support a final decision on whether a site or facility complies with the appropriate criteria. Flow diagrams are provided to show how the different surveys support the overall process, along with descriptions of the information obtained through each type of survey.
- **Section 2.5** presents major considerations that relate to the decision-making and survey-design processes. This section, in addition to the examples discussed in detail throughout the manual, focuses on residual radioactive material in surface soils and on building surfaces. Recommended survey designs for demonstrating compliance are presented, along with the rationale for selecting these designs.
- **Section 2.6** recognizes that the methods presented in MARSSIM may not represent the most appropriate survey design at all sites. Some alternative methods for applying the RSSI process are discussed. Different methods for demonstrating compliance that are technically defensible may be developed with the approval of the responsible regulatory agency.

MARSSIM provides an approach that is technically defensible and flexible enough to be applied to a variety of site-specific conditions. Applying this approach to release criteria, including dose- or risk-based criteria, provides a consistent approach to protecting human health and the environment. The manual's performance-based approach to decision-making provides the flexibility needed to address compliance demonstration at individual sites.

2.2 Understanding Key MARSSIM Terminology and Survey Unit Classification

2.2.1 Key MARSSIM Terminology

The first step in understanding the RSSI process is accomplished by understanding this manual's scope, the terminology, and the concepts. Some terms were developed specifically for MARSSIM, for the purposes of this manual, while other commonly used terms were adopted. This section explains some of the terms, roughly in the order of their presentation in the manual. The italicized terms in this section are all defined in the **glossary** of this document.

The process described in MARSSIM begins with the premise that release criteria have already been established. The methods presented in MARSSIM are generally applicable and are not dependent on the value of the release criteria.

Release criteria are regulatory limits expressed in terms of dose (millisieverts/year or millirem/year) or risk (cancer morbidity or cancer mortality) or concentrations of radioactive material specified in regulations or standards. The terms "release limit" and "cleanup standard" are also used to describe this term. Release criteria that are typically based on dose (e.g., total effective dose [TED], committed effective dose [CED], total effective dose equivalent [TEDE], or committed effective dose equivalent [CEDE]) or risk (e.g., risk of cancer incidence [morbidity] or risk of cancer death [mortality]) generally cannot be measured directly.

Exposure pathway modeling is an analysis of various *exposure pathways* and scenarios used to convert dose or risk into concentration. Exposure pathway modeling is used to calculate a radionuclide-specific predicted concentration of radioactive material or surface area concentration of radioactive material of specific nuclides that could result in a dose or risk equal to the release criteria within the required evaluation period. In this manual, such a concentration is termed the *derived concentration guideline level (DCGL)*.¹ In many cases, DCGLs can be derived from applicable requirements or regulatory agency guidance based on default modeling input parameters (e.g., screening-level analyses) if site conditions are consistent with the underlying assumptions in the default modeling or screening analyses; in other cases, it may be necessary to develop site-specific parameters. In general, the units for the DCGL are the same as the units for measurements performed to demonstrate compliance (e.g., becquerel/kilogram [Bq/kg] or picocurie/gram [pCi/g], becquerel/square meter [Bq/m²] or decays per minute [dpm]/100 square centimeters [cm²]). This allows direct comparisons between the survey results and the DCGL. **Appendix D, Section D.1.6**, discusses the uncertainty associated with using DCGLs to demonstrate compliance.

An *investigation level* is a derived media-specific, radionuclide-specific concentration that is based on the release criteria, that, if exceeded, triggers a response, such as further investigation or remediation. An investigation level may be used early in the process to identify areas requiring further investigation; it may also be used as a screening tool during compliance demonstration to identify potential problem areas. A DCGL is an example of a specific investigation level that is based on the release criteria.

While the derivation of DCGLs is outside the scope of MARSSIM, it is important to understand the assumptions that form the basis for this derivation of DCGLs to ensure consistency with the

¹ If the scenario for statistical hypothesis testing (refer to **Section 2.5.1**) is not explicitly stated, the default terms "derived guideline concentration level" or "DCGL" and "lower bound of the gray region" or "LBGR" will be used. If using Scenario B, please substitute "action level" or "AL" and "upper bound of the gray region" or "UBGR" (i.e., "discrimination limit" or "DL") for these terms, respectively.

statistical approach used to demonstrate compliance with regulatory criteria. For example, the estimated dose, and consequently the cleanup level or DCGL, may be sensitive to assumptions regarding the lateral extent (i.e., area) of residual radioactive material for relatively small exposure areas (e.g., areas that do not approximate an infinite source for external radiation exposure, or areas that would not support crop cultivation in quantities consistent with the assumed annual consumption rates of contaminated produce for the resident farmer scenario). Other important factors may include depth of residual radioactive material, chemical and physical form of the source, hydrogeological considerations, and potential exposure scenarios. For more information on environmental pathway modeling, MARSSIM users should² consult their regulator's guidance on the topic.

MARSSIM defines two potential DCGLs based on the area of residual radioactive material:

- *Evenly distributed activity*—If the residual radioactive material is evenly distributed over a large area, MARSSIM looks at the average or median concentration of radioactive material over the entire area. The $DCGL_W$ (the DCGL used when applying the Wilcoxon Rank Sum [WRS] or Sign tests; refer to **Section 2.5.1.2**)³ is derived based on assuming an average concentration over a wide area in the exposure pathway modeling.
- *Small areas of elevated concentrations of radioactive material*—If the residual radioactive material appears as small areas of elevated concentrations of radioactive material⁴ within a larger area, MARSSIM also considers the results of individual measurements. The $DCGL_{EMC}$ (the DCGL used for the elevated measurement comparison [EMC], refer to **Section 2.5.3**) is derived separately for these small areas and generally from different exposure assumptions than those used for larger areas.

The *gray region* is a range of values of the parameter of interest for a survey unit where the consequences of making a decision error are relatively minor. In *Scenario A*, the upper bound of the gray region (UBGR) is set equal to the $DCGL_W$, and the lower bound of the gray region (LBGR) is chosen on a site-specific basis. In *Scenario B*, the UBGR is set equal to the discrimination limit (DL), and the LBGR is set equal to the action level (AL).

Scenario A uses a null hypothesis that assumes the concentration of radioactive material in the survey unit exceeds the $DCGL_W$. Scenario A is sometimes referred to as “presumed not to comply” or “presumed not clean.”

Scenario B uses a null hypothesis that assumes the concentration of radioactive material in the survey unit is less than or equal to the AL. Scenario B is sometimes referred to as “indistinguishable from background” or “presumed clean.”

² MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

³ The “W” in $DCGL_W$ historically stood for Wilcoxon Rank Sum test, which is the statistical test recommended in MARSSIM for demonstrating compliance when the radionuclide is present in background. However, as the Sign test is also a recommended test in MARSSIM for demonstrating compliance when the radionuclide is not present in background, the term now colloquially refers to “wide-area” or “average.”

⁴ A small area of elevated concentration of radioactive material, or maximum point estimate of residual radioactive material, might also be referred to as a “hot spot.” This term has been purposefully omitted from MARSSIM because the term often has different meanings based on operational or local program concerns.

Surface soil is the top layer of soil on a site that is available for direct exposure, growing plants, and resuspension of particles for inhalation. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Historically, this layer has often been represented as the top 15 centimeters (6 inches) of soil (40 CFR Part 192), but it will vary depending on radionuclide, surface characteristics, measurement method, and pathway modeling assumptions. For the purposes of MARSSIM, surface soil may also include other media types, such as gravel fill, concrete, or asphalt paving, but this should specifically be discussed with the regulator. Similarly, a *building surface* is defined as the thickness of building surface material that can be measured using direct measurement or scanning techniques and will vary depending on radionuclide, surface characteristics, measurement technique, and pathway modeling assumptions.

A *site* is any installation, facility, or discrete, physically separate parcel of land, or any building or structure or portion thereof, that is being considered for survey and investigation. *Area* is a general term referring to any portion of a site, up to and including the entire site.

Remediation includes those actions that are consistent with a permanent remedy taken instead of, or in addition to, a removal action in the event of a release or threatened release of a hazardous substance into the environment. Remediation is intended to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment.

Decommissioning is a term for the process of removing a facility or site safely from service and reduce the concentration of residual radioactive material to a level that permits release of the property and termination of the license and other authorization for site operation.

The *final status survey* (FSS) is the survey in the RSSI process that is used to demonstrate compliance with the release criteria.

A *survey unit* is a physical area consisting of structures or land areas of specified size and shape at a site for which a separate decision will be made as to whether or not the unit meets the release criteria. (This decision is made as a result of the FSS.) Survey units are established to facilitate the survey process and the statistical analysis of survey data. The size and shape of the survey unit are based on such factors as the potential for residual radioactive material, the expected distribution of residual radioactive material, and any physical boundaries (e.g., buildings, fences, roads, soil type, and surface water body) at the site. Survey units are generally formed by grouping contiguous site areas with a similar use history and the same classification of potential for residual radioactive material.

Measurement in MARSSIM is used interchangeably to mean (1) the act of using a detector to determine the level or quantity of radioactive material on a surface or in a sample of material removed from a medium being evaluated, or (2) the quantity obtained by the act of measuring.

Direct measurements of radioactive material are obtained by placing the detector near the surface or medium being surveyed for a prescribed amount of time. An indication of the resulting concentration of radioactive material is read out directly.

Sampling is the process of collecting a portion of an environmental medium as being representative of the locally remaining medium. The collected portion, or aliquot, of the medium is then analyzed to identify the radionuclide and determine the concentration. *Sample* may also refer to a set of individual measurements drawn from a population whose properties are studied

to gain information about the entire population. The latter is primarily used for statistical discussions.

Scanning is a measurement technique performed by moving a portable radiation detector at a specified speed and distance next to a surface to detect radiation.

A *site-specific scanning survey* represents an approach for evaluating residual levels of radioactive material where scan measurements may be used to limit the number of required direct measurements or samples. In some cases, it may even be used to replace the need for direct measurements or samples for a single or multiple survey units as used for statistical testing.

The *graded approach* is defined as the process where the level of application of managerial controls for an item or work is determined according to the intended use of the results and the degree of confidence needed in the quality of the results. To make the best use of resources for decommissioning, MARSSIM places greater survey efforts on areas that have, or had, the highest potential for residual radioactive material. The FSS uses statistical tests to support decision-making. These statistical tests are performed using survey data from areas with common characteristics, such as potential for residual radioactive material, which are distinguishable from other areas with different characteristics.

Categorization is the act or result of separating areas or survey units into one of two categories: impacted areas and non-impacted areas. Areas that have no reasonable potential to contain concentrations of residual radioactive material above background are categorized as non-impacted areas. These areas have no radiological impact from site operations and are typically identified early in the cleanup process. Areas with a possibility of containing residual radioactive material in excess of natural background or fallout levels are categorized as impacted areas.

Classification is the act or result of separating areas or survey units into one of three designated classes—*Class 1 area*, *Class 2 area*, or *Class 3 area*—according to the area's radiological characteristics. Survey unit classification determines the FSS design and the procedures used to develop this design. Preliminary area classifications, made earlier in the MARSSIM process, are useful for planning subsequent surveys.

The *background reference area*, or simply *reference area*, is a geographical area from which representative reference measurements are performed for comparison with measurements performed in specific survey units. If the radionuclide of concern is present in the background, or if the measurement system used to determine concentration in the survey unit is not radionuclide specific, background measurements are compared to the survey unit measurements to determine the concentration of residual radioactive material. The site radiological reference area is defined as an area that has similar physical, geological, chemical, radiological, and biological characteristics as the survey unit(s) being investigated but that has not been affected by site activities (i.e., non-impacted).

The *Data Life Cycle* is the process of planning the survey, implementing the survey plan, and assessing the survey results before making a decision. Survey planning uses the *Data Quality Objectives* (DQO) *process*, which is a series of logical steps that guides managers or staff to create a plan for the resource-effective acquisition of environmental data, to ensure that the survey results are of sufficient quality and quantity to support the final decision. *Measurement Quality Objectives* (MQOs) are the specific analytical data requirements of the DQOs. *Quality assurance* (QA) is an integrated system of management activities involving planning,

implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the customer. *Quality control* (QC) is the overall system of technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet the stated requirements established by the customer, operational techniques, and activities that are used to fulfill requirements for quality. QA/QC procedures are performed during implementation of the survey plan to collect information necessary to evaluate the survey results. *Data Quality Assessment* (DQA) is the scientific and statistical evaluation of data to determine if the data are of the right type, quality, and quantity to support their intended use.

A systematic process and structure for quality should be established to provide confidence in the quality and quantity of data collected to support decision-making. The data used in decision-making should be supported by a planning document that records how QA and QC are applied to obtain the types and quality of results that are needed and expected. Several terms are used to describe a variety of planning documents, some of which document only a small part of the survey design process. MARSSIM uses the term *Quality Assurance Project Plan* (QAPP) to describe a written document outlining the procedures a monitoring project will use to ensure the data it collects and analyzes meet project requirements. This term conforms to American National Standards Institute (ANSI)/American Society for Quality (ASQ) national consensus guidance ANSI/ASQ E4-2014, “Quality Management Systems for Environmental Information and Technology Programs—Requirements with Guidance for Use” (ANSI/ASQC 2014), and U.S. Environmental Protection Agency (EPA) guidance (EPA 2002a, 2024), and its use is recommended to promote consistency. The use of the term QAPP in MARSSIM does not exclude the use of other terms (e.g., Decommissioning Plan, Sampling and Analysis Plan, Field Sampling Plan) to describe survey documentation, provided that the information included in the documentation supports the objectives of the survey. The QAPP is a plan for obtaining data of sufficient quality and quantity to satisfy data needs; it describes policy, organization, and functional activities and includes DQOs and MQOs.

2.2.2 Classification Assessment

Impacted areas are divided into three classifications:

- **Class 1 Areas:** Areas that have, or had prior to remediation, a potential for residual radioactive material (based on site operating history) or known residual radioactive material (based on previous radiological surveys) above the DCGL_w. Examples of Class 1 areas include the following:
 - site areas previously subjected to remedial actions⁵
 - locations where leaks or spills are known to have occurred
 - former burial or disposal sites
 - waste storage sites

⁵ Remediated areas are identified as Class 1 areas because the remediation process often results in less than 100 percent removal of the radioactive material. The residual radioactive material that remains on the site after remediation is often associated with relatively small areas with elevated levels of radioactive material. This results in a non-uniform distribution of the radionuclide and a Class 1 classification. If an area is expected to have no potential to exceed the DCGL_w (i.e., a Class 2 area before remediation) and was remediated for reasons other than an exceedance of the DCGL_w, the remediated area would still be classified as Class 2 for the FSS.

- *Class 2 Areas:* Areas that have, or had prior to remediation, a potential for residual radioactive material or known residual radioactive material, but are not expected to exceed the DCGL_W. To justify changing an area's classification from Class 1 to Class 2, the existing data (from the Historical Site Assessment [HSA], scoping surveys, or characterization surveys) should provide a high degree of confidence that no individual measurement would exceed the DCGL_W. Other justifications for this change in an area's classification may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 2 for the FSS include the following:
 - locations where radioactive materials were present in an unsealed form (e.g., process facilities)
 - transport routes with potential residual radioactive material
 - areas downwind from stack release points
 - upper walls, roof support frameworks, and ceilings of buildings or rooms subjected to airborne radioactive material
 - areas where low concentrations of radioactive materials were handled
 - areas on the perimeter of former radiological control areas
- *Class 3 Areas:* Any impacted areas that are not expected to contain any residual radioactive material or are expected to contain concentrations of residual radioactive material at a small fraction of the DCGL_W, based on site operating history and previous radiological surveys. To justify changing an area's classification from Class 1 or Class 2 to Class 3, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence that there is either no residual radioactive material, or that any levels of residual radioactive material are a small fraction of the DCGL_W. Other justifications for this change in an area's classification may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 3 include buffer zones around Class 1 or Class 2 areas, and areas with very low potential for residual radioactive material but insufficient information to justify a non-impacted classification.

Class 1 areas have the greatest potential for residual radioactive material and, therefore, receive the highest degree of survey effort for the FSS using a graded approach, followed by Class 2, and then by Class 3.

Survey units should be classified as Class 1 unless there is sufficient justification for classifying the survey unit as Class 2 or Class 3. Likewise, the classification of a survey unit should not be reduced without sufficient justification.

Non-impacted areas do not receive any level of survey coverage, because they have no reasonable potential for residual radioactive material. Non-impacted areas are determined on a site-specific basis from information collected during site identification, the HSA, and scoping and characterization surveys. Examples of areas that would be non-impacted rather than impacted usually include administrative, residential, or other buildings that have not contained radioactive materials except such devices as smoke detectors or exit signs with sealed radioactive sources.

2.3 Making Decisions Based on Survey Results

Compliance demonstration is simply a decision as to whether a survey unit meets the release criteria. For most sites, this decision is based on the results of one or more surveys. When survey results are used to support a decision, the decision-maker⁶ needs to ensure that the data will support that decision with satisfactory confidence. Uncertainty in the survey results is unavoidable, so the possibility of errors in decisions supported by the survey results is unavoidable. For this reason, actions must be taken to manage the uncertainty in the survey results so that sound and defensible decisions can be made. These actions include proper survey planning to control known causes of uncertainty, proper application of QC procedures during implementation of the survey plan to detect and control significant sources of error, and careful analysis of uncertainty before the data are used to support decision-making. These actions describe the flow of data throughout each type of survey and are combined in the Data Life Cycle, as shown in **Figure 2-1**.

There are four phases of the Data Life Cycle:

- *Planning Phase:* The survey design is developed and documented using the DQO process. QA/QC procedures are developed and documented in the QAPP. The QAPP is the principal product of the planning process, which incorporates the DQOs as it integrates all technical and quality aspects for the life cycle of the project, including planning, implementation, and assessment. The QAPP contains plans for survey operations and provides a specific format for obtaining the type and quality of data needed for decision-making. The QAPP elements are presented in the order of the Data Life Cycle and are grouped into two types of elements: (1) project management and (2) collection and evaluation of environmental data (ANSI/ASQ 2014). The DQO process is described in **Appendix D** and applied in **Chapters 3, 4, and 5** of this manual. Development of the QAPP is described in **Appendix D** and applied throughout the RSSI process.
- *Implementation Phase:* The survey is carried out in accordance with the standard operating procedures and the QAPP, and it generates raw data. **Chapters 6 and 7** and **Appendix H** provide information on the selection of data collection techniques. The QA and QC measurements, discussed in **Chapters 6 and 7**, also generate data and other important information that will be used during the assessment phase.
- *Assessment Phase:* The data generated during the implementation phase first are verified to ensure that the standard operating procedures specified in the QAPP were followed and that the measurement systems were performed in accordance with the criteria specified in the QAPP. Then the data are validated to ensure that the results of data collection activities support the objectives of the survey as documented in the QAPP or permit a determination that these objectives should be modified. The DQA process is then applied using the validated data to determine whether the quantity and quality of the data satisfy their intended use. Updates to the conceptual site model are considered. The DQA process is described in **Appendix D** and is applied in **Chapter 8**. The development of the conceptual site model is described in **Chapter 3**; the application and updates are described in **Chapters 4 and 5**.

⁶ The term “decision-maker” is used throughout this section to describe the person, team, board, or committee responsible for the final decision regarding release of the survey unit.

- *Decision-Making Phase:* A decision is made, in coordination with the regulatory agency, based on the conclusions drawn from the assessment process. The ultimate objective is to make technically defensible decisions with a specified level of confidence (Chapter 8).

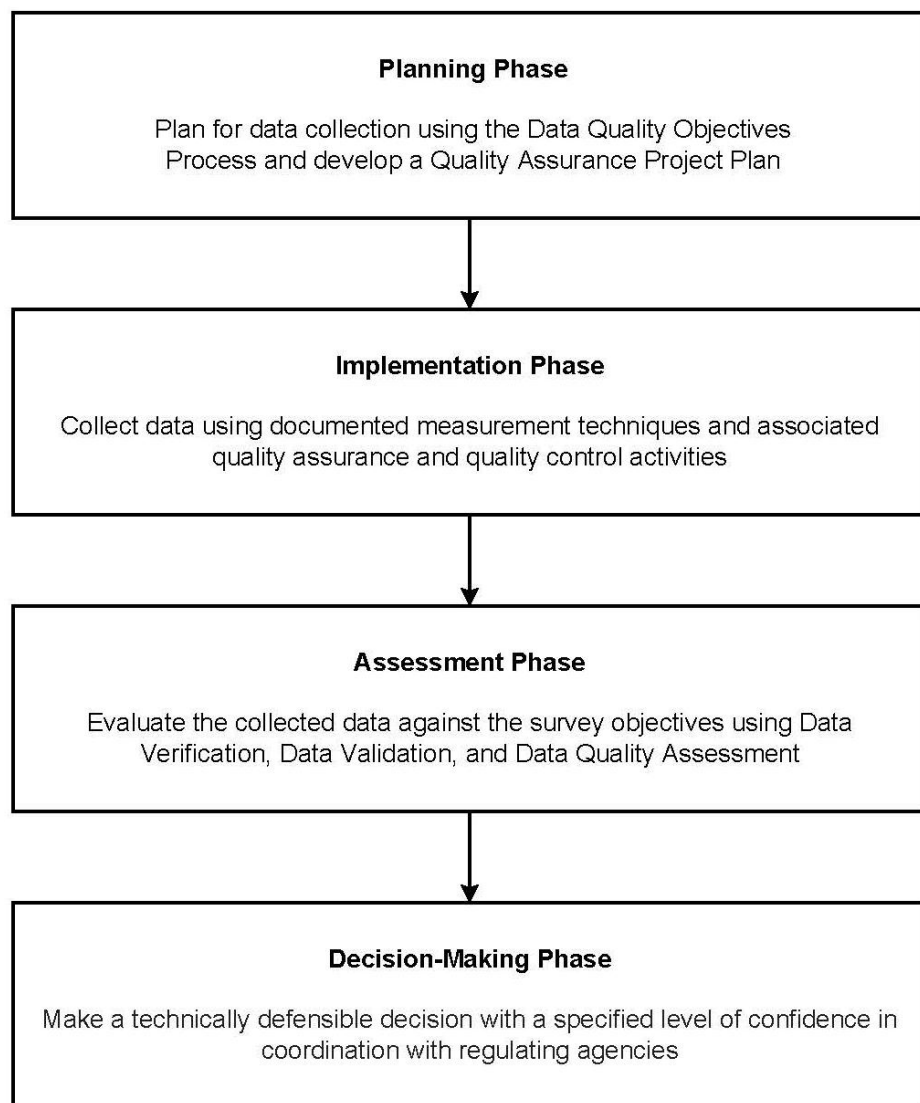


Figure 2-1 The Data Life Cycle

2.3.1 Planning Effective Surveys—Planning Phase

The first step in designing effective surveys is planning. The DQO process is a series of planning steps based on the scientific method for establishing criteria for data quality and developing survey designs (ANSI/ASQ 2014; EPA 2006a, 1987a, 1987b). Planning radiation surveys using the DQO process improves the survey effectiveness and efficiency, and thereby the defensibility of decisions. Proper data collection planning minimizes expenditures by eliminating unnecessary, duplicative, or overly precise data. Using the DQO process ensures that the type, quantity, and quality of environmental data used in decision-making will be

appropriate for the intended application. MARSSIM supports the use of the DQO process to design surveys for input to both evaluation techniques (EMC and the statistical test). The DQO process provides systematic procedures for defining the criteria that the survey design should satisfy, including whether to perform site-specific scanning surveys (refer to **Section 4.8.3.1**) or scanning surveys in conjunction with direct measurements/sampling, what type of measurements to perform, when and where to perform measurements, the level of decision errors for the survey, and how many measurements to perform.

The level of effort associated with planning a survey is based on the complexity of the site. Large and complicated sites generally receive a significant amount of effort during the planning phase, while smaller sites may not require as much planning. In addition, the complexity of the survey depends not only on the size of the site or survey unit, but also on the physical and chemical characteristics of the site and the radioactive materials on the site. This graded approach defines data quality requirements according to the type of survey being designed, the risk of making a decision error based on the data collected, and the consequences of making such an error. This approach provides a more effective survey design combined with a basis for judging the usability of the data collected.

DQOs are qualitative and quantitative statements derived from the outputs of the DQO process that do the following:

- Clarify the study objective.
- Define the most appropriate type of data to collect.
- Determine the most appropriate conditions (e.g., environmental, legal, safety) for collecting the data.
- Specify limits on decision errors, which will be used as the basis for establishing the quantity and quality of data needed to support the decision.

The DQO process consists of seven steps, as shown in **Figure 2-2**. Each step is discussed in detail in **Appendix D**. Although all of the outputs of the DQO process are important for designing efficient surveys, there are some that are referred to throughout the manual. These DQOs are mentioned briefly here and are discussed in detail throughout MARSSIM and in **Appendix D**.

to comply” or “presumed not clean.” Scenario B uses a null hypothesis that assumes the concentration of radioactive material in the survey unit is less than or equal to the AL. Scenario B is sometimes referred to as “indistinguishable from background” or “presumed clean” (**Section 5.3.1**).

- State the null hypothesis (H_0). For Scenario A, the concentration of residual radioactive material in the survey unit exceeds the release criteria (**Section 2.5, Appendix D, Section D.1.6**). For Scenario B, the residual radioactive material in the survey unit does not exceed the release criteria (**Section 2.5, Appendix D, Section D.1.6**).
- Specify a gray region where the consequences of decision errors are considered relatively minor. For Scenario A, the UBGR is defined as the $DCGL_W$, and the LBGR is a site-specific variable generally chosen to be a conservative (slightly higher) estimate of the average concentration of residual radioactive material remaining in the survey unit and adjusted to provide an acceptable value for the relative shift. For Scenario B, the LBGR is the AL, and the UBGR is defined by a DL that can be reliably distinguished from the AL (**Section 5.3.3.1, Appendix D, Section D.1.6.3**).
- Define decision errors and assign their probability limits for the chosen scenario (A or B). The probability of making a Type I decision error (α) or a Type II decision error (β) is a site-specific variable (**Section 5.3.2, Appendix D, Section D.1.6**).
- Estimate the standard deviation of the measurements in the survey unit. The standard deviation (σ) is a site-specific variable, typically estimated from preliminary, postremediation survey data.
- Specify the relative shift (Δ/σ). The relative shift is equal to the width of the gray region (Δ)—which in Scenario A is equal to ($DCGL_W - LBGR$) and for Scenario B is equal to ($DL - AL$)—divided by an estimate of the uncertainty (σ). The relative shift is generally designed to have a value greater than 1 (**Section 5.3.3.2, Section 5.3.4**).
- Select a survey strategy based on the measurement requirements and site classifications to include one of the following:
 - a combination of scanning and direct measurements or sample collection and analysis
 - scanning only, provided that the scanning measurement system meets the detection capability and uncertainty requirements of a site-specific scanning survey design (**Section 4.8.3.1, Section 5.3.6.1, Section 5.3.9**)
- For surveys using the Sign or WRS test, calculate the estimated number of measurements (N) and specify the measurement locations required to demonstrate compliance. The number of measurements depends on the relative shift, Type I and Type II decision error rates, and the potential for small areas of elevated activity (**Sections 5.3.3 and 5.3.4**).
- Determine the percentage of scanning coverage for survey units based on the assigned classification of the survey unit and relative shift. Class 1 areas and survey units will have scan coverage of 100 percent, while the scan coverage of Class 2 and Class 3 areas and survey units will vary between 10 percent and 100 percent as a function of the

relative shift (**Section 5.3.6**). (For Class 3 areas, scanning can be lower than 10 percent if sampling or direct measurements, or both, are taken in areas judged to have the highest potential for residual radioactive material.)

- Specify the documentation requirements for the survey, including survey planning documentation. Documentation supporting the decision on whether or not the site complies with the release criteria is determined on a site-specific basis (**Appendix D, Section D.2**).
- Specify the required MQOs for all measurement techniques (scanning, direct measurement, and sample analysis) specified in the QAPP. The MQOs are unique for each measurement system (**Sections 6.2–6.4**).

MQOs are an important subset of inputs into the DQO process that define performance requirements and objectives for the measurement system. MQOs that should be considered include the following:

- *Measurement method uncertainty (u_M)*: This is the predicted uncertainty of the measured value that would be calculated if the method were applied to a hypothetical sample with a specified concentration, typically the release limit. Reasonable values for measurement method uncertainty can be predicted for a particular measurement technique based on typical values for specific parameters (e.g., count time, efficiency) and previous surveys of the areas being investigated. The MQO for the required measurement method uncertainty is calculated based on the width of the gray region and is related to the minimum detectable concentration (MDC).
- *Detection capability*: The MDC is recommended as the MQO for defining the detection capability of the measurement system, which is the net response level that can be expected to be seen using a detector with a fixed level of confidence. To account for cases in which decisions are being made based on multiple measurements, the MDC should be less than 50 percent of the DCGL in Scenario A and the DL in Scenario B.

A common practice has been to select a measurement method based on the MDC. For example, Section 4.7.1 of MARSSIM Revision 1 (NRC 2000) states, “During survey design, it is generally considered good practice to select a measurement system with an MDC between 10–50% of the DCGL [AL].” Such guidance implicitly recognizes that for cases in which the decision to be made concerns the mean⁷ of a population that is represented by multiple measurements, criteria based on the MDC may not be sufficient and a somewhat more stringent requirement is needed. The requirement that the MDC (approximately 3–5 times the true measurement method standard deviation [σ_M]) be 10 percent to 50 percent of the AL is tantamount to requiring that σ_M be 0.02 to 0.17 times the AL—in other words, the relative standard deviation should be approximately 10 percent at the AL. However, the concentration at which the relative standard deviation is 10 percent is the conventional value chosen to serve as a minimum quantifiable concentration (MQC).⁸ Thus, a requirement that is often stated in terms of

⁷ In MARSSIM, “average” and “mean” both refer to the arithmetic mean.

⁸ Appendix C to the Multi-Agency Radiological Laboratory Analytical Protocols (MARLAP) (NRC 2004) contains more information on the MQC.

the MDC may be more naturally expressed in terms of the MQC, such as by saying that the MQC should not exceed the AL.

- *Range:* The method range is the lowest and highest concentration of an analyte that a method can accurately detect. The expected concentration range for a radionuclide of concern may be an important MQO. Most radiation measurement techniques are capable of measuring over a wide range of radionuclide concentrations. However, if the expected concentration range is large, the range should be identified as an important measurement method performance characteristic, and an MQO should be developed. The MQO for the acceptable range should be a conservative estimate. This will help prevent the selection of measurement techniques that cannot accommodate the actual concentration range.
- *Specificity:* Specificity is the ability of the measurement method to measure the radionuclide of concern in the presence of interferences. To determine whether specificity is an important MQO, the planning team needs information on expected concentration ranges for the radionuclides of concern and other chemical and radionuclide constituents, along with chemical and physical attributes of the residual radioactive material being investigated.
- *Ruggedness:* For a project that involves field measurements that are performed in difficult or variable environments, or laboratory measurements that are complex in terms of chemical and physical characteristics, the measurement method's ruggedness may be an important MQO. Ruggedness refers to the relative stability of the measurement technique's performance when small variations in method parameter values are made. For field measurements, the changes may include temperature, humidity, or atmospheric pressure. For laboratory measurements, variability in sample conditions (e.g., pH) or laboratory conditions may be important. To determine whether ruggedness is an important measurement method performance characteristic, the planning team needs detailed information on the chemical and physical characteristics of the soil or surfaces being investigated and operating parameters for the radiation instruments used by the measurement technique.

Precision, bias, representativeness and detection capability, comparability, and completeness are the Data Quality Indicators recommended for estimating the amount of error for survey data (EPA 2002a). They are discussed in detail in **Appendix D, Section D.4.2.6**.

2.3.2 Evaluating Sources of Variability in Survey Results—Implementation Phase

To encourage flexibility and the use of appropriate measurement techniques for a specific site, MARSSIM does not provide detailed recommendations on specific techniques to be used. Instead, MARSSIM encourages the decision-maker to evaluate available techniques based on the survey DQOs and MQOs. The manual provides information on evaluating whether these objectives have been met, such as the required measurement method uncertainty and MDC.

QC programs can both lower the chances of making an incorrect decision and help the data user understand the level of uncertainty that surrounds the decision (EPA 2002a). As discussed previously, QC data are collected and analyzed during implementation to provide an estimate of the uncertainty associated with the survey results. QC measurements (scans, direct measurements, and samples) are technical activities performed to measure the attributes and

performance of the survey. During any survey, a certain number of measurements should be taken for QC purposes.

2.3.3 Evaluating Survey Results—Assessment Phase

Assessments of environmental data are used to evaluate whether the data meet the objectives of the survey and are sufficient to determine compliance with the DCGL (EPA 1992a, 1992b, 2006a). The assessment phase of the Data Life Cycle consists of three phases: data verification, data validation, and DQA.

- Data verification is used to ensure that the requirements stated in the planning documents are implemented as prescribed (refer to **Appendix D.4.1**).
- Data validation is used to ensure that the results of the data collection activities support the objectives of the survey as documented in the QAPP or to permit a determination that these objectives should be modified (refer to **Appendix D.4.2**).
- DQA is the scientific and statistical evaluation of data to determine whether the data are of the right type, quality, and quantity to support their intended use (EPA 2006a). DQA helps complete the Data Life Cycle by providing the assessment needed to determine that the planning objectives are achieved (refer to **Section 8.2**). **Figure 2-3** illustrates where data verification, data validation, and DQA fit into the assessment phase of the Data Life Cycle.

There are five steps in the DQA process:

- (1) Review the DQOs, MQOs, and survey design.
- (2) Conduct a preliminary data review.
- (3) Select the statistical test(s).
- (4) Verify the assumptions of the statistical test(s).
- (5) Draw conclusions from the data.

The strength of DQA is its design that progresses in a logical and efficient manner to promote an understanding of how well the data meet the intended use. The assessment phase is described in more detail in **Appendix D. Section 2.6** discusses the flexibility of the Data Life Cycle and describes the use of survey designs other than those described later in MARSSIM.

2.3.4 Uncertainty in Survey Results

Uncertainty in survey results arises primarily from two sources—survey design and measurement:

- (1) Survey design uncertainty occurs when the survey design is unable to capture the complete extent of variability that exists for the radionuclide distribution in a survey unit. Because it is impossible in every situation to measure the concentration of residual radioactive material at every point in space and time, the survey results will be incomplete to some degree. It is also impossible to know with complete certainty the concentration of residual radioactive material at locations that were not measured, so the incomplete survey results give rise to uncertainty. The greater the natural or inherent variation in residual radioactive material, the greater the uncertainty associated with a decision based on the survey results. The unanswered question is, “How well do the survey results represent the true level of residual radioactive material in the survey unit?”

- (2) Measurement uncertainty is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurement. Random measurement uncertainties show up as variations among repeated measurements and affect the precision of the measurement method. Systematic uncertainties show up as measurements that are biased, yielding results that are consistently higher or lower than the true value. Measurement uncertainty is discussed in **Section 6.4**.

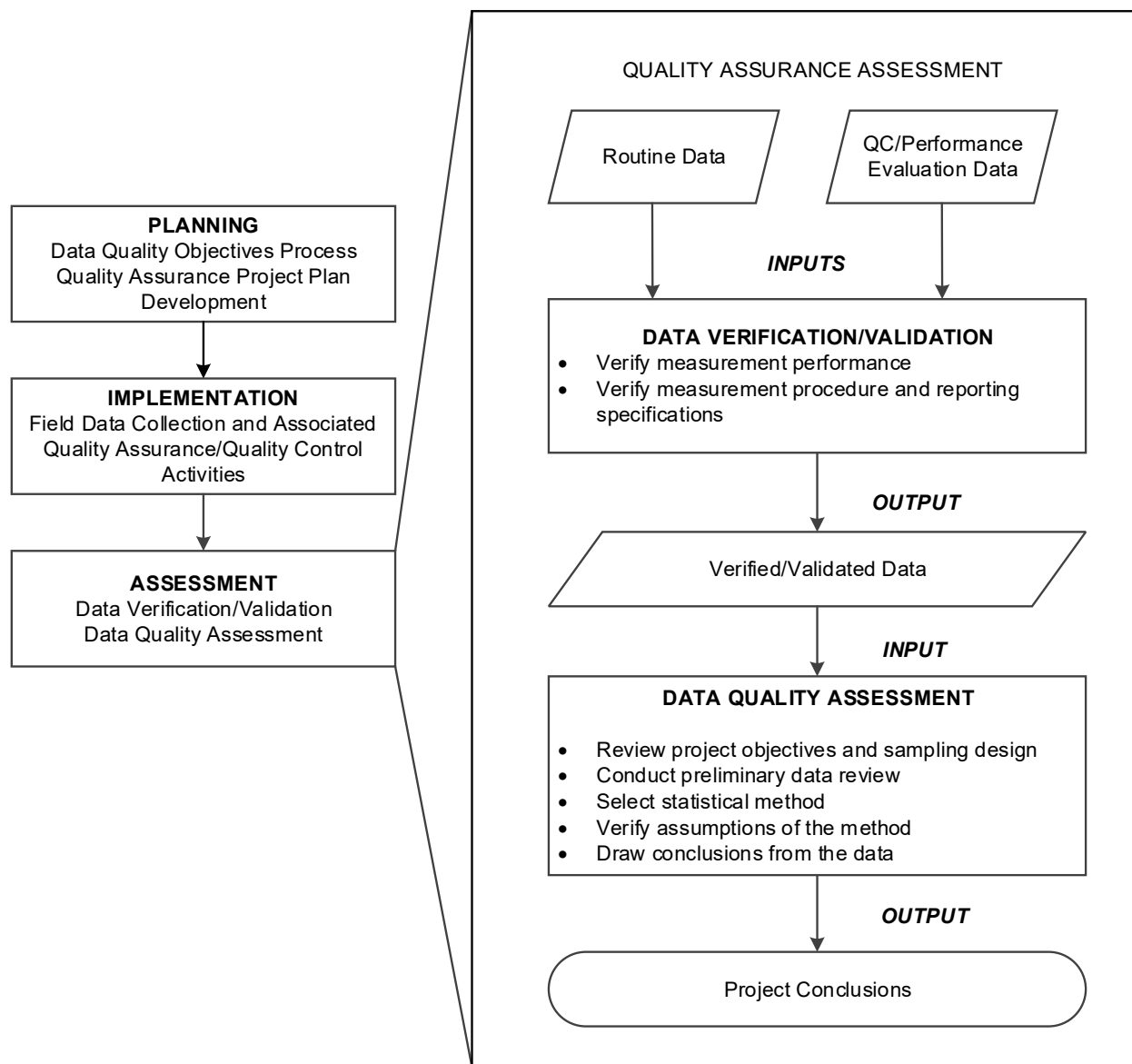


Figure 2-3 The Assessment Phase of the Data Life Cycle (EPA 2006a)

MARSSIM uses the Data Life Cycle to control and estimate the uncertainty in the survey results on which decisions are made. Adequate planning should minimize known sources of uncertainty. QC data collected during implementation of the survey plan can provide an

estimate of the uncertainty. Statistical hypothesis testing or comparison to an upper confidence limit (UCL) during the assessment phase provides a level of confidence in the final decision. There are several levels of decisions included within each survey type. Some decisions are quantitative, based on the numerical results of measurements performed during the survey. Other decisions are qualitative, based on the available evidence and best professional judgment. The Data Life Cycle can and should be applied consistently to both types of decisions.

2.3.5 Reporting Survey Results

The process of reporting survey results is an important consideration in planning the survey. Again, the level of effort for reporting should be based on the complexity of the survey. A simple survey with relatively few results may require a single report, while a more complicated survey may require several reports to meet the objectives of the survey. Reporting requirements for individual surveys should be developed during planning and clearly documented in the QAPP. These requirements should be developed with cooperation from the people performing the analyses (e.g., the analytical laboratory should be consulted on reporting results for samples). The Health Physics Society (EPA 1980c) and MARLAP give several suggestions for reporting survey results:

- *Report the actual result of the analysis.* Do not report data as “less than the detection limit.” Even negative results and results with large uncertainties can be used in the statistical tests to demonstrate compliance. Results reported only as “< MDC” cannot be fully used and, for example, complicate even such simple analyses as estimating an average. Although the nonparametric tests described in **Sections 8.3–8.4** and the UCL comparison described in **Section 8.5** can accommodate situations in which up to 40 percent of the results are non-detects, it is better to report the actual results.
- *Report results using the correct units and the correct number of significant digits.* The choice of whether to report results using International System units (e.g., Bq/kg, Bq/m²) or conventional units (e.g., pCi/g, dpm/100 cm²) is made on a site-specific basis. Generally, MARSSIM recommends reporting that all results be reported in the same units as the DCGLs. Sometimes the results may be more convenient to work with as counts directly from the detector. In these cases, the user should determine the appropriate units for a specific survey based on the survey objectives. MARLAP; National Institute of Standards and Technology (NIST) Technical Note 1297, “Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results,” issued September 1994 (NIST 1994); and the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Guide 98, “Guide to the Expression of Uncertainty in Measurement,” issued 1993 (ISO/IEC 1993), suggest reporting the uncertainty to one or two significant figures, with the measurement reported to match.
- *Report the measurement uncertainty for every result or series of results, such as for a measurement system.* This uncertainty, while not directly used for demonstrating compliance with the release criteria, is used for survey planning and data assessment throughout the RSSI process. In addition, the uncertainty is used for evaluating the performance of measurement systems using QC measurement results (as described in **Section 6.2** for scans and direct measurements, and in **Section 7.2** for laboratory analysis of samples). The uncertainty is also used for comparing individual measurements to the AL, which is especially important in the early stages of the RSSI

process (scoping, characterization, and remedial action support surveys described in **Section 2.4**) when decisions are made based on a limited number of measurements. **Section 6.4** discusses methods for calculating the measurement uncertainty.

- *Report the MDC for the measurement system as well as the method used to calculate the MDC.* The MDC is an a priori estimate of the capability for detecting an activity concentration with a specific measurement system (EPA 1980a). As such, this estimate is valuable for planning and designing radiation surveys. Optimistic estimates of the MDC (calculated using ideal conditions that may not apply to actual measurements) overestimate the ability of a technique to detect residual radioactive material, especially when scanning for alpha or low-energy beta radiations. This can invalidate survey results, especially for scanning surveys. Using a more realistic MDC during scoping and characterization surveys, as described in **Section 6.3**, helps in the proper classification of survey units for FSSs and minimizes the possibility of designing and performing subsequent surveys because of errors in classification. **Appendix N** discusses this further. Estimates of the MDC that minimize potential decision errors should be used for planning surveys.

Reporting requirements for individual surveys should be developed during planning and clearly documented in the QAPP.

2.4 Radiation Survey and Site Investigation Process

The Data Life Cycle discussed in **Section 2.3** is the basis for the performance-based approach in MARSSIM. The RSSI process is a series of surveys designed to demonstrate compliance with dose- or risk-based criteria for sites with residual radioactive material. The size, complexity, and amount of existing information on the site will determine how many of the surveys in the series will be necessary.

The RSSI process includes six principal steps:

- (1) site identification
- (2) HSA
- (3) scoping survey
- (4) characterization survey
- (5) remedial action support survey
- (6) FSS

Each of these steps is briefly described in **Sections 2.4.1–2.4.6** and described in more detail in **Chapter 5**. In addition, **Section 2.4.7** gives a brief description of regulatory agency confirmation and verification survey process. Because MARSSIM focuses on demonstrating compliance with release criteria, specifically by using an FSS, some of these surveys have additional objectives that are not fully discussed in MARSSIM (e.g., health and safety of workers, supporting selection of values for exposure pathway model parameters).

Table 2-1 provides a simplified overview of the principal steps in the RSSI process and how the Data Life Cycle can be used in an iterative fashion within the process. Specifically, it provides an overview of how the Data Life Cycle (Plan, Implement, Assess, and Decide) can be used to support each of the steps in the RSSI process up through the FSS.

Table 2-1 The Data Life Cycle⁹ Used to Support the RSSI Process

RSSI Process	Data Life Cycle	MARSSIM Methodology
Site Identification	—	Provides information on identifying potential radiation sites (Section 3.3)
Historical Site Assessment	Historical Site Assessment Data Life Cycle	Provides information on collecting and assessing existing site data (Sections 3.4–3.9) and potential sources of information (Appendix F)
Scoping Survey	Scoping Data Life Cycle	Discusses the purpose and general approach for performing scoping surveys, especially as sources of information when planning FSSs (Section 5.2.1)
Characterization Survey	Characterization Data Life Cycle	Discusses the purpose and general approach for performing characterization surveys, especially as sources of information when planning FSSs (Section 5.2.2)
Remedial Action Support Survey	Remedial Action Data Life Cycle	Discusses the purpose and general approach for performing remedial action support surveys, especially as sources of information when planning FSSs (Section 5.2.3)
Final Status Survey	Final Status Data Life Cycle	Provides detailed information for planning FSSs (Chapter 4, Section 5.3), selecting measurement techniques (Chapter 6, Chapter 7, Appendix H), and assessing the data collected during FSSs (Chapter 8, Appendix D)

The flowcharts in **Figure 2-4** through **Figure 2-7** present the principal steps and decisions in the site investigation process and show the relationship of the survey types to the overall assessment process. As shown in these figures, there are several sequential steps in the site investigation process, and each step builds on information provided by its predecessor. Properly applying each sequential step in the RSSI process should provide a high degree of assurance that the release criteria have not been exceeded.

⁹ The steps of the Data Life Cycle can be found in **Figure 2-1**. The DQO process for each of the steps can be found in **Figure 2-2**.

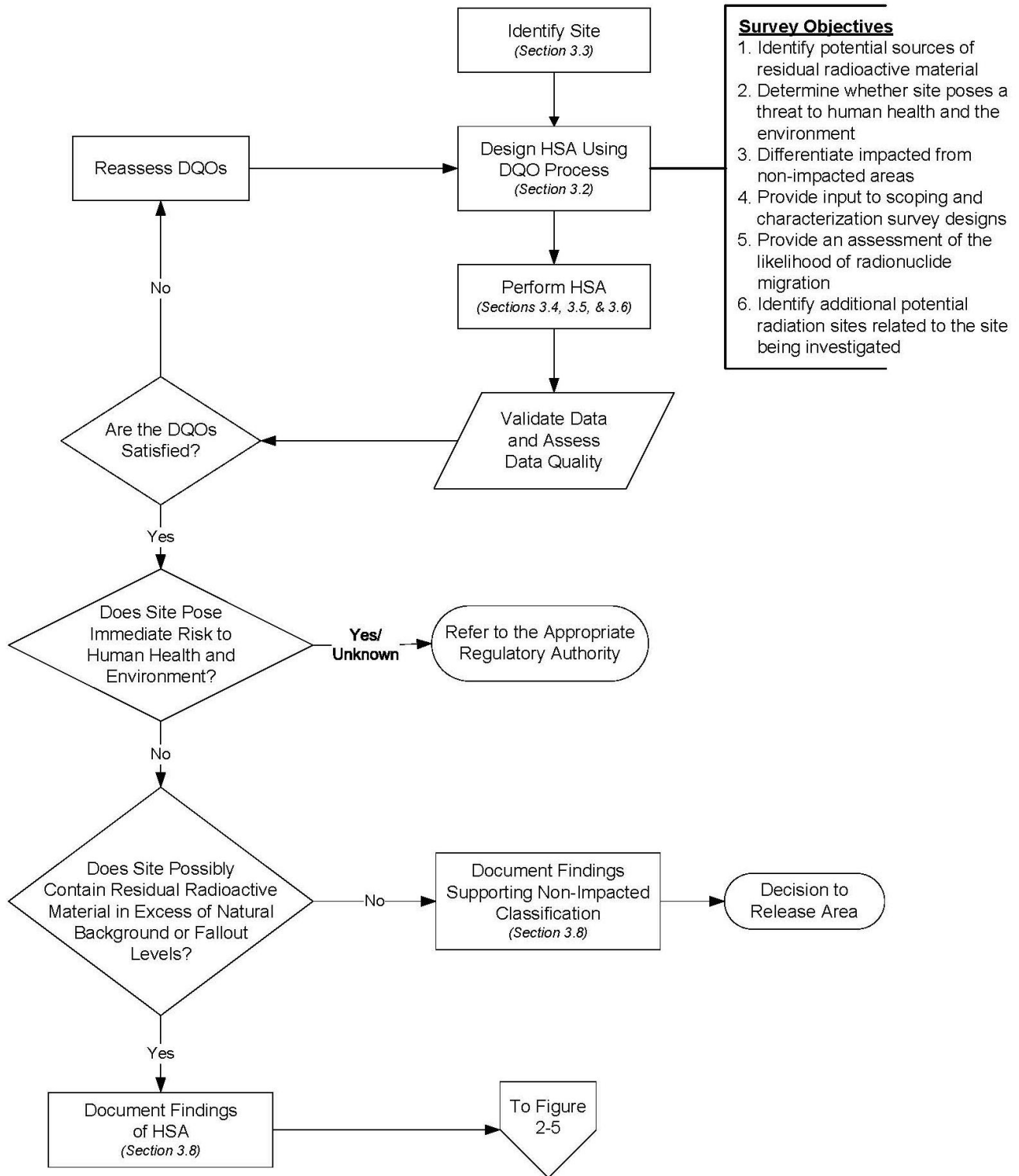


Figure 2-4 The HSA Portion of the RSSI Process

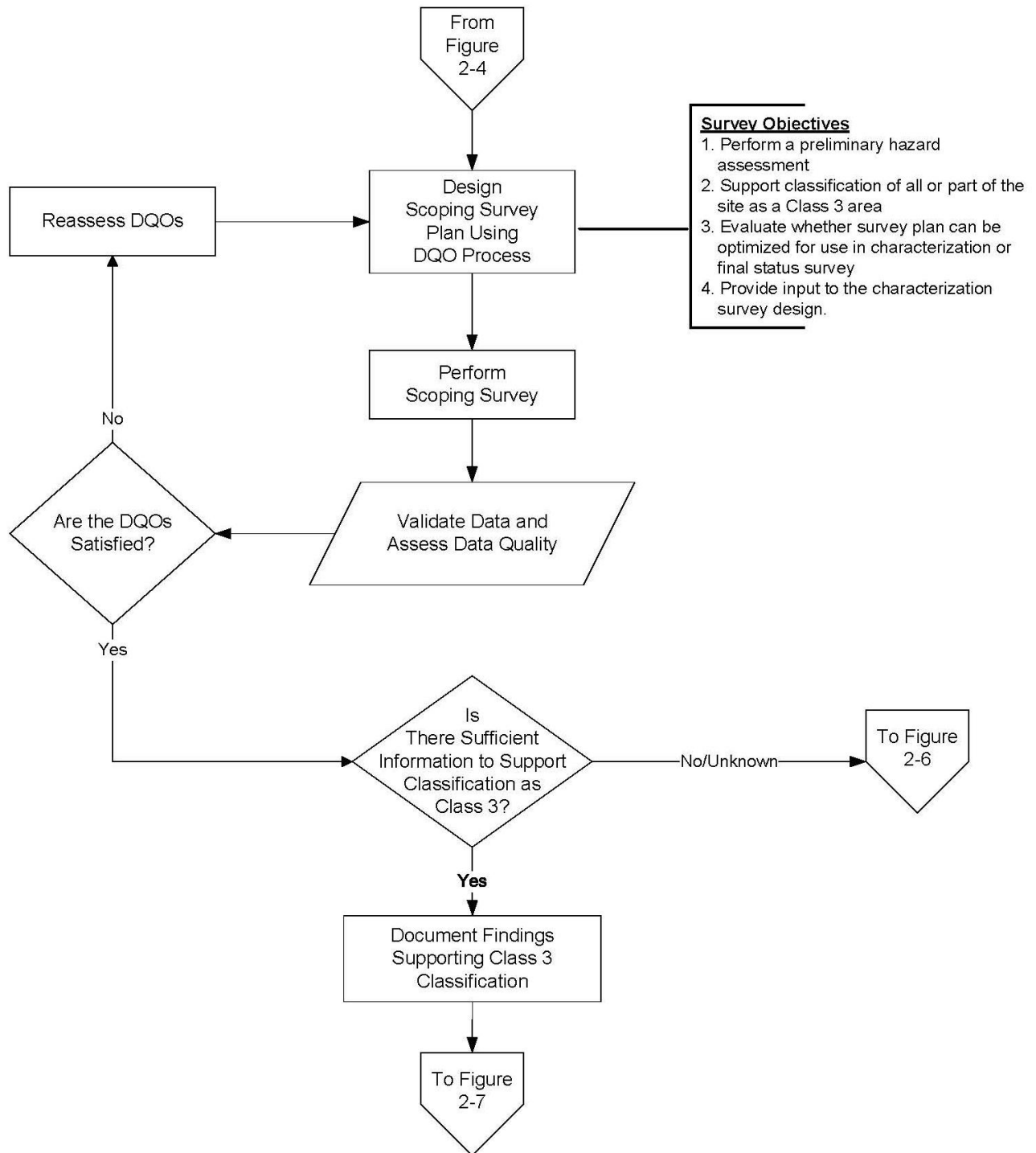
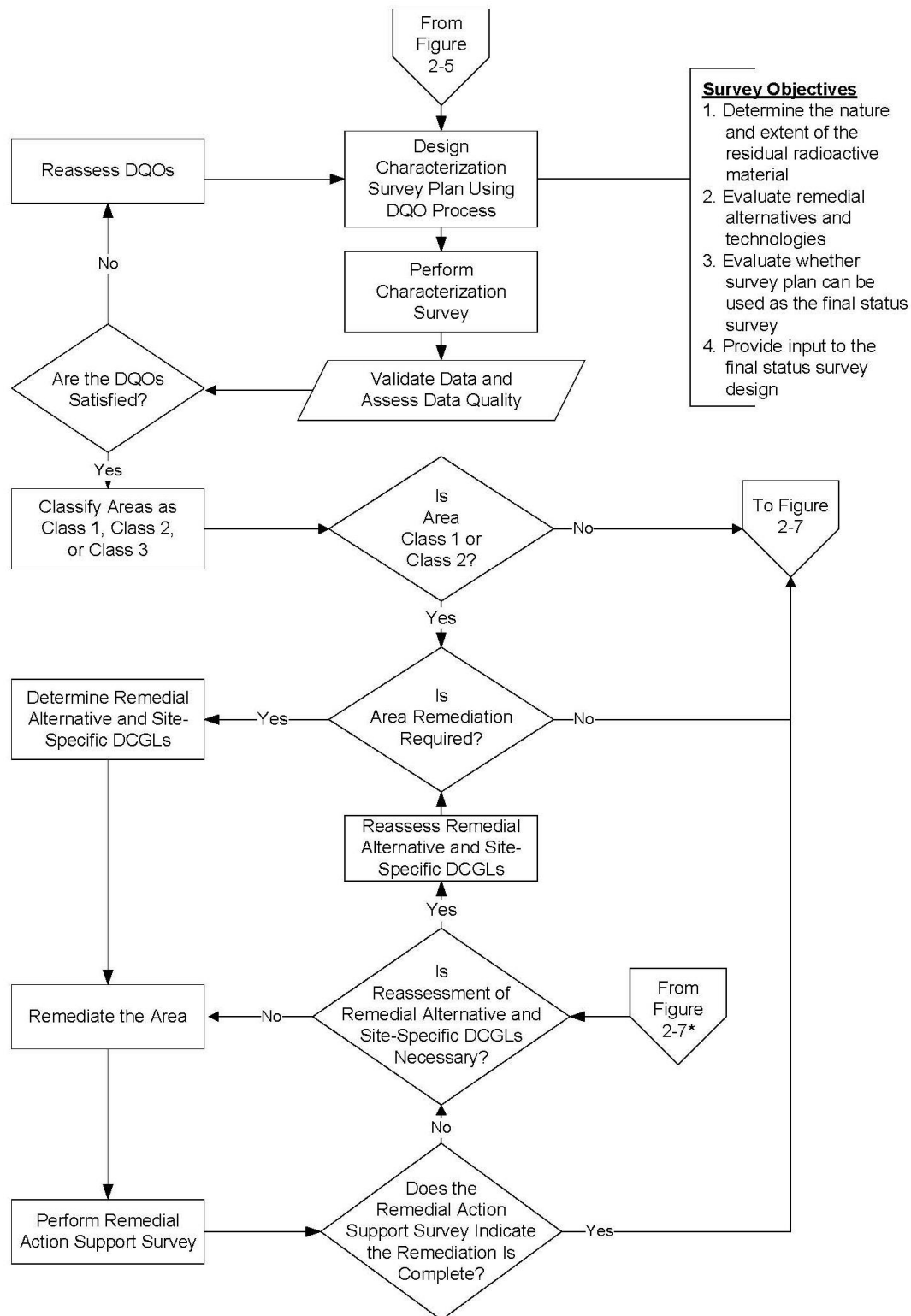
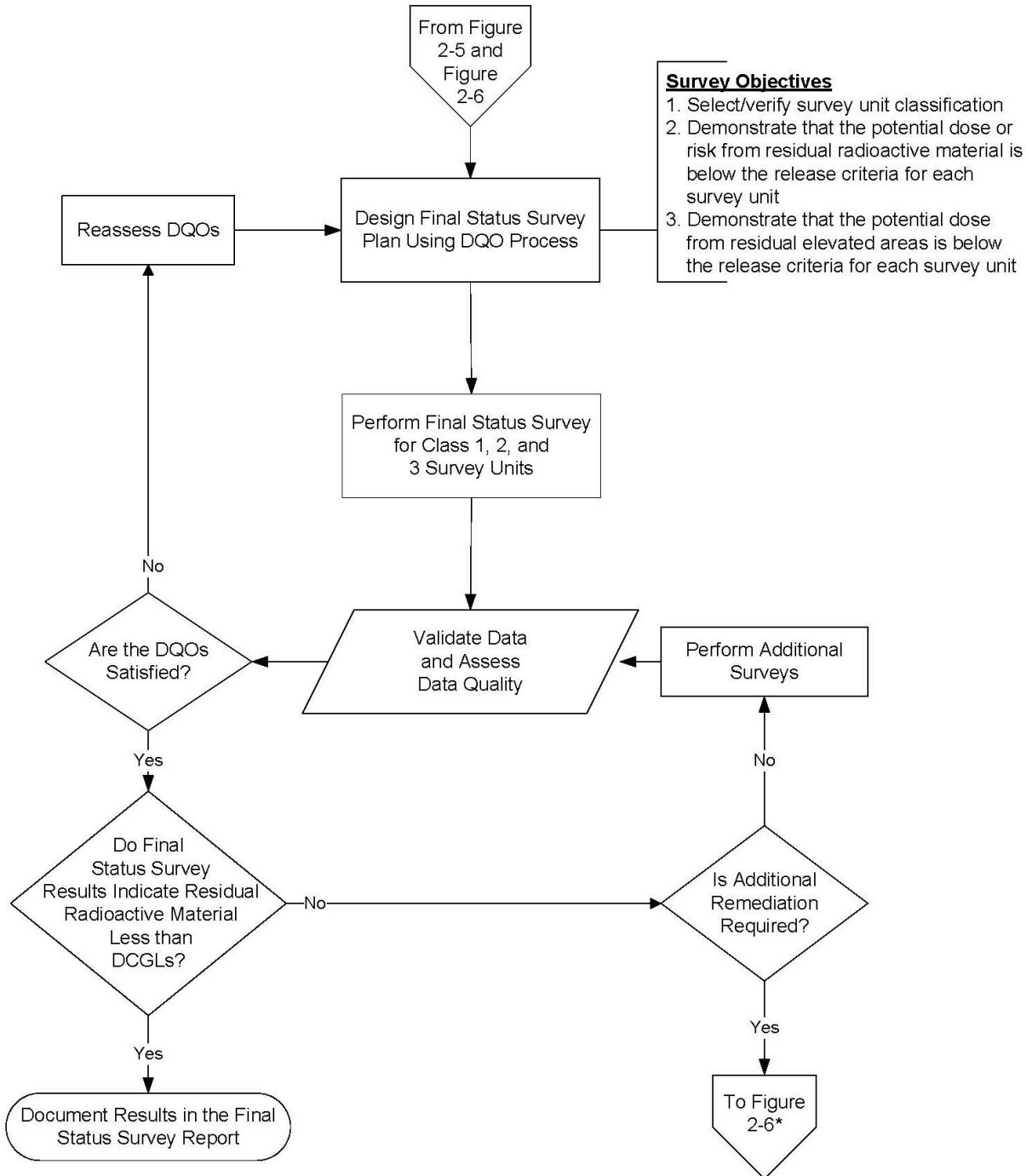


Figure 2-5 The Scoping Survey Portion of the RSSI Process



* The point where survey units that fail to demonstrate compliance in the FSS in Figure 2-7 re-enter the process

Figure 2-6 The Characterization and Remedial Action Support Survey Portion of the RSSI Process



* Connects with the remedial action support survey portion of the process in Figure 2-6

Figure 2-7 The FSS Portion of the RSSI Process

2.4.1 Site Identification

Often, sites where radioactive material is known or suspected to have been used or stored are readily identified before decommissioning or cleanup. Any facility preparing to terminate a

U.S. Nuclear Regulatory Commission (NRC) or Agreement State license may be identified as a site. Formerly terminated NRC licenses may also become sites for the EPA Superfund Program. Portions of military bases or U.S. Department of Energy (DOE) facilities may be identified as sites based on records of authorization to possess or handle radioactive materials. Where records are incomplete, site identification can be more difficult. In addition, information obtained during the performance of survey activities may identify additional potential radiation sites related to the site being investigated. More detailed information on site identification is provided in **Section 3.3**.

2.4.2 Historical Site Assessment

The primary purpose of the HSA is to collect existing information concerning the site and its surroundings.

The HSA has the following primary objectives:

- Identify potential sources of residual radioactive material.
- Determine whether sites pose an imminent threat to human health and the environment.
- Differentiate impacted from non-impacted areas.
- Provide input to scoping and characterization survey designs.
- Provide an assessment of the likelihood of migration of radioactive material.
- Identify additional potential sites containing radioactive material related to the site being investigated.

The HSA typically consists of three phases: identification of a candidate site, preliminary investigation of the facility or site, and site visits or inspections. Information collected during the HSA is then used to evaluate the site.

2.4.3 Scoping Survey

If the data collected during the HSA indicate that an area is impacted, a scoping survey may be performed. Scoping surveys provide site-specific information based on limited measurements.

The scoping survey has the following primary objectives:

- Perform an initial assessment of the radiological characteristics at the site.
- Support classification of all or part of the site as a Class 3 area, if appropriate.
- Evaluate whether the survey plan can be optimized for use in the characterization survey or FSS.
- Provide data to complete the site prioritization scoring process (Comprehensive Environmental Response, Compensation, and Liability Act [CERCLA] and Resource Conservation and Recovery Act [RCRA] sites only).
- Provide input to the characterization survey design, if necessary.

Scoping surveys are often conducted after the HSA is completed and typically consist of judgment measurements based on the HSA data. If the results of the HSA indicate that an area is Class 3 and no residual radioactive material is found during a scoping survey, the area may be classified as Class 3, and a Class 3 FSS is performed. If the scoping survey locates residual radioactive material, the area may be considered as Class 1 or Class 2 for the FSS, and a characterization survey is typically performed. Information should be collected to identify situations that require immediate radiological attention. For sites where the CERCLA requirements are applicable, the scoping survey should collect sufficient data to complete the Hazard Ranking System scoring process. For sites where the RCRA requirements are applicable, the scoping survey should collect sufficient data to complete the National Corrective Action Prioritization System scoring process. Sites that meet the National Contingency Plan criteria for a removal should be referred to the Superfund removal program (EPA 1996c).

Appendix F compares the MARSSIM approach to CERCLA and RCRA requirements.

2.4.4 Characterization Survey

If the results of the HSA and scoping survey indicate that an area could be classified as Class 1 or Class 2 for the FSS, a characterization survey may be warranted. The characterization survey is planned based on the HSA and any scoping survey results. This type of survey typically is a detailed radiological environmental characterization of the area.

The characterization survey has the following primary objectives:

- Determine the nature and extent of the residual radioactive material.
- Collect data to support evaluation of remedial alternatives and technologies.
- Support a hazard assessment of the potential dose and risk to workers or the public during remediation.
- Evaluate whether the survey plan can be optimized for use in the FSS.
- Support remedial investigation/feasibility study requirements (CERCLA sites only) or facility investigation/corrective measures study requirements (RCRA sites only).
- Provide input to the FSS design.

The characterization survey can be the most comprehensive of all the survey types and typically generates the most data. It can include preparing a reference grid, taking systematic or judgment measurements, and performing surveys of different media (e.g., surface soils, interior and exterior surfaces of buildings). The decision as to which media will be surveyed is site specific and will be addressed throughout the RSSI process.

2.4.5 Remedial Action Support Survey

If an area is adequately characterized and has concentrations of residual radioactive material above the DCGLs, a remediation plan should be prepared. A remedial action support survey is performed while remediation is being conducted and guides the remediation in a real-time mode.

Remedial action support surveys are conducted to do the following:

- Support remediation activities.
- Determine when a site or survey unit is ready for the FSS.
- Provide updated estimates of site-specific parameters used for planning the FSS.

This manual does not provide information on the routine operational surveys used to support remediation activities. The determination that a survey unit is ready for an FSS following remediation is an important step in the RSSI process. In addition, remedial activities result in changes to the distribution of residual radioactive material within the survey unit. For most survey units, the site-specific parameters used during FSS planning (e.g., variability in the radionuclide concentration, probability of small areas of elevated activity) will need to be re-established following remediation. Obtaining updated values for these critical parameters should be considered when planning a remedial action support survey.

2.4.6 Final Status Survey

The FSS is used to demonstrate compliance with release criteria. This type of survey is the major focus of this manual.

The FSS has the following primary objectives:

- Verify that survey unit classification is correct.
- Demonstrate that the total potential dose or risk from all residual radioactive material in each survey unit is below the release criteria.
- Demonstrate that the potential dose or risk from any small areas of elevated concentration of radioactive material is below the release criteria for each survey unit, if necessary.

The FSS provides data to demonstrate that all radiological parameters satisfy the established guideline values and ALs. Data from other surveys conducted during the RSSI process—such as scoping, characterization, and remedial action support surveys—can provide valuable information for planning an FSS, provided they are of sufficient quality.

Professional judgment in sampling is often used for locating and characterizing the extent of residual radioactive material at a site. However, MARSSIM focuses on planning the FSS, which uses a more systematic approach to sampling. Systematic sampling is based on rules that endeavor to achieve the representativeness in sampling consistent with the application of statistical tests.

2.4.7 Regulatory Agency Confirmation and Verification Survey

The regulatory agency responsible for the site often confirms whether the site may be released. Terms for this process can include confirmatory surveys or independent verification. This confirmation may be accomplished by the agency or an impartial party either as an ongoing activity during site remediation or after remediation and the FSS have been completed. Although some actual measurements may be performed, much of the work required for confirmation and verification will involve evaluation and review of documentation and data from survey activities, though the evaluation may include site visits to observe survey and measurement procedures or split-sample analyses by the regulatory agency's laboratory.

Therefore, accounting for confirmation and verification activities during the planning stages is important to each type of survey. In some cases, an impartial party may perform post-remedial sampling and analysis. The review of survey results should include verifying that the DQOs and MQOs are met, evaluating the analytical data used to demonstrate compliance, and verifying that the statistical test results support the decision to release the site.

2.5 Demonstrating Compliance with Dose- or Risk-Based Criteria

MARSSIM presents a process for demonstrating compliance with dose- or risk-based criteria. The RSSI process provides flexibility in planning and performing surveys based on site-specific considerations. Dose- or risk-based criteria usually allow one to account for radionuclide and site-specific differences.

The FSS is designed to demonstrate compliance with the release criteria. The earlier surveys in the RSSI process are performed to support decisions and assumptions used in the design of the FSS. These preliminary surveys (e.g., scoping, characterization) may have other objectives in addition to compliance demonstration that need to be considered during survey planning but that are not fully discussed in this manual. For this reason, MARSSIM focuses on FSS design. To allow maximum flexibility in the survey design, MARSSIM provides information on designing a survey using the RSSI process. This allows users with few resources available for planning to develop an acceptable survey design. The following sections present the rationale for the development of the information in MARSSIM. Users with available planning resources may investigate alternative survey designs for site-specific applications using the information provided in **Section 2.6**.

2.5.1 The Decision to Use Statistical Tests

The objective of compliance demonstration is to provide an acceptable level of confidence that the release criteria are not exceeded. As previously stated, 100 percent confidence in a decision cannot be proven because the data always contain some uncertainty. The use of statistical methods is necessary to provide a quantitative estimate of the probability that the average concentration of the radioactive material results in an exceedance of the release criteria. Statistical methods allow for control of the probability of making decision errors and a scientifically defensible extrapolation from a set of measurements to the survey unit (EPA 1994b).

Clearly stating the null hypothesis is necessary before statistical hypothesis testing can be performed. MARSSIM provides the option to establish the null hypothesis under either Scenario A or Scenario B. The Scenario A null hypothesis in MARSSIM is that the concentration of residual radioactive material in the survey unit exceeds the release criteria. The Scenario B null hypothesis in MARSSIM is that the concentration of residual radioactive material in the survey unit does not exceed the release criteria. Sufficient evidence is needed to show that the site does or does not meet the release criteria, depending on the scenario selected. This evidence of proof is particularly significant for Scenario B (i.e., sufficient power to reject the null hypothesis) to ensure that a site that does not meet the release criteria is not released due to an inadequate survey or design.

Because Scenario B assumes a site meets the release criteria until proven otherwise, it should only be used when Scenario A is not a viable method and regulators have agreed on the use of Scenario B. Regardless of the scenario selected, the probability of rejecting the null hypothesis (i.e., the statistical power) will depend on the variability in the survey unit and the tolerable Type II error (i.e., β or false negative). Under Scenario A, this type of decision error can result in

deciding that a survey unit does not meet the release criteria when it actually does. However, under Scenario B, this type of decision error can result in deciding that a survey unit does meet the release criteria when it actually does not. For this reason, the value of β under Scenario B should be chosen carefully and in consultation with regulatory authorities.

Because inadequate statistical power under Scenario B can result in a decision error that a survey meets release criteria when it does not, individuals designing a MARSSIM survey using Scenario B should make conservative assumptions for σ so that, even if the variability in the survey unit is higher than expected, the power of the resulting survey ($1-\beta$) will still be sufficient to ensure that survey units with residual radioactive material in excess of the DCGL will be discovered at least $1-\beta$ percent of the time (refer to Appendix E for examples). To ensure adequate statistical power, a retrospective power analysis that indicates that regulatory agency requirements for β were met needs to be completed after Scenario B MARSSIM surveys.

Chapter 8 and **Appendix M** give more information on performing retrospective power analyses.

The information needed to perform a statistical test is determined by the assumptions used to develop the test. MARSSIM recommends the use of nonparametric statistical tests because these tests use fewer assumptions and, consequently, require less information to verify these assumptions. If a large number of measurements will be made, such as when site-specific scanning surveys are performed, then MARSSIM recommends comparison to a UCL. If the radionuclide is not part of the natural background and radionuclide-specific measurements will be made, MARSSIM recommends the Sign test. If the radionuclide is part of the natural background, or radionuclide-specific measurements will not be made, MARSSIM recommends the WRS test. For Scenario B, MARSSIM also recommends the Quantile test and, as stated in the paragraph above, a retrospective power analysis. These additional tests provide assurance that when the null hypothesis is not rejected, it is not because there is insufficient power in the statistical tests. The retrospective power analysis can also be useful for Scenario A in identifying the reasons why the null hypothesis was not rejected.

Site conditions can potentially affect the validity of statistical tests. The distribution of residual radioactive material is particularly of concern. Is the residual radioactive material distributed uniformly, or is it located in small areas? Is the residual radioactive material present in the surface soil or on building surfaces, or does it extend into the subsurface? MARSSIM addresses only surface soil and building surfaces for the FSS to demonstrate compliance. This represents a situation that is expected to commonly occur at sites with residual radioactive material, and it allows the survey design to account for the ability to directly measure surface radioactivity using scanning techniques. Radioactive material in other media may be identified during the HSA or preliminary surveys (i.e., scoping, characterization, remedial action support). If radioactive material in other media (e.g., subsurface soils) is identified, methodologies for demonstrating compliance other than those described in this manual may need to be developed or evaluated. For materials and equipment, a supplement to MARSSIM is available, the Multi-Agency Radiation Survey and Assessment of Materials and Equipment (MARSAME) manual (NRC 2009). Situations where scanning techniques may not be effective (e.g., volumetric building residual radioactivity and subsurface radioactive material) are discussed in existing guidance (EPA 1989a, 1994a, 2001; NRC 2012b, 2022a, 2024a).

2.5.1.1 Small Areas of Elevated Activity

While the development of DCGLs is outside the scope of MARSSIM, this manual assumes that DCGLs will be developed using exposure pathway models that assume a relatively uniform

distribution of radioactive material. While this represents an ideal situation, small areas of elevated activity are a concern at many sites.

MARSSIM addresses the concerns regarding small areas of elevated activity by using a simple comparison to an investigation level as an alternative to statistical methods. Using the EMC is a conservative approach, because additional investigation is required unless every measurement is below the investigation level. For Class 1 survey units, the investigation level for this comparison is called the $DCGL_{EMC}$. The $DCGL_{EMC}$ can be higher than the $DCGL_W$ due to the lower dose or risk resulting from a smaller area of radioactive material. In the case of multiple areas of elevated activity in a survey unit, a posting plot (discussed in **Section 8.2.2.2**) or similar representation of the distribution of activity in the survey unit can be used to determine any pattern in the location of these areas.

If elevated levels of residual radioactive material are found in an isolated area in addition to residual radioactive material distributed relatively uniformly across the survey unit, the unity rule (**Section 4.4**) can be used to ensure that the total dose or risk meets the release criteria. If there is more than one of these areas, a separate term can be included in the calculation for each area of elevated activity. As an alternative to the unity rule, the dose or risk from the actual distribution of residual radioactive material can be calculated if there is an appropriate exposure pathway model available. Note that these considerations generally only apply to Class 1 survey units, since areas of elevated activity should not be present in Class 2 or Class 3 survey units. **Section 4.5.3.7** discusses criteria for areas of elevated activity.

2.5.1.2 Relatively Uniform Distribution of Residual Radioactive Material

As discussed in **Section 2.5.1.1**, the development of a DCGL starts with the assumption of a relatively uniform distribution of residual radioactive material. Some variability in the measurements is expected. This is primarily due to a random spatial distribution of residual radioactive material and uncertainties in the measurement process.

With a site-specific scanning survey, the UCL for the mean derived from the arithmetic mean, the variance, and the number of the measurements would represent the parameter of interest for demonstrating compliance. Survey units where a large number of measurements are taken can use this technique. **Section 8.5** gives instructions on generating a UCL from site-specific scanning survey data.

When statistical sampling is performed, whether the radionuclide of concern is present in background helps determine the form of the statistical test. The WRS test is recommended for comparisons of survey unit radionuclide concentrations with background. When the radionuclide of concern is not present in background, the Sign test is recommended. **Section 8.3** and **Section 8.4** contain instructions on performing these tests.

The WRS and Sign tests are designed to determine whether the level of residual radioactive material uniformly distributed throughout the survey unit exceeds the $DCGL_W$. Because these methods are based on the rank of data points or the number of measurements below the DCGL, the statistical tests are tests of the median. When the underlying measurement distribution is symmetric, the mean is equal to the median. When the underlying distribution is asymmetric, these tests are still true tests of the median but only approximate tests of the mean (Hardin and Gilbert 1993). The assumption of symmetry is less restrictive than that of normality, because the normal distribution is itself symmetric. If, however, the measurement distribution is skewed to the right, the mean will generally be greater than the median. In severe cases, the mean may exceed the $DCGL_W$ while the median does not. For this reason, MARSSIM recommends

comparing the arithmetic mean of the survey unit data to the $DCGL_W$ as a first step in the interpretation of the data (refer to **Section 8.2.2.1**). A mean survey unit concentration less than the $DCGL_W$ is a necessary, but not sufficient, condition for a survey unit to meet the release criteria.

The WRS test compares the distribution of a set of measurements in a survey unit to that of a set of measurements in a reference area. In Scenario A, the test is performed by first adding the value of the $DCGL_W$ to each measurement in the reference area. The values in the combined set of survey unit data and adjusted reference area data are listed, or ranked, in increasing numerical order. If the ranks of the adjusted reference site measurements are significantly higher than the ranks of the survey unit measurements, the survey unit demonstrates compliance with the release criteria.

The Quantile test is a statistical test to account for non-uniform distributions of radioactive material. The Quantile test was developed to detect differences between the survey unit and the reference area that consist of a shift to higher values in only a fraction of the survey unit. The Quantile test is only performed when Scenario B is used, and only if the null hypothesis is not rejected for the WRS test. Using the Quantile test and the WRS test in tandem results in higher statistical power to identify survey units that do not meet the release criteria than either test by itself.

The Sign test compares the distribution of a set of measurements in a survey unit to a fixed value, namely the $DCGL_W$. First, the value for each measurement in the survey unit is subtracted from the $DCGL_W$. The resulting distribution is tested to determine whether the center of the distribution is greater than zero. If the adjusted distribution is significantly greater than zero, the survey unit demonstrates compliance with the release criteria.

Chapter 8 and **Appendix I** provide information on performing the statistical tests and presenting graphical representations of the data.

2.5.1.3 Discrete Radioactive Particles

Discrete radioactive particles (DRPs) can be characterized broadly as a small, localized (discrete) volume of relatively highly radioactive material (compared with the surrounding, more dispersed radioactivity for a site). DRPs typically constitute a single particle or a few particles significantly more radioactive than the average low-level concentration of the surrounding soil or materials. From a general standpoint, the discrete particles will significantly exceed any $DCGL_{EMC}$ for an area. While the particles can have unique characteristics, typically DRPs are less than 1 millimeter in any dimension, are generally insoluble in water, and have high activity (NRC 2024b, 2024c).

The planning team should check with the appropriate regulatory agency to determine its expectations for identifying and handling DRPs. DRPs are generally outside the scope of MARSSIM from the perspective of survey design and consideration for unconditional site release. However, an encounter with DRPs during the RSSI process does carry with it the need to address potential worker health and safety concerns, as well as potential future exposures to members of the public should the site be released with known DRPs. Issues with DRPs should be discussed early with the responsible regulatory agency, so that appropriate consideration can be given to measures for identifying, quantifying, and controlling them.

The potential for DRPs should be identified early in the site characterization phase, starting with the HSA to identify past events that could lead to the generation (and dispersal) of DRPs.

Follow-up investigations should be taken for further determining the likelihood of DRPs and measures needed for detecting and controlling them. DRPs can also be created during remediation itself, such as through grinding or welding highly radioactive components. Guidance on remediation of DRPs is outside the scope of MARSSIM.¹⁰ However, recognizing the radiological hazards, appropriate radiation safety measures should be carefully discussed with responsible agencies.

Given the potential health hazards arising from contact exposures to DRPs, survey activities aimed at discovering particles deemed to be hazardous should be conducted early in the sequence of survey types, for example, as part of the scoping surveys of areas likely to contain DRPs. Based on the definitions in MARSSIM **Section 2.2**, areas of sites expected to contain DRPs will be appropriately identified as Class 1, invoking the necessary planning and 100 percent survey coverage. The EMC process should not be applied to DRPs. However, removal of DRPs may enable the EMC process to be used appropriately if it can be shown that the remaining elevated areas reflect dispersed radioactive materials and not highly localized DRPs.

DRPs are most likely to be discovered by scanning techniques, and the DQO and MQO processes should identify instrument response patterns that would indicate the presence of DRPs. If historical analyses or preliminary surveys reveal the presence of DRPs, then the MQOs for all remaining survey activities should anticipate the measurement of area/volumetric and point sources. This naturally leads to establishing separate measurement detection limits and measurement uncertainty requirements that may have an effect on the selection of instrumentation and scanning procedures.

2.5.2 Categorization and Classification

The process of categorizing and classifying a survey unit determines the level of survey effort based on the potential for residual radioactive material. Areas are initially categorized as impacted or non-impacted based on the results of the HSA. Non-impacted areas have no reasonable potential for residual radioactive material and require no further evidence to demonstrate compliance with the release criteria, although documentation of the decision to categorize an area as non-impacted would still be needed. When planning the FSS, impacted areas may be further classified into survey units. If a survey unit is given a less restrictive classification than is warranted, the potential for making decision errors increases. For this reason, all impacted areas are initially assumed to be Class 1. Class 1 areas require the highest level of survey effort because they are known to have concentrations of residual radioactive material above the DCGL_W, or the residual radioactive material concentrations are unknown.

Information indicating the potential or known residual radioactive material concentration is less than the DCGL_W can be used to support reclassification of an area or survey unit as Class 2 or Class 3.

A certain amount of information is necessary to demonstrate compliance with the release criteria. The amount of this information that is available and the level of confidence in this information are reflected in the area classification. The initial assumption for affected areas is that none of the necessary information is available. This results in a default Class 1 classification.

¹⁰ Sources of further information include Hamby et al. 2023, Benke et al. 2022, Altic and King 2023, and NRC 2024b and 2024c.

Not all of the information available for an area will have been collected for purposes of compliance demonstration. For example, data are collected during characterization surveys to determine the extent, and not necessarily the amount, of residual radioactive material. This does not mean that the data do not meet the objectives for compliance demonstration, but it may mean that statistical tests would be of little or no value because the data have not been collected using appropriate protocols or design. Rather than discard potentially valuable information, MARSSIM allows for a qualitative assessment of existing data (**Chapter 3**). Non-impacted areas represent areas where all of the information necessary to demonstrate compliance is available from existing sources. For these areas, no statistical tests are considered necessary. A classification as Class 2 or Class 3 indicates that some information describing the potential for residual radioactive material is available for that survey unit. The data collection recommendations are modified to account for the information already available, and the statistical tests are performed on the data collected during the FSS. The HSA (described in **Chapter 3**) is used to provide an initial categorization for the area of impacted or non-impacted based on existing data and professional judgment.

2.5.3 Design Considerations for Small Areas of Elevated Activity

Scanning surveys are typically used to identify small areas of elevated activity. The size of the area of elevated activity that the survey is designed to detect affects the $DCGL_{EMC}$, which in turn determines the ability of a scanning technique to detect these areas. Larger areas have a lower $DCGL_{EMC}$ and are more difficult to detect than smaller areas.

The percentage of the survey unit to be covered by scans is also an important consideration. For an area with 100 percent coverage, the entire surface area of the survey unit has been covered by the field of view of the scanning instrument. Such a level of coverage provides a high level of confidence that all areas with elevated concentrations of radioactive material have been identified, and it is recommended for all Class 1 survey units. If the available information concerning the survey unit provides information demonstrating that areas of elevated concentrations of radioactive material may not be present, the survey unit may be classified as Class 2 or Class 3. Because there is already some level of confidence that areas of elevated activity are not present, 100 percent coverage may not be necessary to demonstrate compliance. **Section 5.3.6** provides information on determining the scanning area for Class 2 and 3 areas. For Class 2 areas, the scanning area will be based on the width of the gray region and the uncertainty, typically somewhere between 10–100 percent of the area, with a combination of systematic scanning and scanning in areas judged to have the highest potential for residual radioactive material. For Class 3 areas, the scanning area is the same as for Class 2 survey units, except for surveys that collect samples or direct measurements, or both, in which case the scanning area can be less than 10 percent and is typically only in areas judged to have the highest potential for residual radioactive material. A general recommendation when deciding which areas to scan is to always err in the direction that minimizes the decision error. In general, scanning the entire survey unit is less expensive than finding areas of elevated concentrations of radioactive material later in the survey process. Finding such areas will lead to performing additional surveys due to survey unit misclassification.

Another consideration for scanning surveys is the selection of scanning locations. This is not an issue when 100 percent of the survey unit is scanned. Whenever less than 100 percent of the survey unit is scanned, a decision must be made on what areas should be scanned. The general recommendation is that when large amounts of the survey unit are scanned (e.g., more than 50 percent), the scans should be systematically performed along transects of the survey unit. When smaller amounts of the survey unit are scanned, selecting areas based on

professional judgment may be more appropriate and efficient for locating areas of elevated activity (e.g., drains, ducts, piping, ditches, floor joints, sumps). A combination of 100 percent scanning in portions of the survey unit based on professional judgment and less coverage (e.g., 20–50 percent) for all remaining areas may result in an efficient scanning survey design for some survey units. **Section 5.3.6** contains further detail on determining the scanning area.

2.5.4 Design Considerations for Relatively Uniform Distributions of Residual Radioactive Material

The survey design for areas with relatively uniform distributions of residual radioactive material is primarily controlled by classification and the requirements of the statistical test. Again, the recommendations provided for Class 1 survey units are designed to minimize the decision error. Recommendations for Class 2 or Class 3 surveys may be based on existing information if the level of confidence associated with this information is sufficient.

The first consideration is the identification of survey units. The identification of survey units may be accomplished early (e.g., scoping) or late (e.g., final status) in the survey process but must be accomplished before performing an FSS. Early identification of survey units can help in planning and performing surveys throughout the RSSI process. Late identification of survey units can prevent misconceptions and problems associated with reclassification of areas based on the results of subsequent surveys. The area of an individual survey unit is determined based on the area classification and modeling assumptions used to develop the DCGL_W. **Section 4.6.2** discusses the identification of survey units.

When performing surveys for which the Sign or WRS test is used, another consideration is the estimated number of measurements to demonstrate compliance using the statistical tests. **Sections 5.3.3** and **5.3.4** describe the calculations used to estimate the number of measurements. These calculations use information that is usually available from planning or from preliminary surveys (i.e., scoping, characterization, remedial action support).

The following information is needed to perform these calculations:

- acceptable values for the probabilities of making Type I or Type II decision errors
- the estimates of the measurement variability in the survey unit (σ_s) and the reference area (σ_r) if necessary
- the shift (Δ)

MARSSIM recommends that site-specific values be determined for each of these parameters. When selecting site-specific values for decision error rates and the shift (Δ), MARSSIM recommends that an initial value be selected and adjusted to develop a survey design that is appropriate for a specific site. For Scenario A, the DCGL_W is chosen as the UBGR, and the LBGR is typically chosen to represent a conservative (slightly higher) estimate of the average concentration of residual radioactive material remaining in the survey unit at the beginning of the FSS. For Scenario B, the AL is chosen as the LBGR and the UBGR is the DL, a value that represents how much effort will be taken to determine there is no residual radioactive material above the AL. For decision error rates, a value that minimizes the risk of making a decision error is recommended for the initial calculations. The number of measurements can be recalculated using different values for the LBGR, DL, or decision error rates until an appropriate survey

design is obtained.¹¹ A prospective power curve (refer to **Appendix M**) that considers the effects of these parameters can be very helpful in designing a survey and considering alternative values for these parameters and is highly recommended.

To ensure that the desired power is achieved with the statistical test and to account for underestimated values of the measurement variability, MARSSIM recommends increasing the estimated number of measurements calculated using the formulas in **Sections 5.3.3** and **5.3.4** by 20 percent to account for a reasonable amount of uncertainty in the parameters used to calculate and still allow flexibility to account for some lost or unusable data. Insufficient numbers of measurements may result in failure to achieve the DQO for power and result in increased Type II decision errors, where survey units below the release criteria fail to demonstrate compliance in Scenario A. Of more concern to the regulator, Type II decision errors for Scenario B lead to the incorrect release of survey units with average or median concentrations above the release criteria.

Once survey units are identified and the number of measurements is determined, measurement locations should be selected. The statistical tests assume that the measurements are taken from random locations within the survey unit. A systematic grid with a random starting point is used for Class 1 and Class 2 survey units. A systematic grid with a random starting point or a random survey design is used for Class 3 survey units.

2.5.5 Developing an Integrated Survey Design

To account for assumptions used to develop the $DCGL_w$ and the possibility of small areas of elevated activity, if required, an integrated survey design should be developed to include all the design considerations. An integrated survey design combines a scanning survey for areas of elevated activity with random measurements for relatively uniform distributions of radioactive material. **Table 2-2** presents the recommended conditions for demonstrating compliance for an FSS based on classification (refer to **Table 5-5** for further detail on the scanning approach).

¹¹ Note that for some areas, an appropriate survey design may not be possible within initial survey design constraints, such as the requirements for α and survey power ($1-\beta$), available funds, and estimated values for the average and variability of the concentration of residual radioactive material remaining at the site. In these cases, the planning team will have to reconsider the survey design constraints or its decision to conduct an FSS, in consultation with the regulator.

Table 2-2 Recommended Conditions for Demonstrating Compliance Based on Survey Unit Classification for an FSS

Survey Unit Classification	Statistical Test(s) ^a	Elevated Measurement Comparison	Sampling and Direct Measurements ^b	Scanning Approach
Impacted: Class 1	Yes	Yes	Systematic	100% Coverage
Impacted: Class 2	Yes	Yes	Systematic	10–100% Systematic/Judgmental
Impacted: Class 3	Yes	Yes	Random or Systematic	10–100% ^c Judgmental
Non-Impacted	No	No	No	None

^a Statistical tests may consist of the Sign test, WRS test, Quantile test, or comparison to a UCL, depending on the survey design chosen.

^b For site-specific scanning surveys, sampling and direct measurements may be minimized.

^c For surveys using sampling or direct measurements (or both), this percentage can be lower than 10 percent judgmental.

Random-start systematic grids are used for Class 1 and Class 2 survey units because there is an increased probability of small areas of elevated activity. The use of a systematic grid allows the decision-maker to draw conclusions about the size of any potential areas of elevated activity based on the area between measurement locations, while the random starting point of the grid provides an unbiased method for determining measurement locations for the statistical tests. The random-start numbers should be furnished by an unbiased source to ensure that the survey results are similarly unbiased.

Random measurement patterns are used for Class 3 survey units to ensure that the measurements are independent and meet the requirements of the statistical tests.

Site-specific scanning surveys can be used in place of direct measurements or sampling (or both) and analysis if the scanning measurement system has an MDC that is less than 50 percent of the DCGL_W and meets requirements for measurement method uncertainty. When scanning is used alongside sampling or direct measurements, it is used to identify locations within the survey unit that exceed the investigation level. These locations are marked and receive additional investigations to determine the concentration, area, and extent of the residual radioactive material. For Class 1 areas, scanning surveys are designed to detect small areas of elevated activity that are not detected by the measurements using the systematic grids. For this reason, the measurement locations and the number of measurements may need to be adjusted based on the sensitivity of the scanning technique (refer to **Section 5.3.5**). This is also the reason for recommending 100 percent coverage for the scanning survey.

Scanning surveys in Class 2 areas are also performed primarily to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the measurement locations are not adjusted based on sensitivity of the scanning technique, and scanning is only performed in portions of the survey unit. The level of scanning effort should be proportional to the potential for finding areas of elevated activity. In Class 2 survey units that have concentrations of residual radioactive material closer to the release criteria or a higher variability across the survey unit, a larger portion of the survey unit would be scanned; for survey units that are closer to background or have a lower variability, scanning a smaller portion of the survey

unit may be appropriate. Class 2 survey units have a lower probability for areas of elevated activity than Class 1 survey units, but some portions of the survey unit may have a higher potential than others. Judgmental scanning surveys would focus on the portions of the survey unit with the highest probability for areas of elevated activity. If most of the survey unit has an equal probability for areas of elevated activity, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks are performed.

Class 3 areas have the lowest potential for areas of elevated activity. For site-specific scanning surveys, the scanning area and methodology are the same as for Class 2, but for surveys that contain both statistical sampling and scanning, scanning surveys should be performed in areas of highest potential (e.g., corners, ditches, drains) based on professional judgment. This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that no errors were made in the classification of the area.

2.6 Flexibility in Applying MARSSIM Approach

Section 2.5 describes the development of a generic survey design that applies the performance-based approach presented in **Sections 2.3–2.4** to design a survey for a site with residual radioactive material in surface soils, building surfaces, or both. Obviously, this design cannot be uniformly applied at every site with residual radioactive material, so flexibility has been provided in the form of a performance-based approach. This approach encourages the user to develop a site-specific survey design to account for site-specific characteristics. It is expected that most users will adopt the portions of the MARSSIM methodology that apply to their site. In addition, changes to the overall survey design that account for site-specific differences would be presented as part of the survey plan. The plan should also demonstrate that the extrapolation from measurements performed at specific locations to the entire site or survey unit is performed in a technically defensible manner.

Where **Section 2.5** describes the development of a generic survey design that will be applicable at most sites with residual radioactive material in surface soils, building surfaces, or both, this section describes the flexibility available within the MARSSIM for designing a site-specific survey design. Alternative methods for demonstrating compliance are briefly described, and references for obtaining additional information on these alternative methods are provided.

Figure 2-8 illustrates the RSSI process in terms of area classification and lists the major decision to be made for each type of survey. The flowchart demonstrates one method for quickly estimating the survey unit classification early in the MARSSIM process based on limited information. This figure is useful for visualizing the classification process, but site-specific characteristics may cause variation from this scheme. This illustration is not designed to comprehensively consider every possibility that may occur at individual survey units.

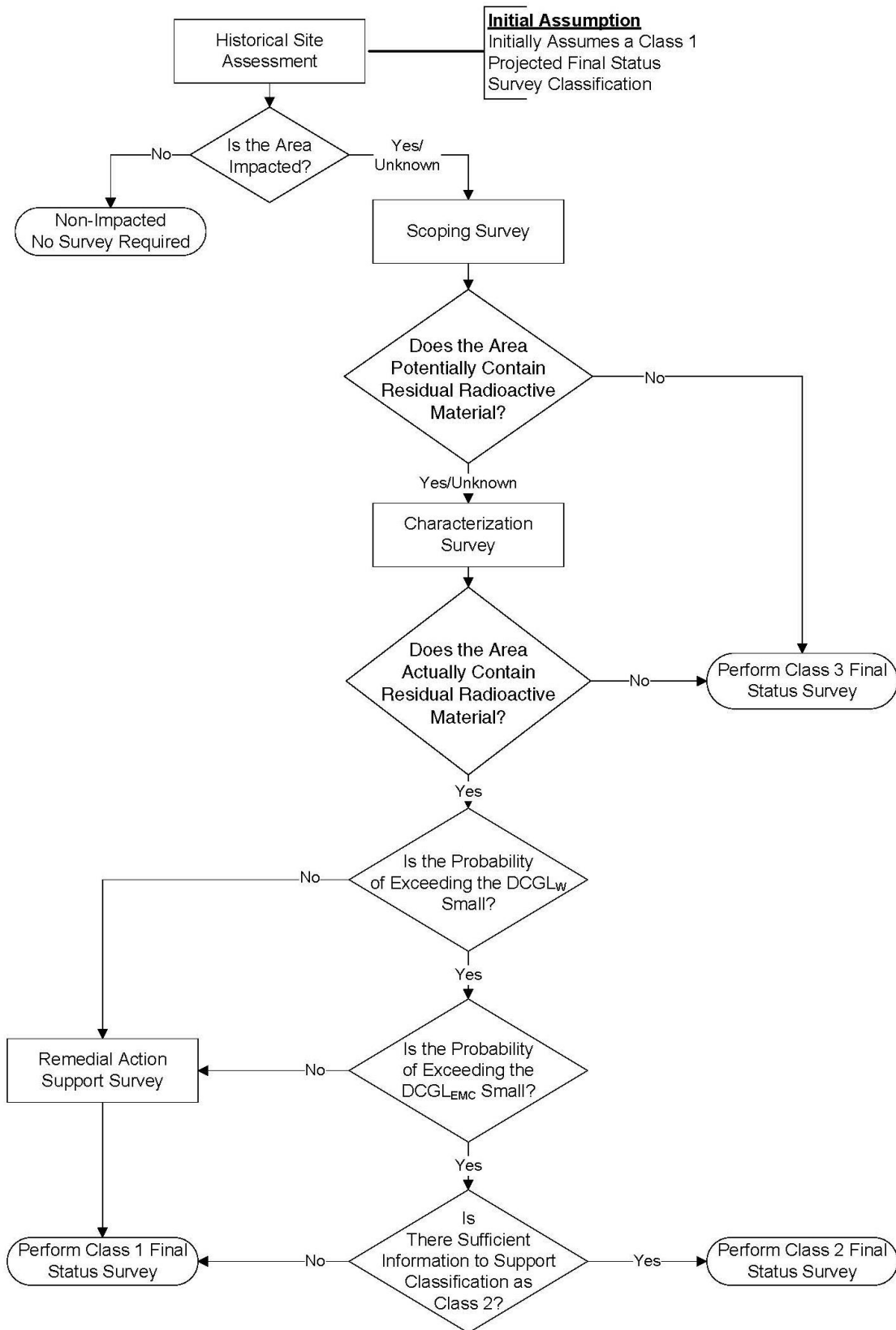


Figure 2-8 RSSI Process in Terms of Area Classification

2.6.1 Alternative Statistical Methods

MARSSIM encourages the use of statistics to provide a quantitative estimate of the probability of compliance with the release criteria at a site. While it is unlikely that any site will be able to demonstrate compliance with dose- or risk-based criteria without at least considering the use of statistics, MARSSIM recognizes that the use of statistical tests may not always provide the most effective method for demonstrating compliance. For example, MARSSIM recommends a simple comparison to an investigation level in place of complicated statistical tests to evaluate the presence of small areas of elevated activity.

MARSSIM recommends the use of nonparametric statistical tests for evaluating environmental data. There are two reasons for this recommendation: (1) Environmental data are usually not normally distributed, and (2) there is often a significant number of qualitative survey results (e.g., less than MDC). Either one of these conditions means that parametric statistical tests may not be appropriate. If one can demonstrate that the data are normally distributed and that there are sufficient results to support a decision concerning the survey unit, parametric tests will generally provide higher power (or require fewer measurements to support a decision concerning the survey unit). The tests to demonstrate that the data are normally distributed generally require more measurements than the nonparametric tests. EPA provides guidance on selecting and performing statistical tests to demonstrate that data are normally distributed (EPA 2006a). Guidance is also available for performing parametric statistical tests (NRC 1992; EPA 1989a, 1994a, 2006a).

There are a wide variety of statistical tests designed for use in specific situations. These tests may be preferable to the generic statistical tests recommended in MARSSIM when the underlying assumptions for these tests can be verified. **Table 2-3** lists several examples of statistical tests that may be considered for use at individual sites or survey units. It also includes a brief description of the tests and references for obtaining additional information. Applying these tests may require consultation with a statistician.

2.6.2 Integrating MARSSIM with Other Survey Designs

2.6.2.1 *Accelerated Cleanup Models*

There are a number of approaches designed to expedite site cleanups. These approaches can save time and resources by reducing sampling, preventing duplication of effort, and reducing inactive time periods between steps in a cleanup process. Although **Section 2.4** describes the RSSI process recommended in MARSSIM as one with seven principal steps, MARSSIM is not intended to be a serial process that would slow site cleanups. Rather, MARSSIM supports existing programs and encourages approaches to expedite site cleanups. Planning in MARSSIM promotes saving time and resources.

Table 2-3 Examples of Alternative Statistical Tests

Alternative Test 1—Sample Tests (No Reference Area Measurements)	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Student's <i>t</i>-Test	Normal	Parametric test for H_0 : Mean $< t$	<i>Guidance for Data Quality Assessment</i> , EPA QA/G-9, p. 3.2-2 (EPA 2006a).	Appropriate if data appear to be normally distributed and symmetric.	Relies on a non-robust estimator for μ and σ . Sensitive to outliers and departures from normality.
<i>t</i>-Test Applied to Logarithms	Lognormal	Parametric test for H_0 : Median $< t$	<i>Guidance for Data Quality Assessment</i> , EPA QA/G-9, p. 3.2-2 (EPA 2006a).	A well-known and easy-to-apply test. Useful for a quick summary of the situation if the data are skewed to right.	Relies on a non-robust estimator for σ . Sensitive to outliers and departures from lognormality.
Minimum Variance Unbiased Estimator for Lognormal Mean	Lognormal	Parametric estimates for mean and variance of lognormal distribution	<i>Statistical Methods for Environmental Pollution Monitoring</i> , p. 164 (Gilbert 1987).	A good parametric test to use if the data are lognormal.	Inappropriate if the data are not lognormal.
Chen Test	Skewed to right, including lognormal	Parametric test for H_0 : Mean > 0	<i>Journal of the American Statistical Association</i> (90), p. 767 (Chen 1995).	A good parametric test to use if the data are lognormal.	Applicable only for testing H_0 : "survey unit is clean." Concentrations must be significantly greater than 0 to fail. Inappropriate if the data are not skewed to higher values.

Alternative Test 1—Sample Tests (No Reference Area Measurements)	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Bayesian Approaches	Varies, but a family of probability distributions must be selected	Parametric test for H_0 : Mean < L	<i>Optimal Statistical Decisions</i> (DeGroot 2005).	Permits use of subjective “expert judgment” in interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
Bootstrap	No restriction	Nonparametric; uses resampling methods to estimate sampling variance	<i>The Annals of Statistics</i> (22), p. 2011–2030 (Hall and Mammen 1994).	Avoids assumptions concerning the type of distribution.	While interpreting results may be intuitive, the method may seem to be a black box compared to classical statistical methods for those not familiar with the approach.
Lognormal Confidence Intervals Using Bootstrap	Lognormal	Uses resampling methods to estimate one-sided confidence interval for lognormal mean	<i>The Statistician</i> (43), p. 395 (Angus 1994).	Nonparametric method applied within a parametric lognormal model.	Computer-intensive analysis is required. Accuracy of the results can be difficult to assess.

Alternative Test 2—Sample Tests (Reference Area Measurements Are Required)	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Student’s t-Test	Symmetric, normal	Parametric test for difference in means H_0 : $\mu_x < \mu_y$	<i>Guidance for Data Quality Assessment</i> , EPA QA/G-9, p. 3.3-2 (EPA 2006a).	Easy to apply. Performance for non-normal data are acceptable.	Relies on a non-robust estimator for σ ; therefore, test results are sensitive to outliers.

Alternative Test 2—Sample Tests (Reference Area Measurements Are Required)	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Mann-Whitney Test	No restrictions	Nonparametric test difference in location $H_0: \mu_x < \mu_y$	<i>Nonparametric Statistical Methods</i> (Hollander 2014).	Equivalent to the WRS test. Similar to resampling, because test is based on set of all possible differences between the two datasets.	Assumes that the only difference between the test and reference area median concentrations is a shift in location.
Kolmogorov-Smirnov	No restrictions	Nonparametric test for any difference between the two distributions	<i>Nonparametric Statistical Methods</i> (Hollander 2014).	A robust test for equality of two sample distributions against all alternatives.	May reject because variance is high, although mean is in compliance.
Bayesian Approaches	Varies, but a family of probability distributions must be selected	Parametric tests for difference in means or difference in variance	<i>Bayesian Inference in Statistical Analysis</i> (Box and Tiao 2011).	Permits use of “expert judgment” in the interpretation of data.	Decisions based on expert judgment may be difficult to explain and defend.
Two-Sample Quantile Test	No restrictions	Nonparametric test for difference in shape and location	<i>Statistical Methods for Evaluating the Attainment of Cleanup Standards, Vol. 3</i> , p. 7.1 (EPA 1994b).	Will detect whether survey unit distribution exceeds reference distribution in the upper quantiles.	Applicable only for testing H_0 : “survey unit is clean.” Survey unit residual radioactive material concentrations must be significantly greater than 0 to fail.

Alternative Test 2—Sample Tests (Reference Area Measurements Are Required)	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Sign Test when Background Is Present	No restrictions	Nonparametric test for difference in location assuming uniform background	<i>Decommissioning Health Physics: A Handbook for MARSSIM Users</i> , 2 nd Edition (Abelquist 2014).	None.	Less powerful than the WRS test because of assumptions concerning background distributions. Not recommended.*
Bootstrap and Other Resampling Methods	No restrictions	Nonparametric; uses resampling methods to estimate sampling variance	<i>The Annals of Statistics</i> (22), p. 2011 (Hall and Mammen 1994).	Avoids assumptions concerning the type of distribution. Generates informative resampling distributions for graphing.	While interpreting results may be intuitive, the method may seem to be a black box compared to classical statistical methods for those not familiar with the approach.

Alternative To Statistical Tests	Probability Model Assumed	Type of Test	Reference	Advantages	Disadvantages
Decision Theory	No restrictions	Incorporates loss function in the decision theory approach	<i>Statistical and Cost-Benefit Enhancements to the DQO Process for Characterization Decisions</i> , DOE/EM-0316 (DOE 1996).	Combines elements of cost-benefit analysis and risk assessment into the planning process.	Limited experience in applying the method to compliance demonstration and decommissioning. Computer-intensive analysis required.

* Subtraction of a single background concentration (e.g., average activity concentration in background) from each survey unit measurement is not recommended as background represents a distribution of values and a two-sample test is more appropriate.

Abbreviations: H_0 = null hypothesis; t = t -test statistic, L = Bayesian test statistic; μ = true mean; σ = standard deviation.

The following are examples of sites that used an integrated survey approach:

- Sandia National Laboratories in New Mexico used a combination of the observational approach, process knowledge, judgmental soil sampling, and Global Positioning System (GPS)/gamma survey techniques to identify and remediate potential residual radioactive material during execution of the Environmental Restoration Project there. Depleted uranium was almost exclusively the material of concern. There were 268 individual designated test locations on the site, ranging from tens of square meters to hundreds of acres, necessitating the application of a flexible, graded approach, as appropriate. GPS/gamma in situ surveys were particularly valuable in cost-effectively screening large areas and identifying sub-areas that warranted more rigorous investigation than other, non-affected areas. As-completed survey maps and data files consisted of ArcGIS figures generated from the GPS/gamma surveys (before and after), supplemented by analytical laboratory results that were correlated to the GPS/gamma surveys when both were used. Use of in situ GPS/gamma surveys complemented by ArcGIS analytical tools enabled convenient statistical treatment of thousands of data points, making demonstration of successful remediation much easier to present, as well as easier for stakeholders to understand. **Section 6.3.3** contains additional information on continuously collected data (CCD) surveys that obtain radiological survey and location information. **Section 8.2.2.3** discusses good practices for processing CCD using geographic information system (GIS) software.
- At the DOE's Hanford Site, the parties to the Tri-Party Agreement negotiated a method to implement the CERCLA process in order to (1) accelerate the assessment phase, and (2) coordinate RCRA and CERCLA requirements whenever possible, thereby resulting in cost savings. The Hanford Past Practice Strategy was developed in 1991 to accelerate decision-making and initiation of remediation, such as by maximizing the use of existing data consistent with DQOs (DOE 1991). Pacific Northwest National Laboratory (PNNL) developed Visual Sample Plan (VSP), which implements the MARSSIM methodology to design radiological surveys and evaluate the results of FSSs. PNNL is updating VSP to include tools for data importation, visualization, and analysis of CCD (refer to Fagan et al. 2024), among other improvements.
- The Adaptive Sampling and Analysis Programs at the Environmental Science Division of Argonne National Laboratory quantitatively fuse soft data (e.g., historical records, aerial photos, nonintrusive geophysical data) with hard sampling results to estimate residual radioactive material extent, measure the uncertainty associated with these estimates, determine the benefits from collecting additional samples, and assist in siting new sample locations to maximize the information gained (DOE 2001). PNNL is also incorporating tools in VSP to facilitate subsurface sample location optimization and decision support (Huckett et al. 2022).

2.6.2.2 Composite Sampling

In some scenarios, it could be advantageous to composite individual samples for follow-up analysis rather than treat each sample individually. This approach can provide a better measure of the average concentration with a smaller number of analyses. However, composite sampling, also referred to as incremental sampling, has disadvantages that must be overcome. Information about the individual sample increments that make up a composite is lost. This loss of information is a concern when testing to determine whether a radionuclide of concern exceeds a threshold (e.g., a $DCGL_{EMC}$) over a specific area because of possible dilution to one

3 HISTORICAL SITE ASSESSMENT

3.1 Introduction

The Radiation Survey and Site Investigation (RSSI) process uses a graded approach that starts with the Historical Site Assessment (HSA) and, as needed, can later be followed by other surveys that lead to the final status survey (FSS). The HSA is an investigation to collect existing information describing a site's complete history from the start of site activities to the present time. During the HSA process, additional information is collected to categorize the site or areas within the site as impacted or non-impacted and to make preliminary site classification assessments. This chapter covers the following topics:

- **Section 3.1** provides an overview of the HSA.
- **Section 3.2** describes the Data Quality Objectives (DQO) process, used to establish criteria for planning HSA data collection activities.
- **Section 3.3** describes how site identification is used to establish a site or an area within a site as having the potential to have residual radioactive material based on prior activities at the site.
- **Section 3.4** describes the preliminary investigation, used to obtain sufficient information to determine an initial categorization of a site or survey unit.
- **Section 3.5** explains how site reconnaissance is used to gather sufficient information to support decisions on further action.
- **Section 3.6** covers the evaluation of HSA data to differentiate sites that need further action from those that pose little to no threat to human health and the environment.
- **Section 3.7** describes how to use the data gathered from the HSA to determine the next step in the RSSI process.
- **Section 3.8** covers the preparation of an HSA report to summarize what is known about a site, assumptions and inferences made about the site, activities conducted during the HSA, and all researched information.
- **Section 3.9** reviews the HSA process.
- **Figure 3-1** presents a flowchart of HSA activities, and **Figure 3-2** provides initial categorization of the site or survey unit¹ as impacted or non-impacted.

¹ **Section 4.6.2** discusses the identification of survey units.

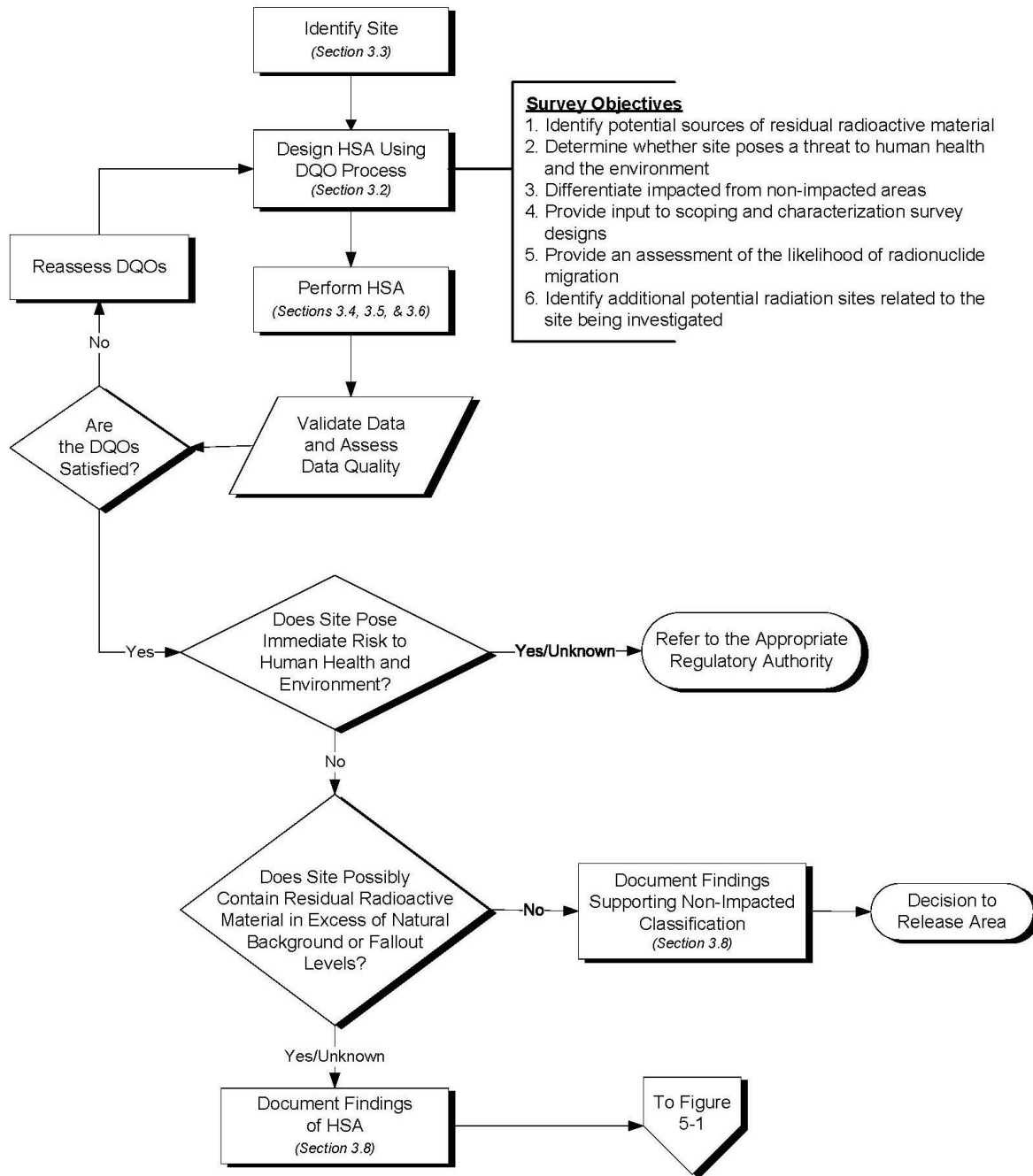


Figure 3-1 HSA Process Flowchart

The HSA may provide information needed to calculate derived concentration guideline levels (DCGLs), initially described in **Section 2.2**, as well as information that reveals the magnitude of a site's DCGLs. This information is used for comparing historical data to potential DCGLs and determining the suitability of the existing data for assessment of the site. The HSA also supports emergency response and removal activities within the context of the U.S. Environmental Protection Agency's (EPA) Superfund program, fulfills public information needs, and furnishes appropriate information about the site early in the RSSI process. For a large number of sites,

such as currently licensed facilities, site identification and reconnaissance may not be needed. For certain response activities, such as reports concerning the possible presence of radioactive material, preliminary investigations may consist more of site reconnaissance and a scoping survey in conjunction with the collection of historical information.

This chapter describes three sections of an HSA: (1) identification of a candidate site (**Section 3.3**), (2) preliminary investigation of the facility or site (**Section 3.4**), and (3) site reconnaissance (**Section 3.5**). The site reconnaissance is not a scoping survey, however, because the intent is to find physical conditions that may affect the investigative process and not to collect measurements. The HSA is followed by an evaluation of the site based on information collected during the HSA.

The amount of detailed information and effort needed to conduct an HSA depends on the type of site, associated historical events, regulatory framework, and availability of documented information. For example, information for an HSA is readily available at some facilities that routinely maintain records throughout their operations, such as licensees of the U.S. Nuclear Regulatory Commission (NRC) or Agreement States. At other facilities, such as Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, a comprehensive search may be necessary to gather information for an HSA (refer to **Appendix F**). In the former case, the HSA is essentially complete, and a review of the following sections will serve to ensure that the information justifies the recommendation. In the latter case, the HSA process has identified data gaps that will be addressed in subsequent scoping or characterization surveys. For example, for sites with less historical background information, key data for designing surveys may not be available, such as radionuclides present, ratios, or variability. In still other cases, in which the HSA describes sealed sources or small amounts of radionuclides, the site may qualify for a simplified decommissioning procedure (refer to **Appendix B**).

3.2 Data Quality Objectives

The DQO process assists in directing the planning of data collection activities performed during the HSA. Information gathered during the HSA can also support the DQOs of subsequent surveys.

Three inputs to the HSA/DQO process are expected:

- (1) Identification of an individual or a list of planning team members, including the decision-maker (DQO Step 1, **Appendix D, Section D.1**)
- (2) concise description of the problem (DQO Step 1, **Appendix D, Section D.1**)
- (3) initial classification of the site and survey unit as impacted or non-impacted (DQO Step 4, **Appendix D, Section D.2.2**)

Other inputs may accompany these three, and this added information may be useful in supporting subsequent applications of the DQO process.

The planning team clarifies and defines the DQOs for a site-specific survey. This multidisciplinary team of technical experts offers the greatest potential to solve the problems encountered in designing a survey. Including a stakeholder group representative is an important consideration when assembling this team. Once formed, the team can also consider the role of public participation in this assessment and the possible surveys to follow. The number of team members is directly related to the scope and complexity of the problem. For a small site or

simplified situations, planning may be performed by the site owner. For a large, complex facility, the team may include project managers, site managers, scientists, engineers, community and local government representatives, health physicists, statisticians, and regulatory agency representatives. A reasonable effort should² be made to include other individuals—that is, specific decision-makers or data users—who may use the study findings sometime in the future.

The role of the regulatory agency representatives is to facilitate survey planning—without direct participation in survey plan development—by offering comments and information based on past precedent, current guidance, and potential pitfalls. A regulatory agency representative may also be included at specific sites when needed (e.g., CERCLA).

The planning team is generally led by a member who is referred to as the decision-maker. This individual is often the person with the most authority over the study and may be responsible for assigning the roles and responsibilities to planning team members. Overall, the decision-making process arrives at final decisions based on the planning team's recommendations. The problem or situation description provides background information on the fundamental issue to be addressed by the assessment (EPA 2006c). The following steps may be helpful during DQO development:

- (1) Describe the conditions or circumstances surrounding the problem or situation and the reason for undertaking the survey.
- (2) Describe the problem or situation as it is currently understood by briefly summarizing existing information.
- (3) Conduct literature searches and interviews.
- (4) Examine past or ongoing studies to ensure that the problem is correctly defined. Consider breaking complex problems into more manageable pieces.

Section 3.4 provides information on gathering existing site data and determining the usability of these data.

The initial classification of the site involves evaluating the historical information gathered during the preliminary investigation and developing a conceptual model. Conceptual models describe a site or facility and its environs and present hypotheses regarding the radionuclides for known and potential residual radioactive material (EPA 1987a, 1987b). The classification of the site and development of a conceptual model are discussed in **Section 3.6**.

Several steps in the DQO process may be addressed initially during the HSA. This information or decision may be based on limited or incomplete data. As the site assessment progresses and as decisions become more difficult, the iterative nature of the DQO process allows for re-evaluation of preliminary decisions. This is especially important for classification of sites and survey units where the final classification is not made until the FSS is planned.

² The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

3.3 Site Identification

A site may already be known for its prior use and presence of radioactive materials. Elsewhere, potential radioactive materials sites may be identified through such situations and information as the following:

- records of authorization to possess or handle radioactive materials, including—
 - NRC or NRC Agreement State License
 - U.S. Department of Energy facility records
 - Naval Radioactive Materials Permit
 - U.S. Air Force Master Materials License
 - Army Radiation Authorization
 - State Authorization for Naturally Occurring and Accelerator Produced Radioactive Material (NARM)
- notification to government agencies of possible releases of radioactive substances
- citizens filing a petition under Section 105(d) of the Superfund Amendments and Reauthorization Act of 1986 (EPA 1986a)
- ground and aerial radiological surveys
- contacts with knowledge of the site

Once identified, the name, location, and current legal owner or custodian (where available) of the site should be recorded.

3.4 Preliminary Investigation

The preliminary investigation serves to collect readily available information concerning the facility or site and its surroundings. The investigation is designed to obtain sufficient information to provide initial categorization of the site or survey unit as impacted or non-impacted. Information on the potential distribution of residual radioactive material may be used for classifying each site or survey unit as Class 1, Class 2, or Class 3 and is useful for planning scoping and characterization surveys.

Table 3-1 provides a set of questions that can be used to assist in the preliminary investigation. Apart from obvious cases, this table focuses on characteristics that identify a previously unrecognized or known but undeclared source of potential residual radioactive material. Furthermore, these questions may identify confounding factors for selecting reference sites.

Table 3-1 Questions Useful for the Preliminary Investigation

Question	Purpose of Question
Was the site ever licensed for the manufacture, use, or distribution of radioactive materials under Agreement State Regulations, NRC licenses, or Armed Services permits, or for the use of highly classified radioactive material covered under Section 91(b) of the Atomic Energy Act of 1954, sometimes referred to as 91(b) material, including material associated with current nuclear weapons, legacy nuclear weapons maintenance wastes, residuals from nuclear weapons accidents/incidents, and residuals from nuclear reactor operations?	Indicates a higher probability that the area is impacted.
Did the site ever have permits to dispose of or incinerate radioactive material on site? Is there evidence of such activities?	Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
Has the site ever had deep wells for injection or permits for such?	Indicates a higher probability that the area is impacted.
Did the site ever have permits to perform research with radiation-generating devices or radioactive materials except medical or dental x-ray machines?	Research that may have resulted in the release of radioactive material indicates a higher probability that the area is impacted.
As a part of the site's radioactive materials license, were there ever any soil moisture density gauges (americium-beryllium or plutonium-beryllium sources) or radioactive thickness monitoring gauges stored or disposed of on site?	Leak-test records of sealed sources may indicate whether a storage area is impacted. Evidence of radioactive material disposal indicates a higher probability that the area is impacted.
Was the site used to create radioactive material by activation?	Indicates a higher probability that the area is impacted.
Were radioactive sources stored at the site?	Leak-test records of sealed sources may indicate whether or not a storage area is impacted.

Question	Purpose of Question
Is there a site history of releases or events that could lead to the presence of discrete radioactive particles (DRPs)? Have DRPs been identified during past facility operations, including recent dismantling activities, with potential release outside routine radiological controls?	Exposure to DRPs can be a worker health and safety concern during investigation and remediation, or a potential public exposure concern after the site is released, that is not addressed by the routine exposure modeling covered by MARSSIM. DRPs are outside the scope of MARSSIM, and their potential presence or discovery requires coordination with the responsible regulatory agency.
Were any facilities on the site used as a weapons storage area? Was weapons maintenance ever performed at the site?	Indicates a higher probability that the area is impacted.
Was there ever any decontamination, maintenance, or onsite storage of ships, vehicles, or planes with residual radioactive material?	Indicates a higher probability that the area is impacted.
Is there a record of any aircraft accident at or near the site (e.g., depleted uranium counterbalances, thorium alloys, radium dials)?	May include other considerations, such as evidence of radioactive material that was not recovered.
Are there records indicating use or storage of radium dials and other radioactive luminous devices as a source?	Indicates a higher probability that the area is impacted.
Was there ever any radiopharmaceutical manufacturing, storage, transfer, or disposal on site?	Indicates a higher probability that the area is impacted.
Was animal research ever performed at the site?	Evidence that radioactive material was used for animal research indicates a higher probability that the area is impacted.
Was naturally occurring radioactive material (NORM) or technologically enhanced naturally occurring radioactive material (TENORM)—such as uranium, thorium, or radium compounds—used in manufacturing, research, or testing at the site, or were these compounds stored at the site?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.

Question	Purpose of Question
Has the site ever been involved in the processing or production of NORM or TENORM (e.g., radium, fertilizers, phosphorus compounds, vanadium compounds, refractory materials, rare earth elements, or precious metals) or mining, milling, processing, or production of uranium or thorium?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
Were coal or coal products used on site? If yes, did combustion of these substances leave ash or ash residues on site? If yes, are runoff or production ponds on site?	May indicate other considerations, such as a potential increase in background variability.
Was there ever any onsite disposal of material known to be high in NORM (e.g., monazite sands used in sandblasting or uranium/thorium ores)?	May indicate other considerations, such as a potential increase in background variability.
Did the site contain or use pipe from the oil and gas industries?	Indicates a higher probability that the area is impacted or results in a potential increase in background variability.
Is there any reason to expect that the site may contain radioactive material (other than previously listed)?	Refer to Section 3.7 .

Appendix G to this document provides a general listing and cross-reference of information sources—each with a brief description of the information contained in each source.

3.4.1 Existing Radiation Data

Sources of useful information for an HSA include site files; monitoring data; former site evaluation data; and Federal, State, and local investigations or emergency actions. Existing site data may provide specific details about the identity, concentration, and areal distribution of residual radioactive material. However, these data should be examined carefully for the following reasons:

- Previous survey and sampling efforts may not be compatible with HSA objectives or may not be extensive enough to fully characterize the facility or site.
- Measurement protocols and standards may not be known or compatible with HSA objectives (e.g., quality assurance/quality control procedures, limited analysis rather than full-spectrum analysis) or may not be extensive enough to fully characterize the facility or site.
- Conditions may have changed since the site was last sampled (i.e., substances may have been released, migration may have spread the residual radioactive material,

additional waste disposal may have occurred, or decontamination may have been performed).

Existing data can be evaluated using the Data Quality Assessment process described in **Appendix D**. (Also refer to DOE 1987 and EPA 1992a, 1992b, 2006a, and 2024 for additional guidance on evaluating data.)

3.4.1.1 Licenses, Site Permits, and Authorizations

The facility or site radioactive materials license and supporting or associated documents are potential sources of information for licensed facilities. If a license does not exist, there may be a permit or other document that authorized site operations involving radioactive material. These documents may specify the quantities of radioactive material authorized for use at the site, the chemical and physical form of the materials, operations for which the materials are (or were) used, locations of these operations at the facility or site, and total quantities of material used at the site during its operating lifetime.

The NRC, the EPA, and State agencies maintain files on a variety of environmental programs. These files may contain permit applications and monitoring results with information on specific waste types and quantities, sources, type of site operations, and operating status of the facility or site. **Appendix G** lists some of these information sources.

3.4.1.2 Operating Records

Records and other information sources useful for site evaluations include those describing onsite activities, current and past radiation control procedures, and past operations involving the following:

- demolition
- effluent releases
- discharge to sewers or onsite septic systems
- production of residues
- land filling
- waste and material storage
- pipe and tank leaks
- spills and accidental releases
- release of facilities or equipment from radiological controls
- onsite or offsite radioactive and hazardous waste disposal
- radiological surveys (e.g., routine surveys, release surveys, surveys after spill cleanup)

Some records may be or may have been classified for national security purposes or as containing confidential business information, and means should be established to review all pertinent records. Past operations should be summarized in chronological order, along with information about permits and approvals. Estimates of the total amount of radioactive material disposed of or released at the site and the physical and chemical form of the radioactive material should also be included. Records on waste disposal, environmental monitoring logs, site inspection reports, license applications, operational permits, waste disposal material balance and inventory sheets, and purchase orders for radioactive materials are useful for estimating total activity. Information on accidents—such as fires, flooding, spills, unintentional releases, or leakage—should be collected, because they indicate potential sources of residual radioactive material. Possible areas of localized radioactive material should be identified.

Site plats or plots, blueprints, drawings, and sketches of structures are especially useful to illustrate the location and layout of buildings, as well as building/structural modifications over time on the site. Site photographs, aerial surveys, and maps can help verify the accuracy of these drawings or indicate changes after the drawings were prepared. Processing locations, waste streams to and from the site, and the presence of stockpiles of raw materials and finished product should be noted on these photographs and maps. Buildings or outdoor processing areas may have been modified or converted to other uses or configurations. The locations of sewers, pipelines, electric lines, water lines, and similar features should also be identified. This information facilitates planning the site reconnaissance and subsequent surveys and developing a site conceptual model, increasing the efficiency of the survey program.

Corporate contract files may also provide useful information during subsequent stages of the RSSI process. Older facilities may not have complete operational records, especially for obsolete or discontinued processes. Financial records may also provide information on purchasing and shipping that, in turn, help to reconstruct a site's operational history.

While operating records can be useful tools during the HSA, the investigator should be careful not to place too much emphasis on this type of data. These records are often incomplete and lack information on substances previously not considered hazardous. Out-of-date blueprints and drawings may not show modifications made during the lifetime of a facility, but they may be useful to identify additional areas that should be investigated.

3.4.2 Contacts and Interviews

Investigators should conduct interviews with current or previous employees to collect first-hand information about the site or facility and to verify or clarify information gathered from records. Interviews cover general topics, such as radioactive waste handling procedures. Results from interviews conducted early in the process are useful in guiding subsequent data collection activities.

Interviews scheduled late in the data gathering process can also be very useful. Questions can be directed to specific areas of the investigation that need additional information or clarification.

Photographs and sketches can be used to assist the interviewer and allow the interviewees to recall information of interest. Conducting interviews on site where the employees performed their tasks often stimulates memories and facilitates information gathering. In addition to interviewing managers, engineers, and facility workers, interviews may be conducted with laborers and truck drivers to obtain information from their perspective.

The investigator should be cautious in the use of interview information. Whenever possible, anecdotal evidence should be assessed for accuracy, and results of interviews should be backed up with supporting data. To ensure that specific information is confirmed and properly recorded, it may be advisable to hire trained investigators and take affidavits.

3.5 Site Reconnaissance

The objective of the site reconnaissance or site visit is to gather sufficient information to support a decision regarding further action. Reconnaissance activity is not a risk assessment, a scoping survey, or a study of the full extent of residual radioactive material at a facility or site. The reconnaissance offers an opportunity to record information concerning hazardous site conditions as they apply to conducting future survey work. In this regard, information describing physical hazards, structural integrity of buildings, or other conditions defines potential problems

that may impede future work. Site reconnaissance is most applicable to sites with less available information and may not be necessary at other sites having greater amounts of records, such as NRC-licensed facilities.

To prepare for the site reconnaissance, begin by reviewing what is known about the facility or site and identify data gaps. Given the site-specific conditions, consider whether a site reconnaissance is necessary and practical. This type of effort may be deemed necessary if a site is abandoned or not easily observed from areas of public access, or if file searches disclose little information. These same circumstances may also make a site reconnaissance risky for health and safety reasons—in view of the many unknowns—and may make entry difficult. This investigative step may be less critical for active facilities whose operators grant access and provide requested information. The investigator should arrange for proper site access and prepare an appropriate health and safety plan, if required, before initiating the site visit.

Investigators should acquire signed consent forms from the site or equipment owner to gain access to the property to conduct the reconnaissance. Investigators are to determine whether State and Federal officials, and local individuals, should be notified of the reconnaissance schedule. If needed, local officials should arrange for public notification. Guidance on obtaining access to sites can be found in Adams 1987.

A study plan should be prepared before the site reconnaissance to anticipate every reconnaissance activity and identify specific information to be gathered. This plan should incorporate a survey of the site's surroundings and provide details for activities that verify or identify the location of nearby residents, worker populations, drinking water or irrigation wells, and foods, as well as other information about the site environs.

Materials and equipment for a site reconnaissance should be prepared in advance. This includes a camera to document site conditions, as well as health and safety monitoring instruments, including a radiation detection meter, a Global Positioning System (GPS) receiver or extra copies of topographic maps to mark target locations, water distribution areas, and other important site features.

A logbook is critical to keeping a record of field activities and observations as they occur. MARSSIM recommends that the logbook be completed in waterproof ink, preferably by one individual. Furthermore, each page of the logbook should be signed and dated, including the time of day, after the last entry on the page. Corrections should be documented and approved. Alternatively, a computerized logbook may also be used, with the adequate provision of controls to ensure appropriate quality assurance and version control. For example, logbook entries should be signed daily and closed out, so that future revisions would require date/time stamping and signature of the individual making changes.

3.6 Evaluation of Historical Site Assessment Information

The main purpose of the HSA is to determine the current status of the site or facility, but the data collected may also be used to differentiate sites that need further action from those that pose little or no threat to human health and the environment. The information gathered during this screening process can show the need for additional surveys or may be sufficient to recommend a site release. Because much of the information collected during HSA activities is qualitative, and analytical data may be of unknown quality, many decisions regarding a site are the result of professional judgment.

Historical analytical data indicating the presence of residual radioactive material in environmental media (surface soil, subsurface soil, surface water, groundwater, air, or buildings) can be used to support the hypothesis that radioactive material was released at the facility or site. A decision that the site does not meet the release criteria can be made regardless of the quality of the data, its attribution to site operations, or its relationship to background levels. In such cases, elevated results are sufficient to support the hypothesis—it is not necessary to definitively demonstrate that a problem exists. Conversely, historical analytical data can also be used to support the hypothesis that no release has occurred. However, these data should not be the sole basis for this hypothesis. If historical analytical data constitute the principal evidence for ruling out the presence of residual radioactive material, the data must be of sufficient quality to clearly demonstrate that a problem does not exist.

In most cases, it is assumed there will be some level of process knowledge available in addition to historical analytical data. If process knowledge suggests that no residual radioactive material should be present, and the historical analytical data also suggest that no residual radioactive material is present, the process knowledge provides an additional level of confidence and supports categorizing the area as non-impacted. However, if process knowledge suggests no residual radioactive material should be present, but the historical analytical data indicate the presence of residual radioactive material, the area will probably be categorized as impacted.

The following sections describe the recommended information to accurately and completely support a site release recommendation. If some of the information is not available, it should be identified as a data need for future surveys. Data needs are collected during Step 3 of the DQO process, as described in **Appendix D, Section D.1.3. Section 3.6.5** provides information on professional judgment and how it may be applied to the decision-making process.

3.6.1 Identify Potential Sources of Residual Radioactive Material

An efficient HSA gathers information sufficient to identify the radionuclides used at the site, including their chemical and physical form. The first step in evaluating HSA data is to estimate the potential for residual radioactive material from these radionuclides.

Site operations are a strong indicator of the potential for residual radioactive material (NRC 1992). Compliance and incident reporting records are also strong indicators of the potential for residual radioactive material. An operation that handled only encapsulated sources is expected to have a low potential for residual radioactive material—assuming that the integrity of the sources was not compromised. A review of leak-test records for such sources may be adequate to demonstrate the low probability of residual radioactive material. A chemical manufacturing process facility would likely have residual radioactive material in piping, ductwork, and process areas, with a potential for residual radioactive material in soil where spills, discharges, or leaks occurred. Sites using large quantities of radioactive ores—especially those with outside waste collection and treatment systems—are likely to have residual radioactive material on the premises. If loose dispersible materials were stored outside or process ventilation systems were poorly controlled, then windblown surface deposition of residual radioactive material may be possible.

Investigators should consider how long the site was operational. If enough time elapsed since the site discontinued operations, radionuclides with short half-lives may no longer be present in significant quantities. In this case, calculations demonstrating that residual activity could not exceed the DCGL may be sufficient to evaluate the potential residual radioactive material at the site. A similar evaluation can be made based on knowledge of a radionuclide's chemical and physical form. Such a determination relies on records of radionuclide inventories, chemical and

physical forms, total amounts of material and activity in waste shipments, and purchasing records to document and support this decision. However, a number of radionuclides experience significant decay product ingrowth, which should be considered when evaluating existing site information.

3.6.2 Identify Potential Areas with Residual Radioactive Material

Information gathered during the HSA should be used to provide an initial categorization of the site areas as impacted or non-impacted.

Impacted areas are either known to contain residual radioactive material based on radiological surveillance or are suspected of containing it based on historical information. This includes areas where one of the following may have occurred:

- Radioactive material was used and stored.
- Records indicate spills, discharges, or other unusual occurrences that could result in the spread of radioactive material.
- Radioactive material was buried or disposed.

Areas immediately surrounding or adjacent to these locations are also considered impacted because of the potential for the inadvertent spread of radionuclides.

Non-impacted areas are those areas where there is no reasonable possibility for residual radioactive material based on site history or previous survey information. The criteria used for this distinction need not be as strict as those used to demonstrate final compliance. However, the reasoning for categorizing an area as non-impacted should be maintained as a written record.

All potential sources of radioactive material in impacted areas should be identified and their dimensions recorded (in two or three dimensions, to the extent they can be measured or estimated). Sources can be delineated and characterized through visual inspection during the site reconnaissance; interviews with knowledgeable personnel; and historical information concerning disposal records, waste manifests, and waste sampling data. The HSA should address potential residual radioactive material from the site whether it is physically within or outside of site boundaries. This approach describes the site in a larger context, but as noted in **Chapter 1**, MARSSIM's scope concerns releasing a site and does not include areas outside a site's boundaries.

3.6.3 Identify Potential Media with Residual Radioactive Material

The next step in evaluating the data gathered during the HSA is to identify media at the site with a potential for containing residual radioactive material. Identification of those media that do not contain residual radioactive material and those that may contain it is necessary for both preliminary area classification (**Section 4.6.1**) and planning subsequent survey activities.

This section provides information on evaluating the likelihood for release of radioactive material into the following environmental media: surface soil, subsurface soil, sediment, surface water, groundwater, air, and buildings. Although MARSSIM's scope is focused on surface soils and building surfaces, other media will still need to be considered.

The evaluation will result in a finding either of suspected residual radioactive material or of no suspected residual radioactive material. The finding may be based on analytical data, professional judgment, or a combination of both.

Subsequent sections describe the environmental media and pose questions pertinent to each type. Each question is accompanied by a commentary. Carefully consider the questions within the context of the site and the available data. Avoid spending excessive amounts of time on particular questions, because answers to every question are unlikely to be available at each site. Questions that cannot be answered based on existing data can be used to direct future surveys of the site. Also, keep in mind the numerous differences in site-specific circumstances and that the questions do not identify every characteristic that might apply to a specific site. Additional questions or characteristics identified during a specific site assessment should be included in the HSA report (**Section 3.8**; EPA 1991a).

3.6.3.1 *Surface Soil*

Surface soil is the top layer of soil on a site that is available for direct exposure, growing plants, and resuspension of particles for inhalation. Surface soil may also be defined as the thickness of soil that can be measured using direct measurement or scanning techniques. Historically, this layer has often been represented as the top 15 centimeters (cm) (6 inches [in.]) of soil (40 CFR Part 192), but it will vary depending on radionuclide, surface characteristics, measurement method, and pathway modeling assumptions. For the purposes of MARSSIM, surface soil may also include other media types, such as gravel fill, concrete, or asphalt paving, but should specifically be discussed with the regulator. For many sites where radioactive material was used, one first assumes that radioactive material on the site exists on surfaces, and the evaluation is used to identify areas of high and low probability of residual radioactive material (Class 1, Class 2, or Class 3 areas).

- *Were all radiation sources used at the site encapsulated sources?* A site where only encapsulated sources were used would be expected to have a low potential for residual radioactive material. A review of the leak-test records and documentation of encapsulated source location may be adequate to make a finding of no suspected residual radioactive material.
- *Were radiation sources used only in specific areas of the site?* Evidence that radioactive material was confined to certain areas of the site may be helpful in determining which areas are impacted and which are non-impacted.
- *Was surface soil regraded or moved elsewhere for fill or construction purposes?* This helps identify additional potential sites of residual radioactive material.
- *Are there any washwater/wastewater discharges from buildings to surface soil?* This helps identify additional sites of residual radioactive material adjacent to current/historical buildings that handled radioactive material.
- *Are sources of radioactive material poorly contained or prone to runoff?* This helps identify additional sites of residual radioactive material adjacent to current/historical radioactive material storage areas.

3.6.3.2 Subsurface Soil and Other Subsurface Media

Subsurface soil and other subsurface media are defined as any solid materials beneath the surface soil layer. The purpose of these subsurface investigations is to locate and define the lateral and vertical extent of the potential residual radioactive material in the subsurface.

Subsurface measurements can be expensive, especially for beta- or alpha-emitting radionuclides. To effectively use project resources, subsurface investigations should be biased (e.g., limited to known or potential areas containing subsurface radioactive material). After identifying areas of subsurface concern, further subsurface investigations would be necessary to delineate the lateral and vertical extent of radioactive material during the remedial investigation and design phase. The latter would aid in planning the necessary resources (e.g., budgets, contractors, obtaining access) and setting the schedule for the remedial action phase.

- *Is there evidence of changes in surface features?* Understanding the development history of an area can aid the investigation in identifying subsurface areas of potential concern. Historically, industrial wastes potentially containing radioactive material were used as fill material (e.g., to fill in old streams, wetlands, low-lying areas) or as subgrade material (e.g., beneath buildings, basement floors). Changes in surface features over time can affect the distribution of radioactive material. Reviewing historical records can be of great benefit in identifying subsurface areas of potential concern and in providing subsequent cost effective and defensible graded approaches to better characterize the site. Examples of helpful records include aerial photographs, topography maps, railroad/road maps, navigation maps, Sanborn Fire Insurance Maps, tax maps, construction photographs, postcards, and correspondence.
- *Are there areas of known or suspected residual radioactive material in surface soil?* Residual radioactive material in surface soil can migrate deeper into the soil. Surface soil sources should be evaluated based on radionuclide mobility, soil permeability, and infiltration rate to determine the potential for residual radioactive material in the subsurface. Computer modeling may be helpful for evaluating these types of situations.
- *Is there a groundwater plume without an identifiable source?* Radioactive material in groundwater indicates that a source of residual radioactive material is present. If no source is identified during the HSA, residual radioactive material in the subsurface is a probable source.
- *Is there potential for enhanced mobility of radionuclides in soils?* Radionuclide mobility can be enhanced by the presence of solvents or other chemicals that affect the sorption capacity of soil.
- *Is there evidence that the surface has been disturbed?* Recent or previous excavation activities are obvious sources of surface disturbance. Areas with developed plant life (forested or old growth areas) may indicate that the area remained undisturbed during the operating life of the facility. Areas where vegetation is removed during previous excavation activity may be distinct from mature plant growth in adjacent areas. If a site is not purposely replanted, vegetation may appear in a sequence starting with grasses that are later replaced by shrubs and trees. Typically, grasslands recover within a few years, sagebrush or low ground cover appears over decades, and mature forests may take centuries to develop.

- *Is there evidence of subsurface disturbance?* Non-intrusive, non-radiological measurement techniques may provide evidence of subsurface disturbance. Magnetometer surveys can identify buried metallic objects, and ground-penetrating radar can identify subsurface anomalies such as trenches or dump sites. Techniques involving special equipment are discussed in **Section 6.9**.
- *Are surface structures present?* Structures constructed during a site's operational history may cover residual radioactive material below ground. Some consideration for residual radioactive material that may exist beneath parking lots, buildings, or other onsite structures may be warranted as part of the investigation. There may be underground piping, drains, sewers, or tanks that caused the spread of residual radioactive material.

3.6.3.3 Surface Water

Surface waters include streams and rivers, lakes, coastal tidal waters, and oceans. Note that certain ditches and intermittently flowing streams also qualify as surface water. The evaluation determines whether radionuclides are likely to migrate to surface waters or their sediments. Where a previous release is not suspected, the potential for future release depends on the distance to surface water and the flood potential at the site. One can also consider the interaction between soil and water in relation to seasonal factors, including soil cracking because of freezing, thawing, and desiccation that influence the dispersal or infiltration of radionuclides.

- *Is surface water nearby?* The proximity of residual radioactive material to local surface water is essentially determined by runoff and radionuclide migration through the soil. The definition for *nearby* depends on site-specific conditions and the time performance period. If the terrain is flat, precipitation is low, and soils are sandy, *nearby* may be within several meters. If annual precipitation is high or occasional precipitation events are high, within 1,200 meters (3/4 mile) might be considered nearby.
- *Is the waste quantity particularly large?* Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance (i.e., a greater risk or hazard) than a *large* quantity of solid material stored in watertight containers.
- *Is the drainage area large?* The drainage area includes the area of the site itself plus the upgradient area that produces runoff flowing over the site. Larger drainage areas generally produce more runoff and increase the potential for residual radioactive material in surface water.
- *Is precipitation heavy?* If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause precipitation to pool on the site. Otherwise, these characteristics may contribute to high runoff rates that carry radionuclides overland to surface water. Total annual precipitation exceeding 1 meter (40 in.), or a once-in-2-years 24-hour precipitation event exceeding 5 cm (2 in.) might be considered "heavy."

The amount of precipitation varies for locations across the continental United States from high (e.g., approximately 200 cm/year [y] [89 in./y], Mt. Washington, New Hampshire) to low values (e.g., approximately 10.7 cm/y [4.2 in./y], Las Vegas, Nevada). Certified data on precipitation rates for locations throughout the United States can be obtained from the National Centers for Environmental Information (<https://www.ncei.noaa.gov>).

- *Is the infiltration rate low?* Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Paved sites prevent infiltration and generate runoff.
- *Are sources of residual radioactive material poorly contained or prone to runoff?* Proper containment that prevents radioactive material from migrating to surface water generally uses engineered structures such as dikes, berms, run-on and runoff control systems, and spill collection and removal systems. Sources prone to releases through runoff include leaks, spills, exposed storage piles, or intentional disposal on the ground surface. Sources not prone to runoff include underground tanks, aboveground tanks, and containers stored in a building.
- *Is a runoff route well defined?* A well-defined runoff route—along a gully, trench, berm, wall, etc.—will more likely contribute to migration to surface water than a poorly defined route. However, a poorly defined route may contribute to dispersion of radioactive material to a larger area of surface soil.
- *Has deposition of waste into surface water been observed?* Indications of this type of activity will appear in records from past practice at a site or from information gathered during personal interviews.
- *Is discharge from the site to surface water probable?* The hydrogeology and geographical information of the area around and inside the site may be sufficiently documented to indicate discharge locations.
- *Does analytical or circumstantial evidence suggest residual radioactive material in surface water?* Any condition considered suspicious can be considered circumstantial evidence.
- *Is the site prone to flooding?* The Federal Emergency Management Agency publishes flood insurance rate maps that delineate 100-year and 500-year flood plains. Ten-year floodplain maps may also be available. Generally, a site on a 500-year floodplain is not considered prone to flooding.

3.6.3.4 Groundwater

Proper evaluation of groundwater includes a general understanding of the local geology and subsurface conditions. Of particular interest is descriptive information relating to subsurface stratigraphy, aquifers, and groundwater use.

- *Are sources poorly contained?* Proper containment—which prevents radioactive material from migrating to groundwater—generally uses engineered structures, such as liners, layers of low permeability soil (e.g., clay), and leachate collection systems.

- *Is the source likely to affect groundwater?* Underground tanks, landfills,³ surface impoundments, and lagoons are examples of sources that are likely to release residual radioactive material that migrates to groundwater. Aboveground tanks, drummed solid material, or sources inside buildings are less likely to contribute to residual radioactive material in groundwater.
- *Is discharge from the site to groundwater probable?* The hydrogeology and geographical information of the area around and inside the site may be sufficiently documented to indicate discharge locations.
- *Is waste quantity particularly large?* Depending on the physical and chemical form of the waste and its location, *large* is a relative term. A *small* quantity of liquid waste may be of more importance (i.e., greater risk or hazard) than a *large* quantity of solid material stored in watertight containers.
- *Is precipitation heavy?* If the site and surrounding area are flat, a combination of heavy precipitation and low infiltration rate may cause precipitation to pool on the site. Otherwise, these characteristics may contribute to high runoff rates that carry radionuclides overland to surface water. Total annual precipitation exceeding 1 meter (40 in.), or a once-in-2-years 24-hour precipitation event exceeding 5 cm (2 in.) might be considered “heavy.”

The amount of precipitation varies for locations across the continental United States from high (e.g., approximately 200 cm/y [89 in./y] in Mt. Washington, New Hampshire) to low values (e.g., approximately 10.7 cm/y [4.2 in./y] in Las Vegas, Nevada). Certified data on precipitation rates for locations throughout the United States can be obtained from the National Centers for Environmental Information (<https://www.ncei.noaa.gov>).

- *Is the infiltration rate high?* Infiltration rates range from very high in gravelly and sandy soils to very low in fine silt and clay soils. Unobstructed surface areas are potential candidates for further examination to determine infiltration rates.
- *Is the site located in an area of karst terrain?* In karst terrain, groundwater moves rapidly through channels caused by dissolution of the rock material (usually limestone) that facilitates migration of radioactive material and chemicals.
- *Is the subsurface highly permeable?* Highly permeable soils favor downward movement of water that may transport radioactive materials. Well logs, local geologic literature, or interviews with knowledgeable individuals may help answer this question.
- *What is the distance from the surface to an aquifer?* The shallower the source of groundwater, the higher the threat of residual radioactive material. It is difficult to determine whether an aquifer may be a potential source of drinking water in the future (e.g., next 1,000 years). Use the shallowest aquifer below the site when determining the distance to the surface.
- *Are suspected radionuclides highly mobile in groundwater?* Mobility in groundwater can be estimated based on the distribution coefficient (K_d) of the radionuclide. Elements with

³ Landfills can affect the geology and hydrogeology of a site and produce heterogeneous conditions. It may be necessary to consult an expert on landfills and the conditions they generate.

a high K_d , like thorium (i.e., $K_d = 3,200 \text{ cm}^3/\text{gram [g]}$), are not mobile, while elements with a low K_d , like hydrogen (i.e., $K_d = 0 \text{ cm}^3/\text{g}$), are very mobile. EPA provides a compilation of K_d values. These values can be influenced by site-specific considerations such that site-specific K_d values need to be evaluated or determined. Also, the mobility of a radionuclide can be enhanced by the presence of solvents or other chemicals.

- *Does analytical or circumstantial evidence suggest residual radioactive material in groundwater?* Evidence for residual radioactive material may appear in current site data; historical, hydrogeological, and geographical information systems records, or as a result of personal interviews.

3.6.3.5 Air

Evaluation of air is different than evaluation of other media with a potential for residual radioactive material. Air is evaluated as a pathway for resuspending and dispersing radioactive material into multiple media (e.g., surface soil, subsurface soil, surface water, and groundwater).

- *Were there observations of releases of radioactive material into the air?* Direct observation of a release to the air might occur where radioactive materials are suspected to be present in particulate form (e.g., mine tailings, waste pile, building exhaust stacks) or adsorbed to particulates (e.g., radioactive material in soil), and where site conditions favor air transport (e.g., dry, dusty, windy).
- *Does analytical or circumstantial evidence suggest a release to the air?* Other evidence for releases to the air might include areas of residual radioactive material in surface soil that do not appear to be caused by direct deposition or overland migration of radioactive material.

For radon/thoron exposure only, are there elevated amounts of radium (Ra) (^{226}Ra and/or ^{224}Ra) in the soil or water that could act as a source of radon/thoron in the air? The source ^{226}Ra (from the uranium-238 decay series) decays to radon-222, which is referred to as radon gas. The source ^{224}Ra (from the thorium-232 decay series) decays to radon-220, which is referred to as thoron gas. Once radon/thoron is produced, the gas may diffuse (escape) from its point of origin into the air. Radon/thoron is readily released from water or construction material sources that are open to air. Soil, however, can retain radon/thoron gas until it has decayed (refer to **Section 6.8**). The rate that radon/thoron is emitted by a solid (i.e., radon flux) can be measured directly to evaluate potential sources of radon/thoron.

- *Is there a prevailing wind direction and a propensity for windblown transport of radioactive material?* Information pertaining to geography, ground cover (e.g., amount and types of local vegetation), meteorology (e.g., wind speed at 7 meters [23 feet] above ground level) for and around the site, and site-specific parameters related to surface soil characteristics enter into calculations used to describe particulate transport. Mean⁴ annual wind speed can be obtained from the National Weather Service surface station nearest to the site.

⁴ In MARSSIM, “average” and “mean” both refer to the arithmetic mean.

3.6.3.6 Structures

Structures used for storage, maintenance, or processing of radioactive materials are potential sources of residual radioactive material or NORM. The questions presented in **Table 3-1** help determine whether a building might be affected by residual radioactive material or NORM. The questions listed in this section are for identifying structures, or portions of structures, that might not be identified using **Table 3-1** but have a potential for residual radioactive material or NORM. **Section 4.9.3.1** also presents useful information on identifying structures with residual radioactive material or NORM.

- *Were adjacent structures used for the storage, maintenance, or processing of radioactive material? Adjacent* is a relative term for this question. A processing facility with a potential for venting radioactive material to the air could deposit residual radioactive material on downwind areas or structures. A facility with little potential for release outside of the structures handling the material would be less likely to deposit radioactive material on areas or structures.
- *Is a building, its addition, or a new structure located on a former radioactive waste burial site or on land with residual radioactive material?* Comparing past and present photographs or site maps and retrieving building permits or other structural drawings and records in relation to historical operations information will reveal site locations where structures may have been built over buried waste or land with residual radioactive material.
- *Was the building constructed using materials containing residual radioactive material or NORM?* Building materials (e.g., concrete, brick, plaster, cement, wood, metal, cinder block) may contain residual radioactive material. Granite is a source of NORM.
- *Does the potentially non-impacted portion of the building share a drainage system or ventilation system with areas with potential residual radioactive material?* Technical and architectural drawings for site structures, along with visual inspections, are required to determine whether this is a concern in terms of current or past operations.
- *Is there evidence that previously identified areas of residual radioactive material were remediated by painting or similar methods of immobilization?* Removable sources of residual radioactive material were sometimes immobilized by painting, partition, or the addition of floor layers (e.g., tiles, carpet, floor wax). These sources may be more difficult to locate and may need special consideration when planning subsequent surveys.

3.6.4 Develop a Conceptual Model of the Site

Starting with project planning activities, available information is gathered and analyzed to develop a conceptual site model. The model is essentially a site diagram showing locations of known radioactive material, areas of suspected residual radioactive material, types and concentrations of radionuclides in impacted areas, media with potential residual radioactive material, and locations of potential reference (background) areas. The diagram should include the general layout of the site, including buildings and property boundaries. When possible, three-dimensional diagrams should be created. The conceptual site model will be upgraded and modified as information becomes available throughout the RSSI process. The process of developing this model is also briefly described in Attachment A of EPA/540/R-95/128, "Soil Screening Guidance: Technical Background Document," issued May 1996 (EPA 1996a).

The model is used to assess the nature and the extent of residual radioactive material; to identify potential sources of residual radioactive material, release mechanisms, exposure pathways, and human and environmental receptors; and to develop exposure scenarios. Further, this model helps identify data gaps and determine media to be sampled, and it assists in the development of strategies for data collection. Site history and preliminary survey data generally are extremely useful sources of information for developing this model. The conceptual site model should include known and suspected sources of residual radioactive material, the types of radioactive material, and affected media. Such a model can also illustrate known or potential routes of migration and known or potential human and environmental receptors.

The site should be classified or initially divided into similar areas. Classification may be based on the operational history of the site or observations made during the site reconnaissance (refer to **Section 3.5**). After the site is classified using current and past site characteristics, the site or facility should be further divided based on anticipated future use. This classification can help (1) assign limited resources to areas that are anticipated to be released without restrictions, and (2) identify areas with little or no possibility of unrestricted release. **Figure 3-2** shows an example of how a site might be classified in this manner. Further classification of a site may be possible based on site disposition recommendations (unrestricted versus release with passive controls).

3.6.5 Professional Judgment

In some cases, traditional sources of information, data, models, or scientific principles are unavailable, unreliable, conflicting, or too costly or time consuming to obtain. In these instances, professional expert judgment may be the only practical tool available to the investigator or regulator. Expert judgment, or “expert elicitation,” means using the judgments obtained from experts about their field of expertise that are explicitly stated and documented for review and appraisal by others. It is a formal, highly structured, and well-documented process for obtaining the judgment of multiple experts regarding a scientific inquiry or decision-making (NRC 1990). For most instances, the issue is not whether to use judgment, but whether to use it in an explicit and disciplined fashion or in an ad hoc manner. An important interrelated question is when and whose judgment should be used. For this guidance, it is often useful to formalize the elicitation and use of judgment for significant technical, environmental, and socioeconomic problems. For general applications, this type of judgment is a routine part of scientific investigation where knowledge is incomplete. For MARSSIM guidance, professional judgment can be used as an independent review of historical data to support decision-making during the HSA or the use of statistical tools or methodology. Professional or expert judgment should be used as necessary, particularly if data are not reasonably obtainable by collection, experimentation, or field measurements, or when the cost of data collection is prohibitive.

Typically, the process of recruiting professionals for expert judgment should be documented and as unbiased as possible. The credentials of the selected individual or individuals should enhance the credibility of the elicitation, and their ability to communicate their reasoning is a primary determinant of the quality of the results. Qualified expert professionals can be identified by different sources, including the planning team, professional organizations, government agencies, universities, consulting firms, and public interest groups. The selection criteria for the professionals should include potential conflict of interest (economic or personal), evidence of expertise in a required topic, objectiveness, and availability.

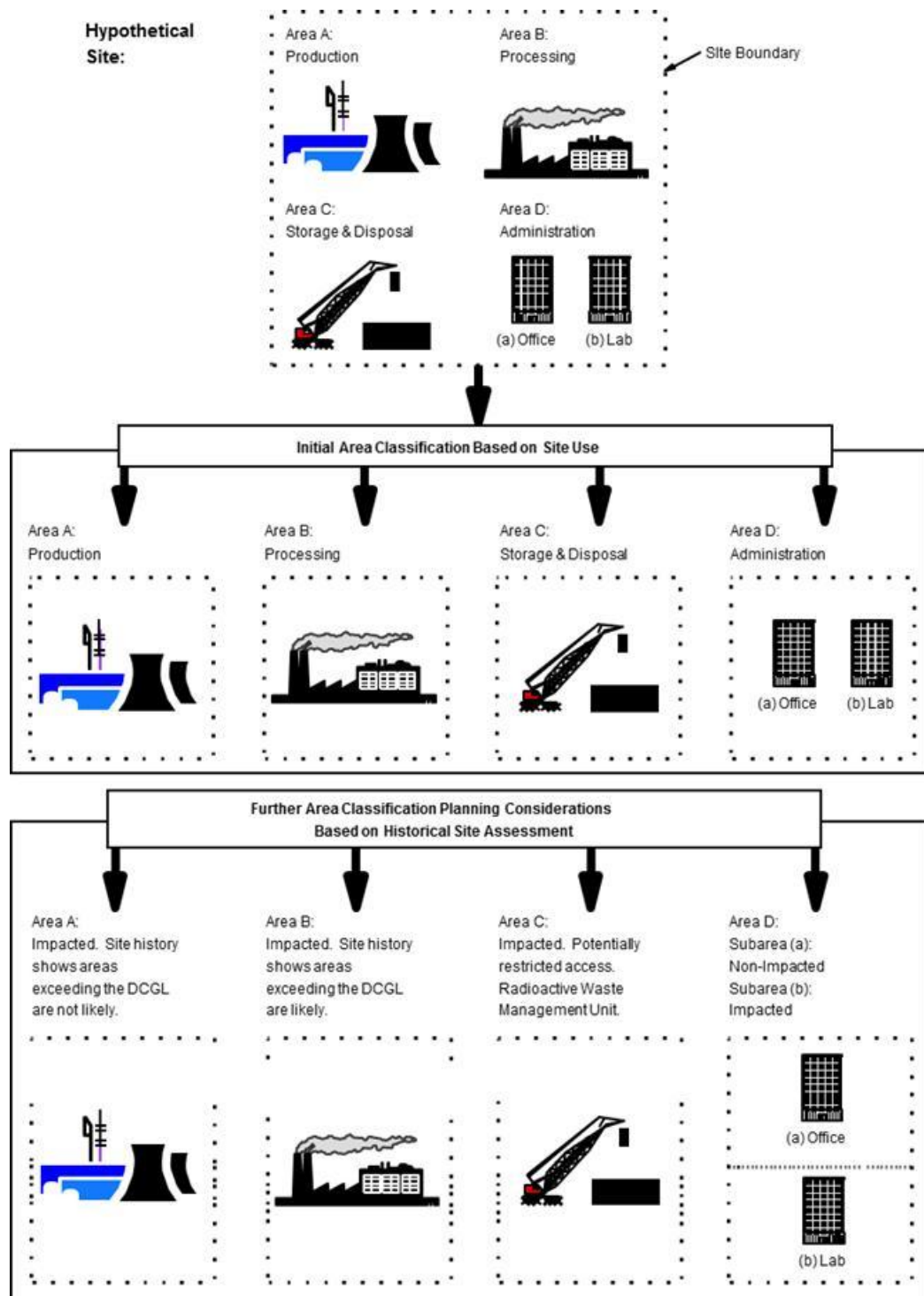


Figure 3-2 Example Showing How a Site Might Be Categorized Before Cleanup Based on the HSA

3.7 Determining the Next Step in the Site Investigation Process

Upon completion, the HSA will support one of three possible recommendations:

- (1) An emergency action may be necessary to reduce the risk to human health and the environment, such as a Superfund removal action, which is discussed in detail by EPA (EPA 1988a).
- (2) The site or area is categorized as impacted, and further investigation is needed before a decision regarding final release can be made. The area may be classified as Class 1, Class 2, or Class 3, and a scoping survey or a characterization survey may be performed as necessary. Information collected during the HSA can be very useful in planning these subsequent survey activities.
- (3) The site or area is categorized as non-impacted, a term that is applied if there is no reasonable potential to contain radionuclide concentration(s) or radioactive material above background (10 CFR Part 50). The site or area can be released for unrestricted use.

As stated in **Section 1.1**, the purpose of this manual is to describe a process-oriented approach for demonstrating that the concentration of residual radioactive material does not exceed the release criteria. The highest probability of demonstrating this can be obtained by sequentially following each step in the RSSI process. In some cases, however, performing each step in the process is not practical or necessary. This section provides information on how the results of the HSA can be used to determine the next step in the process.

The best method for determining the next step is to review the purpose for each type of survey described in **Chapter 5**. For example, a scoping survey is performed to provide sufficient information for determining (1) whether the present residual radioactive material warrants further evaluation, and (2) initial estimates of the level of effort for decontamination and for preparing a plan for a more detailed survey. If the HSA demonstrates that this information is already available, a scoping survey is not needed. On the other hand, if the information obtained during the HSA is limited, a scoping survey may be necessary to narrow the scope of the characterization survey.

The exception to conducting additional surveys before an FSS is the use of HSA results to release a site. Generally, the analytical data collected during the HSA are not adequate to statistically demonstrate compliance for impacted areas as described in **Chapter 8**. This means that the decision to release the site will be based on professional judgment. This determination will ultimately be decided by the responsible regulatory agency.

3.8 Historical Site Assessment Report

A narrative report is generally the best format to summarize what is known about the site, what is assumed or inferred, activities conducted during the HSA, and all researched information. A supporting reference should be cited for each factual statement given in the report. Copies of references (i.e., those not generally available to the public) should be attached to the report. The narrative portion of the report should be written in plain English and avoid the use of technical terminology.

A sample HSA report format is provided in **Example 3-1**. Additional information not identified in the outline may be requested by the regulatory agency at its discretion. The level of effort to produce the report should reflect the amount of information gathered during the HSA.

3.9 Review of the Historical Site Assessment

The planning team should ensure that someone (a first reviewer) conducts a detailed review of the HSA report for internal consistency and as a quality control mechanism. A second reviewer with considerable site assessment experience should then examine the entire information package to ensure consistency and to provide an independent evaluation of the HSA conclusions. The second reviewer also evaluates the package to determine whether special circumstances exist such that radioactive material may be present but not identified in the HSA. Both the first reviewer and the second independent reviewer should examine the HSA written products to ensure internal consistency in the report's information, summarized data, and conclusions. The site review ensures that the HSA's recommendations are appropriate. Reviewers who conduct site visits can provide more assessment of the HSA report.

An important quality assurance objective is to find and correct errors. A significant inconsistency indicating either an error or a flawed conclusion, if undetected, could contribute to an inappropriate recommendation. Identifying such a discrepancy directs the HSA investigator and site reviewers to re-examine and resolve the apparent conflict.

Under some circumstances, experienced investigators may have differing interpretations of site conditions and draw differing conclusions or hypotheses regarding the likelihood of residual radioactive material. Any such differences should be resolved during the review. If a reviewer's interpretations contradict those of the HSA investigator, the two should discuss the situation and reach a consensus. This aspect of the review identifies significant points about the site evaluation that may need detailed explanation in the HSA narrative report to fully support the conclusions. Throughout the review, the HSA investigator and site reviewers should keep in mind the need for conservative judgments in the absence of definitive proof to avoid underestimating the presence of residual radioactive material, which could lead to an inappropriate HSA recommendation.

Example 3-1: HSA Report Format

1. Glossary of Terms, Acronyms, and Abbreviations
2. Executive Summary
3. Purpose of the Historical Site Assessment
4. Property Identification
 1. Physical Characteristics
 1. Name—EPA ID# (if applicable), owner/operator name, address
 2. Location—street address, city, county, State, geographical coordinates
 3. Topography—U.S. Geological Survey 7.5-minute quadrangle or equivalent
 4. Stratigraphy
 2. Environmental Setting
 1. Geology
 2. Hydrogeology
 3. Hydrology
 4. Meteorology
5. Historical Site Assessment Methodology
 1. Approach and Rationale
 2. Boundaries of Site
 3. Documents Reviewed
 4. Property Inspections
 5. Personal Interviews
6. History and Current Usage
 1. History—years of operation, type of facility, description of operations, regulatory involvement permits and licenses, waste handling procedures
 2. Current Usage—type of facility, description of operations, probable source types and sizes, description of spills or releases, waste manifests, radioactive inventories, emergency or removal actions
 3. Adjacent Land Usage—sensitive areas, such as wetlands or preschools

7. Findings

1. Potential Sources of Residual Radioactive Material
2. Potential Areas with Residual Radioactive Material
 1. Impacted Areas—Known and Potential
 2. Non-Impacted Areas
 3. Potential Media with Residual Radioactive Material
 4. Related Environmental Concerns

8. Conclusions

9. References

10. Appendices

- A. Conceptual Model and Site Diagram Showing Classifications
- B. List of Documents
- C. Photo Documentation Log
 - a. Original Photographs of the Site and Pertinent Site Features

4 CONSIDERATIONS FOR PLANNING SURVEYS

4.1 Introduction

4.1.1 Purpose

This chapter is intended to introduce the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) user to general considerations for planning MARSSIM-based surveys by presenting areas of consideration common to a Radiation Survey and Site Investigation (RSSI) with an emphasis on final status surveys (FSSs). Detailed technical information about planning surveys will follow in the subsequent chapters. For the purposes of this chapter, it is assumed that a Historical Site Assessment (HSA) has been performed, and the results are available to the survey design team.

4.1.2 Scope

MARSSIM discusses four types of surveys, described in more detail in **Chapter 5**:

- (1) scoping
- (2) characterization
- (3) remedial action support (RAS)
- (4) final status

However, the emphasis in MARSSIM is on FSSs of surface soils, building surfaces, and outdoor areas (e.g., parking lots and other paved surfaces) to demonstrate compliance with cleanup regulations. This emphasis on FSSs should¹ be kept in mind during the design phase of all surveys. The topics discussed in this chapter focus on planning the FSS.

4.1.3 Overview of Survey Planning

The following sections of this chapter introduce many potentially unfamiliar concepts, terms, and definitions specifically related to planning surveys. Informal definitions will be given in this chapter; however, the reader should refer to the **glossary** for complete definitions. This chapter discusses the following topics related to survey planning:

- *Data Quality Objectives (DQO) process*: The DQO process is used to develop performance and acceptance criteria that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.
- *Survey types*: There are four MARSSIM survey types: scoping, characterization, RAS, and final status. This chapter emphasizes FSSs.
- *Unity rule*: The unity rule is used when more than one radionuclide is present at a concentration that is distinguishable from background and where a single concentration comparison does not apply. In this case, the mixture of radionuclides is compared

¹ MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

or more increments with elevated activity concentrations by the other composite increments. Composite sampling should not be used when the AL ($DCGL_W$) is near the analytical detection limit or the natural background concentration level. When using composite sampling, it may be necessary to reduce the investigation level ($DCGL_W$ for a Class 2 survey unit or $DCGL_{EMC}$ for a Class 1 survey unit). Appendix O to NUREG-1757, Volume 2, Revision 2, discusses the use of such modified investigation levels.

Compositing involves combining and homogenizing multiple soil samples. The composite is then analyzed to give an average value for soil concentration in the composited sample volume. These scenarios generally involve situations in which analytical costs are high or required MDC_{SCAN} values in Class 1 survey units are difficult to achieve, possibly due to the presence of hard-to-detect radionuclides, both of which could increase analytical costs and reduce detection capability. With an appropriately adjusted investigation level, composite sampling can increase the ability of the survey to detect elevated areas by increasing the number of locations sampled.

Composite sampling may be used to estimate the mean concentration of a radionuclide of concern as may be applied for the type or scope of surveys being performed, including scoping, characterization, remedial action support, and final status surveys. Before selecting a composite sampling approach, an analyst should recognize that although an equivalent or better estimate of the mean may result from this approach, there is a loss of crucial information regarding the overall variability of the radionuclides of concern within the study area. It has limited applications for Scenario B cases (indistinguishable from background) when information on background variability is important. In general, the design of the sampling regime should be based on the normal MARSSIM approach (e.g., number and locations) for the area class; suitability (or advantages) of compositing samples before analysis may then be determined considering the advantages and disadvantages.

The Soil Screening Guidance for Radionuclides (EPA 2000a, 2000b) is a tool developed by the EPA to help standardize and accelerate the evaluation and cleanup of radioactively contaminated soils at sites on the National Priorities List where future residential land use is anticipated. The guidance provides a methodology for calculating risk-based, site-specific soil screening levels for radionuclides in soil that may be used to identify areas needing further investigation at listed sites. The Soil Screening Guidance assumes that there is a low probability of residual radioactive material and does not account for small areas of elevated activity. The approach for evaluating the composite sample uses a simple decision rule based on comparing the maximum contaminant concentrations of composite samples with surface soil screening levels (the Max test) to determine whether further investigation is needed for a particular exposure area. Because the EPA Soil Screening Guidance is designed as a screening tool with specific values for decision error levels, the bounds of the gray region and the number and location of measurements are developed to support the screening objectives. This EPA screening approach is somewhat different than the typical MARSSIM application and may be appropriate for screening Class 3 areas. However, with appropriate evaluations and applications, this approach may also be suitable for Class 1 and 2 areas. Applicable statistical testing of results using this screening approach would still be required to determine acceptable levels of residual radioactive materials.

Appendix O to NUREG-1757, Volume 2, Revision 2, and Vitkus (2012) provide additional guidance that may be considered, including information on when composite sampling would and would not be appropriate, a method for determining the number of increments in a composite and the number of composite samples needed for statistical testing, and the derivation of

modified investigation levels. They describe in detail an approach for incorporating composite sampling into survey designs.

The Interstate Technology and Regulatory Council has developed a structured Incremental Sampling Methodology (ISM) (Interstate Technology and Regulatory Council 2020) that offers a structured composite sampling and processing protocol that reduces data variability and provides a reasonably unbiased estimate of mean contaminant concentrations in a volume of soil targeted for sampling. ISM provides representative samples of specific soil volumes defined as decision units by collecting numerous increments of soil (typically, 30 to 100 increments) that are combined, processed, and subsampled according to specific protocols.

ASTM International (ASTM) D6051-15 (reapproved 2023), “Standard Guide for Composite Sampling and Field Subsampling for Environmental Waste Management Activities” (ASTM 2023b), contains useful guidance for developing procedures for composite sampling.

Early discussions with responsible regulatory agencies should be initiated if composite sampling will be used for characterization. Agreement on the scope and methodology should be reached before incorporating composite sampling into FSSs.

against default concentrations by applying the unity rule. This is accomplished by determining the ratio between (1) the concentration of each radionuclide in the mixture and (2) an appropriate derived concentration guideline level (DCGL) for each radionuclide in the mixture. The sum of the ratios for all radionuclides in the mixture should not exceed 1.

- *Radionuclides and DCGLs:* The design team needs to determine the radionuclides of concern and final form of the DCGLs. The DCGLs are typically based on dose (or risk) pathway modeling, which is used to determine release criteria expressed in measurable radiological quantities. These can be a soil concentration, surface (areal) concentration, or external dose (or exposure) rate.
- *Area and site considerations:* Properly classifying areas as impacted or non-impacted, identifying survey units, and selecting reference areas are critical for the successful execution of an FSS.
- *Statistical considerations:* MARSSIM recommends the use of statistical hypothesis testing in all but the simplest of surveys (refer to **Appendix B**). The MARSSIM user must be conversant with the statistical concepts discussed in the manual and should consider incorporating a statistician in the design team.
- *Measurements:* The detection capabilities of all the measurement techniques (including sampling) must be evaluated to ensure that the DQOs and Measurement Quality Objectives (MQOs) are met.
- *Site preparation:* Site preparation should start early, including efforts to gain permission to access the site, ensure that the survey team and equipment can operate safely, and establish the logistical means to perform the survey.
- *Health and safety:* Worker health and safety is a high priority, so each site must have a documented health and safety plan.
- *Survey design examples:* A few simplified examples are presented in **Section 4.12** to illustrate the process for planning surveys.

4.2 Data Quality Objectives Process

DQOs were introduced in **Chapter 1**, expanded upon in **Chapter 2**, and discussed in detail in **Appendix D**. The survey design team must be familiar with the DQO process to properly design a survey. The DQO process can be summarized in seven steps:

- (1) State the problem.
- (2) Identify the decisions to be made.
- (3) Identify inputs to the decision.
- (4) Define the study boundaries.
- (5) Develop a decision rule.
- (6) Specify limits on decision errors.
- (7) Optimize the survey design.

4.2.1 Planning Phase

Using the DQO process allows the survey design team to use a graded approach to ensure that the level of effort meets the design goals in a technically defensible and cost-effective manner. The intent of any survey is to ensure that the decision-makers have the appropriate type, quantity, and quality of environmental data needed to make the correct decision. DQOs are qualitative and quantitative statements derived from the DQO process that do the following:

- *Clarify the study objective:* The first step in any survey is to determine the objectives of the survey (DQO Steps 1 and 2). Depending on the data available from the previous RSSI activities (e.g., HSA review), the objectives of a survey can range from augmenting HSA information to be used as input in designing a characterization survey to releasing a survey unit. An important part of this clarification is the determination of the initial condition of each survey unit: The survey unit is assumed to be “above the release criteria” (Scenario A) or “below the release criteria” (Scenario B). **Section 2.5.1** and **Sections D.1.1 and D.1.2 of Appendix D** contain more details.
- *Define the most appropriate type of data to collect:* Once the objectives of the survey have been agreed upon, the design team must determine what data need to be collected (DQO Step 3). Implicit in this step is the determination of the radionuclides of concern, choice of equipment, detection limits, analytical methods, and statistical tests that will be used to meet the objectives of the survey.
- *Determine the most appropriate conditions for collecting the data:* In general, the “study boundaries” of a survey (DQO Step 4) are spatial; for example, the selection of the survey units. However, if the objective of the survey is to collect data for classification, then the spatial boundary of the survey might be the entire site under consideration. Throughout the RSSI process, decisions need to be made; for example, based on a review of the HSA’s conclusions and the results of scoping/characterization surveys, the decision-maker will determine survey unit boundaries and classifications.
- *Specify limits on decision errors that will be used as the basis for establishing the quantity and quality of data needed to support the decision:* To make decisions, the outputs of the survey must be in a form amenable to decision-making (DQO Step 5). MARSSIM recommends the use of statistical hypothesis testing to make decisions to release a survey unit. Because of the overall uncertainty in the surveying process, there is always a chance of a decision error (e.g., incorrectly concluding that a survey unit meets the release criteria, when in fact it does not). The chance of a decision error cannot be eliminated; however, it can be controlled (DQO Step 6). The survey design team must be aware of the chance of making decision errors and take measures to control them (e.g., collecting more samples, using more precise measurement techniques, and using better surveying and sampling designs).

When the previous steps are completed, the survey design team can optimize the survey plan (DQO Step 7); the team might need to work through this step several times to arrive at the best design. **Appendix D** discusses the planning phase of the data life cycle in detail. The MARSSIM user should read and be conversant with **Appendix D**.

Regardless of the survey type under consideration, the DQOs remain the overarching guide for planning; the design team needs to explain the “who, what, where, when, why, and how” for a survey.

4.2.2 Quality System

MARSSIM requires that all environmental data collection and use take place in accordance with a site-specific systematic planning process that incorporates industry-established quality assurance (QA) and quality control (QC). The goal of a QA/QC program is to identify and implement sampling and analytical methodologies that limit the introduction of error into analytical data. For MARSSIM data collection and evaluation, a quality system is needed to ensure that radiation surveys produce results that are of the type and quality needed and expected for their intended use. A quality system is a management system that describes the elements necessary to plan, implement, and assess the effectiveness of QA/QC activities. This system establishes many functions, including the following:

- quality management policies and guidelines for the development of organization- and project-specific quality plans
- criteria and guidelines for assessing data quality
- assessments to ascertain the effectiveness of QA/QC implementation
- training programs related to QA/QC implementation.

A quality system ensures that MARSSIM decisions will be supported by sufficient data of adequate quality and usability for their intended purpose, and it further ensures that such data are reliable, appropriately documented, and technically defensible. MARSSIM uses the project-level components of a quality system as a framework for planning, implementing, and assessing environmental data collection activities.

In accordance with the environmental data quality system described in **Appendix D**, all environmental data collection and use are to take place in accordance with a site-specific systematic planning process that consists of planning, implementation, and assessment phases. The results of the systematic planning process are usually documented in a Quality Assurance Project Plan (QAPP). A QAPP integrates all technical and quality aspects and defines in detail how specific QA/QC activities will be implemented during the survey project. Specific departments and agencies set their own procedures for developing QAPPs. Multiple agencies have adopted the Uniform Federal Policy for QAPPs (UFP-QAPP) (EPA 2005b, 2005c, 2005d, 2012), which was developed to provide procedures and guidance for consistently implementing the American National Standards Institute (ANSI)/American Society for Quality (ASQ) national consensus standard ANSI/ASQ E4, “Quality Systems for Environmental Data and Technology Programs—Requirements with Guidance for Use,” version issued in 2004 (ANSI/ASQ 2004), for the collection and use of environmental data. (ANSI/ASQ E4 was revised as “Quality Management Systems for Environmental Information and Technology Programs—Requirements with Guidance for Use” in 2014 [ANSI/ASQ 2014].) The UFP-QAPP is presented in three volumes:

- (1) Part 1, UFP-QAPP Manual (EPA-505-B-04-900A, DTIC ADA 427785) (EPA 2005b)
- (2) Part 2A, UFP-QAPP Workbook (EPA-505-B-04-900C, DTIC ADA 427486) (EPA 2005c)
- (3) Part 2B, Quality Assurance/Quality Control Compendium: Minimum QA/QC Activities (EPA-505-B-04-900B, DTIC ADA 426957) (EPA 2005d)
- (4) Optimized UFP-QAPP Worksheets (revision to Part 2A) (EPA 2012)

Using this scientific, logical approach to planning for data collection and assessment at a site helps ensure that the amounts and types of data collected are appropriate for decision-making and that the physical, environmental, chemical, and radiological characteristics of the site are adequately defined. The development of a QAPP is one of the first team-based QA/QC activities performed in the project planning stage.

The objective of the UFP-QAPP is to provide a single national consensus document for consistently and systematically implementing the project-specific requirements of ANSI/ASQ E4 and help ensure the quality, objectivity, utility, and integrity of environmental data. Information on selecting the number and type of QC measurements for a specific project is provided in Section 3.4 and Tables 4, 5, and 6 of the UFP-QAPP, Part 1; and Worksheet 28 of the UFP-QAPP, Part 2A, and Optimized UFP-QAPP Worksheets.

The UFP-QAPP, Part 2B, specifies the minimum QA/QC activities for all environmental data collection and use. However, this matrix of minimum requirements is not meant to be a replacement for a site-specific QAPP. A wide range of site-specific guidelines for data collection activities stated in the survey plan should be determined that relate to the ultimate use of the data. These guidelines include, but are not limited to, the following:

- types of decisions that will be supported by the data
- project quality objectives
- acceptance criteria for data quality indicators (also known as measurement performance criteria²)
- survey plan, including the location of environmental and QC samples and measurements
- types of radionuclides and analyses that require laboratory analysis (onsite, field, or fixed laboratory)

The QA/QC activities specified in the QA matrix represent a minimum list of activities. Other QA/QC activities may be added, depending on the decisions to be made and on site-specific conditions. The matrix of minimum QA/QC activities is organized by the following:

- survey type (i.e., scoping or characterization) for surveys before the FSS
- data uses (e.g., confirmatory measurements) for RAS surveys
- data type (i.e., screening versus definitive data)
- project stage (i.e., plan, implement, assess, decide)

4.3 Survey Types

4.3.1 Scoping

MARSSIM defines a scoping survey as a type of survey that is conducted to identify (1) radionuclides present, (2) relative radionuclide ratios, and (3) general concentrations and extent of residual radioactive material. In conjunction with an HSA, the results of a scoping survey can help determine (1) preliminary radionuclides of concern, (2) interim site and survey

² Measurement performance criteria are acceptance limits selected for project-specific sampling and analytical systems that will be used to judge whether project quality objectives are met.

unit boundaries, (3) initial area classifications, (4) data gaps, (5) initial estimates of the level of effort for remediation, and (6) information for planning a more detailed survey, such as a characterization survey. **Section 5.2.1** describes methods for planning, conducting, and documenting scoping surveys.

4.3.2 Characterization

MARSSIM defines a characterization survey as a type of survey that includes facility or site sampling, monitoring, and analysis activities to determine the horizontal and vertical extent and nature of residual radioactive material. Characterization surveys provide the basis for acquiring the necessary technical information to develop, analyze, and select appropriate cleanup techniques. Characterization surveys can be developed to meet a very broad range of objectives, many of which are outside the scope of MARSSIM. The guidance in **Section 5.2.2** concentrates on providing characterization survey planning information with an emphasis on the FSS design.

4.3.3 Remedial Action Support

MARSSIM defines remedial action as an action consistent with a permanent remedy either instead of or in addition to a removal action in the event of a release or threatened release of a hazardous substance into the environment. A remedial action is intended to prevent or minimize the release of hazardous substances so that they do not migrate and cause substantial danger to present or future public health or welfare or the environment. An RAS survey supports remediation activities and is used to monitor the effectiveness of remediation efforts intended to reduce residual radioactive material to acceptable levels. The general objectives of an RAS survey are to (1) support remediation activities, (2) determine when a site or survey unit is ready for the FSS, and (3) provide updated estimates of site-specific parameters to use for planning the FSS. **Section 5.2.3** describes methods for planning, conducting, and documenting an RAS survey.

4.3.4 Final Status

4.3.4.1 Survey

MARSSIM defines an FSS as measurements and sampling to describe the radiological conditions of a site, following completion of remediation activities (if any) in preparation for release. An FSS is performed to demonstrate that a survey unit meets the agreed-upon release criteria. In other words, the FSS is designed to answer the question, “Does the concentration of residual radioactive material in each survey unit satisfy the predetermined criteria for release for unrestricted use or, where appropriate, for use with designated limitations (restricted release)?” The primary objective of MARSSIM is to provide guidance for the FSS. The design of FSSs is discussed in detail in **Section 5.3**, with the remainder of MARSSIM expanding on the design, execution, and assessment of FSSs.

Figure 4-1 illustrates the sequence of activities described in this chapter and their relationship to the survey design process.

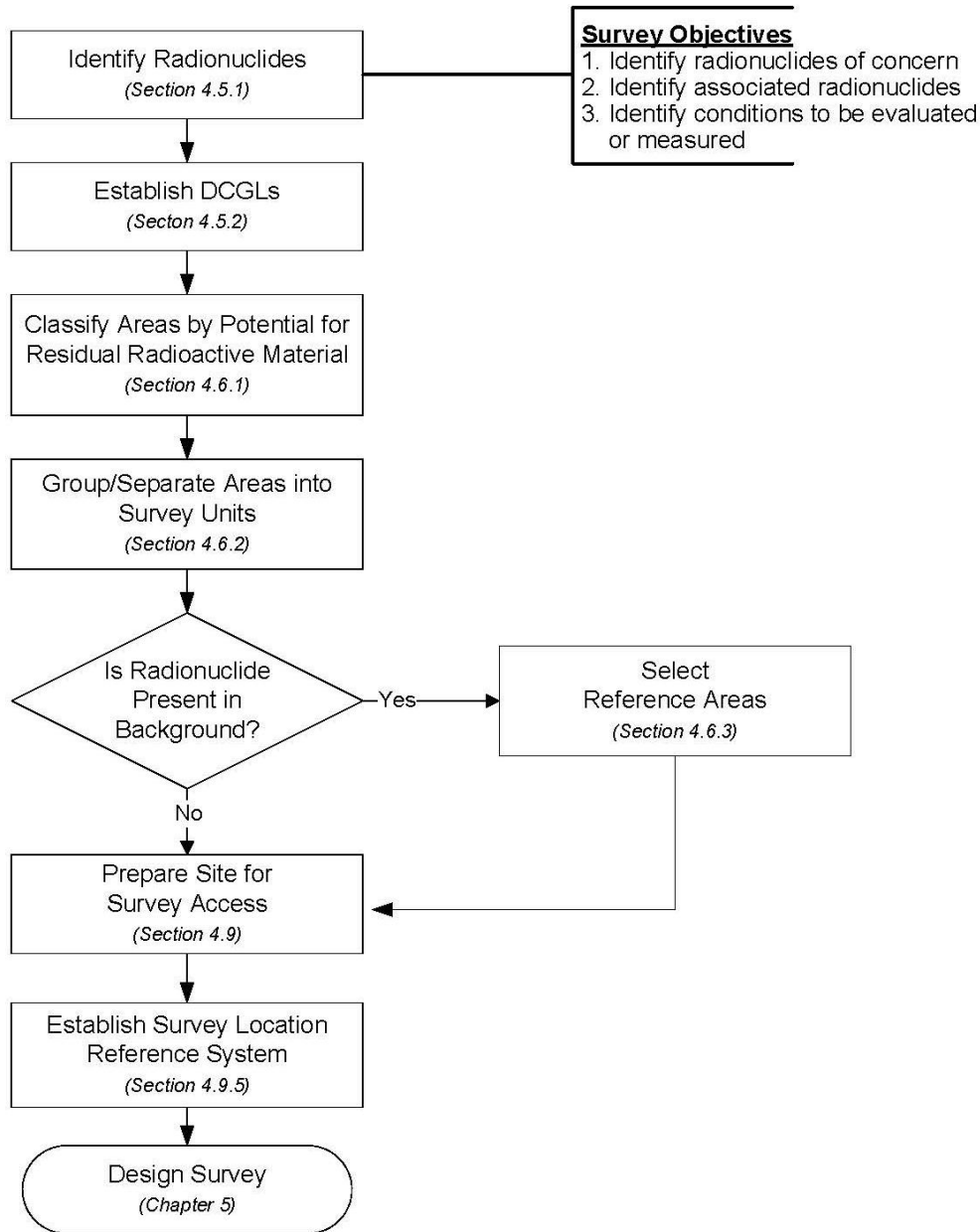


Figure 4-1 Major Steps in MARSSIM Field Survey Design

4.3.4.2 Verification Process

Historically, regulators commissioned verification surveys after the completion of an FSS. However, the application of the DQO process to the verification process has led to the development of more effective processes, such as in-process decommissioning inspections (Abelquist 2014). For example, the U.S. Nuclear Regulatory Commission (NRC) (NRC 2022b) and the U.S. Department of Energy (DOE) (DOE 2011c) require verification inspections of some sort; these documents can be used as guides for including verification processes in the FSS design project. The personnel who plan and execute an FSS should be familiar with independent verification (IV) process and be prepared to work with regulators and their

contractors to support the verification process during all phases of the FSS. Abelquist 2014 provides an example decommissioning inspection plan that might be useful when designing an FSS.

Bailey 2008 summarizes the experiences from IV activities by the Oak Ridge Institute for Science and Education in support of DOE decommissioning projects. In conclusion, Bailey 2008 states the following:

Independent verification should be integrated into the planning stages rather than after the cleanup contractor has completed the remediation work and demobilized from the site. The IV of onsite remediation and FSS activities should be coordinated and if possible implemented in parallel with the contractor to minimize schedule impacts. A well-implemented and thorough IV program for a site requires IV involvement throughout the D&D [decontamination and decommissioning] process. Independent verification is not a substitute for routine contractor quality assurance; however, IV activities often improve the contractor's performance. IV recommendations often improve the contractor's FSS procedures and results, while increasing the probability of complete remediation and documentation.

4.3.5 Simplified Procedures

The design team should be aware that under certain conditions (e.g., sites where radioactive materials have been used or stored only in the form of nonleaking, sealed sources, or radioactive materials with a short half-life), a simplified procedure might be used to demonstrate regulatory compliance. The design team should refer to **Appendix B** and seek regulatory approval before using this simplified procedure.

4.3.6 A Note on Subsurface Assessments

Many users might need to assess subsurface residual radioactive materials. Strictly speaking, this is beyond the scope of MARSSIM; however, the general concepts contained in MARSSIM (e.g., the DQO process, statistical survey and sampling design) may be appropriate to address subsurface residual radioactive materials. As always, any approach to site decommissioning needs to be discussed with the appropriate regulatory authorities.

4.4 The Unity Rule

The unity rule is used to ensure that the total dose (risk) from all sources (or media) and all radionuclides associated with each source does not exceed the release criteria. It is to be used when more than one radionuclide is present and distinguishable from background and a single concentration does not apply. Essentially, this means that if measurements of different quantities are made at a location, then the unity rule must be used. For example, the unity rule would be used if two radionuclides are measured in each soil sample or if gross alpha and gross beta measurements are made at each location and the results are being compared to specific DCGLs.

The total amount of anything, whether dose, counts, or activity, is simply the sum of its parts (M_i):

$$\text{Total} = M_1 + M_2 + \cdots + M_i + \cdots + M_n = \sum_{i=1}^n M_i \quad \text{Equation 4-1}$$

Dividing both sides of **Equation 4-1** by the total yields the following fundamental equation (**Equation 4-2**):

$$1 = f_1 + f_2 + \cdots + f_i + \cdots + f_n = \sum_{i=1}^n f_i \quad \text{Equation 4-2}$$

The basic statement of this equation is that sum of all fractions must add to unity (1).

When using the sum of fractions to demonstrate compliance in MARSSIM, each fraction (f) is determined by dividing each “part” (e.g., the concentration of residual radioactive material due to a specific radionuclide or source) by the respective release criterion (e.g., a DCGL). In an FSS for a survey unit to be released, the dose or risk from all radionuclides and all sources in a survey unit must be less than or equal to the applicable release criterion, and the sum of fractions for multiple radionuclides or sources must be less than or equal to unity:

$$\text{Total Dose or Risk} = \sum_{i=1}^n (\text{Dose or Risk Component})_i \leq \text{Release Criterion} \quad \text{Equation 4-3}$$

Dividing the terms in **Equation 4-3** by the applicable release criterion gives the following:

$$\frac{\text{Total Dose or Risk}}{\text{Release Criterion}} = \sum_{i=1}^n \left(\frac{\text{Dose or Risk Component}}{\text{Release Criterion}} \right)_i \leq 1 \quad \text{Equation 4-4}$$

If the dose/risk components and release criteria are expressed as concentrations (e.g., express the dose/risk as concentration and release criteria as DCGLs as discussed above),

Equation 4-4 can be written as follows in terms of concentrations:

$$\sum_{i=1}^n \left(\frac{\text{Dose or Risk Component}}{\text{Release Criterion}} \right)_i = \sum_{i=1}^n \frac{C_i}{\text{DCGL}_i} \leq 1 \quad \text{Equation 4-5}$$

where:

C_i = concentration of the i th component (e.g., radionuclide or source) leading to dose or risk

DCGL_i = derived concentration guideline level of the i th component (e.g., radionuclide or source) leading to dose or risk

This is the traditional form of the unity rule as used and defined in MARSSIM.

Other applications of **Equation 4-1** or derivatives, such as deriving a gross activity DCGL, will be covered in the corresponding section of this and other chapters as needed.

4.5 Radionuclides

4.5.1 Radionuclides of Concern

During the design of an FSS, the survey team should thoroughly review all the remediation activities conducted before the FSS to determine the radionuclides of concern and their expected concentrations in each survey unit. The team should also determine whether the concentrations of the radionuclides of concern in the background need to be accounted for in

the FSS design; for example, if a radionuclide is not present in the background, the FSS can be designed based on the one-sample Sign³ test.

If neither remedial action nor HSA data exist, then the survey design team should make the identification of the radionuclides of concern a primary objective of the team's actions. Whether through an HSA, a scoping survey, a characterization survey, or some combination of these, the team must make an initial characterization of the types, concentrations, and distribution of the residual radioactive material at the site.

4.5.2 Release Criteria and Derived Concentration Guideline Levels

The decommissioning process ensures that residual radioactive material will not result in individuals being exposed to unacceptable levels of radiation dose or risk. Regulatory agencies establish radiation dose standards based on risk considerations and scientific data relating dose to risk. These radiation dose standards are the fundamental release criteria; however, they are not measurable. To translate these release criteria into measurable quantities, residual levels of radioactive material corresponding to the release criteria are derived (calculated) by analysis of various pathways (e.g., direct radiation, inhalation, and ingestion) and scenarios (e.g., resident farmer, industrial, recreational) through which exposures could occur.

The resulting DCGLs are usually presented in terms of surface or volumetric activity concentrations per unit area or mass of material, respectively (typically becquerels [Bq] per square meter [m²] or disintegrations per minute [dpm]/square centimeter [cm²], or Bq/kilogram [kg] or picocuries [pCi]/gram [g], respectively). The details of the derivation of DCGLs are beyond the scope of MARSSIM. However, the survey design team should understand how the DCGLs were derived, because the models and assumptions used to derive DCGLs can drive how measurements are made. For example, if DCGLs for soil were derived based on an assumption that the residual radioactive material was restricted to the top 15 centimeters (cm) of soil, a condition verified in a characterization survey, then for the FSS it would not be appropriate to collect soil samples from the top 30 cm of soil. In some cases, generally applicable screening values are available from the relevant regulatory agency. In other cases, DCGLs derived for site-specific conditions can be used with permission of the relevant regulatory agency.

There are two types of DCGLs applicable to satisfying decommissioning objectives:

- (1) The DCGL for average concentrations over a wide area (DCGL_W) is the mean⁴ concentration of residual radioactive material within a survey unit that corresponds to the release criteria (e.g., regulatory limit in terms of dose or risk).
- (2) The DCGL elevated measurement comparison (DCGL_{EMC}) accounts for the smaller area of elevated residual radioactive material and is typically derived based on dose (or risk) pathway modeling. The DCGL_{EMC} is always greater than or equal to the DCGL_W.

The contributions to dose or risk from both the uniform area and areas of elevated residual radioactive material, if applicable, must meet the condition expressed in **Equation 8-13** in

³ The Sign test is a statistical test to demonstrate compliance with the release criteria when the radionuclide of concern is not present in background.

⁴ The mean is sum of the values divided by the number of measurements and is commonly called the average. In MARSSIM, "average" and "mean" both refer to the arithmetic mean.

Section 8.6.2. The development of regulatory requirements leading to the establishment of a DCGL_{EMC} is beyond the scope of MARSSIM and is determined strictly through the requirements of regulatory agencies. Therefore, it is important to work with the applicable regulatory agency to determine whether requirements for a DCGL_{EMC} should be consistent with the approach presented in MARSSIM or those in regulatory documents. The DCGL_{EMC} and associated requirements for areas of elevated radioactive material may not be necessary for all sites, especially where residual radioactive materials are relatively uniform or there is an absence of localized elevated levels relative to the remainder of the survey unit. **Section 5.3.5** contains more discussion about elevated areas of radioactive material and their consideration during radiological survey activities.

The MARSSIM user should remember five things about release criteria and DCGLs:

- (1) The fundamental release criteria are dose or risk based and cannot be measured.
- (2) The fundamental release criteria are translated into measurable DCGLs.
- (3) The determination of acceptable DCGLs must be coordinated with the regulator.
- (4) The derivation of radionuclide-specific DCGLs is beyond the scope of MARSSIM.
- (5) The application of radionuclide-specific DCGLs to derive operational DCGLs (refer to **Section 4.5.3** for a definition) for FSSs is the responsibility of MARSSIM user.

4.5.3 Applying Derived Concentration Guideline Levels

This section focuses on introducing the application and modifications of DCGLs to derive operational DCGLs for various situations commonly encountered while planning FSSs. An operational DCGL is any modification or combination of radionuclide-specific DCGLs to derive a measurable quantity (e.g., a gross beta activity DCGL). The simplest application of a DCGL is when a single radionuclide is distributed uniformly throughout a survey unit. When multiple radionuclides are present in a survey unit, (1) the ratios of the concentrations of radionuclides are roughly constant (correlated), or (2) the concentrations are unrelated. Statistical tests can be performed to calculate the degree of correlation among the concentrations. Ultimately, sound judgment must be used when interpreting the results of the calculations. If there is no physical reason for the concentrations to be correlated, then they are likely not. However, if there is sound evidence of correlation, then that evidence should be used. The survey design team should consult closely with the appropriate regulatory agency during the design phase.

Fundamentally, the measurement of residual radioactive material involves one or more of the following:

- radionuclide-specific analyses
- gross activity measurements
- external radiation measurements

The choice of the operational DCGL depends on the types of measurements being made. If multiple radionuclides are considered using gross activity measurements, then it might be acceptable to use the smallest DCGL of the radionuclides present. To use surrogate measurements to demonstrate compliance, all significant radionuclides should be identified, the contributions of the various radionuclides should be known, and DCGLs should be developed for each of the radionuclides of concern. If there is a well-established correlation between

radionuclide concentrations, then a weighted gross activity DCGL or surrogate-based DCGL might be acceptable. If no correlation exists or a combination of the above options is proposed, then the unity rule must be used.

4.5.3.1 *Derived Concentration Guideline Levels for a Single Radionuclide*

For a single radionuclide, compliance is easy to demonstrate if all the measurements in the survey unit are below the DCGL. Otherwise, an appropriate statistical test must be used. This is straightforward when there is one radionuclide (e.g., strontium/yttrium-90 [⁹⁰Sr/Y]) where radioactive decay products are included in the DCGL. If the radioactive decay products are not included in the DCGL but the radioactive decay products are present, the survey team must use one of the methods outlined below. Additionally, the methods described below can be used for radionuclides that are not part of the same decay chain (e.g., presence of a mix of fission products, such as strontium-90 (⁹⁰Sr) and cesium-137 (¹³⁷Cs)).

If a DCGL for the parent of a serial decay chain includes contributions from the progeny, then the direct application of that DCGL is possible. It is incumbent on the design team to determine if the radionuclides of concern are parents of a decay series and if progeny are accounted for in all DCGLs. For example, values for natural thorium (Th_{nat}) and natural uranium (U_{nat}) typically include progeny; however, the design team must confirm this. **Section 4.5.3.8** discusses serial radioactive decay.

4.5.3.2 *Most Conservative Derived Concentration Guideline Level Approach for Multiple Radionuclides*

If there are multiple radionuclides in a survey unit, then it might be possible to use the lowest (most restrictive) DCGL. Note that if DCGL_{min} is the lowest of the DCGLs, then **Equation 4-6** applies, and DCGL_{min} may be applied to the total activity concentration rather than using the unity rule:

$$\frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \cdots + \frac{C_n}{DCGL_n} \leq \frac{(C_1 + C_2 + \cdots + C_n)}{DCGL_{min}} \leq 1 \quad \text{Equation 4-6}$$

The goal is then to demonstrate that the ratio of the total concentration of all radionuclides to DCGL_{min} is less than 1, or alternatively that the total concentration of all radionuclides is less than DCGL_{min}. Although this option may be considered, in many cases it will be too conservative to be useful. Furthermore, the ease of detection must be taken into account during the DQO process if use of the DCGL_{min} is being considered.

4.5.3.3 *Derived Concentration Guideline Levels for Multiple Radionuclides in Known Ratios (Surrogate Measurements)*

For sites with multiple radionuclides, it may be possible to measure just one of the radionuclides and still demonstrate compliance for all radionuclides present by using surrogate measurements. If there is an established ratio among the concentrations of the radionuclides in a survey unit, then the concentration of every radionuclide can be expressed in terms of any one of them. The measured radionuclide is often called a *surrogate radionuclide* for the others. In this case, the unity rule can be used to derive a new, modified DCGL for the surrogate radionuclide, which accounts for the dose or risk contributions of the other radionuclides that are not measured.

The fundamental aspect of the unity rule is that the sum of the ratios of the concentrations to the DCGLs for each radionuclide should be less than or equal to one, as shown in **Equation 4-7**:

$$\sum_{i=1}^n \frac{C_i}{\text{DCGL}_i} \leq 1 \quad \text{Equation 4-7}$$

where:

C_i = concentration of the i th radionuclide
 DCGL_i = DCGL of the i th radionuclide

The terms in the denominator are the original, unmodified DCGLs for all the radionuclides in the survey unit. However, when using a surrogate radionuclide, the design team needs to ensure that the DCGL for the surrogate radionuclide is modified ($\text{DCGL}_{\text{S-mod}}$) to account for the presence of all the radionuclides. This is done by applying the unity rule as shown in **Equation 4-8**:

$$\frac{C_s}{\text{DCGL}_{\text{S-mod}}} \leq 1 \quad \text{Equation 4-8}$$

where:

C_s = concentration of the surrogate radionuclide
 $\text{DCGL}_{\text{S-mod}}$ = modified DCGL for the surrogate radionuclide

Here, $\text{DCGL}_{\text{S-mod}}$ is the DCGL for the surrogate radionuclide modified so that it represents all radionuclides that are present in the survey unit. The $\text{DCGL}_{\text{S-mod}}$ is a variation of the unity rule that uses established ratios as shown in **Equation 4-9**:

$$\text{DCGL}_{\text{S-mod}} = \frac{1}{\left(\frac{1}{\text{DCGL}_{\text{S-unmod}}} + \frac{R_2}{\text{DCGL}_2} + \dots + \frac{R_i}{\text{DCGL}_i} + \dots + \frac{R_n}{\text{DCGL}_n} \right)} \quad \text{Equation 4-9}$$

where:

$\text{DCGL}_{\text{S-unmod}}$ = DCGL of the surrogate radionuclide before modification
 DCGL_i = DCGL of the i th radionuclide for $i = 2, \dots, n$
 R_i = established ratio of the concentration of the i th radionuclide to the concentration of the surrogate radionuclide for $i = 2, \dots, n$

$\text{DCGL}_{\text{S-mod}}$ is then used for survey design purposes as described in **Chapter 5**. An example calculation of a surrogate DCGL and additional discussion are shown in **Section 4.12.2.2**.

This scheme is applicable only when radionuclide-specific measurements of the surrogate radionuclide are made. It is unlikely to apply when the surrogate radionuclide appears in background, as background variations would increase the uncertainty in the calculation of the surrogate measurements to unacceptable levels.

When using surrogates, it is often difficult to establish a consistent ratio between two or more radionuclides. Rather than follow prescriptive guidance on acceptable levels of variability for the

surrogate ratio, a more reasonable approach may be to review the data collected to establish the ratio and to use the DQO process to select an appropriate ratio from those data and assess the feasibility of using surrogates. The benefit of using the surrogate approach is avoiding the need to perform costly wet chemistry analyses on each sample. This benefit should be considered relative to the difficulty in establishing the surrogate ratio, as well as the potential consequence of unnecessary investigations that result from decision errors that may arise from using a “conservative” surrogate ratio (i.e., determining that the site is dirty when the site is clean). Selecting a conservative surrogate ratio ensures that potential exposures from individual radionuclides are not underestimated. The surrogate method can only be used with confidence when dealing with the same media in the same surroundings—for example, soil samples with similar physical and geological characteristics. The planning team will need to consult with the regulatory agency for concurrence on the approach used to determine the surrogate ratio.

The potential for shifts or variations in the radionuclide ratios means that the surrogate method should be used with caution. Physical or chemical differences among the radionuclides may produce different migration rates, causing the radionuclides to separate and changing the radionuclide ratios. Remediation activities have a reasonable potential to alter the surrogate ratio established before remediation. MARSSIM recommends that when the ratio is established before remediation, additional post-remediation samples should be collected to ensure that the data used to establish the ratio are still appropriate and representative of the existing site condition. If these additional post-remediation samples are not consistent with the data gathered before remediation, surrogate ratios should be re-established.

4.5.3.4 Gross Activity Derived Concentration Guideline Levels for Multiple Radionuclides in Known Ratios

If multiple radionuclides with their own DCGLs are present, a gross activity DCGL can be developed. This approach enables field measurement of gross activity (e.g., Bq/m²), rather than determination of individual radionuclide activity, for comparison to the DCGL. The gross activity DCGL for surfaces with multiple radionuclides is calculated as follows:

- (1) Determine the relative fraction, f_i of the total activity contributed by each of the n radionuclides present for $i = 1, \dots, n$.
- (2) Obtain the $DCGL_i$ for each i th radionuclide present for $i = 1, \dots, n$.
- (3) Substitute the values f_i and $DCGL_i$ in **Equation 4-10** for $i = 1, \dots, n$.

$$DCGL_{\text{gross}} = \frac{1}{\left(\frac{f_1}{DCGL_1} + \frac{f_2}{DCGL_2} + \dots + \frac{f_i}{DCGL_i} + \dots + \frac{f_n}{DCGL_n} \right)} \quad \text{Equation 4-10}$$

This process can be used to calculate a gross activity DCGL to be used as a $DCGL_w$ or a $DCGL_{EMC}$. **Example 4-6** in **Section 4.12.2.3.2** illustrates the calculation of a gross activity DCGL.

Just as in the case of surrogate radionuclides, note that **Equation 4-10** might not work for sites having unknown or highly variable relative fractions of radionuclides throughout the site. In these situations, the best approach may be to select the most conservative surface DCGL from the mixture of radionuclides present (**Section 4.5.3.2**) or use the unity rule (**Section 4.5.3.5**). If the radionuclide with the most restrictive DCGL cannot be measured or is hard to detect with field instruments, the DQOs must be revisited to determine the best approach. If the mixture contains radionuclides that cannot be measured using field survey equipment, laboratory

analyses of surface materials may be necessary. The investigator should check with the regulator as to whether the use of a gross activity DCGL is appropriate for the site.

4.5.3.5 *Derived Concentration Guideline Levels for Multiple Radionuclides with Unrelated Concentrations*

If the concentrations of the different radionuclides appear to be unrelated in the survey unit, the surrogate approach cannot be used. There is little choice but to measure the concentration of each radionuclide and use the unity rule. The alternative would involve performing gross measurements (e.g., alpha or beta) and applying the most restrictive DCGL_w to all radionuclides.

As discussed in **Section 4.4**, the fundamental release criterion is that the sum of all the radiation dose (risk) from all the residual radionuclides in a survey unit must be less than or equal to the dose or risk criteria. In terms of DCGLs, the unity rule states that for a survey unit to meet the release criteria, the sum of the ratios of the concentrations of each radionuclide to their respective DCGLs must be less than or equal to one, as shown in **Equation 4-11**:

$$\frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \cdots + \frac{C_i}{DCGL_i} + \cdots + \frac{C_n}{DCGL_n} \leq 1 \quad \text{Equation 4-11}$$

where:

C_i = concentration of the i th radionuclide for $i = 1, \dots, n$
 $DCGL_i$ = DCGL of the i th radionuclide for $i = 1, \dots, n$

By using the unity rule in this manner, the design team creates an effective DCGL of 1. Note that the DCGL is no longer expressed as a concentration; it is a unitless sum of fractions. To apply the unity rule, the design team must calculate the sum of the ratios (SOR) or weighted sum (T) of the ratios in the survey unit for each quantity measured at a given location, as illustrated in **Equation 4-12** and **Example 4-10** in **Section 4.12.4**.

$$T = \frac{C_1}{DCGL_1} + \frac{C_2}{DCGL_2} + \cdots + \frac{C_i}{DCGL_i} + \cdots + \frac{C_n}{DCGL_n} \quad \text{Equation 4-12}$$

where:

C_i = concentration in the sample of the i th radionuclide for $i = 1, \dots, n$
 $DCGL_i$ = DCGL of the i th radionuclide for $i = 1, \dots, n$

In a given sample, the concentration of each radionuclide is divided by its DCGL (normalization). This weighted sum, T , and its standard deviation, $\sigma(T)$, will be used in the statistical tests to determine whether a survey unit can be released. The standard deviation in the weighted sum is calculated as shown in **Equation 4-13**:

$$\sigma(T) = \sqrt{\left[\frac{\sigma(C_1)}{DCGL_1}\right]^2 + \left[\frac{\sigma(C_2)}{DCGL_2}\right]^2 + \cdots + \left[\frac{\sigma(C_i)}{DCGL_i}\right]^2 + \cdots + \left[\frac{\sigma(C_n)}{DCGL_n}\right]^2} \quad \text{Equation 4-13}$$

where:

$\sigma(C_i)$ = estimate of uncertainty in the concentration in the sample of the i th radionuclide for $i = 1, \dots, n$

$DCGL_i =$ DCGL of the i th radionuclide for $i = 1, \dots, n$

Note that if there is a fixed ratio between the concentrations of some radionuclides but not others, a combination of the methods in **Section 4.5.3.4** and **Section 4.5.3.5** may be used. The appropriate value of the DCGL with the concentration of the measured surrogate radionuclide should replace the corresponding terms in **Equation 4-12** and **Equation 4-13**. **Example 4-10** in **Section 4.12.4** illustrates the calculation of the weighted sum and its associated uncertainty for two radionuclides.

During the planning stage, data from characterization, scoping, or other surveys can be used to estimate the values of T and $\sigma(T)$ in the survey unit to determine the number of samples needed for the statistical tests.

Although this chapter does not discuss interpreting the data from an FSS (**Chapter 8**), a note on how T is used can be helpful at this point. If the sum of the normalized concentrations is below 1.0 for every sample in a survey unit, compliance has been demonstrated. If a survey unit has several individual locations where T_i exceeds 1, this does not mean that the survey unit fails to meet the release criteria. If any individual T_i exceeds 1, then, as for the case for a single radionuclide, an appropriate statistical test and the elevated measurement comparison test must be performed.

4.5.3.6 *The Use of External Radiation Measurements as a Surrogate*

In lieu of using measurements of radionuclide concentrations to determine compliance with release criteria, the DQO process can be used to determine whether in situ measurements of external radiation levels (e.g., exposure rates) can be used, particularly for radionuclides that deliver the majority of their dose through the direct radiation pathway. This approach can be desirable because external radiation measurements are generally easier to make and less expensive than measuring radionuclide concentrations.

This method requires the establishment of a consistent ratio for the surrogate and unmeasured radionuclides. The appropriate exposure rate DCGL could also account for radionuclides that do not deliver the majority of their dose through the direct radiation pathway. This is accomplished by determining the fraction of the total activity represented by radionuclides that do deliver the majority of their dose through the direct radiation pathway and weighting the exposure rate limit by this fraction (refer to the surrogate discussion in **Section 4.5.3.3**). Note that the previously mentioned considerations for establishing consistent ratios in **Section 4.5.3.3** also apply to this surrogate approach. The regulatory agency should be consulted before using this surrogate approach.

4.5.3.7 *Small Areas of Elevated Activity*

The concept of the elevated measurement comparison and $DCGL_{EMC}$ for small areas of elevated activity was introduced in **Section 4.5.2**. The $DCGL_{EMC}$ accounts for the smaller area of elevated residual radioactive material and is equal to or greater than the $DCGL_W$. Recall that the development of regulatory requirements leading to the establishment of a $DCGL_{EMC}$ is beyond the scope of MARSSIM and is determined strictly through the requirements of regulatory agencies. Therefore, it is important to work with the applicable regulatory agency to determine whether requirements for establishing a $DCGL_{EMC}$ are consistent with the approach presented in MARSSIM or those in regulatory documents.

Section 8.6.2 (refer to **Equation 8-13**) addresses the use of $DCGL_{EMCs}$ along with the $DCGL_W$ for assessing compliance. It indicates that the sum of fractions for each radionuclide, source, and elevated area, as applicable, should be summed to assess compliance with the release criteria. This approach can be overly conservative in certain cases. For example, if several DCGLs are developed for use in **Equation 8-13** without modifying occupancy times, an analyst may inadvertently assume that a receptor is located in the center of multiple elevated areas and in the larger survey unit at the same time, leading to unrealistic, if not physically impossible, exposure times.

Abelquist (2008 and 2010) compares various approaches for addressing elevated areas of radioactive material. Abelquist calculated area factors that were significantly higher than those calculated using other approaches. Abelquist's work supports the use of alternative approaches to considering elevated areas of residual radioactive material when traditional methods yield unacceptable results. Guidance on the consideration of elevated areas of residual radioactivity also appears in Chapter 5 and Appendix I of NUREG-1757, "Consolidated Decommissioning Guidance," Volume 2, Revision 2, "Characterization, Survey, and Determination of Radiological Criteria," issued July 2022 (NRC 2022a). If elevated areas are risk-significant for a particular site, the cognizant regulatory agency should be consulted to determine acceptable methods for addressing elevated areas.

All the methods used to modify individual DCGLs to account for multiple radionuclides can be used to modify the $DCGL_{EMC}$. When the ratios among the radionuclides is unknown, the unity rule inequality for the elevated measurement comparison is as shown in **Equation 4-14**:

$$\frac{C_1}{DCGL_{EMC,1}} + \frac{C_2}{DCGL_{EMC,2}} + \dots + \frac{C_i}{DCGL_{EMC,i}} + \dots + \frac{C_n}{DCGL_{EMC,n}} \leq 1 \quad \text{Equation 4-14}$$

In **Equation 4-14**, C_i is concentration of the i th radionuclide for $i = 1, \dots, n$, and $DCGL_{EMC,i}$ is the $DCGL_{EMC}$ for i th radionuclide for $i = 1, \dots, n$.

Areas of elevated activity may have different radionuclide ratios relative to the larger survey unit as a whole due to either redistribution of radionuclides or different events, which would lead to different assumptions for the design and evaluation of radiation surveys for areas of elevated activity. Also, radionuclide ratios may change for sites following remediation. Spatial and temporal heterogeneity in radionuclide ratios should be considered during the design of FSSs.

The use of **Equation 4-14** may not be appropriate for scanning. For scanning, minimum detectable concentration (MDC) considerations are a little more nuanced than for discrete sampling. For example, when scanning for areas with potentially elevated concentrations of residual radioactive material, the scan MDC should be below the DCGL—preferably at a fraction (approximately 50 percent)⁵ of the DCGL. In a Class 1 survey unit, the scan MDC should be less than the $DCGL_{EMC}$. **Sections 5.3.5.1 and 5.3.5.2** contain additional information. The radionuclide yielding the lowest detector response may or may not have the most restrictive DCGL.

As illustrated in **Equation 4-15**, to use the surrogate (known ratios) method for the elevated measurement comparison, the $DCGL_{EMC}$ for the surrogate radionuclide is replaced as follows:

⁵ Refer to **Section 2.3.1** on detection capability.

$$DCGL_{EMC,S-mod} = \frac{1}{\frac{1}{DCGL_{EMC,S-unmod}} + \frac{R_2}{DCGL_{EMC,2}} + \dots + \frac{R_i}{DCGL_{EMC,i}} + \dots + \frac{R_n}{DCGL_{EMC,n}}} \quad \text{Equation 4-15}$$

where:

$DCGL_{EMC,S-unmod}$ = unmodified $DCGL_{EMC}$ for the first radionuclide

R_i = concentration ratio of the i th radionuclide to the first radionuclide for $i = 2, \dots, n$

$DCGL_{EMC,i}$ = $DCGL_{EMC}$ for the i th radionuclide for $i = 2, \dots, n$

As discussed in **Section 2.5.1.1**, if a survey unit has more than one elevated area, a separate term should be included in the unity rule calculation for each area of elevated activity. As an alternative to the unity rule, the dose or risk from the actual distribution of residual radioactive material can be calculated if there is an appropriate exposure pathway model available.

4.5.3.8 A Note on Serial Radioactive Decay

For decay series (e.g., thorium and uranium) whose radionuclides emit alpha, beta, and gamma radiation, compliance with building surface activity DCGLs may be demonstrated by assessing alpha, beta, or gamma radiations. However, relying on the use of alpha surface measurements often proves problematic because of the highly variable level of alpha attenuation by rough, porous, and dusty surfaces. Beta measurements typically provide a more accurate assessment of thorium and uranium on most building surfaces because surface conditions cause significantly less attenuation of beta particles than alpha particles. Beta measurements, therefore, may provide a more accurate determination of surface activity than alpha measurements. The presence of gamma-emitting radionuclides can introduce uncertainty into the beta measurements, and field measurement techniques need to be used to account for the gamma interference at each beta measurement location.

The relationship of beta and alpha emissions from decay chains or various enrichments of uranium should be considered when determining the surface activity for comparison with the DCGL values. When the initial member of a decay chain has a long half-life, the concentration of radioactive material associated with the subsequent members of the series will increase at a rate determined by the individual half-lives until all members of the decay chain are present at activity levels equal to the activity of the parent. This condition is known as secular equilibrium.

Section 4.12.2.1 provides an example of the calculation of the beta activity $DCGL_W$ for thorium-232 (^{232}Th) in equilibrium with its decay products.

4.5.4 Investigation Levels

The survey design should include the development of investigation levels during the DQO process for the FSS. A measurement result is compared to an investigation level to indicate when additional action might be necessary (e.g., a measurement that exceeds the $DCGL_W$ in a Class 2 area). Investigation levels can be radionuclide-specific levels of radioactive material or an instrument response (e.g., counts per minute). **Section 5.3.8** contains additional discussions of investigation levels.

4.5.5 Conclusions

The foregoing discussion of DCGLs highlights the following:

- Measurements can be made for specific radionuclides, typically through gamma spectrometry or radiochemical analyses.
- The FSS design team should be familiar with the operational DCGLs and their applications.
- Gross activity measurements—typically gross alpha or beta concentrations—can be made, especially on building surfaces.
- Measurement of surrogate quantities can be used based on known relationships among the various radionuclides.
- The use of surrogates or ratios determined from data collected before the FSS must be approved by the appropriate regulatory authorities, and if remediation or other activities occur that could affect the ratios, additional support for the assumed ratios or revisions to the ratios is needed.
- The unity rule can be used to determine the DCGLs for use in the design of the FSS when multiple radionuclides or sources are present.
- If DCGLs are modified for use of surrogates, that modification will affect instrument selection.

The choice of how the DCGLs are applied and measured affects the statistical methods, reference area selection, and other design features of a survey. For example, MARSSIM recommends using the Wilcoxon Rank Sum (WRS) test if the radionuclides are present in the background or if gross activity measurements are made (refer to **Section 8.2.3**).

4.6 Area and Site Considerations

4.6.1 Area Classification

All areas of a site will not have the same potential for residual radioactive material and, accordingly, will not need the same level of survey coverage to demonstrate compliance with the established release criteria. The process will be more efficient if the survey is designed so that areas with higher potential for residual radioactive material (based in part on results of the HSA discussed in **Chapter 3**) will receive a higher degree of survey effort. The following is a discussion of site area classifications.

Non-impacted areas: These are areas that have no reasonable potential to contain concentrations of residual radioactive material above background and do not need any level of survey coverage. Those areas have no radiological impact from site operations and are typically identified during the HSA (**Chapter 3**). Reference areas are normally selected from non-impacted areas (**Section 4.6.3**).

Impacted areas: Areas with a possibility of containing residual radioactive material in excess of natural background or fallout levels. They can be classified into three classes:

- (1) *Class 1 areas:* Areas that have, or had prior to remediation, a potential for residual radioactive material (based on site operating history) or known residual radioactive material (based on previous radiological surveys) above the DCGL_w. Examples of Class 1 areas include the following:

- site areas previously subjected to remedial actions⁶
- locations where leaks or spills are known to have occurred
- former burial or disposal sites
- waste storage sites

Note that areas containing residual radioactive material in excess of the DCGL_w prior to remediation should be classified as Class 1 areas. Justification is not required for a Class 1 designation, unlike a Class 2 or Class 3 designation. The less restrictive the classification, the greater the justification required.

- *Class 2 areas:* Areas that have, or had prior to remediation, a potential for residual radioactive material or known residual radioactive material, but are not expected to exceed the DCGL_w. To justify changing an area's classification from Class 1 to Class 2, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence that no individual measurement would exceed the DCGL_w. Other justifications for this change in an area's classification may be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 2 for the FSS include the following:
 - locations where radioactive materials were present in an unsealed form (e.g., process facilities)
 - transport routes with potential residual radioactive material
 - areas downwind from stack release points
 - upper walls, roof support frameworks, and ceilings of buildings or rooms subjected to airborne radioactive material
 - areas where low concentrations of radioactive materials were handled
 - areas on the perimeter of former radiological control areas
- *Class 3 areas:* Any impacted areas that are not expected to contain any residual radioactive material or are expected to contain concentrations of residual radioactive material at a small fraction of the DCGL_w, based on site operating history and previous radiological surveys. To justify changing an area's classification from Class 1 or Class 2 to Class 3, the existing data (from the HSA, scoping surveys, or characterization surveys) should provide a high degree of confidence that there is either no residual radioactive material, or that any levels of residual radioactive material are a small fraction of the DCGL_w. Other justifications for this change in an area's classification may

⁶ Remediated areas are identified as Class 1 areas because the remediation process often results in less than 100 percent removal of the residual radioactive material. The residual radioactive material that remains on the site after remediation is often associated with relatively small areas with elevated concentrations of radioactive material. This results in a non-uniform distribution of the radionuclide and a Class 1 classification. If an area is expected to have no potential to exceed the DCGL_w (i.e., a Class 2 area before remediation) and was remediated for reasons other than an exceedance of the DCGL_w, the remediated area would still be classified as Class 2 for the FSS.

be appropriate based on the outcome of the DQO process. Examples of areas that might be classified as Class 3 include the following:

- buffer zones around Class 1 or Class 2 areas
- areas with very low potential for residual radioactive material but insufficient information to justify a non-impacted classification

Classification is a critical step in the survey design process, as well as for the FSS (refer to **Table 2-2**). Class 1 areas have the greatest potential for residual radioactive material and, therefore, receive the highest degree of survey effort, followed by Class 2 and then Class 3 areas. All areas should be considered Class 1 areas unless some basis for classification as Class 2 or Class 3 is provided.

The FSS plan should describe the criteria for designating areas as Class 1, 2, or 3. Compliance with the classification criteria should be demonstrated in the FSS report. A thorough analysis of HSA findings (**Chapter 3**) and the results of scoping and characterization surveys provide the basis for an area's classification. As a survey progresses, reevaluation of this classification may be necessary based on newly acquired survey data. For example, if residual radioactive material at concentrations that are a substantial fraction of the DCGL_W is identified in a Class 3 area, an investigation and reevaluation of that area should be performed to determine whether the Class 3 area classification is appropriate. Typically, the investigation will result in part or all of the area being reclassified as Class 1 or Class 2. If survey results identify residual radioactive material in a Class 2 area exceeding the DCGL or suggest that there may be a reasonable potential that residual radioactive material is present in excess of the DCGL, an investigation should be initiated to determine whether all or part of the area should be reclassified as Class 1. **Section 5.3.8** contains more information on investigations and reclassifications.

4.6.2 Identification of Survey Units

A survey unit is a physical area consisting of structures or land areas of specified size and shape at a site for which a separate decision will be made as to whether or not the unit meets the release criteria. This decision is made as a result of the FSS. Therefore, the survey unit is the primary entity for demonstrating compliance with the release criteria.

To facilitate survey design and ensure that the survey data points for a specific site are relatively uniformly distributed among areas of similar potential for residual radioactive material, the site is divided into survey units that share a common history or other characteristics or are naturally distinguishable from other portions of the site. A site may be divided into survey units at any time before the FSS. Areas that have been classified can be one survey unit or multiple survey units. For example, HSA or scoping survey results may provide sufficient justification for partitioning the site into Class 1, 2, or 3 areas. Note, however, that dividing the site into survey units is critical only for the FSS; scoping, characterization, and RAS surveys may be performed without dividing the site into survey units.

A survey unit cannot include areas that have different classifications. A survey unit's characteristics should be consistent with exposure pathway modeling that is used to convert dose or risk into radionuclide concentrations. For indoor areas classified as Class 1, each room may be designated as a survey unit. Indoor areas may also be subdivided into several survey units of different classification, such as separating floors and lower walls from upper walls and ceilings (and other upper horizontal surfaces) or subdividing a large warehouse based on floor area.

Survey units should be limited in size based on classification, exposure pathway modeling assumptions, and site-specific conditions. The suggested areas for survey units are provided in **Table 4-1**.

Table 4-1 Suggested Area for Survey Units

Classification	Structures (Floors, Walls, and Ceilings)	Land Areas
Class 1	Up to 100 m ²	Up to 2,000 m ²
Class 2	Up to 1,000 m ²	Up to 10,000 m ²
Class 3	No Limit	No Limit

The limitation on survey unit size ensures that the density of the measurements or samples is commensurate with the potential for residual radioactive materials in excess of the DCGL_w. The rationale for selecting a larger survey unit area should be developed using the DQO process (**Section 2.3**) and fully documented.

Special considerations may be necessary for survey units with structure surface areas less than 10 m² or land areas less than 100 m². In this case, the number of data points required for the statistical tests may be unnecessarily large and not appropriate for smaller survey unit areas. Instead, some specified level of survey effort should be determined based on the DQO process and with the concurrence of the regulatory agency. For such small survey units, site-specific scanning surveys or in situ measurement may be more appropriate. The data generated from these smaller survey units should be obtained based on judgment, rather than on systematic or random design, and compared individually to the DCGLs.

Another consideration may be for sites with large areas of residual radioactive materials (e.g., technologically enhanced naturally occurring radioactive material) where a 2,000 m² Class 1 survey unit size would be impractical or cost prohibitive and where site-specific scanning or survey methods and use of composite sampling can provide reasonable quantification of levels and spatial variation (**Section 1.1**). Such a situation should be identified, and an approach discussed with responsible regulatory agencies, early in the development stage.

One example special case for FSSs occurs at Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) sites whose radioactive materials are from the processing of uranium or thorium ores for their source material content. **Section 4.12.8** contains more details for UMTRCA sites.

4.6.3 Selection of Reference Areas

Certain radionuclides may also occur at significant levels as part of background in the media of interest (e.g., soil, building material). Examples include members of the naturally occurring uranium, thorium, and actinium series; potassium-40; carbon-14 (¹⁴C); and tritium (³H). ¹³⁷Cs and other radionuclides are also present in background as a result of fallout (Wallo et al. 1994). Establishing a distribution of background concentrations is necessary to identify and evaluate contributions attributable to site operations. Determining background levels for comparison with the conditions determined in specific survey units entails conducting surveys in one or more reference areas to define the background radiological conditions of the site. NUREG-1505, Revision 1, "A Nonparametric Statistical Methodology for the Design and Analysis of Final

Status Decommissioning Surveys: Interim Draft Report for Use and Comment,” issued June 1998 (NRC 1998a), provides additional information on reference areas.

The recommended site reference area should have similar physical, chemical, geological, radiological, and biological characteristics as the survey unit being evaluated. Reference areas should be selected from non-impacted areas, but they are not limited to natural areas undisturbed by human activities. Reference areas should not be part of the survey unit being evaluated. In some situations, a reference area may be contiguous to the survey unit being evaluated, as long as the reference area does not have any residual radioactive material resulting from site activities. For example, background measurements may be taken on the structure surface in a room that was never used for radiological operations that is adjacent to a room under investigation. This option should be discussed with the regulatory agency during survey planning.

Reference areas provide a location for background measurements that are used for comparisons with survey unit data. The radioactive material present in a reference area would ideally be the same as in the survey unit, had the survey unit never been affected by site operations. If a site includes physical, chemical, geological, radiological, or biological variability that is not represented by a single reference background area, selecting more than one reference area may be necessary. Additionally, the concentration of some radionuclides may vary over short (hours to days), medium (months or years), or long (centuries) timeframes. NUREG-1501, “Background as a Residual Radioactivity Criterion for Decommissioning: Appendix A to the Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC Licensed Nuclear Facilities—Draft Report for Comment,” issued August 1994 (NRC 1994), provides more detailed information about sources of temporal variability and methods to account for this variability.

It may be difficult to find a reference area within a residential or industrial complex for comparison to a survey unit if the radionuclides of potential concern are naturally occurring. Background may vary greatly due to different construction activities that have occurred at the site. Examples of construction activities that change background include the following:

- leveling
- excavating
- adding fill dirt
- importing rocks or gravel to stabilize soil or underlay asphalt
- manufacturing asphalt with different matrix rock
- using different pours of asphalt or concrete in a single survey unit; layering asphalt over concrete
- layering different thicknesses of asphalt, concrete, rock, or gravel
- covering or burying old features, such as railroad beds or building footings

Background variability may also increase due to the concentration of fallout in low areas of parking lots or under downspouts, where runoff water collects and evaporates. Variations in background of a factor of 5 or more can occur in the space of a few meters.

There are a number of possible actions to address these concerns. NUREG-1505 provides a methodology for considering variability in reference area concentrations. Reviewing and reassessing the selection of reference areas may also be necessary. Selecting different reference areas to represent individual survey units is another possibility. More attention may also be needed in selecting survey units and their boundaries with respect to different areas of potential or actual background variability. More detailed scoping or characterization surveys may be needed to better understand background variability. Using radionuclide-specific measurement techniques instead of gross radioactive material measurement techniques may also be necessary. If a reference area that satisfies the above recommendations is not available, consultation with the regulatory agency is recommended. Alternate approaches may include using published studies of radionuclide distributions. However, published reports may not truly reflect the conditions at the site.

Verifying that a reference area is appropriate for a survey can be accomplished using the techniques described or referenced in **Chapter 8**. Verification provides assurance that assumptions used to design the survey are appropriate and defensible. This approach can also prevent decision errors that may result from selecting an inappropriate reference area.

If the radionuclides of interest do not occur in background, or the background levels are known to be a small fraction of the $DCGL_w$ (e.g., <10 percent), the survey unit radiological conditions may be compared directly to the specified $DCGL_w$, and reference area background surveys are unnecessary. If the background is not well defined at a site and the decision-maker is willing to accept the increased probability of incorrectly failing to release a survey unit (Type II error) under Scenario A, the reference area measurements can be eliminated and the Sign test performed as described in **Section 8.3**.

4.7 Statistical Considerations

The primary practical objective of an FSS survey is to answer the question, “Can this survey unit be released to the satisfaction of the regulator?” In other words, the design team needs to be able to *confidently* demonstrate compliance (or non-compliance) with the dose- or risk-based release criteria expressed as a measurable quantity (DCGL). This need for a demonstrable, quantitative confidence necessitates planning for statistical hypothesis testing.

The statistical concepts used in MARSSIM were introduced in **Section 2.5**. This chapter reinforces and builds on those concepts with respect to the design of an FSS. The MARSSIM user should be familiar with the statistical discussions throughout **Chapters 2, 5, and 8** and **Appendices D and I**. Consultations with statisticians can be very valuable for surveys that rely on statistical methods for their design and assessment of the collected data.

4.7.1 Basic Terms

Before designing an FSS, the planning team should be familiar with the following statistical terms:

- sample⁷ mean
- sample standard deviation

⁷ The term “sample” here is a statistical term and should not be confused with laboratory samples. For the calculation of these basic statistical quantities, data may consist of scan data, direct measurement data, or laboratory sample data. Refer also to the **glossary** definition of sample.

- sample median⁸
- parametric and nonparametric tests
 - Sign test
 - WRS⁹ test
 - Student's *t*-test
- Type I and Type II errors
- statistical power
- lower boundary of the gray region (LBGR)
- upper boundary of the gray region (UBGR)
- relative shift (Δ/σ)
- null and alternative hypotheses

The MARSSIM user will encounter these and other statistical terms many times in this document and while designing, performing, and assessing the results of an FSS. The use of these terms will be kept to a minimum in this chapter, but this in no way diminishes their importance. For this chapter, statistical terms will be defined when they are introduced.

4.7.2 Recommended Statistical Tests

How well a statistical test meets its objective depends on the difference between the assumptions used to develop the test and the actual conditions being measured. Parametric tests, such as Student's *t*-test, rely upon the results fitting some known distribution, like a normal distribution. Nonparametric statistics are recommended in MARSSIM because they are based on less restrictive assumptions than parametric tests. MARSSIM recommends the use of the WRS test if the radionuclides of concern are present in the background or if gross activity measurements are made. If the radionuclides of concern are not present in the background or present only to a slight degree, then the Sign test is recommended.

4.7.3 Considerations on the Choice of a Statistical Test

The choice of a statistical test should be part of the DQO process during the design phase of the FSS. The choice of the statistical test is influenced by factors such as how the DCGLs are expressed (gross activity, radionuclide specific, sum or ratios [unity rule]), the distribution of residual radioactive material in the survey unit (relatively uniform versus small areas of elevated activity), and the number of reference units needed. Concurrently, the number of samples needed depends on the DCGL, the standard deviation of the residual radioactive material in both the survey and reference units, the desired confidence in the conclusions (Type I and Type II errors), and the statistical test under consideration (refer to **Sections 5.3.3** and **5.3.4** for details, and example calculations in **Sections 4.12.3** and **4.12.4**). Ensuring a reasonable level of confidence that any areas of elevated activity are detected might require additional samples.

⁸ The median is the middle value of the dataset when the number of data points is odd, and it is the average of the two middle values when the number of data points is even. Thus, 50 percent of the data points are above the median, and 50 percent are below the median.

⁹ This test is also called the Mann-Whitney U test, Mann-Whitney-Wilcoxon test, or Wilcoxon-Mann-Whitney test.

Once the FSS is completed, the assumptions used to select the statistical test are examined to determine whether the conditions are met for the test. As part of the DQO process, the design team should plan for the possibility that the initial assumptions were not correct.

4.7.4 Deviations from MARSSIM Statistical Test Recommendations

The guidance and recommendations in MARSSIM are meant to be a set of practices generally acceptable for use in designing an FSS. However, the flexibility of the DQO process allows for the use of more cost-effective methods, if they are acceptable to the regulator. An example is presented in **Section 4.12.7**.

4.7.5 An Important Statistical Note

For FSSs, the parameter of interest is the mean concentration of residual radioactive material in a survey unit. The nonparametric statistical tests recommended in MARSSIM are tests of the median value. For data that are from a skewed right distribution, the mean could significantly exceed the median. Therefore, the team planning the FSS should include a comparison step in the survey to ensure that the mean is less than the DCGL_w. **Section 8.2.2** contains further information.

4.8 Measurements

Based on the potential radionuclides of interest, their associated radiations, how the DCGLs are expressed, the types of media (e.g., soil, structure surfaces), and the number of measurements to be evaluated, the detection capabilities of various measurement methods (which consist of a combination of a measurement technique and instrument) must be determined and documented. Note that “measurements” includes both direct (field) measurements and laboratory analyses.

4.8.1 Quality Control and Quality Assurance

For both field measurements (**Chapter 6**) and laboratory analyses (**Chapter 7**), the FSS design team must plan to collect data to evaluate the performance of measurement and analytical methods (including data collection). These data are called measurement and instrument performance indicators. The DQO and MQO processes are used to determine which indicators are important and included in the QAPP. The following are examples of measurement and instrument performance indicators:

- *Instrument background readings:* Background readings before and after a series of measurements are used as part of the process to ensure that an instrument was functioning properly.
- *Instrument response checks:* Checking the instrument response with the same source in the same geometry over the course of surveying can help ensure that the instrument was working properly during the survey.
- *Field blanks:* These are samples prepared in the field using certified clean sand, soil, or other media and sent to the laboratory for analysis. Field blanks are used to assess contamination associated with sampling and laboratory procedures.
- *Performance evaluation samples:* These are used to assess the overall bias and uncertainty in the laboratory’s analytical processes.

4.8.2 Measurement Quality Objectives

Although specifically for laboratory analyses, the performance characteristics discussed in the Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP) (NRC 2004) should be considered when establishing MQOs. These include, but are not limited to, the following:

- the method's uncertainty at a specified concentration, usually at the UBGR (expressed as a standard deviation)
- the method's detection capability (expressed as the MDC)
- the method's quantification capability (expressed as the minimum quantifiable concentration)
- the method's range, which defines the method's ability to measure the radionuclide of concern over some specified range of concentration
- the method's specificity, which refers to the ability of the method to measure the radionuclide of concern in the presence of interferences
- the method's ruggedness, which refers to the relative stability of method performance for small variations in method parameter values

Project-specific method performance characteristics should be developed as necessary and may or may not include the characteristics listed here. When lists of performance characteristics that affect measurability have been identified, the planning team should develop MQOs describing the project-specific objectives for potential measurement techniques. Potential measurement techniques should then be evaluated against the MQOs to determine whether they are capable of meeting the objectives for measurability.

The International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Guide 98, "Guide to the Expression of Uncertainty in Measurement," issued in 1993 (ISO/IEC 1993); National Institute of Standards and Technology (NIST) Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," issued September 1994 (NIST 1994); Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME) (NRC 2009); MARLAP; and **Chapter 6** of this manual provide information on determining measurement uncertainty. **Chapter 6** of this manual and NRC report NUREG-1507, Revision 1, "Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions," issued August 2020 (NRC 2020), discuss the concept of detection capabilities and provide guidance on determining detection capabilities and selecting appropriate measurement methods. Although MARSAME and MARLAP include the concept of quantification capability, MARSSIM takes a different approach by incorporating requirements for quantification capability into detection capability with the requirement that the MDC be less than the UBGR and by recommending that the MDC be less than 50 percent (refer to **Section 2.3.1**) of the UBGR (refer to **Chapter 6**). **Chapter 6** also discusses instruments and survey techniques for scans and direct measurements, and **Chapter 7** provides information on sampling and laboratory analysis. **Appendix H** describes typical field and laboratory equipment, as well as instrument capabilities.

4.8.3 Types of Measurement Methods

Instruments should be identified for each of the three types of measurement techniques planned for the FSS: (1) scanning, (2) direct, and (3) laboratory measurements. Scanning and direct measurements are referred to as field measurements. In some cases, the same instrument or type of instrument may be used for performing several measurement techniques. For example, a gas proportional counter can be used for surface scanning measurements and laboratory measurements of smear samples. Once the instruments are selected, appropriate measurement techniques and standard operating procedures should be developed and documented. The measurement techniques describe how the instrument will be used to perform the required measurements.

4.8.3.1 *Scanning Measurements*

Scanning is an in situ measurement technique performed by moving a portable radiation detector at a specified speed and distance next to a surface to detect radiation. Scanning measurements are generally used to identify areas that may be elevated and should be evaluated further, such as those exceeding an established investigation level. Scanning can identify areas of elevated activity that might otherwise be missed by direct or sample measurements (e.g., measurements made with a systematic grid).

4.8.3.1.1 Scanning Measurements in General

In general, scanning surveys are used in conjunction with direct measurements, and the measurements, not the scanning data, are used for the quantitative statistical testing. As discussed in **Section 5.3.6**, the determination of scanning coverage for a survey unit is based on the assigned classification and relative shift. Class 1 areas and survey units will have scan coverage of 100 percent, while the scan coverage of Class 2 and Class 3 areas and survey units will vary between 10 percent and 100 percent as a function of the relative shift (**Section 5.3.6**).

4.8.3.1.2 Site-Specific Scanning Measurements

In general, MARSSIM does not recommend an FSS based only on site-specific scanning surveys. However, through the DQO process and consultation with the regulator, an FSS based on scanning measurements alone might be allowed.

For certain situations, typically with well-defined and readily detectable radionuclide distributions, it may be feasible (and advantageous in terms of time and costs) to curtail the requirements for the two-phased measurement process (scanning followed by direct measurements or sampling, or both). For these situations, a site-specific scanning survey may be used to limit the number of required direct measurements or samples, and in some cases, it may even be used to replace the need for direct measurements or samples for a single or multiple survey units used to support statistical testing. To support the statistical testing for demonstrating that a survey unit meets the release criteria (i.e., DCGLs), the scanning survey data need to be sufficiently robust in terms of data quality and data density (number of data points). Automated survey systems lend themselves to the performance of these types of surveys.

A site-specific scanning approach should be used only for circumstances in which the measurement method has sufficient detection capability to meet the MQOs to both quantify the

average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material.

The use of radiation measurement instruments with automated data capture tools (i.e., data logging) has numerous advantages over the normal user observation and manual data recording. Coupled with location instruments, such as the Global Positioning System (GPS) and light detection and ranging (LiDAR), these systems can also support data mapping and geospatial analyses. Recording detector position during scanning measurements enables the generation of two-dimensional (or three-dimensional) maps of detector readout over the scanned surface, for example by using geographic information system (GIS) technologies.

Site-specific scanning surveys will require site-specific validation samples for establishing scanning detector response. This requires establishing the correlation of scanning measurements to the radionuclide(s) of concern to ensure that the method can reliably detect concentrations at a fraction of the DCGL_W under the conditions expected at the site. This validation can be accomplished at any point in the RSSI process (after remediation if remediation is performed). During the FSS process, verification scan measurements are needed, including selective rescanning (over a nominal 5 percent of the scanning area) and static measurements, especially for areas where scanning measurements may be elevated relative to the area in general. Any area with multiple scanning measurements above established investigation levels should be subjected to verification measurements (rescanning, static, and physical samples with quantitative analysis). The regulator should be consulted for guidance on the level of effort needed to validate scanning-based compliance surveys.

The following conditions (DQOs) should be met for the application of site-specific scanning surveys:

- Scan MDCs (**Section 6.3.2**) should be less than 50 percent of the DCGL_W. Establishing the scan MDC at a fraction of the DCGL_W ensures a sufficiently robust detection system and scanning method for the key radionuclide(s) of concern, considering decay mode and emission (e.g., alpha, beta, photon).
- Scanning measurements should be recorded by an integrated instrument data-logging system. Location should also be included where feasible, such as using an integrated GPS or LiDAR system, or both.
- Measurements should be reproducible (e.g., fixing a detector at a constant distance from a surface).
- Data integrity and security should be ensured by maintaining secured datasets, following the chain of custody, and tracking changes.
- Site-specific validation samples are required for establishing the correlation of scanning instrument response to the radionuclide distribution. Representativeness of an established correlation needs to consider variation across a site, including changes in background and variation in radionuclide distribution.
- A minimum of 5 percent of the area should be subjected to validation rescanning.
- Scanning measurements indicating areas of elevated areas greater than the DCGL_W should be subjected to verification measurements or samples, or both.

Chapters 5 and 6 contain additional information.

4.8.3.2 *Direct Measurements*

A direct measurement is an in situ measurement of radioactive material obtained by placing the detector near the surface or media being surveyed for a prescribed amount of time. An indication of the resulting concentration of radioactive material is read out directly. Making direct measurements is analogous to collecting samples, and the results are often treated in a similar manner. Direct measurement of alpha, beta, and gamma radiation for an FSS requires the use of instruments and techniques that meet the DQOs and MQOs (e.g., MDC). When selecting instruments and techniques, the design team needs to consider the following:

- type and amounts of radionuclides potentially present
- required detection limits
- distance from the surface being monitored and field of view
- type of measurement—rate or scaler (integrated) (e.g., counts in 5 minutes)
- duration of integrated counts
- radiation background (including interferences from nearby radiation sources)

All direct measurements and their locations should be recorded. **Chapter 6** contains additional information.

4.8.3.3 *Laboratory Measurements*

When planning for collecting samples as part of an FSS, the design team should use the DQO process to determine the need for sample collection and laboratory analyses. All laboratories under consideration to analyze samples should have written procedures that document their analytical capabilities for the radionuclides of concern and a QA/QC program that documents adherence to established criteria. The survey design team should also consider any appropriate laboratory accreditation. Accreditation, QA/QC, and other appropriate documentation should be available for review by the survey design team (with appropriate restrictions for proprietary or other controlled information). Once a qualified laboratory has been chosen, the design team should involve the laboratory early in the design process and maintain communication throughout execution and data evaluation and interpretation. **Chapter 7** contains more information on the sampling and preparation for laboratory measurements.

Additionally, MARLAP contains extensive information for the planning, implementation, and assessment of projects that require laboratory analysis of radionuclides. Like MARSSIM, MARLAP aims to provide a flexible approach to ensure that the radioanalytical data are of the right quality and appropriate for the needs of the user.

Some items that should be considered when planning for laboratory analyses include the following:

- sample media
- number of samples
- type and number of QC samples
- amount of material needed by the laboratory
- analytical bias and precision
- detection limits
- costs

- required turnaround time
- sample preservation and shipping requirements
- measurement documentation requirements
- sample tracking needs (e.g., chain of custody requirements)

4.8.3.4 *Selecting a Radioanalytical Laboratory*

It is advisable to select a radiochemical laboratory as early as possible in the survey planning process so that it may be consulted on the analytical methodology and the sampling activities. Federal procurement procedures may require additional considerations beyond the method described here. The procurement of laboratory services usually starts with the development of a request for proposal that includes a statement of work describing the analytical services to be procured. The careful preparation of the statement of work is essential to the selection of a laboratory capable of performing the required services in a technically competent and timely manner.

Six criteria should be considered:

- (1) well-documented procedures, instrumentation, and trained personnel to perform the necessary analyses
- (2) analysts who are experienced in performing the same or similar analyses
- (3) satisfactory performance evaluation results from formal monitoring or accreditation programs
- (4) adequate capacity to perform all analyses within the desired timeframe
- (5) internal QC program
- (6) protocols for method performance documentation, sample tracking and security, and documentation of results

The design team should review that laboratory's documentation concerning MDC calculations, reporting procedures, calibrations, QA/QC, and accreditation to ensure that the FSS DQOs will be met. **Section 7.4** provides more details.

When samples are collected for laboratory analyses, communications among the project manager, field personnel, and laboratory personnel are vital to a successfully executed FSS. The survey design team should strive to establish communications with the laboratory early in the design process; when this is not possible, a radiochemist or health physicist with radiochemical training should be consulted. **Section 7.3** contains additional information on laboratory communications.

4.8.4 **Selection of Instruments for Field Measurements**

4.8.4.1 *Reliability and Robustness*

Investigators should choose reliable instruments that are suited to the physical and environmental conditions at the site and capable of meeting the MQOs. The MQOs should include the measurement method uncertainty, which is typically established at the UBGR (usually the DCGL_w). The required measurement method uncertainty is perhaps the most

important MQO to be established during the planning process. Determining a realistic value for the measurement method uncertainty for field measurements is a challenging calculation, typically requiring the use of specialized software. However, ensuring that the measurement method uncertainty meets the requirement set for it at the UBGR will ensure that the measurement method can reliably perform measurements at the most critical concentration level for the survey.

4.8.4.2 *Detection Capability*

The detection capability (sensitivity) or the ability to detect radiation or radioactive material with some quantifiable level of confidence is a critical factor in the design of an FSS. This capability is most often referred to as the MDC for direct measurements, or the scan MDC for scanning measurements. The formal MARSSIM definition of the MDC is “the a priori activity concentration that a specific instrument and technique that has a specified probability (typically 95 percent) of producing a net count (or count rate) above the critical level.” Informally, the MDC is the concentration of radioactive material that can be detected reliably; if radioactive material is present at the MDC with a specified probability of 95 percent, then the measurement process will determine its presence 95 percent of the time. The MDC is a factor of both the instrumentation and the technique or procedure being used. For scanning, human factors also need to be taken into account. **Section 6.3** gives details on how to calculate MDCs. The design team should be aware that there are other methods to calculate MDCs (especially for direct and laboratory measurements) discussed in the scientific literature. The DQO process should be used to determine which method best suits the needs of the FSS. This method and results should be approved by the appropriate regulatory agency.

Having low MDCs is valuable when designing the FSS. If measured values are less than the MDC, then the values can be quite variable and lead to high values for the standard deviation (σ) of the measured values in the survey unit or reference area. High values for σ can be accommodated in the statistical tests described in **Chapter 8** for the FSS, but a large number of measurements are needed to account for the variability.

Early in the project, low MDCs help in the identification of areas that can be classified as non-impacted or Class 3 areas. These decisions are usually based on fewer numbers of samples, and each measurement is evaluated individually. Using an optimistically low estimation of the MDC (refer to **Section 2.3.5**) for these surveys may result in the misclassification of a survey unit and cleaning up an area with no residual radioactive material or, alternatively, performing an FSS in an area with residual radioactive material. Selecting a measurement technique with a well-defined MDC or a conservative estimate of the MDC ensures the usefulness of the data for making decisions for planning the FSS. For these reasons, MARSSIM recommends using a realistic or conservative estimate of the MDC instead of an optimistic estimate. A realistic MDC can be determined by ensuring that a priori determinations, for example of background levels, are representative of actual measurement conditions at the time of measurement.

4.8.4.3 *Dynamic Range*

The expected concentration range for a radionuclide of concern can be an important factor in the overall measurement method performance. Most radiation measurement techniques are capable of measuring over a wide range of radionuclide concentrations. However, if the expected concentration range is large, the range should be identified as an important measurement method performance characteristic, and an MQO should be developed. The MQO

for the acceptable range should be a conservative estimate. This will help prevent the selection of measurement techniques that cannot accommodate the actual concentration range.

4.8.4.4 Calibration

Calibration refers to the determination and adjustment of the instrument response in a particular radiation field of known intensity. Proper calibration procedures are essential to providing confidence in measurements made to demonstrate compliance with release criteria. The FSS design team should review and understand **Section 6.6.4**.

The instrument should be calibrated for the radiations and energies of interest at the site (**Section 6.6.4**). Instrument calibrations should be traceable to an accepted standards organization, such as NIST.¹⁰ Operational checks of instrument performance should be conducted routinely and frequently to ensure that the instrument response is maintained within acceptable ranges and that any changes in instrument background are not attributable to radioactive contamination of the detector.

Considerations for the use and calibration of instruments include the following:

- the radiation type for which the instrument is designed
- the radiation energies within the range of energies for which the instrument is designed
- the environmental conditions for which the instrument is designed
- the influencing factors, such as magnetic and electrostatic fields, for which the instrument is designed
- the orientation of the instrument, such that geotropic (gravity) effects are not a concern
- the manner the instrument is used, such that it will not be subject to mechanical or thermal stress beyond that for which it is designed

At a minimum, each measurement system (detector/readout combination) should be calibrated annually, and the response of the detector to a check source should be established following calibration (ANSI 2013). Instruments may require more frequent calibration if recommended by the manufacturer. Recalibration of field instruments is also required if an instrument fails a performance check or if it has undergone repair or any modification that could affect its response. The system should be calibrated to minimize potential errors during data transmission and retransmission. The user may decide to perform calibrations following industry-recognized procedures (ANSI 1997, NCRP 1978, NCRP 1985, NCRP 1991, ISO 1988, HPS 1994a, HPS 1994b), or the user can choose to obtain calibration by an outside service, such as a major instrument manufacturer or a health physics services organization. Calibrations should include devices used to determine the position or location of samples or measurements, as recommended by the manufacturer.

Section 4.12.5 includes additional technical details about instrument efficiencies and example calculations.

¹⁰ The NIST policy on traceability can be found at <https://www.nist.gov/calibrations/traceability> (NIST 2024).

4.8.4.5 Specificity

Specificity is the ability of the measurement method to measure the radionuclide of concern in the presence of interferences. To determine whether specificity is an important measurement method performance characteristic, the planning team will need information about expected concentration ranges for the radionuclides of concern and other chemical and radionuclide constituents, along with chemical and physical attributes of the soil or surface being measured. The importance of specificity depends on the following:

- the chemical and physical characteristics of the soil or surface
- the chemical and physical characteristics of the residual radioactive material
- the expected concentration range for the radionuclides of concern

If potential interferences are identified (e.g., inherent radioactive material, similar radiations), an MQO should be established for specificity.

4.8.4.6 Instrumentation Examples

Table 4-2 lists common radionuclides along with recommended instruments for field measurement methods that have proven effective based on past survey experience in the decommissioning industry. This table provides a general indication of the detection capability of commercially available instruments for field measurements. As such, **Table 4-2** may be used to provide an initial evaluation of instrument capabilities for some common radionuclides at the example DCGLs listed in the table. For example, consider a surface with americium-241 (^{241}Am). **Table 4-2** indicates that ^{241}Am is detectable at the example DCGLs and that viable direct measurement instruments include gas-flow proportional (alpha mode) and alpha scintillation detectors.

Many radiation detection instruments can be used for both direct and scanning measurements. The example DCGLs in **Table 4-2** are given for direct measurements only. Issues of detectability (MDC) for scanning are more complicated than for direct measurements and depend on things such as human response, height above the surface, and scanning speed.

Table 4-2 should not be interpreted as providing specific values for an instrument's detection capability, which is discussed in **Section 6.3**. In addition, NRC draft report NUREG-1506, "Measurement Methods for Radiological Surveys in Support of New Decommissioning Criteria: Draft Report for Comment," issued August 1995 (NRC 1995), and NUREG-1507 provide further information on factors that may affect survey instrumentation selection.

Table 4-2 Examples of Field Measurement Instruments

Nuclide	Structure Surfaces		Land Areas		Example Instruments		
	Example DCGL (Bq/m ²)	Detectable	Example DCGL (Bq/kg)	Detectable	Building Surface Activity	Soil Activity	Exposure Rate
³ H	2.0×10 ⁸	No	4.1×10 ³	No	ND ^a	ND	ND
¹⁴ C	6.2×10 ⁶	Yes	4.4×10 ²	No	GPβ	ND	ND
⁵⁴ Mn	5.4×10 ⁴	Yes	5.6×10 ²	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
⁵⁵ Fe	7.5×10 ⁶	No	3.7×10 ⁵	No ^b	ND	ND (ISγ)	ND (ISγ)
⁶⁰ Co	1.2×10 ⁴	Yes	1.4×10 ²	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
⁶³ Ni	3.0×10 ⁶	Yes	7.8×10 ⁴	No	GPβ	ND	ND
⁹⁰ Sr	1.5×10 ⁴	Yes	6.3×10 ¹	No ^b	GPβ, GM	ND (GM, GPβ)	ND
⁹⁹ Tc	2.2×10 ⁶	Yes	7.0×10 ²	No	GPβ, GM	ND	ND
¹³⁷ Cs	4.7×10 ⁴	Yes	4.1×10 ²	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
¹⁵² Eu	—	Yes	3.2×10 ²	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
²²⁶ Ra (C) ^c	—	Yes	2.6×10 ¹	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ
²³² Th (C) ^c	—	Yes	4.1×10 ¹	Yes	GPα, αS, GPβ	γS, ISγ	PIC, γS, ISγ
²³⁸ U (C)	—	Yes	1.9×10 ¹	Yes	GPα, αS, GPβ, ISγ	γS, ISγ, GPβ	PIC, γS, ISγ
²³⁹ Pu	—	Yes	8.5×10 ¹	No ^b	GPα, αS	ND (ISγ)	ND
²⁴¹ Am	—	Yes	7.8×10 ¹	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ

Abbreviations: GPα: gas-flow proportional counter (α mode); GM: Geiger-Mueller survey meter; GPβ: gas-flow proportional counter (β mode); PIC: pressurized ionization chamber; αS: alpha scintillation survey meter; γS: gamma scintillation (gross); ISγ: in situ gamma spectrometry; ND: not detectable.

^a Example DCGLs are provided only for discussion and are based on values given in Tables B.1 and B.2 of NRC report NUREG-1757, Volume 1, Revision 2, "Decommissioning Process for Materials Licensees," issued September 2006 (NRC 2006). Example DCGLs should not be used in place of approved DCGLs.

^b Possibly detectable at limits for areas of elevated activity.

^c For decay chains having two or more radionuclides of significant half-life that reach secular equilibrium, the notation "(C)" indicates that the direct measurement techniques assume the presence of decay products in the chain.

4.8.5 Selection of Sample Collection Methods

Sample characteristics—such as sample depth, volume, area, moisture level, and composition, as well as sample preparation techniques that may alter the sample—are important planning considerations for DQOs. Sample preparation may include, but is not limited to, removing extraneous material, homogenizing, splitting, drying, compositing, and doing final preparations of samples. Dose or risk pathway modeling should be representative of actual survey conditions, to the extent practical, and modeling limitations should be well documented and assessed. The sampling method should then consider assumptions made in the dose or risk pathway modeling used to determine radionuclide DCGLs. For example, the modeling should reflect the actual depth and area of residual radioactive material in the survey unit, and sampling should be compatible with how the source was represented in the modeling. If a direct measurement or scanning technique is used, it should also consider the compatibility of the technique with the assumptions made in the dose or risk pathway modeling.

Investigators should be aware of conceptual models or assumptions made in commonly used codes used to derive DCGLs to ensure comparisons to DCGLs are compatible with the modeling or to justify averaging approaches. For example, screening codes may assume the residual radioactive material is located in the top 15 cm of surface soil. If subsurface residual radioactivity material below about 15 cm is present, simply averaging concentrations over a larger thickness of residual radioactivity for comparison with the screening values may not be appropriate (e.g., the DCGLs for a larger thickness of residual radioactivity material could be lower). Some dose modeling codes can be used to derive DCGLs for source thicknesses greater than 15 cm. However, if vertical heterogeneity in radionuclide concentrations is present and the dose modeling shows that the dose or risk is more sensitive to surface concentrations (e.g., DCGLs do not change significantly for source thicknesses greater than 15 cm), then diluting shallower surface soils with lower concentration subsurface soils may also lead to an underestimate of dose. DCGLs may be derived for surface and subsurface soils, and depth discrete sampling consistent with the derivation of DCGLs may be needed. Similarly, models may be based on dry weight, which may necessitate either drying samples or data transformation to account for dry weight. The DQOs and subsequent direction to the laboratory for analysis might include removal of material not relevant for characterizing the sample, such as pieces of glass, twigs, rocks, pebbles, or leaves. In all cases, it is important to understand the modeling assumptions and how the data collected will be compared to DCGLs derived from the modeling to ensure the fidelity of the statistical survey results.

Both sample depth and area are considerations in determining appropriate sample volume, and sample volume is a key consideration for determining the laboratory MDC. The depth should also correlate with the conceptual model developed in **Chapter 3** and upgraded throughout the RSSI process. For example, if data collected during the HSA indicate that residual radioactive material may exist to a certain depth, then samples should be deep enough to support the survey objectives, such as for the scoping or characterization survey. Taking samples as a function of depth might also be a survey design objective, such as for scoping, characterization, or remediation support. Although some models and codes may allow for the input of (or can be manipulated to consider) heterogeneous radionuclide distributions, other models and codes may assume the presence of uniform residual radioactive material. If the models are incapable of representing the complexity of the sources, data may need to be processed for use in the model. Impacts associated with the modeling simplifications should be well understood and documented.

Additionally, the design team needs to consider both data needs and data quality indicators as determined from the DQO process. The design team should review the information in **Section 7.2** when designing the sampling portion of the FSS plan. The decision-maker and the survey planning team need to identify the data needs for the survey being performed, including the following:

- type of samples to be collected or measurements to be performed (**Chapter 5**)
- radionuclide(s) of interest (**Section 4.5**)
- number of samples to be collected (**Sections 5.3.3–5.3.5**)
- type and frequency of field QC samples to be collected (**Section 4.8**)
- amount of material to be collected for each sample (**Section 4.8.3** and **Section 7.5**)
- sampling locations and frequencies (**Section 5.3.7**)
- standard operating procedures to be followed or developed (**Chapter 6**)
- target detection capabilities for each radionuclide of interest (**Section 6.3**)
- measurement method uncertainty (**Section 6.4**)
- cost of the methods being evaluated (cost per analysis and total cost) (**Appendix H**)
- necessary turnaround time
- sample preservation and shipping requirements (**Section 7.6**)
- specific background for each radionuclide of interest (**Section 4.5**)
- DCGL for each radionuclide of interest (**Section 4.5**)
- measurement documentation requirements (**Section 5.3.11**)
- sample tracking requirements (**Section 7.8**)

In addition to the above items, the design team needs to consider the following data quality indicators:

- precision
- bias
- representativeness
- comparability
- completeness
- others as discussed in **Section 7.2.2.6**

Section 7.2 contains a detailed discussion of the DQOs and MQOs for sampling.

Under some circumstances, it might be useful to assess the radionuclide concentrations on different size fractions to better assess transport processes assumed in some dose models. **Chapters 6** and **7** present more detail regarding the application of these survey planning considerations.

4.8.6 Selection of Measurement Techniques

In practice, the DQO process is used to obtain a proper balance among the various measurement techniques (scanning, direct, and laboratory). In general, there is an inverse correlation between the cost of a specific measurement technique and the detection levels being sought. Depending on the survey objectives, important considerations include survey costs and choosing an appropriate measurement method.

A certain minimum number of direct measurements or samples may be needed to demonstrate compliance with the release criteria based on certain statistical tests (refer to **Section 5.3.2**).

Alternatively, if there is sufficient detection capability and an acceptable level of measurement method uncertainty, a site-specific scanning survey technique (refer to **Sections 4.8.3.1 and 6.6.1.1**) can (with the proper application of the DQO process and regulatory approval) be used to demonstrate compliance with the DCGL_w. The potential for areas of elevated residual radioactive material may also have to be considered for designing scanning surveys, as the need to identify areas of elevated activity may affect the number of measurements. Some measurements may provide information of a qualitative nature to supplement other measurements. An example of such an application is in situ gamma spectrometry to demonstrate the absence (or presence) of specific radionuclides.

Assuming the residual radioactive material can be detected, either directly or by measuring a surrogate radionuclide in the mixture, the next decision point depends on whether the radionuclide being measured is present in background. Gross measurement methods will likely be more appropriate for measuring concentrations of radioactive materials on surfaces in structures, scanning for locations of elevated activity, and determining exposure rates. Radionuclide-specific measurement techniques, such as gamma spectrometry, provide a marked increase in detection capability over gross measurements because of their ability to screen out contributions from other sources. **Figure 4-2** illustrates the sequence of steps in determining the type of survey design needed—that is, whether field measurement techniques can be applied at a particular site along with sampling or if a site-specific scanning survey design is more appropriate. The selection of appropriate instruments for scanning, direct measurement, and sampling and analysis should be survey specific.

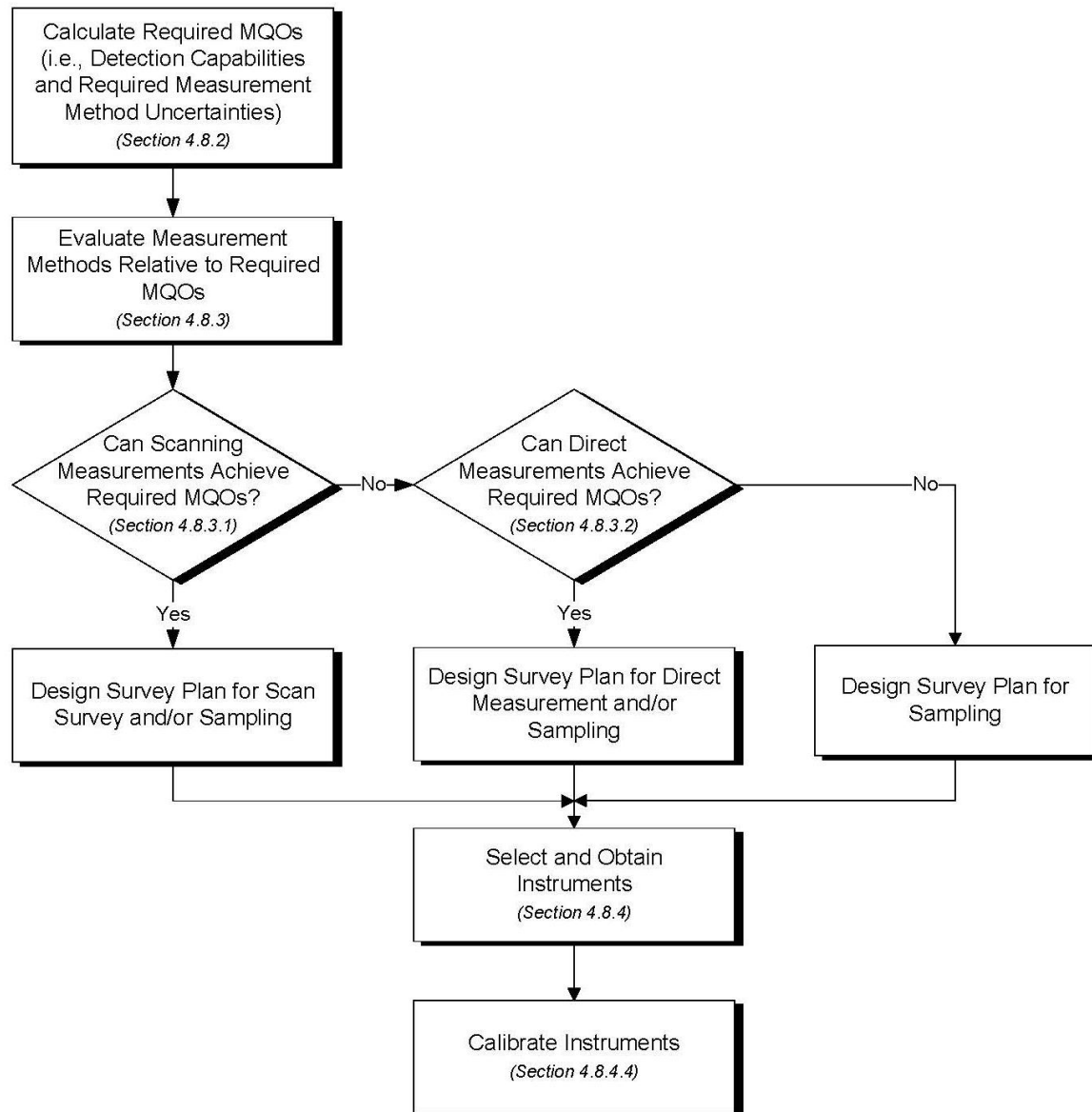


Figure 4-2 Sequence of Preliminary Activities Leading to an FSS Design

4.8.7 Data Conversion

Radiation survey data are usually obtained in units, such as the number of counts per unit time, which have no intrinsic meaning relative to DCGLs. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units. Alternatively, the DCGL can be converted into the same units used to record survey results. Either method relies on understanding the instrument response (efficiency). The FSS design team should use the DQO process to determine and document the proper methods used to compare instrument results and DCGLs. **Sections 4.12.6 and 6.7** provide additional details.

4.8.8 Additional Planning Considerations Related to Measurements

4.8.8.1 *Selecting a Field Service Provider*

The survey design team should start the process of selecting a service provider to perform field data collection early in the planning process. The following criteria should be considered:

- validated standard operating procedures
- experience with similar data collection activities
- satisfactory performance evaluations or technical review results
- adequate capacity to perform all the data collection activities
- internal QC program
- protocols for method performance documentation, sample tracking and security, and documentation of results

More details can be found in **Section 6.5**.

4.8.8.2 *Radon Measurements*

In some cases, radon may be detected within structures that do not contain residual radioactive material; conversely, some structures that contain residual radioactive material may not yield detectable radon or thoron. Investigators should consult with the regulator about the applicability of radon or thoron measurements as part of a site survey.

If radon or thoron (or both) is a concern for the FSS, the design team should work with the appropriate regulatory agency to determine the applicability of radon and thoron measurements. Because of the widespread nature of indoor air radon and thoron, many States have developed requirements for certification or qualification of people who perform services related to radon and thoron services. Therefore, as part of the qualifications for the service provider, the design team should determine whether the measurement provider or the laboratory analyzing the measurements is required to be certified nationally or by the State or locality where the work is being performed. State radon contacts can be found at <https://www.epa.gov/radon>. As a general principle, the Federal Government's reliance on privately developed voluntary consensus-based standards is to be preferred over the Federal Government developing such standards. Current radon/thoron standards of practice can be viewed at <https://www.epa.gov/radon/radon-standards-practice>.

More details can be found in **Section 6.8**.

4.8.8.3 *Specialized Equipment*

The survey team must plan for using any specialized equipment other than radiation detectors (e.g., GPS, local microwave or sonar beacons and receivers, laser positioning systems). Because these specialized systems are continuously being modified and developed for site-specific applications, it is not possible to provide detailed descriptions of every system. **Section 6.9** gives examples of specialized equipment that have been applied to RSSIs.

4.9 Site Preparation

Site preparation involves obtaining consent for performing the survey, establishing the property boundaries, evaluating the physical characteristics of the site, accessing surfaces and land areas of interest, and establishing a reference coordinate system. Site preparation may also include removing equipment and materials that restrict access to surfaces. The presence of furnishings or equipment will restrict access to building surfaces and add more items that the survey should address.

4.9.1 Consent for Survey

When facilities or sites are not owned by the organization performing the surveys, consent from the site or equipment owner should be obtained before conducting the surveys. All appropriate Federal, State, Tribal, and local officials, as well as the site owner and other affected parties, should be notified of the survey schedule. **Section 3.5** discusses consent for access, and additional information related to the Comprehensive Environmental Response, Compensation, and Liability Act is available from the U.S. Environmental Protection Agency (EPA) (EPA 1987c).

4.9.2 Property Boundaries

Property boundaries may be determined from property survey maps furnished by the owners or from plat maps obtained from city or county tax maps. Large-area properties and properties with obscure boundaries or missing survey markers may require the services of a professional land surveyor. A professional land surveyor can also tie a site radiological survey grid into the existing land survey of the site or to an official State or municipal survey grid. Such a tie-in has the advantage of making the radiological survey grid reproducible in the future.

If the radiological survey is only performed inside buildings, a tax map with the buildings accurately located will usually suffice for site/building location designation.

4.9.3 Physical Characteristics of the Site

The physical characteristics of the site will have a significant impact on the complexity, schedule, and cost of a survey. These characteristics include the number and size of structures, type of building construction, wall and floor penetrations, pipes, building condition, total area, topography, soil type, and ground cover. In particular, the accessibility of structures and land areas (**Section 4.9.4**) has a significant impact on the survey effort. In some cases, survey techniques (e.g., in situ gamma spectrometry or scanning surveys discussed in **Chapter 6**) can preclude or reduce the need to gain physical access or use intrusive techniques. This should be considered during survey planning.

4.9.3.1 Structures

Building design and condition will have a marked influence on the survey efforts. The time involved in conducting a survey of building interior surfaces is essentially directly proportional to the total surface area, recognizing that upper wall and ceiling areas require more time than floor and lower wall surveys. For this reason, the degree of survey coverage decreases as the potential for residual radioactive material decreases. Judgment measurements and sampling, which are done in addition to the measurements performed for certain survey designs, are recommended in areas likely to have accumulated deposits of residual radioactive material. As

discussed in **Section 8.6**, judgment measurements and samples are compared directly to the appropriate DCGL.

The condition of surfaces after remedial action may affect the survey process. Removing radioactive material that has penetrated a surface usually involves removing the surface material. As a result, the floors and walls of remediated facilities are frequently badly scarred or broken up and are often very uneven. Such surfaces are more difficult to survey, because it is not possible to maintain a fixed distance between the detector and the surface. In addition, scabbled or porous surfaces may significantly attenuate radiations—particularly alpha and low-energy beta particles. Use of monitoring equipment on wheels is precluded by rough surfaces, and such surfaces also pose an increased risk of damage to fragile detector probe faces. These factors should be considered during the calibration of survey instruments; NRC report NUREG-1507 provides additional information on how to address these surface conditions. The condition of the building should also be considered from a safety and health standpoint before a survey is conducted. A structural assessment may be needed to determine whether the structure is safe to enter.

Expansion joints, stress cracks, drains, and penetrations into floors and walls for piping, conduit, anchor bolts, and similar features are potential sites for accumulation of residual radioactive material and pathways for migration into subfloor soil and hollow wall spaces. Drains, sewers, and septic systems can contain residual radioactive material, and wall/floor interfaces are also likely locations for residual radioactive material. Coring, drilling, or other such methods may be necessary to gain access for surveying. Intrusive surveying may require permitting by local regulatory authorities. Additionally, suspended ceilings may cover areas of potential residual radioactive material, such as ventilation ducts and fixtures. There may be other materials introduced that were not part of the original construction—such as floor tiles, partitions, insulation, additional concrete slabs, and paint—that may cover residual radioactive material.

Exterior building surfaces will typically have a low potential for residual radioactive material; however, several locations should be considered during survey planning. If there are roof exhausts or roof accesses that allow for radioactive material movement, or if the facility is proximal to the air effluent discharge points, the possibility for residual radioactive material on the roof should be considered. Because roofs are periodically resurfaced, radioactive material may be trapped in roofing material, and sampling this material may be necessary. Such roof drainage points as driplines along overhangs, downspouts, and gutters are also important survey locations. Roofs may also accumulate radioactive material from fallout, or roof materials may contain elevated levels of naturally occurring radioactive material (e.g., elevated uranium in roof tar). Wall penetrations for process equipment, piping, and exhaust ventilation are potential locations for exterior residual radioactive material. Window ledges and outside exits (e.g., doors, doorways, landings, stairways) are also building exterior surfaces that should be addressed.

4.9.3.2 *Building Materials*

In addition to radiological surveys of the building surfaces described in **Section 4.9.3.1**, it may also be necessary to survey any building materials removed from the building as part of its demolition, remediation, or renovation. Guidance for the design and implementation of radiological surveys of these materials is provided in MARSAME.

4.9.3.3 *Land Areas*

Depending on site processes and operating history, the radiological survey may include varying portions of the land areas. Open land or paved areas with a potential for residual radioactive

material include storage areas (e.g., equipment, product, waste, and raw material), liquid waste collection lagoons and sumps, areas downwind of stack release points (based on predominant wind directions on an average annual basis, if possible), and surface drainage pathways. Additionally, roadways and railways that may have been used for transport of improperly contained radioactive materials could also have an accumulation of residual radioactive material.

Building modifications should be reviewed to assess any expansions that might cover former land disposal areas. Other land areas—such as wetlands, marshlands, or low-lying surface areas—where waste material was used as fill material need to be assessed for potential residual radioactive material. In some instances, the waste material is covered with clean backfill material to grade to ground surface. Archived aerial photos, historical maps, and interviews can be used to assess the potential presence of such areas.

Buried piping, underground tanks, fill areas, sewers, spill areas, and septic leach fields that may have received radioactive liquids are locations of possible residual radioactive material that may necessitate sampling of subsurface soil. Information regarding soil type (e.g., clay, sand) may provide insight into the retention or migration characteristics of specific radionuclides. The need for special sampling by coring or split-spoon equipment should be anticipated for characterization surveys.

If radioactive waste has been removed, surveys of excavated areas will be necessary before backfilling with clean fill. If the waste is to be left in place, subsurface sampling around the burial site perimeter may be necessary to assess the potential for future migration.

Additionally, rivers, harbors, shorelines, and other outdoor areas with a potential for residual radioactive material may require survey activities including environmental media (e.g., sediment and biota) associated with these areas.

4.9.4 Clearing to Provide Access

In addition to the physical characteristics of the site, another major consideration is how to address difficult-to-access areas that have a potential for residual radioactive material. Difficult-to-access areas may need significant effort and resources to result in adequate surveys. This section describes common difficult-to-access areas that may have to be considered. The level of effort expended to access such areas should be commensurate with the potential for residual radioactive material. For example, the potential for the presence of residual radioactive material behind walls should be established before significant effort is expended to remove drywall.

4.9.4.1 Structures

When necessary, structures and indoor areas should be sufficiently cleared to permit completion of the survey. Clearing includes providing access to interior surfaces (e.g., drains, ducting, tanks, pits, ceiling areas, equipment) by removing covers, disassembly, or other means of producing adequate openings.

Such building features as ceiling height, construction materials, ducts, and pipes will determine the ease of accessing various surfaces. Scaffolding, cranes, lifts, or ladders may be necessary to reach some surfaces, and dismantling portions of the building may be required.

The presence of furnishings and equipment will restrict access to building surfaces and add more items that the survey should address. Any remaining equipment indirectly involved in the process may need to be dismantled to evaluate the radiological status, particularly of difficult-to-access parts of the equipment. Investigators may also need to remove or relocate certain furnishings, such as laboratory benches and hoods, to obtain access to floors and walls. The amount of effort and resources dedicated to such removal or relocation activities should be commensurate with the potential for residual radioactive material. Where the potential is low, a few spot-checks may be sufficient to provide confidence that covered areas are free of residual radioactive material. In other cases, complete removal may be warranted. MARSAME contains guidance for the survey and assessment of materials and equipment.

Piping, drains, sewers, sumps, tanks, and other components of liquid-handling systems present special challenges because of the difficulty in accessing interior surfaces. Process information, operating history, and preliminary monitoring at available access points will assist investigators in evaluating the extent of sampling and measurements included in the survey. Some specialized survey techniques for drains and sewers have been developed and are effective for the measurement of some radionuclides.

If the building is constructed of porous materials (e.g., wood, concrete, masonry) and the surfaces were not sealed, residual radioactive material may be found in the walls, floors, and other surfaces. It may be necessary to obtain cores of these surfaces for laboratory analysis.

Another accessibility problem is the presence of residual radioactive material beneath tile or other floor coverings. This often occurs because the covering was placed over surfaces containing residual radioactive material, or the joints in tile were not sealed to prevent penetration. The practice in some facilities has been to “fix” radioactive material (particularly alpha emitters) by painting over the surface of the affected area. Thus, actions to obtain access to surfaces, such as removing wall and floor coverings (including paint, wax, or other sealer) and opening drains and ducts, may be necessary to enable representative measurements of the residual radioactive material. This material may also require a radiation survey to ensure no radioactive material was transferred during the removal process. If alpha radiation or very low-energy beta radiation is to be measured, the surface should be free of overlying material, such as dust and water, which may significantly attenuate the radiations.

4.9.4.2 *Land Areas*

If ground cover needs to be removed or if other obstacles limit access by survey personnel or necessary equipment, the time and expense of making land areas accessible should be considered. In addition, contamination control procedures need to be developed to prevent the spreading of radioactive material during ground cover removal or the use of heavy equipment.

Whenever possible, the property owner should perform the removal or relocation of equipment and materials that require special precautions to prevent damage or maintain inventory accountability. Clearing open land of brush and weeds will usually be performed by a professional land-clearing organization under subcontract arrangements. However, survey personnel may perform minor land-clearing activities as needed.

An important consideration before clearing is the possibility of bio-uptake of radionuclides in the plant material to be cleared. Special precautions to avoid exposure of personnel involved in clearing activities may be necessary. Radiological screening surveys should be performed to ensure that cleared material or equipment does not contain residual radioactive material.

The extent of site clearing in specific areas depends primarily on the potential for residual radioactive material to exist in those areas as follows:

- If the radiological history or results of previous surveys indicate a low potential for residual radioactive material in an area, it may be sufficient to perform only minimum clearing to establish a reference coordinate system.
- If residual radioactive material, or a high potential for it, is known to exist, the area needs to be completely cleared to provide access to all surfaces.
- New findings as the survey progresses may indicate that additional clearing is needed.

Open land areas may be cleared by heavy machinery (e.g., bulldozers, bushhogs, hydro-axes). However, care should be exercised to prevent relocation of surface radioactive material or damage to such site features as drainage ditches, utilities, fences, and buildings. Minor land clearing may be performed using manually operated equipment, such as brush hooks, power saws, knives, and string trimmers. Brush and weeds should be cut to the minimum practical height necessary to facilitate measurement and sampling activities (approximately 15 cm). Care should be exercised to prevent unnecessary damage to or removal of mature trees, shrubs, or historical or cultural resources.

Potential ecological or cultural damage that might result from an extensive survey should be considered. If a survey is likely to result in significant or permanent damage to environmental or cultural resources, appropriate environmental and cultural analyses should be conducted before initiating the survey.

4.9.5 Reference Coordinate System

4.9.5.1 Establishment

Reference coordinate systems are established at the site to do the following:

- Facilitate the selection of measurement and sampling locations.
- Provide a mechanism for referencing a measurement to a specific location so that the same survey point can be located again.

A survey reference coordinate system consists of a grid of intersecting lines referenced to a fixed site location or benchmark. Typically, the lines are arranged in a perpendicular pattern, dividing the survey location into squares or blocks of equal area; however, other types of patterns (e.g., three-dimensional, polar) have been used.

The reference coordinate system used for a particular survey should provide a level of reproducibility consistent with the objectives of the survey. For example, commercially available single-frequency GPS devices can typically locate a position to within approximately 5 meters (m), while dual-frequency receivers and augmentation systems can provide real-time precision on the order of a few centimeters. On the other hand, a metal bar can be driven into the ground to provide a long-term reference point for establishing a local reference coordinate system. Some States have official grid systems, and if such a system exists in a particular State, investigators should consider tying a site grid into the official State grid.

Three basic coordinate systems are used for identifying points on a reference coordinate system. Reference coordinate system patterns on horizontal surfaces are usually identified numerically on one axis and alphabetically on the other axis, or in distances in different compass directions from the grid origin. **Figure 4-3** through **Figure 4-5** show examples of structure interior and land area grids. The reference system shown in **Figure 4-3** references grid locations using numbers on the vertical axis and letters on the horizontal axis. The reference system shown in **Figure 4-4** references distances from the (0,0) point using the compass directions N (north), S (south), E (east), and W (west). The reference system shown in **Figure 4-5** references distances along and to the R (right) or L (left) of the baseline. Grids on vertical surfaces may include a third designator, indicating position relative to floor or ground level. Overhead measurement and sampling locations (e.g., ceiling and overhead beams) are referenced to corresponding floor grids.

For surveys of Class 1 and Class 2 areas, basic coordinate system patterns at 1–2 m intervals on structure surfaces and at 10–20 m intervals of land areas may be sufficient for the purpose of identifying FSS locations with a reasonable level of effort. Gridding of Class 3 areas may also be necessary to facilitate referencing of survey locations to a common system or origin, but such grids, for practical purposes, may typically be at larger intervals (e.g., 5–10 m for large structural surfaces and 20–50 m for land areas). For the FSS, the required scanning percentages, number of discrete survey locations for direct measurements, and number of sample locations will depend on the classification of the survey unit (refer to **Chapter 5**).

Figure 4-5 shows an example grid system for an outdoor land area. The first digit or set of digits includes an L or R (separated from the first set by a comma) to indicate the distance from the baseline in units (m) and the direction (left or right) from the baseline. The second digit or set of digits refers to the perpendicular distance from the (0,0) point on the baseline and is measured in hundreds of units. Point A is identified as (100R, 2+00) (i.e., 200 m from the baseline and 100 m to the right of the baseline). Fractional distances between reference points are identified by adding the distance beyond the reference point and are expressed in the same units used for the reference coordinate system dimensions. For example, Point B on **Figure 4-5** is identified as (25R, 1+30).

In addition, a less frequently used reference system is the polar coordinate system, which measures distances along transects from a central point. Polar coordinate systems are particularly useful for survey designs to evaluate effects of stack emissions, where it may be desirable to have a higher density of samples collected near the stack and fewer samples with increasing distance from the stack.

Open land reference coordinate systems should be referenced to a location on an existing State or local reference system or to a U.S. Geological Survey benchmark. (This may require the services of a professional land surveyor.) GPS is capable of locating reference points in terms of latitude and longitude (**Section 6.9** describes positioning systems.)

Following the establishment of the reference coordinate system, a drawing is prepared by the survey team or the land surveyor. This drawing indicates the reference lines, site boundaries, and other pertinent site features and provides a legend showing the scale and a reference compass direction.

The selection of an appropriate marker in the field for a reference coordinate system depends on the characteristics and routine uses of the surface. Where surfaces prevent installation of stakes, the reference line intersection can be marked by painting. Reference coordinate systems on structure surfaces are usually marked by chalk lines or paint along the entire grid

line or at line intersections. Land area reference coordinate systems are usually marked by wooden or metal stakes driven into the surface at reference line intersections.

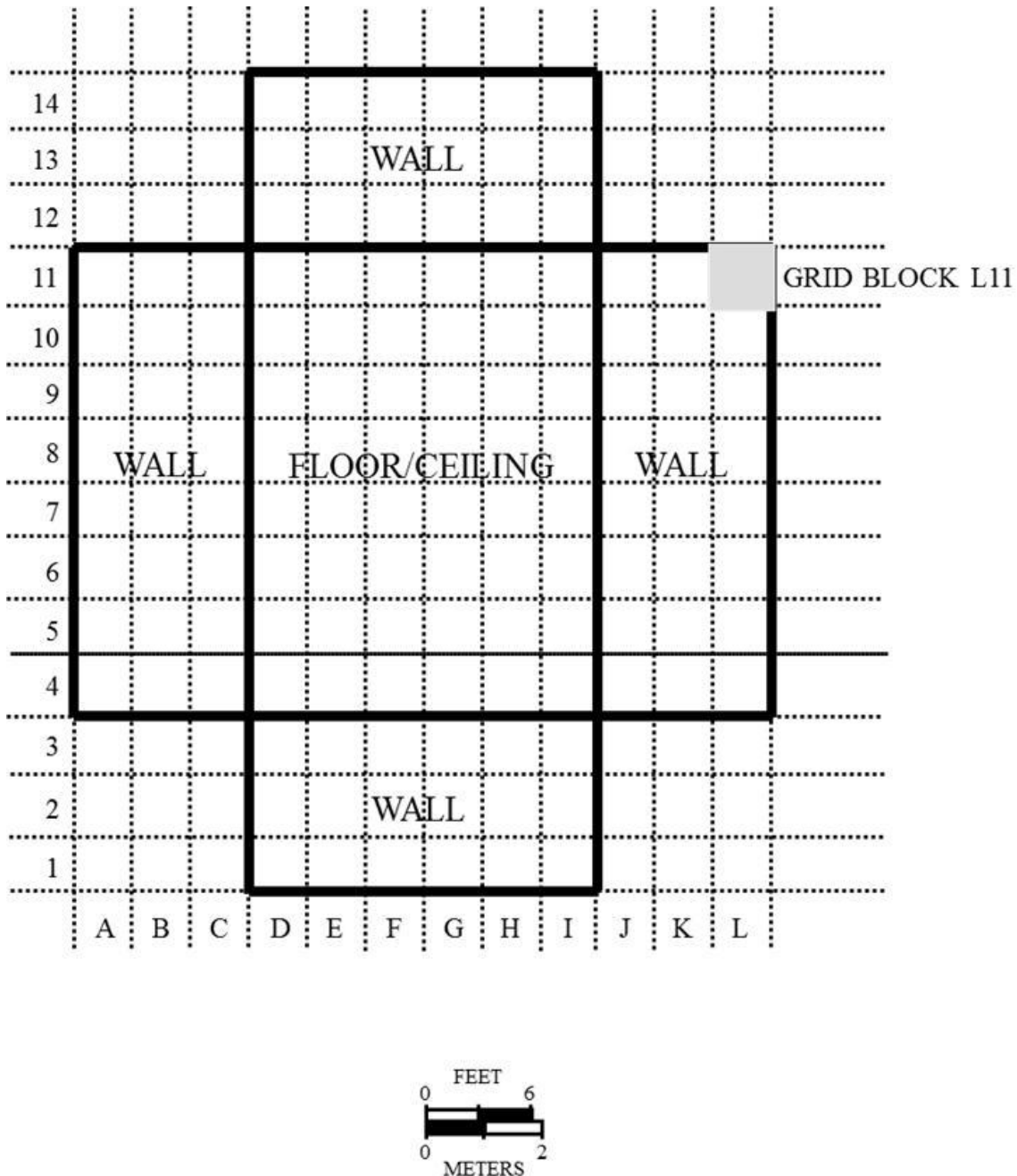


Figure 4-3 Indoor Grid Layout with Alphanumeric Grid Block Designation: Walls and Floors Are Diagrammed as Though They Lay Along the Same Horizontal Plane

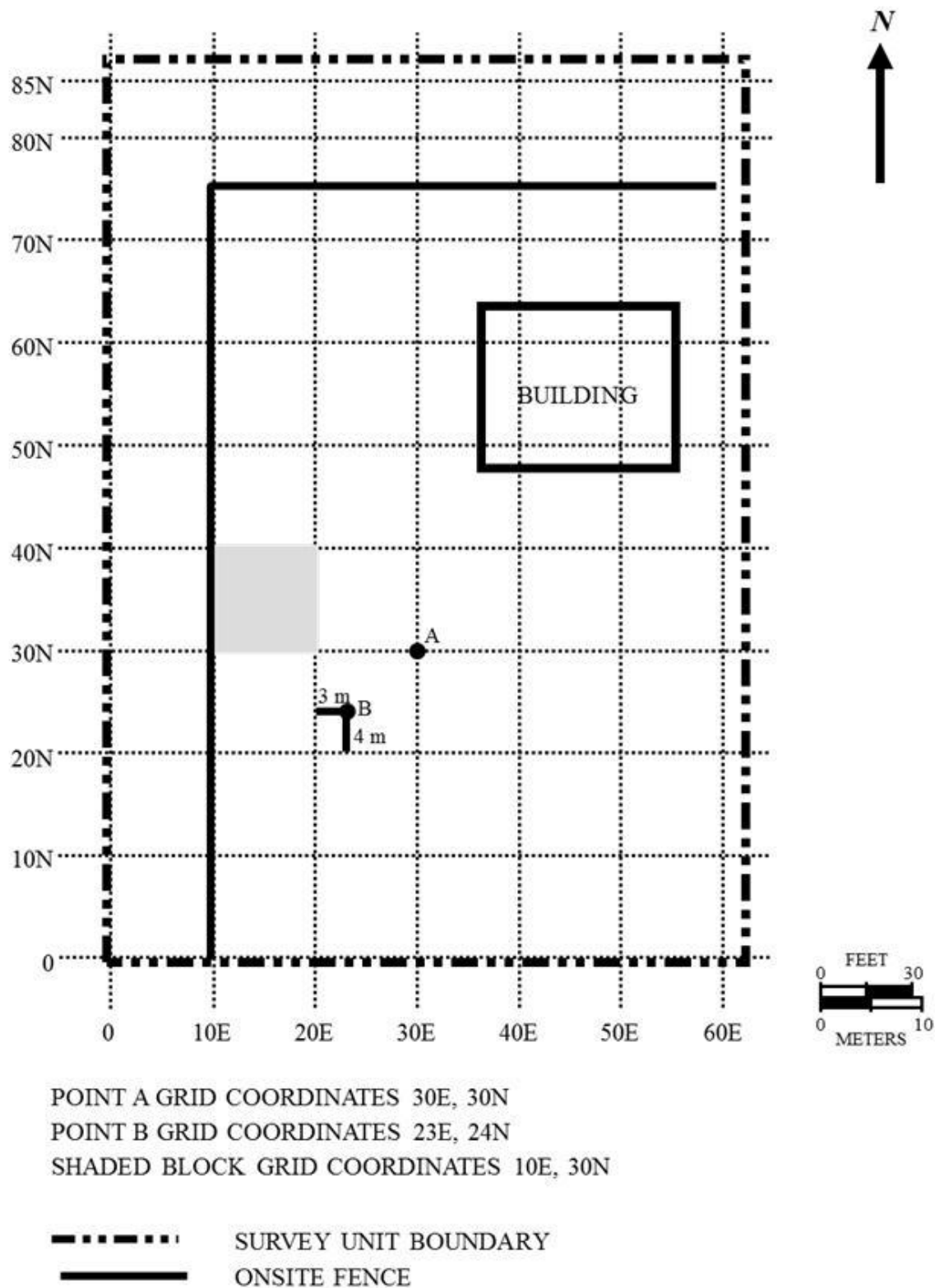
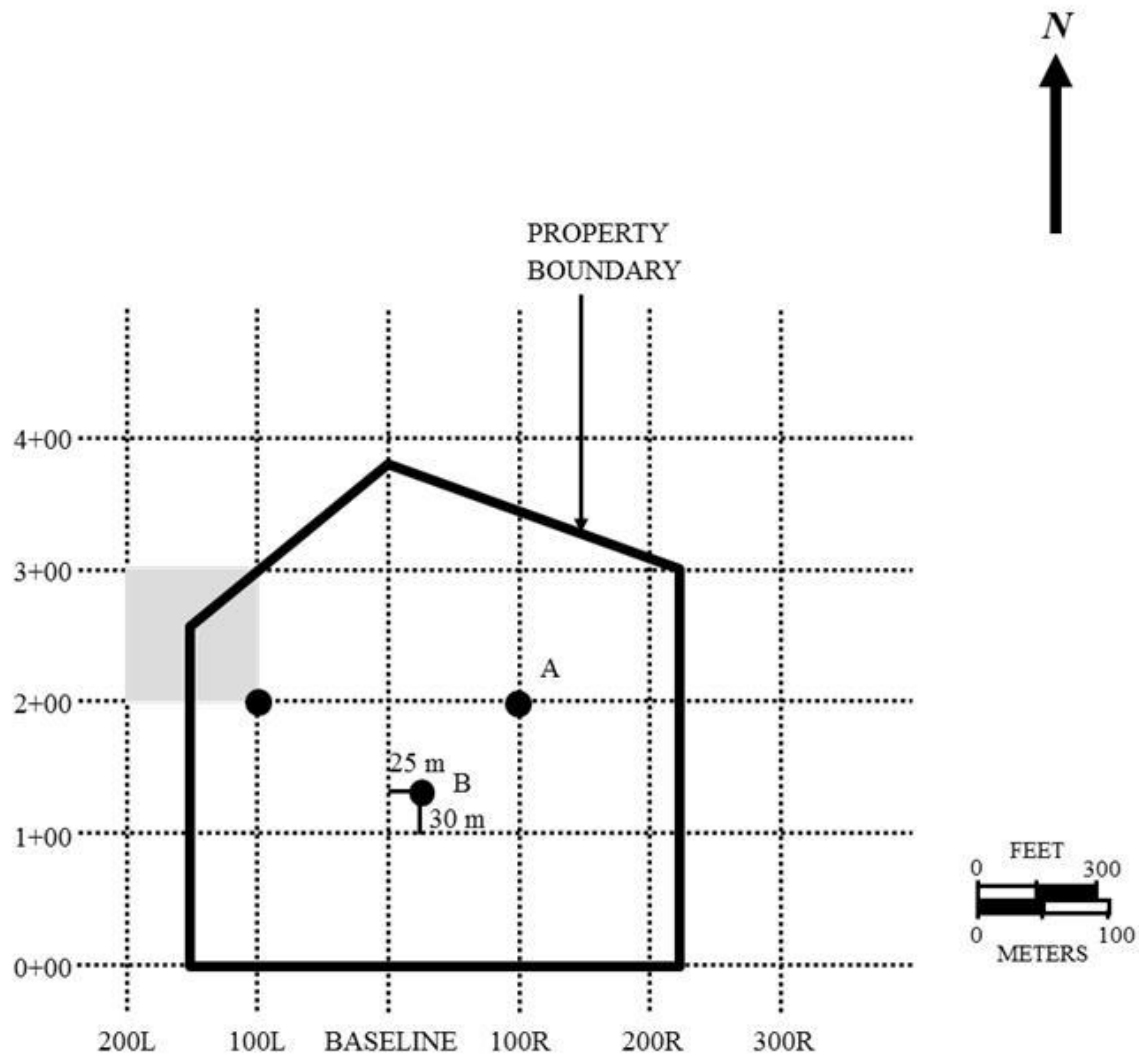


Figure 4-4 Example of a Grid System for Survey of Site Grounds Using Compass Directions



POINT A GRID COORDINATES 100R, 2+00

POINT B GRID COORDINATES 25R, 1+30

SHADED BLOCK GRID COORDINATES 200L, 2+00

Figure 4-5 Example of a Grid System for Survey of Site Grounds Using Distances Left or Right of the Baseline

4.9.5.2 *Quality System Considerations*

The concept of the quality system was introduced in **Section 4.2.2**. The process used to develop the reference coordinate system should be recorded in the survey planning documentation (e.g., the QAPP). Any deviations from the requirements developed during planning should be documented when the reference coordinate system is established.

When the survey reference coordinate system is referenced to a fixed site location or benchmark on a known geographic coordinate system (GCS) or projected coordinate system (projection) (e.g., a State system), or the survey reference coordinate system itself uses a known GCS or projection rather than one of the three basic coordinate systems described in **Section 4.9.5.1**, then the following information should be provided about the actual GCS or projection used:

- name
- units used (e.g., feet, meters)
- zone
- datum
- spheroid
- method used to determine/obtain the coordinates (e.g., GPS)
- estimates of the accuracy and precision of the coordinates
- transformations used to convert from coordinates from one system to another

Ideally, this information should be provided in the spatial reference section of the metadata for the GIS layer containing the data. If a GPS was used to obtain the coordinates, then information should be included about the differential corrections made to the original GPS measurements.

It should be noted that the reference coordinate systems described in this section are intended primarily for reference purposes and do not necessarily dictate the spacing or location of survey measurements or samples. **Section 5.3.7** and **Chapter 8** discuss the establishment of a measurement grid to demonstrate compliance with the DCGLs.

4.10 **Health and Safety**

Health and safety are emphasized as issues potentially affecting the implementation of MARSSIM surveys. The focus of the health and safety program is minimizing environmental and physical hazards (e.g., confined spaces, unstable surfaces, heat and cold stress) where these issues may affect the design and performance of a survey. Work areas and procedures that present potential safety hazards must be identified and evaluated to warn personnel of potential hazards. Personnel must be trained to understand potential physical and chemical safety hazards (e.g., inhalation, adsorption, ingestion, injection/puncturing) and the potential for injury (e.g., slips, trips, falls, burns). In addition, the presence or possibility of such environmental hazards as poison ivy; ticks carrying Lyme disease; and poisonous snakes, spiders, rodents, or insects should be noted. These hazards can affect worker safety and health, as well as the schedule for performing the survey. Some physical hazards require special procedures or precautions. Steep slopes might require special gear for surveyors and instruments or might call for dispensations from the regulatory agency to reduce or eliminate survey efforts in such areas. The potential for the presence of unexploded ordnance requires qualified explosive ordnance disposal personnel to clear the survey unit of unexploded ordnance and accompany survey personnel during the survey.

A job safety analysis (JSA) should be performed before implementing a survey. The JSA offers an organized approach to the task of locating problem areas for material handling safety (OSHA 2002). The JSA should be used to identify hazards and provide inputs for drafting a site-specific health and safety plan (HASP). The HASP will address the potential hazards associated with survey activities and identify methods to minimize the threats posed by those hazards. The HASP will also document proper handling procedures for hazardous substances. The HASP should be prepared concurrently with the survey design, as the information in the HASP may influence the selection of a measurement technique and disposition survey procedures. Radiation work permits may be established to control access to radiologically controlled areas. Radiation work permits contain requirements from the JSA and the HASP, such as dosimetry and personal protective equipment (PPE), as well as survey maps illustrating predicted dose rates and related radiological concerns (e.g., removable or airborne radioactive material). Hazard work permits may be used in place of radiation work permits at sites with primarily physical or chemical hazards.

The JSA and HASP systematically carry out the basic strategy of accident prevention through the recognition, evaluation, and control of hazards associated with a given job, as well as the determination of the safest, most efficient method of performing that job. This process creates a framework for deciding among engineering controls, administrative controls, and PPE for the purpose of controlling or correcting unsafe conditions. Examples of these controls include the following:

- engineering controls, which are physical changes in processes, machinery (e.g., installing guards to restrict access to moving parts during operation), or storage configuration (e.g., using shelves in place of piles or stacks)
- administrative controls, which are changes in work practices and organization (e.g., restricted areas where it is not safe to eat, drink, smoke), including the placement of signs to warn personnel of hazards
- PPE, which is clothing or devices worn by employees to protect against hazards (e.g., gloves, respirator, full-body suits)

Correction measures may incorporate principles of all the controls listed above. The preferred method of control is through engineering controls, followed by administrative controls, and then PPE.

Compliance with all control requirements is mandatory to maintain a safe working environment. Personnel must regard control requirements as a framework to facilitate health and safety, while still taking responsibility for their own well-being. Being wary of safety hazards remains an individual responsibility, and personnel must be aware of their surroundings at all times in work areas.

4.11 Documentation

Concurrently with the FSS design, the design team should begin to draft the FSS report. Reporting requirements for the FSS should be developed during planning and clearly documented in the QAPP. In many cases, before the FSS is started, the regulator will require a report documenting the proposed sampling and surveying plan, including ancillary documentation such as the QAPP. The FSS report should present a complete and unambiguous record of the radiological status of the survey unit, relative to the established DCGLs. To the extent possible, the report should be self-contained and contain a minimum of

information incorporated by reference. **Example 4-1** describes some of the information needed in the report for review of an FSS.

Example 4-1: Information Needed for an FSS Review

The NRC reviews the FSS documentation to “verify that the results of the FSS demonstrate that the site, area, or building meets the radiological criteria for license termination” (NRC 2006). The information typically reviewed by the NRC staff is found in NUREG-1757, Volume 2, Revision 2, including the following:

- an overview of the results of the FSS
- a summary of the DCGLs
- a discussion of any differences from prior submissions
- a description of the method by which the number of samples was determined for each survey unit
- a summary of the values used to determine the number of samples and a justification for these values
- the results for each survey unit
- analytical methods used
- detection limits
- estimates of uncertainties or sample standard deviations
- a description of any changes in initial survey unit assumptions relative to the extent of residual radioactive material

In addition to the items above, the design team should have the following information available (NRC 2006):

- the results of previously conducted in-process inspections and confirmatory surveys
- the licensee’s QA/QC program
- confirmation that the changes to prior submissions are not significant and are technically correct
- issues (1) identified by intervenors and stakeholders and (2) raised in allegations to provide assurance that such issues have been resolved satisfactorily
- descriptions of the survey units to determine whether any special survey situations are present
- results of elevated measurement comparisons
- results of the appropriate statistical tests (e.g., WRS and Sign tests) to confirm that results indicate compliance
- specific parts of the FSS and supporting data that affect the FSS but that were not available when the decommissioning or license termination plan was approved

4.12 Application of Survey Planning Concepts with Example Calculations

This section expands on the content presented in this chapter, provides a general overview, and familiarizes the MARSSIM user with the application of the concepts in **Sections 4.2–4.11** to planning FSSs.¹¹ Greater detail appears in the chapters that follow.

4.12.1 Scenario A and Scenario B

4.12.1.1 Introduction

The planning team may need to determine the appropriate scenario for use in statistical hypothesis testing as the basis for the FSS. Scenario A is the more familiar scenario and the more common situation. Scenario A should be used in cases such as when (1) the site has been remediated, (2) it is assumed that residual radioactive material greater than the DCGL_W is present, or (3) the residual radioactive material is part of the site background and the DCGL_W can be differentiated from background or the radionuclide is not present in background. Occasionally, Scenario A may not be feasible. If the DCGL_W is within the variability of background or the action level (AL) is zero added residual radioactive material, an alternative approach, Scenario B, can be used. Decisions about choosing a scenario and FSS design should be made in consultation with, and with the approval of, the appropriate regulatory authorities.

Regardless of the scenario chosen, the survey design process is the same for both scenarios and discussed further in **Section 5.3**. Additional precautions should be taken for Scenario B, including making conservative assumptions about the standard deviation of the concentrations during planning, applying the quantile test, and using retrospective power calculations. The emphasis of the FSS for each scenario is different:

- Under Scenario A, the mean concentration of radioactive material is presumed to be at or above the DCGL_W or an AL unless there is sufficient¹² evidence to the contrary.
- Under Scenario B, the mean concentration of radioactive material is presumed to be at or below an AL unless there is sufficient evidence to the contrary.

The planning team should remember that the nonparametric statistical tests recommended in MARSSIM make no assumptions about the underlying distribution of data and are tests of the median value of collected data. However, conclusions about the status of a survey unit are based on the mean value of collected data, except for site-specific scanning surveys where conclusions are based on an upper confidence limit (UCL) based on the mean. **Tables 8.3–8.5** summarize the survey results and conclusions for each scenario.

Sophisticated statistical analysis is not always needed when interpreting the results of an FSS. For example, if a radionuclide is not present in the background and radionuclide-specific measurements are made, a finding that all the measurement results are less than the DCGL_W would demonstrate that the survey unit meets the release criteria, and no additional statistical

¹¹ **Appendix A** contains a detailed example of MARSSIM applied to executing FSS for a single radionuclide. This example builds on those in **Chapters 5** and **8**.

¹² “Sufficient” in this context means properly collected and analyzed data needed to make decisions about the condition of the survey unit while keeping decision errors within the values agreed upon during the DQO process.

analysis would be needed. **Chapter 8** has more details on interpreting the survey data. The rest of this section relates to situations requiring additional statistical analysis.

4.12.1.2 Action Level and Discrimination Limit

With the publication of MARSAME in 2009, the concepts of action level (AL) and discrimination limit (DL) were introduced and defined (NRC 2009):

- The AL “is the numerical value [of the quantity of interest] that causes a decision-maker to choose one of the alternative actions.”
- The DL “is the level of radioactivity [radioactive material] selected by the members of the planning team that can be reliably distinguished from the action level.”

In practical terms, an AL is a release criterion expressed in a measurable quantity such as mean concentration of radioactive material in a survey unit (i.e., a DCGL). The DL is used mainly in determining the number of samples needed. For Scenario A, it is typically set at a conservative estimate of the mean concentration of residual radioactive material in a survey unit. In Scenario A, the AL is usually the DCGL_w (UBGR), and the DL is usually the LBGR. In Scenario B, the roles are reversed: the AL is usually the LBGR, and the DL is the UBGR and determined in discussions with regulatory authorities.

For Scenario A, the Type I error rate (α) is set for the AL. If the true mean concentration is equal to the AL, then the survey unit has a probability α of being released when it should not be released. Similarly, and still under Scenario A, the Type II error rate (β) is set at the DL. If the true mean concentration is equal to the DL, then the survey unit has a probability β of failing to be released when it should be released. Here, the power ($1-\beta$) to reject the null hypothesis is that the site is released when it should be released.

Under Scenario B, the roles of the AL and DL are reversed, but α is still evaluated at the AL and β is evaluated at the DL. So, for Scenario B, the α is evaluated at the AL (LBGR) and is the probability of failing to release the site when it should be released. Conversely, β is evaluated at the DL (UBGR) and is the probability of releasing the site when it should not be released. Here, the power ($1-\beta$) to reject the null hypothesis that the site is clean is the probability that a site is correctly not released when the site should not be released.

Example 4-2 provides an illustration of an AL and DL.

Example 4-2: Illustration of an AL and DL

A survey unit has been remediated, and the expected mean concentration is 10 Bq/kg, the DCGL_w is 30 Bq/kg, and values have been set for a Type I error rate (α) of 0.05 and a Type II error rate (β) of 0.2. As a result, the AL is 30 Bq/kg, and it is recommended to set the DL to 10 Bq/kg. If the true mean concentration is equal to the AL, then the probability of concluding (wrongly) that the residual concentration does not equal or exceed the AL is 5 percent. But if the true mean concentration is equal to the DL, then the probability of concluding (wrongly) that the residual concentration exceeds the AL is 20 percent.

4.12.1.3 Hypothesis Testing

The true mean concentration in a survey unit is unknown and unknowable. Although the true mean concentration cannot be measured, data can be collected, and the planning team can

decide whether the collected data are consistent with the assumption that the true mean concentration is equal to or greater than the AL in Scenario A or equal to or less than the AL in Scenario B. The process of collecting and assessing data to make decisions about the data is called hypothesis testing.

Hypothesis testing is central in evaluating the data collected in support of an FSS and places quantitative limits on the uncertainty in reaching decisions about the results of an FSS. Before choosing between Scenario A and Scenario B, the planning team should understand some basics of hypothesis testing as used in the MARSSIM process. **Example 4-3** illustrates the usefulness of hypothesis testing.

Example 4-3: Hypothesis Testing

Consider deck of 52 playing cards. If the deck is fair, the hypothesis is that you would draw a red card at random 50 percent of the time (26 red cards in a 52-card deck). So, if you drew one card 100 times (with replacement), you'd expect that you'd draw a red card about 50 times. If you drew 26 red cards, you would be surprised and suspect that the deck wasn't fair; if you drew 45, you would probably not be surprised and likely conclude that the deck was fair. However, if you start with the hypothesis that the deck isn't fair and the probability of drawing a red card isn't 50 percent, you wouldn't know how many red cards to expect. It would be very difficult to draw any conclusions.

A hypothesis test consists of the following four items:

- (1) ***A model of the data on which the test will be based.*** For example, for an FSS, the residual activity in a survey unit is assumed to be uniformly distributed with a given mean concentration (e.g., AL, DCGL_W) and variation in the data.
- (2) ***Hypotheses about the condition in the survey unit.*** In MARSSIM, these come in pairs: a default or null hypothesis (H_0) and an alternative hypothesis (H_1). The null hypothesis is a statement about what is expected and is usually relatively easy to measure. Together, H_0 and H_1 cover all the possible outcomes. For example, under Scenario A, the null hypothesis is that the mean concentration in the survey unit is equal to or greater than the DCGL_W, and the alternative is that the mean concentration is less than the DCGL_W.
- (3) ***A “test statistic” based on the hypotheses to be tested and the data collected.*** This test statistic parameter is related to the hypotheses that will be used to determine whether the collected data are consistent with (support) the null hypothesis. For the nonparametric tests recommended in MARSSIM, the two test statistics are the number of positive differences (S^+) calculated for the Sign test and, for the WRS test, the sum of the ranks in the reference area (W_r) for Scenario A and the sum of the ranks in the survey unit (W_s) for Scenario B. **Chapter 8** gives further detail on the application of these tests.
- (4) ***Critical values of the test statistic.*** These values of the test statistic will lead an investigator to the reject or fail to reject H_0 . In many elementary statistics textbooks, the terms “rejection region” and “acceptance region” are used for the ranges of test statistic values leading to rejection or acceptance of H_0 .

Two types of error are associated with a hypothesis test: (1) a Type I error, where H_0 is true but the test rejected it, and (2) a Type II error, where H_0 is false but the test failed to reject it. During the planning process, the planning team chooses an upper bound for the probability of committing a Type I error (α) and a Type II error (β), referred to as error rates. This means, if H_0 is true, all the other assumptions about the survey are true, the survey is performed correctly, and it is repeated many (infinite) times, then the value of the test statistic would exceed the critical value (H_0 would be wrongly rejected) at the Type I error rate (e.g., 5 percent). In other words, H_0 would be rejected erroneously (Type I error) at the accepted error rate, α , assuming the surveys were performed correctly each time. Conversely, under the same conditions but now H_0 is not true, then, after many tests, the value of the test statistic would not exceed the critical value (H_0 would wrongly fail to be rejected) at the Type II error rate (e.g., 10 percent). In this case, H_0 would erroneously fail to be rejected (Type II error) at the accepted error rate, β , assuming the surveys were performed correctly each time. The question being asked and answered is “Are the data collected consistent with H_0 within the specified error rates?”

Table 4-3 summarizes hypothesis testing decision errors.

Table 4-3 Hypothesis Testing Decision Errors

Hypotheses (H_0)	Decision about H_0 Fail to Reject	Decision about H_0 Reject
Actual State of H_0 = True	Correct	Type I Error
Actual State of H_0 = False	Type II Error	Correct

4.12.1.4 Number of Samples

Often, the issue of the number of samples required is left for discussion in advanced texts or discussed generally as a matter of resources and availability because hypothesis testing is covered in medical or biostatistics settings where randomized, controlled trials are needed. However, the FSS planning team needs to determine the number of samples to be collected or measurements to be made. The number of samples depends on five items:

- (1) the choice of the Type I error rate (α)
- (2) the choice of the Type II error rate (β)
- (3) an estimate of the variability of results (σ)
- (4) the level (concentration/measurement) at which α is chosen, the AL
- (5) the level (concentration/measurement) at which β is chosen, the DL

The absolute difference between the AL and DL is referred to as the shift and is represented by Δ . The quantity Δ/σ is referred to as the relative shift. MARSAME includes illustrations of the relationship among the parameters if normal distributions are assumed. **Figure 4-6** demonstrates that if Δ is large, then it is easy to distinguish the mean of the measured values from the AL, even if σ is large. Conversely, **Figure 4-7** demonstrates that if Δ is small, it is harder to distinguish the mean from the AL, even if σ is small; consequently, more samples will be needed because Δ/σ is small.

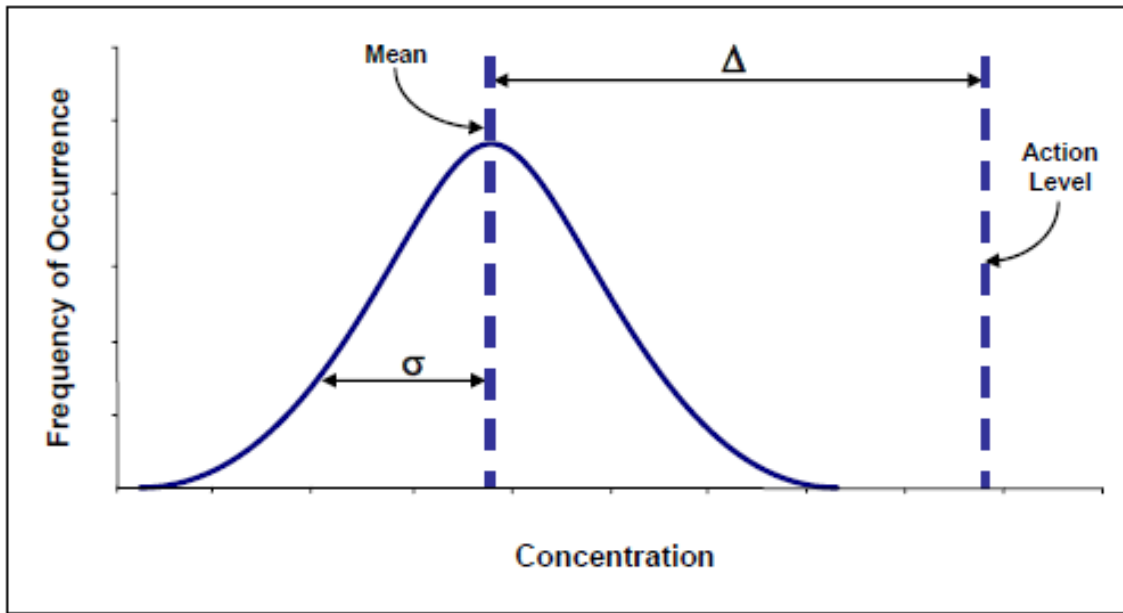


Figure 4-6 Relative Shift, Δ/σ Comparison for Scenario A: σ Is Large, but the Large Δ Results in a Large Δ/σ and Fewer Samples (NRC 2009)

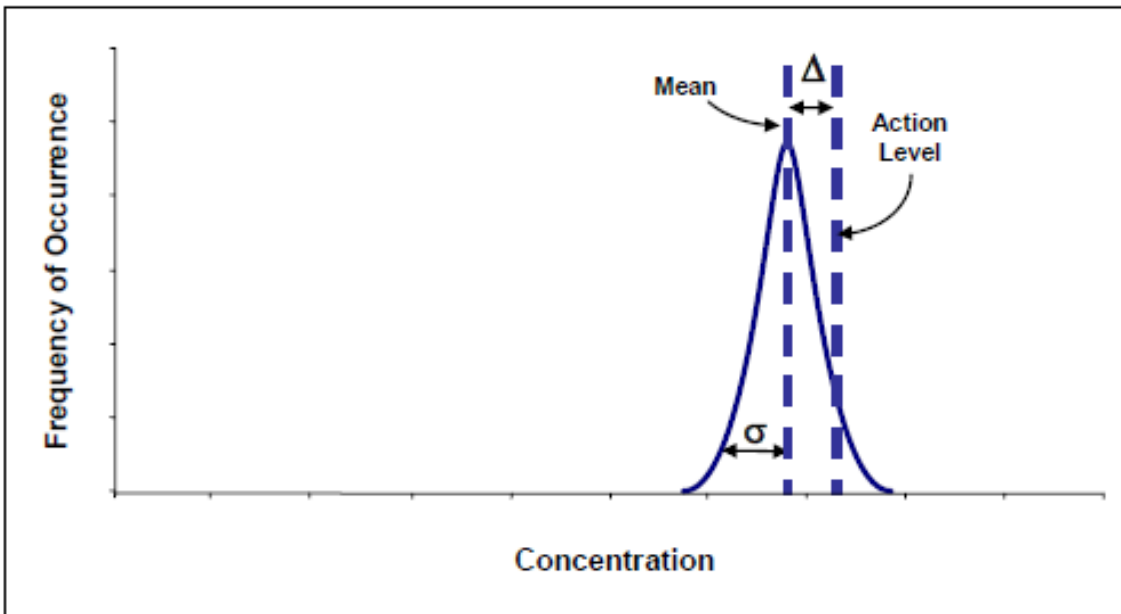


Figure 4-7 Relative Shift, Δ/σ Comparison for Scenario A: σ Is Small, but the Small Δ Results in a Small Δ/σ and More Samples (NRC 2009)

Figure 4-8 depicts the relationships among α , β , σ , and Δ for Scenario A. The x-axis shows the activity concentration, and the y-axis shows the frequency of occurrence, so like **Figure 4-6** and **Figure 4-7**, conceptually, **Figure 4-8** is the result of many measurements. For Scenario B, the relationship is the same except that the location of the AL, DL, α , and β are reversed. Also, the values of α , β , and σ are not necessarily equal.

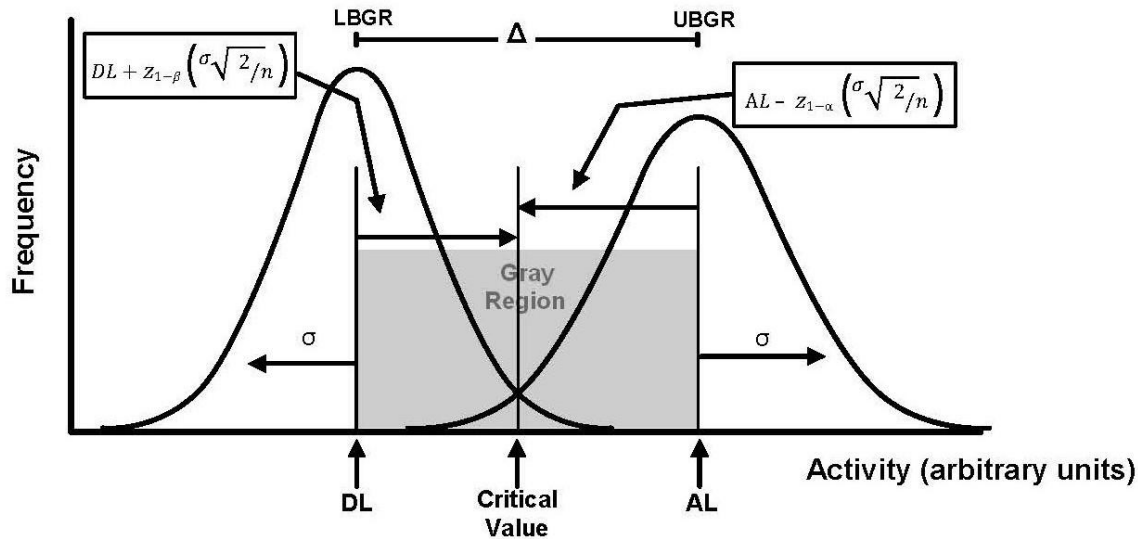


Figure 4-8 The Relationships Among α , β , σ , and Δ for Scenario A

The critical value is that value of the activity for a properly designed and executed survey that would cause the null hypothesis to be rejected; it is fixed when the value for α is chosen. The values for β and the DL are agreed upon by the planning team and regulatory authorities. However, care should be taken not to unacceptably reduce the power ($1-\beta$) and increase the probability of a Type II error.

Although it is beyond the scope of this discussion, the parameters in **Figure 4-8** allow for the calculation of the number of samples needed (n), as shown in **Equation 4-16**:

$$n = \frac{2(z_{1-\alpha} + z_{1-\beta})^2}{\left(\frac{\Delta}{\sigma}\right)^2} \quad \text{Equation 4-16}$$

Here it can be seen that the number of samples required is proportional to the square of the sum in the z-score percentile values (refer to **Sections 6.3.3.1** and **6.3.3.2**) of 1.0 minus the Type I and Type II error rates and inversely proportional to the square of Δ/σ . For the nonparametric statistical tests, the same trends apply, except that the denominator is a complex function of Δ/σ . When using the nonparametric tests recommended in MARSSIM, values of Δ/σ less than about 1 result in a precipitously increasing number of samples, but for values of Δ/σ greater than about 3, there is little change. So, an accurate measure of the standard deviation is essential to ensuring that a near optimum number of samples is collected; however, it is recommended to err on the side of caution and underestimate Δ/σ .

4.12.1.5 Scenario A

Scenario A is the most common and intuitive approach for an FSS. There is a well-defined limit (AL), and the survey team wishes to demonstrate the data collected does not support the null hypothesis—the mean concentration of residual radioactive material in the survey unit exceeds the AL (DCGL_w)—within the agreed-upon Type I and Type II error rates. If a Scenario A survey design is underpowered (failing to reject the null hypothesis when it is false), the survey unit will likely not be released.

Under Scenario A, the AL is the $DCGL_W$, and the DL is that level below the AL at which the probability of failing to release the survey unit is β . During the design phase of the FSS, it is convenient to choose as the DL the expected mean concentration of the residual radioactive material in the survey unit; that is, the level of radioactive material remaining after remediation. In this scenario, the AL ($DCGL_W$) is the UBGR, the DL is the LBGR, and the difference between them is the gray region, Δ . If Δ is relatively small and σ is relatively large (this could be due to large variation in background or the residual radioactive material), a large number of samples will be needed.

4.12.1.6 Scenario B

Scenario B differs from Scenario A in that the null and alternative hypotheses are switched. The mean concentration of radioactive material remaining in the survey unit is presumed to be at or below the AL unless there is sufficient evidence to the contrary. In this case, a few measurements with concentrations of radioactive material above the AL may not be (and usually are not) enough evidence to reject the null hypothesis.

Under Scenario B, the reversal of the null and alternative hypotheses leads to a reversal of the AL and DL as well; the AL is the LBGR, and the DL is the UBGR. The AL could be a regulatory limit, such as a $DCGL$, but it does not necessarily need to be so. Likewise, the AL could be zero activity above background, or it could be based on the variability in potential reference areas, but it does not need to be.

Because the release criterion is based on the concentration of residual radioactive material above background, it might be acceptable to release a survey unit by demonstrating that measured activity in the survey unit is within the range of background variability, and, thus, the survey unit can be released. This approach is referred to as “indistinguishability from background” in Chapter 13 of NUREG-1505. If it can be demonstrated (within acceptable decision errors) that the mean concentration in a survey unit falls within the variation in background, then it can be concluded that any measured activity seen in the survey unit is from variations in background concentrations. This situation can be addressed by Scenario B, although Scenario B is broader and can also just mean that the site is acceptable for release. The initial assumption is that there is no residual radioactive material, and data would be collected to determine whether that assumption should be accepted or rejected, with acceptable Type I and Type II error rates. An underpowered Scenario B survey without a corresponding retrospective power analysis would likely result in accepting the null hypothesis, and the survey unit would be released. Therefore, a retrospective power analysis is essential when the Scenario B null hypothesis is not rejected before release of the survey unit.

4.12.1.7 Conclusion

Historically, MARSSIM recommended the use of Scenario A because, in order to release the survey unit, this scenario requires sufficient evidence to reject the null hypothesis that the mean concentration of residual radioactive material in the survey unit exceeds the $DCGL_W$. Furthermore, as MARLAP states, “Poor or insufficient data often will result in the null hypothesis being retained when it is not true,” and “...the baseline [the condition described by H_0] will continue to be assumed true unless the data are clearly in conflict with it” (NRC 2004). Thus, for Scenario A, if the actual conditions deviate from the assumptions used to design the survey or if associated survey procedures are not followed, the survey unit will likely not be released. Conversely, Scenario B requires sufficient evidence to reject the null hypothesis that the concentration of residual radioactive material does not exceed the AL. Thus, for Scenario B, if

the actual conditions deviate from the assumptions used to design the survey or if associated survey procedures are not followed, the survey unit will likely be released. Therefore, Scenario B should be reserved for cases where Scenario A is impractical. Additionally, the Quantile test (**Section 8.4.3**) and retrospective power analysis (**Section 8.6.2**) are further checks to guard against release of a site that does not meet the release criteria (or if the survey design has insufficient power to reject the null hypothesis). To avoid a situation where the retrospective power analysis indicates insufficient power, it is recommended to include conservative assumptions about the standard deviation of the concentrations (i.e., larger than expected) during survey planning.

MARLAP and Section 5.3.1 of MARSAME contain more information on selecting the appropriate scenario. The choice of Scenario A or Scenario B should be made after careful consideration of the consequences of decision errors and in consultation with, and the approval of, the appropriate regulatory authorities.

4.12.2 Derived Concentration Guideline Level Calculations

4.12.2.1 Decay Series

Example 4-4 illustrates the calculation of the DCGL for a decay series.

Example 4-4: Decay Series

In this example, the surface activity $DCGL_W$ for the entire Th_{nat} decay series is 1,000 Bq/m² (600 dpm/100 cm²), assuming Th_{nat} and its decay products are in secular equilibrium—that is, for each disintegration of ²³²Th, a total of six alpha and four beta particles are emitted in the thorium decay series. Note that in this example, the surface activity $DCGL_W$ of 1,000 Bq/m² is assumed to apply to the total activity from all members of the decay chain. In this situation, the corresponding alpha activity $DCGL_W$ should be adjusted to 600 Bq/m² (360 dpm/100 cm²), and the corresponding beta activity $DCGL_W$ to 400 Bq/m² (240 dpm/100 cm²), in order to be equivalent to 1,000 Bq/m² of natural thorium surface activity. For example, for a surface activity $DCGL_W$ of 1,000 Bq/m², the beta activity $DCGL_W$ is calculated as shown in **Equation 4-17**:

$$DCGL_{W, \text{beta}} = (DCGL_{W, \text{Total}}) \times (\text{fraction of decays that emit beta particles}) \quad \text{Equation 4-17}$$

$$\begin{aligned} &= \left(\frac{1,000 \text{ Bq of chain}}{\text{m}^2} \right) \times \left(\frac{4 \text{ beta Bq}}{\text{Bq of } ^{232}\text{Th}} \right) \\ &= \frac{10 \text{ Bq of chain}}{1 \text{ Bq of } ^{232}\text{Th}} \\ &= \frac{400 \text{ beta Bq}}{\text{m}^2} \end{aligned}$$

(Note: **Equation 4-17** may not be appropriate in all situations. An understanding of the equilibrium conditions assumed in the DCGL is necessary to calculate alpha and beta DCGLs, and other methods may be used.)

For this example, the beta activity $DCGL_W$ corresponding to the $DCGL_W$ for Th_{nat} is 400 beta particles/second/m².

To demonstrate compliance with the beta activity $DCGL_W$ for this example, measurements of beta count rates must be converted to activity using a weighted beta total efficiency that accounts for the energy and yield of each beta particle. For decay chains that have not achieved secular equilibrium, the relative activities between the different members of the decay chain can be determined as previously discussed in **Section 4.5.3.3** for surrogate ratios.

4.12.2.2 Surrogate Derived Concentration Guideline Level

Example 4-5a and **Example 4-5b** illustrate and discuss the application of the surrogate method in two steps: (1) determining the surrogate ratio and (2) calculating the surrogate DCGL.

Example 4-5a: Determining the Surrogate Ratio

Ten soil samples within the survey unit were collected and analyzed for ^{137}Cs and ^{90}Sr to establish a surrogate ratio. The ratios of ^{90}Sr to ^{137}Cs were as follows: 6.6, 5.7, 4.2, 7.9, 3.0, 3.8, 4.1, 4.6, 2.4, and 3.3. An assessment of this example dataset results in a mean ^{90}Sr to ^{137}Cs surrogate ratio of 4.6, with a standard deviation of 1.7, as shown below using **Equations 8-1 and 8-2**:

$$\text{Mean} = \frac{6.6 + 5.7 + \dots + 2.4 + 3.3}{10} = 4.6$$

$$s = \sqrt{\frac{(6.6 - 4.6)^2 + (5.7 - 4.6)^2 + \dots + (2.4 - 4.6)^2 + (3.3 - 4.6)^2}{10 - 1}} = 1.7$$

Various approaches may be used to develop a surrogate ratio from these data, but each must consider the variability and level of uncertainty in the data. One may consider the variability in the surrogate ratio by selecting an upper percentile of the distribution of surrogate ratios (e.g., 97.5th percentile considering a normal distribution) (to yield a conservative value of ^{90}Sr from the measured ^{137}Cs), which is 7.9 in this case, as shown below using **Equation 8-4**:

$$\text{UCL} = 4.6 + 1.96 \times 1.7 = 7.9$$

Similarly, one may select the most conservative value from the dataset (in this case, 7.9, which is also the maximum ratio).

At sites where surrogates are used, a correlation coefficient should be calculated to validate the relationship between the radionuclides. NUREG-1505, Chapter 11, contains additional guidance for evaluating the use of surrogates and the suitability of correlations. In addition, the radioactive ingrowth and decay of radionuclides should be evaluated. Surrogates are most appropriate for sites where the radionuclides are contained in insoluble particulates. The sources of insoluble particulates include the following:

- *Sites processing minerals, such as monazite, thorite, thorianite, and zircon:* The gamma radiation from the decay products here is a useful surrogate for the decay chain, and the insolubility of the minerals precludes changes in the ratios of the parent and progeny.
- *Sites with residual radioactive material from corrosion products from nuclear reactors:* In this case, the gamma radiation from cobalt-60 (^{60}Co) is typically used as a surrogate for other radionuclides, including iron-59, iron-55 (^{55}Fe), cobalt-57, chromium-51, manganese (^{54}Mn), nickel-57, and nickel-63 (^{63}Ni). Note that at this kind of site, the shorter lived radionuclides will decay more rapidly than ^{60}Co , and appropriate decay corrections will need to be evaluated.
- *Sites with plutonium isotopes and ^{241}Am :* At these sites, the gamma radiation from ^{241}Am is a useful surrogate for plutonium-239 (^{239}Pu) and plutonium-240. Note that at this kind

of site, plutonium-241 will continue to decay to ^{241}Am ; therefore, the appropriate decay corrections will need to be made.

- *Sites with thoriated metal (i.e., nickel, tungsten, or magnesium):* The gamma radiation from thorium progeny here can be used as a surrogate, but a thorough evaluation is required to verify that sufficient time has passed to permit the thorium and its progeny to be near a state of secular equilibrium.

Once an appropriate surrogate ratio is determined and approved by the appropriate regulatory agency, the planning team needs to consider how compliance will be demonstrated using surrogate measurements. That is, the planning team must modify the DCGL of the measured radionuclide to account for the inferred radionuclide. This calculation is shown in **Example 4-5b**.

Example 4-5b: Surrogate DCGL Calculation

The modified DCGL for ^{137}Cs must be reduced using **Equation 4-9**:

$$\text{DCGL}_{\text{Cs-mod}} = \frac{1}{\left(\frac{1}{\text{DCGL}_{\text{Cs}}} + \frac{R_{\text{Sr/Cs}}}{\text{DCGL}_{\text{Sr}}} \right)}$$

where $\text{DCGL}_{\text{Cs-mod}}$ is the DCGL of ^{137}Cs ; DCGL_{Sr} is the DCGL of ^{90}Sr , and $R_{\text{Sr/Cs}}$ is the ratio of the concentrations of ^{90}Sr to ^{137}Cs . Assuming that DCGL_{Sr} is 150 Bq/kg, DCGL_{Cs} is 100 Bq/kg, and the ratio of ^{90}Sr to ^{137}Cs is 8 (e.g., from a postremediation characterization survey), the modified DCGL for ^{137}Cs ($\text{DCGL}_{\text{Cs-mod}}$) can be calculated using **Equation 4-9**:

$$\text{DCGL}_{\text{Cs-mod}} = \frac{1}{\left(\frac{1}{100 \text{ Bq kg}^{-1}} + \frac{8}{150 \text{ Bq kg}^{-1}} \right)} = 16 \text{ Bq kg}^{-1}$$

The modified DCGL for ^{137}Cs ($\text{DCGL}_{\text{Cs-mod}}$) is 16 Bq kg⁻¹.

4.12.2.3 Gross Activity Derived Concentration Guideline Level for Radionuclides in Known Ratios

4.12.2.3.1 Determining the Radionuclide Ratios

As with the surrogate ratio method, the relative ratios should be determined through the DQO process and with regulatory approval. Care must be taken to ensure that ratios are applicable to the FSS conditions, such as by making ratio measurements just before starting the FSS.

4.12.2.3.2 General Gross Activity Derived Concentration Guideline Level Calculation

Example 4-6 illustrates a general gross activity DCGL calculation.

Example 4-6: General Gross Activity DCGL Calculation

For this example, the investigator assumes that 40 percent of the total surface activity was contributed by a radionuclide with a DCGL of 8,300 Bq/m² (5,000 dpm/100 cm²), 40 percent by a radionuclide with a DCGL of 1,700 Bq/m² (1,000 dpm/100 cm²), and 20 percent by a radionuclide with a DCGL of 830 Bq/m² (500 dpm/100 cm²). Using **Equation 4-10**, the gross activity DCGL is 1,900 Bq/m² (1,100 dpm/100 cm²):

$$\begin{aligned} \text{DCGL}_{\text{gross}} &= \frac{1}{\frac{f_1}{\text{DCGL}_1} + \frac{f_2}{\text{DCGL}_2} + \frac{f_3}{\text{DCGL}_3}} \\ &= \frac{1}{\frac{0.40}{8,300 \text{ Bq/m}^2} + \frac{0.40}{1,700 \text{ Bq/m}^2} + \frac{0.20}{830 \text{ Bq/m}^2}} \\ &= 1,900 \text{ Bq/m}^2 \end{aligned}$$

Note: If the relative amounts (ratios) were derived from data collected before remediation, then the relative amounts need to be confirmed or verified after remediation but before the FSS.

4.12.2.4 Unity Rule Derived Concentration Guideline Level for Radionuclides with Unrelated Concentrations

Example 4-7 illustrates the unity rule DCGL for radionuclides with unrelated concentrations.

Example 4-7: Unity Rule DCGL for Radionuclides with Unrelated Concentrations

For a given survey unit, data from previous surveys yield the following radionuclide concentrations:

- mean ⁶⁰Co concentration = 41 ± 32 (1σ) Bq/kg
- mean ¹³⁷Cs concentration = 188 ± 153 (1σ) Bq/kg

The DCGL_W values for ⁶⁰Co and ¹³⁷Cs are 130 Bq/kg (3.6 pCi/g) and 410 Bq/kg (11 pCi/g), respectively. Since the concentrations of the two radionuclides appear to be unrelated in the survey unit, the surrogate approach cannot be employed.

The weighted sum (calculated using **Equation 4-12**) is shown below:

$$T = \frac{C_{\text{Co-60}}}{\text{DCGL}_{\text{Co-60}}} + \frac{C_{\text{Cs-137}}}{\text{DCGL}_{\text{Cs-137}}} = \frac{41 \text{ Bq/kg}}{130 \text{ Bq/kg}} + \frac{188 \text{ Bq/kg}}{410 \text{ Bq/kg}} = 0.77$$

The standard deviation of the weighted sum (calculated using **Equation 4-13**):

$$\sigma(T) = \sqrt{\left[\frac{\sigma(C_{\text{Co-60}})}{\text{DCGL}_{\text{Co-60}}}\right]^2 + \left[\frac{\sigma(C_{\text{Cs-137}})}{\text{DCGL}_{\text{Cs-137}}}\right]^2} = \sqrt{\left[\frac{32 \text{ Bq/kg}}{130 \text{ Bq/kg}}\right]^2 + \left[\frac{153 \text{ Bq/kg}}{410 \text{ Bq/kg}}\right]^2} = 0.45$$

The weighted sum would be reported as 0.77 ± 0.45 (1σ). This weighted sum and standard deviation can be used to determine the number of samples required for the FSS based on the statistical tests chose by the design team. **Example 4-10** gives the steps for determining the required number of samples for multiple radionuclides by applying the unity rule.

4.12.3 Required Number of Samples for a Single Radionuclide

Sections 5.3.3 and 5.3.4 contain detailed discussions on determining the required number of data points for the WRS and Sign tests.

4.12.3.1 Wilcoxon Rank Sum Test

Example 4-8 discusses how to determine the number of measurements for the WRS test.

Example 4-8: WRS Test

In this example, the following data (based on data presented in NUREG-1505) were collected for the survey unit and reference area. Under consideration are a single radionuclide that is present in the background and a single survey unit. This process would be repeated for each survey unit and reference area combination. Because the actual activity units are irrelevant to the example, they will be omitted.

Table 4-4 shows data from a postremediation survey.

Table 4-4 Sample Data from a Postremediation Survey

Statistic	Reference Area	Survey Unit	Difference
Mean =	38.8	189.8	151.0
Median =	38.0	188.0	150.0
σ =	6.6	8.1	NA

The DCGL of concern is 160. The design team settled on a Type I error (α) of 0.05 and a Type II error (β) of 0.10.

To determine the appropriate number of measurements, the relative shift must be calculated using **Equation 4-18**:

$$\text{Relative Shift} = \frac{\text{DCGL} - \text{LBGR}}{\sigma} \quad \text{Equation 4-18}$$

The LBGR is often set at the expected median concentration of the radionuclide. However, in this example, the mean is higher than the median. Because it is conservative to set the LBGR at the higher value* (i.e., the expected mean) and to choose the larger value for σ for the reference area or survey unit, that is what the design team does, as shown below:

$$\text{Relative Shift} = \frac{160 - 151.1}{8.1} = 1.1$$

Referring to **Table 5-2**, we see that the recommended number of measurements ($N/2$) is 22 (given a relative shift (Δ/σ) of 1.1, $\alpha = 0.05$, and $\beta = 0.10$).[^] This is the number of samples that must be collected in both the reference area and survey unit, for a total of 44 measurements. Also, this number accounts for missing or unusable data.

* Larger values for the LBGR and σ lead to a smaller relative shift that, in turn, leads to a larger number of required measurements.

[^] Using the median value results in a relative shift of 1.2 and an $N/2$ value of 19.

4.12.3.2 Sign Test

Example 4-9 shows how to determine the number of samples for the Sign test.

Example 4-9: Sign Test

In this example, the data were collected in a postremediation survey for the survey unit and reference area, as shown in **Table 4-5**. Under consideration are a single radionuclide that is not present in the background, or present an insignificant fraction of the DCGL_w, and a single survey unit. The activity levels are compared directly to the DCGL. This process would be repeated for each survey unit. Because the actual activity units are irrelevant to the example, they will be omitted.

Table 4-5 Sample Data from a Postremediation Survey

Statistic	Survey Unit
Mean =	10.9
Median =	11.5
σ =	3.3

The DCGL of concern is 16. The design team settled on $\alpha = 0.05$ and $\beta = 0.05$.

To determine the appropriate number of measurements, the relative shift must be calculated using **Equation 4-18**:

$$\text{Relative Shift} = \frac{\text{DCGL} - \text{LBGR}}{\sigma}$$

The LBGR is often set at the expected median concentration of the radionuclide. Because it is conservative to set the LBGR at the higher of the mean or median, the median is used as shown below:

$$\text{Relative Shift} = \frac{16 - 11.5}{3.3} = 1.4$$

Referring to **Table 5-3**, we see that the required number of measurements (N) is 20 (given a relative shift (Δ/σ) of 1.4, $\alpha = 0.05$, and $\beta = 0.05$). This number accounts for missing or unusable data.

4.12.4 Required Number of Samples for Multiple Radionuclides

Sections 5.3.3–5.3.4 include detailed discussions on determining the required number of data points for the WRS and Sign tests.

Example 4-10 breaks down the steps for determining the required number of samples for multiple radionuclides by applying the unity rule.

Example 4-10a: Applying the Unity Rule

A design team is tasked with classifying a survey unit according to the potential for residual radioactive materials and determining the appropriate number of soil samples to take during the FSS. The contaminants are ^{60}Co and ^{137}Cs , with the following DCGL_W values:

- $\text{DCGL}_{W,\text{Co-60}}$: 130 Bq/kg (3.5 pCi/g)
- $\text{DCGL}_{W,\text{Cs-137}}$: 410 Bq/kg (11 pCi/g)

During the DQO process and with approval of the regulator, the acceptable probability of a Type I error (α) is set to 0.05, and the acceptable probability of a Type II error (β) set to 0.10. (The Type I error is the probability that the statistical test will indicate that the survey unit meets the release criteria when, in fact, it does not. The Type II error is the probability that the statistical test will indicate that the survey unit does not meet the release criteria when, in fact, it does.)

Because compliance must be demonstrated for more than one radionuclide, and each radionuclide will be measured separately, the unity rule will be used, wherein the concentration of each contaminant is normalized to (divided by) its DCGL_W . When this is done, the collective “concentration” of the multiple radionuclides is expressed as the weighted SOR, given as T in **Table 4-6. Section 4.5.3.5** gives details on the SOR.

The data in **Table 4-6**, obtained earlier during the characterization survey, are assumed to be representative of the existing conditions in the survey unit.

Table 4-6 Sample Results for Unity Rule Example

Sample Number	Concentration (Bq/kg) $C_{\text{Co-60}}$	Concentration (Bq/kg) $C_{\text{Cs-137}}$	Normalized Concentration (C/DCGL) $_{\text{Co-60}}$	Normalized Concentration (C/DCGL) $_{\text{Cs-137}}$	T^a
1	104	308	0.80	0.74	1.54
2	33	78	0.25	0.19	0.45
3	30	185	0.23	0.45	0.69
4	41	322	0.32	0.79	1.11
5	78	525	0.60	1.28	1.89
6	26	70	0.20	0.17	0.38
7	4	44	0.03	0.11	0.14
8	0	-11	0.00	-0.03	-0.03
9	59	229	0.45	0.56	1.02
10	37	137	0.28	0.33	0.62
Mean	41	188	0.32	0.46	0.78
Median	35	161	0.27	0.39	0.66
Sample	Sigma (Bq/kg) $C_{\text{Co-60}}$	Sigma (Bq/kg) $C_{\text{Cs-137}}$	Normalized Sigma (σ/DCGL) $_{\text{Co-60}}$	Normalized Sigma (σ/DCGL) $_{\text{Cs-137}}$	T^a
N/A	32	162	0.25	0.39	N/A

^a To be conservative, all the ratios in the table have been rounded up.

Example 4-10b: Sign Test

Although ^{137}Cs is in the background, it is present at such a low concentration (37 Bq/kg [1 pCi/g]) relative to the DCGL that the planning team decides to “eat” background and use the Sign test.

Example 4-10c: Classification

Both the mean (0.78) and median (0.66) of the SOR are less than 1. This indicates that the survey unit might comply with the release criteria without further remediation. That the mean and median differ indicates that the measurements might not be normally distributed. This supports the decision to analyze the FSS data with a nonparametric test (Sign test).

That the value of the SORs for several samples (1, 4, 5, and 9) exceeds 1 indicates that this should be considered a Class 1 survey unit. As discussed in **Section 4.6.1**, areas containing residual radioactive material in excess of the DCGL_w before remediation should be classified as Class 1 areas. In this example, the survey unit has several individual locations where SOR exceeds 1, which is the unity rule DCGL. However, this does not mean that the survey unit fails to meet the release criteria.

Example 4-10d: Determine the Appropriate Number of Systematic Samples

To determine the appropriate number of soil samples, the relative shift is calculated using **Equation 4-18**, as shown below:

$$\text{Relative Shift} = \text{DCGL} - \text{LBGR}\sigma$$

Because the survey unit involves two radionuclides (^{60}Co and ^{137}Cs), the unity rule is used, wherein the concentration of each radionuclide is divided by its DCGL. When this is done, the DCGL for the combined radionuclides effectively becomes 1, using **Equation 4-19**:

$$\text{Relative Shift} = 1 - \text{LBGR}\sigma \quad \text{Equation 4-19}$$

The LBGR is often set at the expected median concentration of the contaminant. However, in this example, the mean is higher than the median. The LBGR will be set at the higher value (i.e., the expected mean) because that is the conservative approach.

Given the fact that the survey unit has multiple contaminants, the expected mean concentration of each radionuclide is divided by its DCGL and T or the SOR is used as the LBGR, applying **Equation 4-20**:

$$\begin{aligned} \text{LBGR} &= \left(\frac{\text{Expected Mean Concentration}}{\text{DCGL}} \right)_{\text{Co-60}} + \left(\frac{\text{Expected Mean Concentration}}{\text{DCGL}} \right)_{\text{Cs-137}} & \text{Equation 4-20} \\ &= \frac{41 \text{ Bq/kg}}{130 \text{ Bq/kg}} + \frac{188 \text{ Bq/kg}}{410 \text{ Bq/kg}} \\ &= 0.32 + 0.46 \\ &= 0.78 \end{aligned}$$

Using **Equation 4-19**, the relative shift calculation then becomes the following:

$$\text{Relative Shift} = \frac{1 - 0.78}{\sigma}$$

Using **Equation 4-13**, the combined sigma (σ) for ^{60}Co and ^{137}Cs using data from **Table 4-6** is the following:

$$\begin{aligned}\sigma &= \sqrt{\left(\frac{\sigma}{\text{DCGL}}\right)_{\text{Co-60}}^2 + \left(\frac{\sigma}{\text{DCGL}}\right)_{\text{Cs-137}}^2} \\ &= \sqrt{(0.25)^2 + (0.39)^2} \\ &= 0.47\end{aligned}$$

The relative shift is then determined as follows, as shown below using **Equation 4-19**:

$$\text{Relative Shift} = \frac{1 - 0.78}{0.47} = 0.47$$

Note that the relative shift and sigma have the same value (0.47), which is a coincidence.

Referring to **Table 5-3**, we see that the recommended number of samples for a relative shift of 0.47 is somewhere between 71 and 107 (given $\alpha = 0.05$ and $\beta = 0.10$). When the relative shift falls between the values in two rows of **Table 5-3**, the number of samples can be conservatively estimated by using the number of samples corresponding to the smaller value of the relative shift. For this example, the number of required samples would be 107.

4.12.5 Instrument and Source Efficiencies

The instrument efficiency (ε_i) is defined as the ratio of the net count rate of the instrument to the surface emission rate of a source for a specified geometry (ISO 2016). For a given instrument, the instrument efficiency depends on the energy of the radiations emitted by the source. The surface emission rate is defined as the number of particles of a given type above a given energy emerging from the front face of the source per unit time. The surface emission rate is the 2π particle fluence that embodies both the absorption and scattering processes that affect the radiation emitted from the source. Thus, the instrument efficiency is determined by the ratio of the net count rate and the surface emission rate.

The source efficiency (ε_s) is defined as the ratio of the number of particles of a given type emerging from the front face of a source to the number of particles of the same type created or released within the source per unit time. The source efficiency takes into account the increased particle emission due to backscatter effects, as well as the decreased particle emission due to self-absorption losses. For an ideal source (i.e., no backscatter or self-absorption), the value of the source efficiency is 0.5. Many real sources will exhibit values less than 0.5, although values greater than 0.5 are possible, depending on the relative importance of the absorption and backscatter processes.

For surface activity measurements, the product of the instrument and source efficiencies is the total efficiency of the instrument (ε_t). The total efficiency is the net count rate of the instrument

divided by the total activity (or concentration) in the specific geometry of interest. It is usually the efficiency of ultimate interest when planning FSSs.

Whatever approach is used to assess multiple radionuclides, the FSS design team needs to account for different instrument responses to the radionuclides of concern. It is important to use an appropriately weighted total efficiency to convert from instrument counts to activity units. This most frequently arises when measuring surface activity. When multiple radionuclides are being measured with the same instrument, a weighted efficiency must be used. Starting with the unity rule in its most general form (**Equation 4-1**), the total number of counts is simply the sum of the counts from each radionuclide j present, as shown in **Equation 4-21**:

$$\text{Total Number of Counts} = A_{\text{Total}} \varepsilon_t = \sum_{j=1}^n A_j \varepsilon_{s,j} \varepsilon_{i,j} \quad \text{Equation 4-21}$$

where:

- A_{Total} = total activity of the n radionuclides
- A_j = activity of the j th radionuclide
- $\varepsilon_{s,j}$ = source efficiency of the j th radionuclide
- $\varepsilon_{i,j}$ = instrument efficiency of the j th radionuclide

If the fraction f_j of each radionuclide in the mix is known, then, as shown in **Equation 4-22**—

$$A_{\text{Total}} \varepsilon_t = \sum_{j=1}^n (A_{\text{Total}} f_j) \varepsilon_{s,j} \varepsilon_{i,j} \quad \text{Equation 4-22}$$

Dividing both sides by A_{Total} yields the total efficiency for the mixture, as shown in **Equation 4-23**:

$$\varepsilon_t = \sum_{j=1}^n f_j \varepsilon_{s,j} \varepsilon_{i,j} \quad \text{Equation 4-23}$$

Example 4-11 illustrates the calculation of a weighted total efficiency for two radionuclides with different instrument efficiencies.

Example 4-11: Calculate a Weighted Total Efficiency for Two Radionuclides with Different Instrument Efficiencies

Consider a site with ^{137}Cs and $^{90}\text{Sr/Y}$, with ^{137}Cs representing 60 percent of the total activity. Therefore, the relative fractions are 0.6 for ^{137}Cs and 0.4 for $^{90}\text{Sr/Y}$. The source efficiency for both ^{137}Cs and $^{90}\text{Sr/Y}$ is 0.5. The corresponding instrument efficiencies for ^{137}Cs and $^{90}\text{Sr/Y}$ are determined to be 0.38 and 0.45, respectively.

The total efficiency can be calculated using **Equation 4-23**, as shown below:

$$\begin{aligned} \varepsilon_t &= f_{\text{Cs}} \varepsilon_{s,\text{Cs}} \varepsilon_{i,\text{Cs}} + f_{\text{Sr/Y}} \varepsilon_{s,\text{Sr/Y}} \varepsilon_{i,\text{Sr/Y}} \\ &= (0.6)(0.5)(0.38) + (0.4)(0.5)(0.45) \\ &= 0.20 \end{aligned}$$

Alternatively, the total efficiencies for each radionuclide can be calculated by multiplying the source efficiency by the instrument efficiency, as shown in the equations below, modified from **Equation 4-23**, as shown in **Equation 4-24**:

$$\varepsilon_{t,Cs} = \varepsilon_{s,Cs} \times \varepsilon_{i,Cs} = (0.5)(0.38) = 0.19 \quad \text{Equation 4-24}$$

$$\varepsilon_{t,Sr/Y} = \varepsilon_{s,Sr/Y} \times \varepsilon_{i,Sr/Y} = (0.5)(0.45) = 0.22$$

The weighted total efficiency can then be calculated as follows using equations modified from **Equation 4-23**, as shown in **Equation 4-25**:

$$\begin{aligned} \varepsilon_t &= f_{Cs}\varepsilon_{t,Cs} + f_{Sr/Y}\varepsilon_{t,Sr/Y} \\ &= (0.6)(0.19) + (0.4)(0.22) \\ &= 0.20 \end{aligned} \quad \text{Equation 4-25}$$

The weighted total efficiency is 0.20, or 20 percent.

When calculating the weighted total efficiency, one must account for the assumptions underlying the corresponding DCGL, particularly the relative ratios of the radionuclides present. In this case, the relative ratio of ^{137}Cs and $^{90}\text{Sr/Y}$ is needed to calculate the weighted total efficiency. This can be important when dealing with the naturally occurring radionuclide chains (e.g., radium-226 [^{226}Ra] and progeny). The state of secular equilibrium (disequilibrium) would need to be accounted for in determining the weighted total efficiency. **Section 4.12.6** gives an example of calculating the total weighted efficiency for a mixture of radionuclides.

This weighted efficiency discussion addresses considerations for fractional activity. However, more complex situations may be encountered, which must consider things such as radiation emission intensities and branching ratios of decay chains. MARSAME and NUREG-1507 provide some additional examples of these more complex situations.

4.12.6 Data Conversion

Example 4-12 illustrates the data conversion process along with another weighted total efficiency calculation. **Section 6.7** contains additional details.

Example 4-12: Data Conversion Process

A radionuclide laboratory is being decommissioned. Options are being considered for the FSS of surfaces in the laboratory. **Table 4-7** contains information on the radionuclides:

Table 4-7 Sample Radionuclide Information

Radionuclide	DCGL _w Bq m ⁻²	DCGL _w dpm (100 cm ²) ⁻¹	Relative Fraction
¹⁴ C	5.77×10 ⁶	3.46×10 ⁶	0.12
⁶³ Ni	2.72×10 ⁶	1.63×10 ⁶	0.18
⁹⁹ Tc	1.95×10 ⁶	1.17×10 ⁶	0.40
²⁰⁴ Tl	1.33×10 ⁴	8.00×10 ³	0.02
⁹⁰ Sr/Y	1.30×10 ⁴	7.78×10 ³	0.13
¹⁰⁶ Ru/Rh	3.98×10 ⁴	2.39×10 ⁴	0.15

Because the relative ratios are well known, were determined through the DQO process, and were approved by the regulatory agency, gross beta activity measurements will be used to determine compliance with the release criterion for this survey. The gross activity DCGL_w can be determined from **Equation 4-10**:

$$DCGL_{gross} = \frac{1}{\left(\frac{0.18}{2.72 \times 10^6} + \frac{0.12}{5.77 \times 10^6} + \frac{0.40}{1.95 \times 10^6} + \frac{0.02}{1.33 \times 10^4} + \frac{0.13}{1.30 \times 10^4} + \frac{0.15}{3.98 \times 10^4} \right)}$$

$$= 6.42 \times 10^4 \text{ Bq m}^{-2} \text{ (} 3.85 \times 10^4 \text{ dpm (100 cm}^2\text{)}^{-1}\text{)}$$

It has been decided to use a gas-flow proportional counter with a physical probe area of 126 cm² (0.0126 m²) in beta-particle-only mode for the survey. The design team has determined the total efficiencies for the detector in **Table 4-8**:

Table 4-8 Sample Efficiencies for a Detector

Radionuclide	Source Efficiency	Instrument Efficiency	Total Efficiency	Relative Fraction	Weighted Efficiency
¹⁴ C	0.25	0.16	0.04	0.12	0.0048
⁶³ Ni	0.25	0.00	0.00	0.18	0.000
⁹⁹ Tc	0.25	0.64	0.16	0.40	0.064
²⁰⁴ Tl	0.50	0.58	0.29	0.02	0.0058
⁹⁰ Sr/Y	0.50	0.72	0.36	0.13	0.047
¹⁰⁶ Ru/Rh	0.50	1.10	0.55	0.15	0.082
Total =	-	-	-	1.00	0.20

In general, the output of the counter is a gross counting rate or integrated counts in a set counting interval. The relationship between the counter's output and surface activity (A_s) concentration is given by **Equation 6-34** as shown below:

$$A_s = \frac{C_s/t_s}{\varepsilon_t \times W}$$

where:

C_s = integrated net counts recorded by the instrument

t_s = time period over which the counts were recorded

ε_t = total efficiency of the instrument in counts per disintegration, effectively the product of the instrument efficiency (ε_i) and the source efficiency (ε_s)

W = physical probe area

To account for background, **Equation 4-26** (a slightly modified form of **Equation 6-36**) is used:

$$A_s = \frac{C_{s+b}/t_s - C_b/t_b}{\varepsilon_t \times W} = \frac{C_s/t_s}{\varepsilon_t \times W} = \frac{R_{net}}{\varepsilon_t \times W} \quad \text{Equation 4-26}$$

where:

C_b = background counts* recorded by the instrument

t_b = time period over which the background counts were recorded^

R_{net} = net counting rate

* Background measurements should be made on material with no potential for residual radioactive materials from site operations that is similar in composition to the material at the measurement location.

^ The sample and background counting intervals can be different, depending on the desired MDC. Refer to **Section 6.3** and the professional literature for more discussion.

The units for t_s , t_b , and W depend on the desired units for the FSS.

For this example, surface activity measurements are being made on drywall. One measurement location results in the following data:

- $C_b = 1,626$ counts
- $t_b = 5$ minutes
- $C_s = 1,210$ counts
- $t_s = 1$ minute

The net counting rate, in counts per minute (cpm) is calculated using **Equation 4-27**:

$$\begin{aligned} R_{net} &= C_{s+b}/t_s - C_b/t_b && \text{Equation 4-27} \\ &= \frac{1,210 \text{ counts}}{1 \text{ minute}} - \frac{1,626 \text{ counts}}{5 \text{ minutes}} \\ &= (1,210 - 325.2) \text{ cpm} \\ &= 884.8 \text{ cpm} \end{aligned}$$

The net counting rate can be converted to the surface activity concentration, as shown below, using **Equation 4-26**:

$$\begin{aligned} A_s &= \frac{R_{net}}{\varepsilon_t \times W} \\ &= \frac{884.8 \text{ cpm}}{0.20 \text{ (c/d)} \times 0.0126 \text{ m}^2} \\ &= 3.51 \times 10^5 \text{ dpm/m}^2 \end{aligned}$$

In general, either International System (SI) (Bq/m²) or conventional (dpm/100 cm²) units are desired. For SI units, the conversion is straightforward, because 60 dpm is equivalent to 1 Bq, using **Equation 4-26** as shown below:

$$\begin{aligned} A_s &= \left(3.51 \times 10^5 \text{ dpm/m}^2 \right) \times \left(\frac{1 \text{ Bq}}{60 \text{ dpm}} \right) \\ &= 5.83 \times 10^3 \text{ Bq/m}^2 \end{aligned}$$

The conversion to conventional units is shown below, using **Equation 4-26**:

$$\begin{aligned} A_s &= \left(3.51 \times 10^5 \text{ dpm/m}^2 \right) \times \left(\frac{0.01 \text{ m}^2}{100 \text{ cm}^2} \right) \\ &= 3.51 \times 10^3 \text{ dpm/100 cm}^2 \end{aligned}$$

The FSS design team should determine the desired units during the planning phase. After the desired units are chosen, the design team can create spreadsheets or other methods of analyzing the raw counting data to streamline the process. Similarly, any action or investigation levels chosen by the design team should be converted into the proper units. This process needs to be performed for each field measurement instrument and technique.

For example, if it is determined that units of dpm/100 cm² will be used, then the physical probe area should be measured in cm², and **Equation 4-28** can be used for each instrument:

$$A_s = \frac{C_s/t_s - C_b/t_b}{\varepsilon_t \times (W/100)} = \frac{R_{net}}{\varepsilon_t \times (W/100)} \quad \text{Equation 4-28}$$

where t_s and t_b are recorded in minutes (R_{net} is expressed in cpm), and W is recorded in cm² instead of m².

For this example, **Equation 4-26** was used, as shown below:

$$\begin{aligned} A_s &= \frac{884.8 \text{ cpm}}{0.20 \text{ (c/d)} \times (126/100)} \\ &= 3.51 \times 10^3 \text{ dpm/100 cm}^2 \end{aligned}$$

The result is the same as above in this example, as expected.

Additionally, the AL, investigation level, and DCGL can be converted to detector outputs to facilitate timely actions (i.e., expressing ALs in terms of net counting rate might allow the field survey team to alert supervisors about measurements exceeding ALs in close to real time). In this case, the net counting rate corresponding to an AL can be expressed by **Equation 4-29**:

$$R_{net}^{AL} = \varepsilon_t \times W \times A_s^{AL} \quad \text{Equation 4-29}$$

Suppose the design team set an AL at 10 percent of the DCGL_{gross}. The net counting rate corresponding to this value is found using **Equation 4-29**, keeping in mind that 1 Bq is equivalent to 1 disintegration per second (dps):

$$\begin{aligned} R_{net}^{AL} &= 0.20 \times 0.0126 \text{ m}^2 \times (6.42 \times 10^3 \text{ Bq/m}^2) \\ &= 16.2 \text{ counts per second} = 971 \text{ cpm} \end{aligned}$$

Thus, any net count exceeding about 970 cpm would be flagged for investigation. If background rates are relatively constant, an AL can be expressed as a gross counting rate, as well.

4.12.7 Example of a Deviation from a Recommended Statistical Test

Example 4-13 illustrates a deviation from a recommended statistical test.

Example 4-13: Deviation from a Recommended Statistical Test

This example involves a survey unit that contains many different surfaces with potentially different backgrounds (e.g., drywall panels, concrete floor, glass windows, metal doors, wood trim, plastic fixtures), and gross activity measurements are being considered. In this case, MARSSIM recommends the WRS test when gross activity measurements are used; however, the use of the WRS test might require several survey and associated reference units, resulting in an inordinately large number of measurements. Furthermore, “it is not appropriate to make each material a separate survey unit because the dose modeling is based on the dose from the room as a whole and because a large number of survey units in a room would require an inappropriate number of samples” (NRC 2022a). In this situation, the design team should use the DQO process and determine the best approach.

Instead of attempting to use the WRS test and multiple reference units, the design team might investigate the materials to determine if material-specific backgrounds are needed or whether materials with similar background could be grouped and considered as a unit. If this is done, it might be “acceptable to perform a one-sample test (Sign test) on the difference between the paired measurements from the survey unit and from the appropriate reference material” (NRC 2006). Chapter 12 of NUREG-1505 contains details on this method.

In addition to the alternative statistical approach discussed above, the NRC (2006) discusses two additional approaches to resolve this issue. First, if the materials in the survey unit have substantially different backgrounds, then a reference unit containing a similar mix of material might be used, and the WRS test can then be applied. Second, if the materials in the survey unit have similar backgrounds, or if one material predominates, then a reference background from a single material might suffice. Refer to NRC (2006) for more details.

The design team should use the DQO process to investigate any deviations from usual methods and get approval from the regulatory agency before executing the FSS.

4.12.8 Uranium Mill Tailings Radiation Control Act of 1978 Sites

At UMTRCA sites, the EPA's Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (in 40 CFR Part 192) are applicable. However, the technical requirements in these standards are not always consistent with some of the recommendations in MARSSIM. Specifically, the soil cleanup standards for ^{226}Ra and radium-228 are specified as averages over an area of 100 m². (The 40 CFR Part 192 rulemaking used an averaging area of 100 m² as a reasonable footprint for a home. One goal of the 40 CFR Part 192 standards was to protect future homes from indoor radon, and the specified averaging area was a component implemented for the protection of health.) The rules in 40 CFR Part 192 do not establish specific requirements for small areas of elevated radioactive material. At sites where the uranium or thorium mill tailings standards are applicable, the following approach for FSSs is acceptable:

- A survey unit of no greater than 100 m² sections of land should be used, consistent with the regulatory standards.
- The systematic sampling for performance of statistical tests, normally required under the MARSSIM approach, is not required for each survey unit. Instead, compliance with the standard can be demonstrated through the analysis of soil samples or composite soil samples from each survey unit in conjunction with gamma radiation scanning or in situ gamma radiation measurements of each survey unit. When appropriate, gamma radiation scanning or in situ measurements correlated to soil sampling may be used in place of soil sampling.
- Survey units may be classified, as appropriate, and the percentage of the survey unit that is scanned may be adjusted accordingly for Class 1, Class 2, or Class 3 survey units.
- Elevated measurement comparison criteria for small elevated areas of activity may be developed but are not required for the purposes of 40 CFR Part 192.

These minor modifications to the standard MARSSIM radiological survey approach are acceptable for those sites to which the UMTRCA standards are applicable.

5 SURVEY PLANNING AND DESIGN

5.1 Introduction

This chapter is intended to assist the user in planning radiological surveys, with a particular emphasis on designing and conducting a final status survey (FSS) to demonstrate compliance with the release criteria. The survey types that make up the Radiation Survey and Site Investigation (RSSI) process include scoping, characterization, remedial action support (RAS), and final status surveys; depending on the regulatory framework, the process may also include confirmatory or independent verification surveys. Although the scoping, characterization, and RAS surveys have multiple objectives, this manual focuses on those aspects related to supporting the FSS and demonstrating compliance with the release criteria. In general, each of these survey types expands upon the data collected during the previous survey (e.g., the characterization survey is planned with information collected during the scoping survey), up through the FSS. The conduct and extent of scoping and characterization surveys will depend on the available information from the Historical Site Assessment (HSA) and site-specific conditions. The purpose of the FSS is to demonstrate that the release criteria established by the regulatory agency have not been exceeded. This final release objective should¹ be kept in mind throughout the design and planning phases for each of the other survey types. For example, scoping surveys may be designed to meet the objectives of the FSS such that the scoping survey report is also the FSS report. The survey and analytical procedures referenced in this chapter are described in **Chapters 6–7** and **Appendix H**. An example of an FSS, as described in **Section 5.3**, appears in **Appendix A**. In addition, example checklists are provided for each type of survey to assist the user in obtaining the necessary information for planning an FSS. **Appendix N** provides detailed calculations for statistical tests and more detailed derivations of key statistical concepts. It should be consulted when performing survey planning and design.

Scoping surveys—used to augment the HSA and provide input to future survey designs—and survey unit characterization and classification are described in **Section 5.2.1**. **Section 5.2.2** describes characterization surveys performed to determine the nature and extent of residual radioactive material, potential remediation alternatives and technologies, the inputs to pathway analysis and dose or risk assessment models, occupational and public health and safety impacts, and inputs to the FSS design. RAS surveys, performed to support remedial activities, update estimates of site-specific parameters used in FSS planning, and determine when a site or survey unit is ready for an FSS, are described in **Section 5.2.3**. **Section 5.3** covers FSSs, which are performed to demonstrate that a survey unit meets the residual radioactive material release criteria.

Figure 5-1 through **Figure 5-3** provide flowchart diagrams illustrating the survey planning and design process, broken up by survey type.

¹ The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

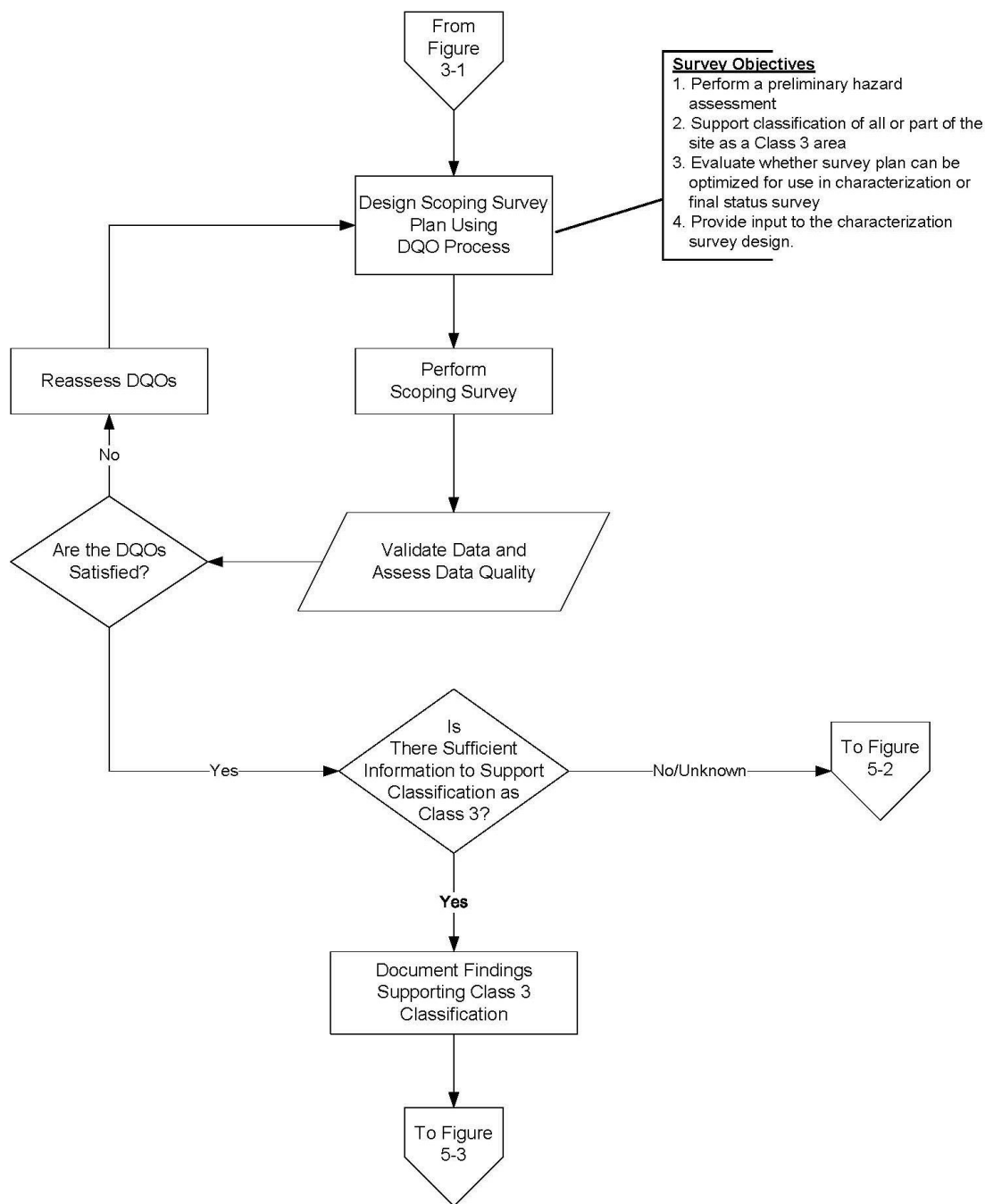
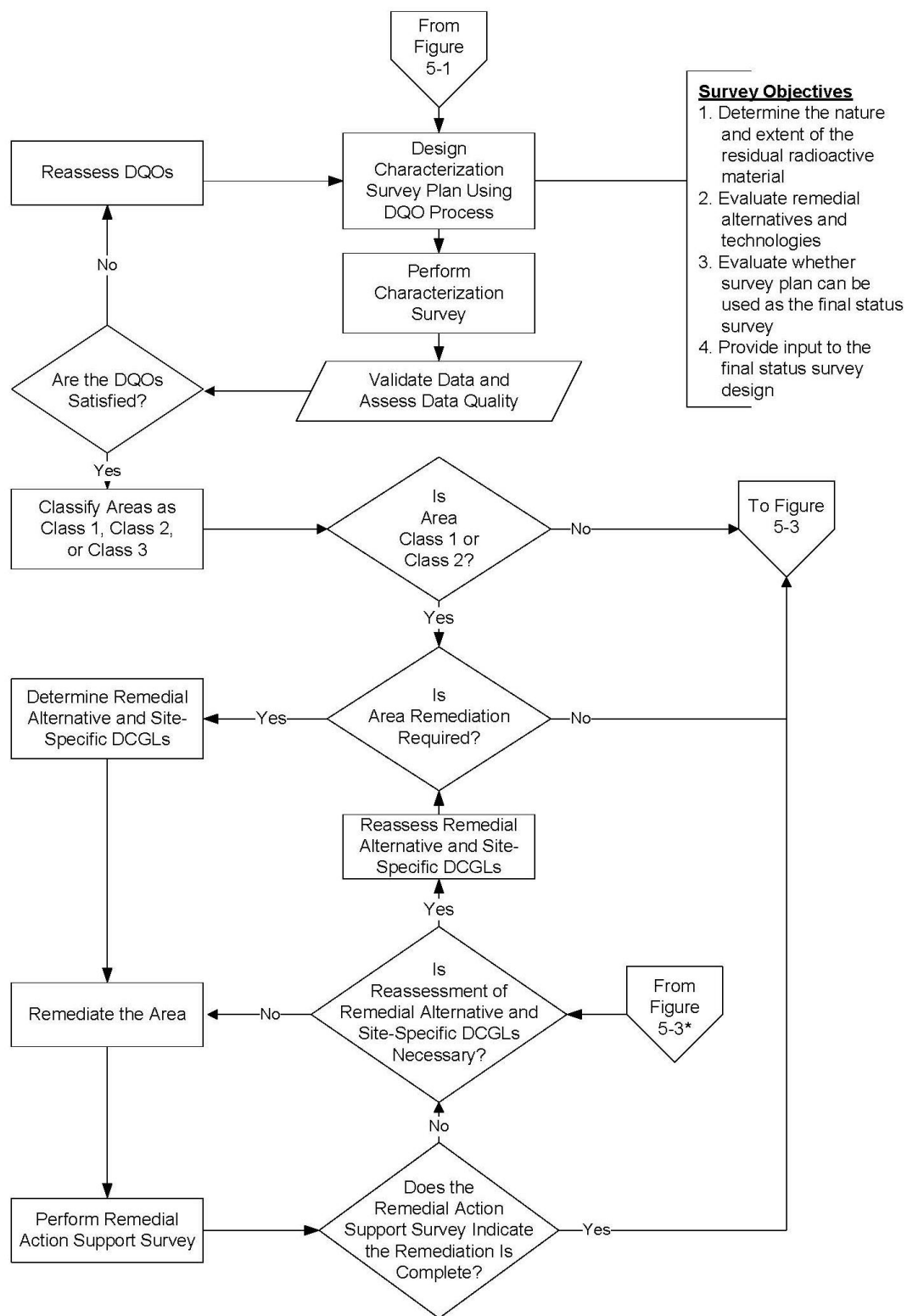
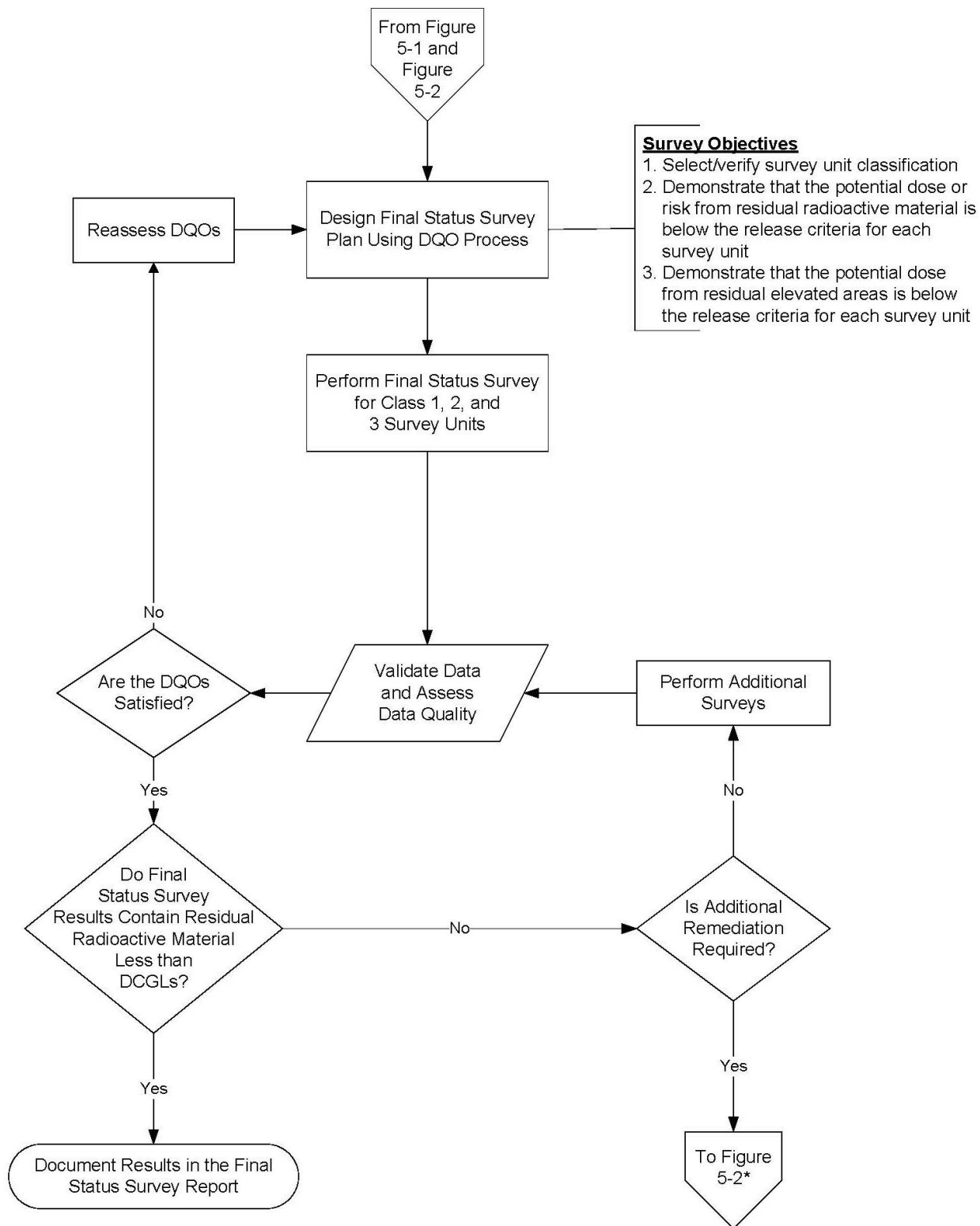


Figure 5-1 The Scoping Survey Portion of the RSSI Process



* The point where survey units that fail to demonstrate compliance in the FSS in Figure 5-3 re-enter the process

Figure 5-2 The Characterization and RAS Survey Portions of the RSSI Process



* Connects with the RAS survey portion of the process in Figure 5-2

Figure 5-3 The FSS Portion of the RSSI Process

5.2 Preliminary Surveys

5.2.1 Scoping Surveys

If the data collected during the HSA indicate that a site or area is impacted, a scoping survey may be performed. The objective of this survey is to augment the HSA for sites with potential residual radioactive material. Specific objectives may include the following:

- performing a preliminary risk assessment and providing data to complete the site prioritization scoring process for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) sites only²
- providing input to the characterization survey design, if necessary
- supporting the classification of all or part of the site as a Class 3 area for planning the FSS
- obtaining an estimate of the variability in the residual radioactive material concentration for the site
- identifying non-impacted areas that may be appropriate for reference areas and estimating the variability in radionuclide concentrations when the radionuclide of interest is present in background

A scoping survey is not a requirement if HSA information meets the needs for designing subsequent surveys, including the FSS. Alternatively, scoping surveys and characterization surveys may be combined, if one survey can be designed to meet the requirements of both survey types. **Section 5.2.2** describes characterization surveys.

Scoping survey information about the general radiation levels at the site, including gross levels of residual radioactive material on building surfaces and in environmental media, is needed when conducting a preliminary risk assessment (as noted above for CERCLA and RCRA sites). If unexpected conditions are identified that prevent completion of the survey, the MARSSIM user should contact the regulatory agency for further guidance. Sites that meet the National Contingency Plan criteria for a removal should be referred to the Superfund Removal program (EPA 1988b).

If the HSA indicates that residual radioactive material above release levels is likely, a scoping survey could be performed to provide initial estimates of the level of effort for remediation and information for planning a more detailed survey, such as a characterization survey. Not all radiological parameters need to be assessed when planning for additional characterization, because data on total surface activity or limited sample collection may be sufficient to meet the objectives of the scoping survey.

Once a review of pertinent site history indicates that an area is impacted, the minimum survey coverage at the site will include a Class 3 area FSS before the site is released. For scoping

² This preliminary assessment usually involves reviewing existing site information like historical records, aerial photographs, and property deeds and conducting a site reconnaissance to gather visual observations about potential contamination sources and surrounding environmental factors (EPA 1992c).

surveys with this objective, identifying radiological decision levels is necessary for selecting instruments and procedures with the capabilities needed to demonstrate compliance with the release criteria. A methodology for planning, conducting, and documenting scoping surveys is described in the following sections.

5.2.1.1 *Survey Design*

Planning a scoping survey involves reviewing the HSA for a site (**Chapter 3**). This process considers available information concerning locations of spills or other releases of radioactive material. Reviewing the radioactive materials license or similar documentation provides information on the identity, locations, and general quantities of radioactive material used at the site. This information helps determine which areas are likely to contain residual radioactive material and, thus, areas where scoping survey activities will be concentrated. The information may also identify one or more non-impacted areas as potential reference areas for establishing background levels (based on instrument response or radioactive material concentration), especially when radionuclides of concern are present in background (**Section 4.6.3**). Following the review of the HSA, appropriate derived concentration guideline levels (DCGLs)³ for the site are selected. These may be adjusted later if a determination is made to use site-specific information to support their development.

If residual radioactive material is identified during the scoping survey, the area may be classified as Class 1 or Class 2 for FSS planning (refer to **Section 4.6.1** for information on initial classification), and a characterization survey is subsequently performed. For scoping surveys that are designed to provide input for characterization surveys, measurements and sampling may not be as comprehensive or performed to the same level of sensitivity necessary for FSSs. The design of the scoping survey should be based on specific Data Quality Objectives (DQOs). **Section 2.3.1** and **Appendix D** describe the information to be collected.

For scoping surveys that potentially serve to release the site or portions of the site from further consideration, the scoping survey design for the Class 3 area should consist of sampling based on the HSA data and professional judgment and must be consistent with the requirements for an FSS. If residual radioactive material is *not* identified, it may be appropriate to characterize the area as non-impacted. **Section 5.3** describes FSSs. However, collecting additional information during subsequent surveys (e.g., characterization surveys) may be necessary to make a final determination as to area classification.

5.2.1.2 *Conducting Surveys*

Scoping survey activities performed for preliminary risk assessment or to provide input for additional characterization include a limited amount of surface scanning, surface activity measurements, and sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials). In this case, scans, direct measurements, and samples are used to examine areas likely to contain residual radioactive material. These activities are conducted based on HSA data, preliminary investigation surveys, and professional judgment.

³ Throughout this chapter, if the scenario is not explicitly stated, the default terms “derived guideline concentration level” or “DCGL” and “lower bound of the gray region” or “LBGR” will be used. If using Scenario B, please substitute “action level” or “AL” and “upper bound of the gray region” or “UBGR” (i.e., “discrimination limit” or “DL”) for these terms, respectively.

Background activity and radiation levels for the area should be determined, including direct radiation levels on building surfaces and radionuclide concentrations in media. Survey locations should be referenced to grid coordinates, if appropriate, or fixed site features. This may be accomplished by establishing a reference coordinate system if residual radioactive material is detected above the DCGLs (**Section 4.9.5**). Samples collected as part of a scoping survey should be maintained under custody from collection through analysis and reporting to ensure the integrity of the results. Sample tracking may include use of a chain of custody, which is the unbroken trail of accountability that ensures the physical security of samples, data, and records (**Section 7.8**).

Scoping surveys that are expected to be used as Class 3 area FSSs should be designed following the procedure in **Section 5.3**. Scoping surveys should also include judgment measurements and sampling in areas likely to have accumulated residual radioactive material (**Section 5.3.9**). However, when performing a scoping survey as a Class 3 FSS, judgment samples should not be part of the statistical sampling population used to make a release decision on a site or survey unit.

5.2.1.3 *Evaluating Survey Results*

Survey data are converted to the same units as the DCGLs (**Section 6.7**). Potential radionuclides of concern at the site are identified using direct measurements or laboratory analysis of samples. The data are compared to the appropriate regulatory DCGLs.

For scoping survey activities that provide an initial assessment of the radiological hazards at the site or input for additional characterization, the survey data are used to identify locations and the general extent of residual radioactive material. Scoping surveys that are expected to be used as Class 3 area FSSs should follow the methodology presented in **Chapter 8** to determine whether the release criteria have been exceeded.

5.2.1.4 *Documentation*

How the results of the scoping survey are documented depends on the specific objectives of the survey. For scoping surveys that provide additional information for characterization surveys, the documentation should contain general information on the radiological status of the site. Survey results should include identification of the potential radionuclides of concern (including the methods used for radionuclide identification), general extent of residual radioactive material (e.g., activity levels, area, and depth), and possibly even relative ratios of radionuclides to facilitate DCGL application. A narrative report or a report in the form of a letter may suffice for scoping survey data that is used to provide input for characterization surveys. Sites being released from further consideration should have a level of documentation consistent with FSS reports (**Section 5.3.11**). **Example 5-1** illustrates a scoping survey checklist, including survey design, conduct of the survey, and evaluation of survey results.

Example 5-1: Example Scoping Survey Checklist

Survey Design

_____ Enumerate Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs). State the objectives of the survey; survey instrumentation capabilities should

be appropriate for the specified survey objectives. Document survey requirements in a project-specific Quality Assurance Project Plan (QAPP).

_____ Review the Historical Site Assessment (HSA) for the following:

_____ Operational history (e.g., problems, spills, releases, or notices of violation) and available documentation (e.g., radioactive materials license)

_____ Other available resources—site personnel, former workers, residents, etc.

_____ Types and quantities of materials that were handled and where radioactive materials were stored, handled, moved, relocated, and disposed

_____ Release and migration pathways

_____ Areas that are potentially affected and likely to contain residual radioactive material (survey activities will be concentrated in these areas)

_____ Types and quantities of materials likely to remain onsite (consider radioactive decay)

_____ Select derived concentration guideline levels (DCGLs) for the site based on the HSA review. (It may be necessary to assume appropriate regulatory DCGLs in order to permit selection of survey methods and instrumentation for the expected radioactive material and quantities.)

Conducting Surveys

_____ Follow the survey design documented in the QAPP. Record deviations from the stated objectives or documented standard operating procedures, and document additional observations made when conducting the survey.

_____ Select instrumentation based on the specific DQOs and MQOs of the survey. Consider instrumentation capabilities for the expected residual radioactive material and quantities.

_____ Determine background activity and radiation levels for the area; include direct radiation levels on building surfaces, radionuclide concentrations in media, and exposure rates.

_____ Record measurement and sample locations referenced to grid coordinates or fixed site features.

_____ For scoping surveys that are conducted as Class 3 area final status surveys (FSSs), follow FSS procedures.

_____ Conduct scoping survey, which involves judgment measurements and sampling based on HSA results:

_____ Perform investigatory surface scanning.

- _____ Conduct limited surface activity measurements.
- _____ Perform limited sample collection (smears, soil, water, vegetation, paint, building materials, subsurface materials).
- _____ Maintain sample tracking.

Evaluating Survey Results

- _____ Compare survey results with the DQOs and MQOs.
- _____ Identify radionuclides of concern.
- _____ Identify impacted areas and the general extent of residual radioactive material.
- _____ Estimate the variability in the residual radioactive material levels for the site.
- _____ Adjust DCGLs based on survey findings. (Parameters used in DCGL development may not be consistent with site conditions/observations.)
- _____ Determine the need for additional action (e.g., none, remediate, more surveys).
- _____ Prepare report for regulatory agency (determine whether a letter report is sufficient).

5.2.2 Characterization Surveys

Characterization surveys may be performed to satisfy a number of specific objectives. Examples of characterization survey objectives may include the following:

- determining the nature and extent of residual radioactive material
- evaluating remediation alternatives (e.g., unrestricted use, restricted use, onsite disposal, offsite disposal)
- input to pathway analysis/dose or risk assessment models for determining site-specific DCGLs (becquerel [Bq]/kilogram [kg], Bq/square meter [m^2])
- estimating the occupational and public health and safety impacts during decommissioning
- evaluating remediation technologies
- providing input to FSS design
- meeting Remedial Investigation (RI)/Feasibility Study (FS) requirements (under a CERCLA program) or RCRA Facility Investigation/Corrective Measures Study requirements (under an RCRA program).

A characterization survey is not a requirement if HSA and scoping survey information meets the needs for designing subsequent surveys, including FSSs. Alternatively, scoping surveys and characterization surveys may be combined if one survey can be designed to meet the

requirements of both survey types. The scope of this manual precludes detailed discussions of characterization survey design for each of these objectives; therefore, the user should consult other references for specific characterization survey objectives not covered. For example, DOE/EM-0142P, "Decommissioning Handbook," issued 1994 (DOE 1994), is a good reference for characterization objectives that are concerned with evaluating remediation technologies or unrestricted/restricted use alternatives. Other references (e.g., Abelquist 2014; EPA 1988b, 2006c; NRC 1994) should be consulted for planning decommissioning actions, including remediation techniques, projected schedules, costs, waste volumes, and health and safety considerations during remedial action. Also, the types of characterization data needed to support risk or dose modeling should be determined from the specific modeling code documentation. This manual concentrates on providing information for the FSS design, with limited coverage on determining the specific nature and extent of residual radioactive material. The specific objectives for providing information relevant to the FSS design include the following:

- estimating the projected radiological status at the time of the FSS, in terms of radionuclides present, concentration ranges and variances, spatial distribution, etc.
- evaluating potential reference areas to be used for background measurements, if necessary
- reevaluating the initial classification of survey units
- selecting instrumentation based on the necessary MQOs
- establishing acceptable Type I and Type II errors with the regulatory agency (refer to **Appendix D** for information on establishing acceptable decision error rates)

Many of these objectives are satisfied by determining the specific nature and extent of residual radioactive material in structures, residues, and environmental media. Additional detail on the performance of characterization surveys designed to determine the general extent of residual radioactive material can be found in the U.S. Nuclear Regulatory Commission's (NRC's) NUREG-1757, "Consolidated Decommissioning Guidance," Volume 2, Revision 2, "Characterization, Survey, and Determination of Radiological Criteria," issued July 2022 (NRC 2022a); American National Standards Institute (ANSI)/Health Physics Society (HPS) standard ANSI/HPS 13.49, "Performance and Documentation of Radiological Surveys," issued 2001 (HPS 2001); ANSI/HPS N13.59, "Characterization in Support of Decommissioning Using the Data Quality Objectives Process," issued 2008 (HPS 2008); and the U.S. Environmental Protection Agency's (EPA's) RI/FS guidance (EPA 1988b, 1993a).

Results of the characterization survey should include the following:

- the identification and distribution of residual radioactive material in buildings, structures, and other site facilities
- the concentration and distribution of radionuclides of concern in surface and subsurface soils
- the distribution and concentration of residual radioactive material in surface water, groundwater, and sediments

- the distribution and concentration of radionuclides of concern in other impacted media, such as vegetation or paint

The characterization should include sufficient information on the physical characteristics of the site, including surface features, meteorology and climatology, surface water hydrology, geology, demography and land use, and hydrogeology. This survey should also address environmental conditions that could affect the rate and direction of radionuclide transport in the environment, depending on the extent of residual radioactive material identified above.

The following sections describe a method for planning, conducting, and documenting characterization surveys. Alternative methodologies may also be acceptable to the regulatory agencies.

5.2.2.1 *Survey Design*

The design of the site characterization survey is based on the specific DQOs for the information to be collected, and it is planned using the HSA and scoping survey results. The DQO process ensures that adequate data with sufficient quality are collected for the purpose of characterization. The site characterization process typically begins with a review of the HSA, which includes available information on site description, operational history, and the type and extent of residual radioactive material (from the scoping survey, if performed). The site description, or conceptual site model as first developed as described in **Section 3.6.4**, consists of the general area, dimensions, and locations of affected areas on the site. A site map should show site boundaries, roads, hydrogeological features, major structures, and other features that could affect decommissioning activities. When available, Global Positioning System (GPS) coordinates should be recorded for major features.

The operational history includes records of site conditions before operational activities, operational activities of the facility, effluents and onsite disposal, and significant incidents—including spills or other unusual occurrences—involving the spread of residual radioactive material around the site and on areas previously released from radiological controls. This review should include other available resources, such as interviews with site personnel, former workers, and residents. Historic aerial photographs and site location maps may be particularly useful in identifying potential areas of residual radioactive material.

The types and quantities of materials that were handled and the locations and disposition of radioactive materials should be reviewed using available documentation (e.g., the radioactive materials license). Release and migration pathways of radionuclides should be identified, as well as areas that are potentially affected and are likely to contain residual radioactive material. The types and quantities of materials likely to remain on site, considering radioactive decay, should be determined.

The characterization survey should clearly identify those portions of the site (e.g., soil, structures, and water) that have been affected by site activities and potentially contain residual radioactive material. The survey should also identify the portions of the site that have not been affected by these activities. In some cases, if no remediation is anticipated, the results of the characterization survey may indicate compliance with DCGLs established by the regulatory agency. When planning for the potential use of characterization survey data as part of the FSS, the characterization data must be of sufficient quality and quantity for that use (refer to **Section 5.3**).

Several processes are likely to occur in conjunction with characterization. These include considering and evaluating remediation alternatives and calculating site-specific DCGLs.

The survey should also provide information on variability in the radionuclide distribution in the survey area. The variability in the concentration of radioactive material in each survey unit contributes to determining the number of data points based on the statistical tests used during the FSS (**Sections 5.3.3–5.3.4**) and the required scan coverage for Class 2 areas. Additionally, characterization data may be used to justify reclassification for some survey units (e.g., from Class 1 to Class 2).

In some cases, judgment sampling is the most appropriate for meeting the data needs. Judgment sampling includes measurements performed at locations selected using professional judgment based on, for example, unusual appearance, location relative to known contaminated areas, high potential for residual radioactive material, and general supplemental information. Examples of situations in which judgment sampling may be the most appropriate include those where residual radioactive material is isolated to locations that can be defined by individual measurements, or in which biased results will provide the data from the areas of highest suspected concentration of residual radioactive material. It should be understood, however, that use of a judgment characterization survey will produce data that is considered biased and that can generally only be used to draw conclusions about individual samples or specific locations rather than to provide quantifiable estimates about a larger aggregate population. As a result, averages of judgment samples (i.e., biased) should not be used to determine the mean⁴ concentration of the residual radioactive material in the survey unit.

For those characterization survey objectives that require statistical evaluation of the data, the sampling plan should be designed to produce unbiased data. Unbiased sampling makes use of random sample selection, whereby each sample has an equal probability of being selected. Unbiased data can be used to provide a measure of the population characteristics, such as the average or mean radioactive material concentration and variance on that mean. One example of when unbiased sample data may be required is the use of a dataset in assessing compliance with dose- or risk-based criteria. Most human health risk assessment protocols (e.g., EPA 1989c) require the computation of a mean and upper confidence limit as the best measure of residual radioactive material in identifying excess lifetime cancer risk or radiation dose to a target population (EPA 2002b, 2006b).

The characterization survey may be used as an FSS for Class 3 areas under the following conditions:

- The characterization survey was planned as an FSS.
- Site or survey unit conditions warrant the use of the characterization survey as the FSS.
- Only randomly selected samples are used as part of the statistical evaluation of the site or survey unit. Any judgment samples collected may not be used as part of the statistical sample count or as part of the statistical evaluation of results.

⁴ In MARSSIM, “average” and “mean” both refer to the arithmetic mean.

It may be also appropriate to combine the principles of judgment and unbiased sampling strategies in designing a sample plan that provides the most representative data but also meets all the DQOs.

Note that because of the site-specific characteristics of residual radioactive material, performing all types of measurements described here may not be relevant at every site. For example, detailed characterization data may not be needed for areas with residual radioactive material well above the DCGLs that clearly require remediation. Judgment should be used in determining the types of characterization information needed to provide an appropriate basis for remediation decisions.

A number of software programs have been developed over the years to facilitate the design of surveys. One such example is Visual Sample Plan, developed by the Pacific Northwest National Laboratory. These software programs can perform calculations to determine the number of locations where measurements should be made or where samples should be collected.

5.2.2.2 *Conducting Surveys*

Characterization survey activities often involve the detailed assessment of various types of building and environmental media, including building surfaces, surface and subsurface soil, surface water, and groundwater. The HSA data should be used to identify the media onsite with a potential for residual radioactive material (see **Section 3.6.3**). Identifying the media that may contain residual radioactive material is useful for preliminary survey unit classification and for planning subsequent survey activities. Selection of survey instrumentation and analytical techniques is typically based on knowledge of the appropriate DCGLs, because remediation decisions are made based on the level of the residual radioactive material as compared to the DCGL. Exposure rate measurements may be needed to assess occupational and public health and safety.

5.2.2.2.1 *Structure Surveys*

Surveys of building surfaces and structures can include surface scanning, surface activity measurements, exposure rate measurements, and sample collection (e.g., smears, subfloor soil, water, paint, building materials). Both field survey instrumentation (**Chapter 6**) and analytical laboratory equipment and procedures (**Chapter 7**) are selected based on their instrumentation capabilities for the expected type and concentration of residual radioactive material. Field and laboratory instruments are described in **Appendix H**.

Background activity and radiation levels for the area should be determined from appropriate background reference areas. Background assessments include surface activity measurements on building surfaces, exposure rates, and concentrations of radioactive material in various media (refer to **Section 4.6.3**). Building reference area measurements should be collected in non-impacted areas within the same building, or in another similar building, provided that the reference area has been constructed with materials of the same type and age. This ensures that the reference area has the same inherent radioactive material and decay time, and therefore background radioactivity, as the impacted area.

Measurement locations should be documented using reference system coordinates, if appropriate, or fixed site features. A typical reference system spacing for building surfaces is 1 meter (m) (about 3 feet). This is chosen to facilitate identifying survey locations and small areas of elevated activity.

Scans should be conducted in areas likely to contain residual radioactive material, based on the results of the HSA and scoping survey.

Both systematic and judgment surface activity measurements are performed. Judgment direct measurements are performed at locations of elevated direct radiation, as identified by surface scans, to provide data on the upper ranges of residual radioactive material levels. Judgment measurements may also be performed in sewers, air ducts, storage tanks, and septic systems and on roofs of buildings, if necessary. Each surface activity measurement location should be carefully recorded on the appropriate survey form.

Exposure rate measurements and media sampling are performed as necessary. For example, subfloor soil samples (e.g., under a raised floor above the ground surface or under a concrete slab) may provide information on the horizontal and vertical extent of residual radioactive material. Similarly, concrete core samples are necessary to evaluate the depth of activated concrete in a reactor facility. Note that one type of radiological measurement may be sufficient to determine the extent of residual radioactive material. For example, surface activity measurements alone may be all that is needed to demonstrate that remediation of an area is necessary; exposure rate measurements would add little to this determination.

Lastly, the measuring and sampling techniques should be commensurate with the intended use of the data, as characterization survey data may be used to guide the FSS design or supplement FSS data, provided that the data meet the selected DQOs and the FSS design requirements.

5.2.2.2.2 Land Area Surveys

Characterization surveys for surface and subsurface soils and media involve employing techniques to determine the lateral and vertical extent and concentrations of radioactive material in the soil. They may be performed using either sampling and laboratory analyses or in situ gamma spectrometry analyses, depending on the instrumentation capabilities of each methodology for the expected radionuclides and concentrations. Note that in situ gamma spectrometry analyses or any direct surface measurement cannot easily be used to determine distributions of radionuclides as a function of depth. Sample collection followed by laboratory analysis introduces several additional sources of uncertainty that need to be considered during survey design. In many cases, a combination of direct measurements and samples is required to meet the objectives of the survey.

Concentrations of radioactive material for various radionuclides in background soil samples should be determined for a sufficient number of soil samples that are representative of the soil in terms of soil type, soil depth, and similar factors. It is important that the background samples be collected in non-impacted areas. Consideration should be given to spatial variations in the background radionuclide concentrations as discussed in **Section 4.6** and NRC draft report NUREG-1501, "Background as a Residual Radioactivity Criterion for Decommissioning: Appendix A to the Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities—Draft Report for Comment," issued August 1994 (NRC 1994).

Sample locations should be documented using GPS; reference system coordinates (refer to **Section 4.9.5**), if appropriate; or fixed site features. A typical reference system spacing for open land areas is 10 m (~30 feet) (NRC 1992). This spacing is somewhat arbitrary and is chosen to facilitate determining survey unit locations and identifying areas of elevated concentrations of radioactive material.

Surface scans for gamma radiation should be conducted in areas likely to contain residual radioactive material. Instrumentation selected should be appropriate to detect the radionuclide(s) of interest. Beta scans may be appropriate if the residual radioactive material is near the surface and beta is the dominant radiation emitted from the residual radioactive material. The detection capability and measurement uncertainty of the scanning technique should be appropriate to meet the DQOs and MQOs.

Both systematic and judgment surface activity measurements should be performed. Judgment direct measurements are performed at locations of elevated direct radiation, as identified by surface scans, to provide data on upper ranges of residual radioactive material levels. Judgment measurements may also be performed in areas where radioactive materials might have accrued, such as in swales, under downspouts, and near access roads, if necessary. Each surface activity measurement location should be carefully recorded on the appropriate survey form.

Both surface and subsurface soil and media samples may be necessary. Subsurface soil samples should be collected where residual radioactive material is present on the surface and where residual radioactive material is known or suspected in the subsurface. Boreholes should be constructed to provide samples representing subsurface deposits.

Exposure rate measurements at 1 m (~3 feet) above the sampling location may also be appropriate. Each surface and subsurface soil sampling and measurement location should be carefully recorded.

5.2.2.2.3 Surface Water and Sediments

Surface water and sediment sampling may be necessary, depending on the potential for these media to contain residual radioactive material. This depends on several factors, including the proximity of surface water bodies to the site, size of the drainage area, total annual rainfall, and spatial and temporal variability in surface water flow rate and volume. **Section 3.6.3.3** contains further criteria to determine the necessity for surface water and sediment sampling.

Characterizing surface water involves techniques that determine the extent and distribution of residual radioactive material. This may be performed by collecting grab samples of the surface water in a well-mixed zone. At certain sites, it may be necessary to collect stratified water samples to provide information on the vertical distribution of residual radioactive material. Sediment sampling should also be performed to assess the relationship between the composition of the suspended sediment and the bedload sediment fractions (i.e., suspended sediments compared to deposited sediments). When judgment sampling is used to find radionuclides in sediments, radioactive sediments are more likely to be accumulated on fine-grained deposits found in low-energy environments (e.g., deposited silt on inner curves of streams).

Radionuclide concentrations in background water samples should be determined for a sufficient number of water samples that are upstream of the site or in areas unaffected by site operations. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Sampling locations should be documented using reference system coordinates, if appropriate, or scale drawings of the surface water bodies. Effects of variability of surface water flow rate should be considered. Surface scans for gamma activity may be conducted in areas likely to

contain residual radioactive material (e.g., along the banks) based on the results of the document review or preliminary investigation surveys.

Surface water sampling should be performed in areas of runoff from active operations, at plant outfall locations, upstream and downstream of the outfall, and at any other areas likely to contain residual radioactive material (see **Section 3.6.3.3**). Measurements of radionuclide concentrations in water should include gross alpha and gross beta radioactivity concentration assessments, as well as any necessary radionuclide-specific analyses. Non-radiological parameters—such as specific conductance, pH, and total organic carbon—may be used as surrogate indicators of potential radioactive material, if a specific relationship exists between the radionuclide concentration and the level of the indicator (e.g., if a linear relationship between pH and the radionuclide concentration in water is found to exist, then the pH may be measured such that the radionuclide concentration can be calculated based on the known relationship rather than performing an expensive nuclide-specific analysis). The use of surrogate measurements is discussed in **Section 4.5.3**.

Each surface water and sediment sampling location should be carefully recorded on the appropriate survey form. Additionally, surface water flow models may be used to illustrate radionuclide concentrations and migration rates.

5.2.2.2.4 Groundwater

Groundwater sampling may be necessary, depending on the local geology, potential for residual radioactive material in the subsurface, and the regulatory framework. Because different agencies handle groundwater compliance in different ways (e.g., EPA's Superfund program and some States require compliance with maximum contaminant levels specified in the Safe Drinking Water Act), the regulatory agency should be contacted if residual radioactive material in groundwater is expected. **Section 3.6.3.4** describes the need for groundwater sampling.

If residual radioactive material in groundwater is identified, the regulatory agency should be contacted at once, because (1) groundwater release criteria and DCGLs should be established by the appropriate agency (**Section 4.5.2**), and (2) the default DCGLs for soil may be inappropriate, because they are usually based on groundwater without any residual radioactive material.

Characterization of residual radioactive material in groundwater should determine the extent and distribution of residual radioactive material, rates and direction of groundwater migration, and the assessment of potential effects of groundwater withdrawal on the migration of residual radioactive material in groundwater. This may be performed by designing a suitable monitoring well network. The actual number and location of monitoring wells depends on the size of the affected area, the type and extent of the residual radioactive material, the hydrogeological system, and the objectives of the monitoring program.

When groundwater samples are taken, background radiation levels should be determined by collecting samples from the same aquifer upgradient of the site and then analyzing them. Any tidal effects and effects of additional wells in the upgradient zone on groundwater flow should be evaluated to aid in selecting the proper location of upgradient background samples. The background samples should not be affected by site operations and should be representative of the quality of the groundwater that would exist if the site had not been affected by the residual radioactive material. Consideration should be given to any spatial or temporal variations in the background radionuclide concentrations.

Sampling locations should be referenced to grid coordinates, if appropriate, or to scale drawings of the groundwater monitoring wells. Construction specifications on the monitoring wells should also be provided, including elevation, internal and external dimensions, types of casings, type of screen and its location, borehole diameter, and other necessary information about the wells.

In addition to organic and inorganic constituents, groundwater sampling and analyses should include all significant radiological constituents. Measurements in potential sources of drinking water should include gross alpha and gross beta assessments, as well as any other radionuclide-specific analyses deemed appropriate based on the HSA. Non-radiological parameters—such as specific conductance, pH, and total organic carbon—may be used as surrogate indicators of the potential presence of certain radionuclides, provided that a specific relationship exists between the radionuclide concentration and the level of the indicator.

Each groundwater monitoring well location should be carefully recorded on the appropriate survey form. Additionally, radionuclide concentrations and sources should be plotted on a map to illustrate the relationship among radionuclides, sources, hydrogeological features and boundary conditions, and property boundaries (EPA 1993b).

5.2.2.2.5 Other Media

Air sampling may be necessary at some sites, depending on the local geology and the radionuclides of potential concern. This may include collecting air samples or filtering the air to collect resuspended particulates. Air sampling is often restricted to monitoring activities for occupational and public health and safety, and it is not required to demonstrate compliance with risk- or dose-based regulations. **Section 3.6.3.5** describes examples of sites where air sampling may provide information useful to designing an FSS. At some sites, radon measurements may be used to indicate the presence of radium, thorium, or uranium in the soil. **Section 6.8** and **Appendix H** provide information on this type of sampling.

In rare cases, vegetation samples may be collected as part of a characterization survey to provide information in preparation for an FSS. Because most risk- and dose-based regulations are concerned with potential future land use that may differ from the current land use, vegetation samples are unsuitable for demonstrating compliance with regulations. There is a relationship between radionuclide concentrations in plants and those in soil (the soil-to-plant transfer factor is used in many models to develop DCGLs), and the plant concentration could be used as a surrogate measurement of the soil concentration. In most cases, a measurement of the soil itself as the parameter of interest is more appropriate and introduces less uncertainty in the result.

5.2.2.3 Evaluating Survey Results

Survey data are converted to the same units as those in which DCGLs are expressed (**Section 6.7**). Laboratory and in situ analyses are performed to identify potential residual radioactive material at the site. Appropriate regulatory DCGLs for the site are selected, and the data are then compared to the DCGLs. For characterization data that are used to supplement FSS data, the statistical methodology in **Chapter 8** should be followed to determine whether a survey unit satisfies the release criteria.

For characterization data that are used to help guide remediation efforts, the survey data are used to identify locations and the general extent of residual radioactive material. The survey results are first compared with DCGLs. Surfaces and environmental media are then differentiated as exceeding DCGLs, not exceeding DCGLs, or not affected, depending on the

measurement results relative to the DCGL value. Direct measurements indicating areas of elevated activity are further evaluated, and the need for additional measurements is determined.

5.2.2.4 Documentation

Documentation of the site characterization survey should provide a complete and unambiguous record of the radiological status of the site. In addition, sufficient information to characterize the extent of residual radioactive material, including all possible affected environmental media, should be provided in the report. This report should also provide sufficient information to support reasonable approaches or alternatives to site remediation. **Example 5-2** presents an example of a characterization survey checklist.

Example 5-2: Example Characterization Survey Checklist

Survey Design

- _____ Enumerate Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs): State the objective of the survey; survey instrumentation capabilities should be appropriate for the specific survey objective.
- _____ Review the Historical Site Assessment and scoping survey results, if performed, for the following:
 - _____ Operational history (e.g., any problems, spills, or releases) and available documentation (e.g., radioactive materials license).
 - _____ Other available resources—site personnel, former workers, residents, etc.
 - _____ Types and quantities of radioactive materials that were handled and where radioactive materials were stored, handled, and disposed of.
 - _____ Release and migration pathways.
 - _____ Information on the potential for residual radioactive material that may be useful during area classification for final status survey (FSS) design. Note: Survey activities will be concentrated in Class 1 and Class 2 areas.
 - _____ Types and quantities of materials likely to remain on site—consider radioactive decay and ingrowth of decay products.
 - _____ Document the survey plan (e.g., Quality Assurance Project Plan, standard operating procedures).

Conducting Surveys

- _____ Select instrumentation based on its capabilities for the expected residual radioactive material and quantities and knowledge of the appropriate derived concentration guideline levels (DCGLs).

- _____ Define background locations and determine background activity and radiation levels for the area; include surface activity levels on building surfaces, radionuclide concentrations in environmental media, and exposure rates.
 - _____ Establish a reference coordinate system. Prepare scale drawings for surface water and groundwater monitoring well locations.
 - _____ Perform thorough surface scans of all areas potentially containing residual radioactive material. Examples of indoor areas include expansion joints, stress cracks, penetrations into floors and walls for piping, conduits, anchor bolts, and wall/floor interfaces. Examples of outdoor areas include radioactive material storage areas, areas downwind of stack release points, dripline and downspout areas, surface drainage pathways, and roadways that may have been used for transport of radioactive materials.
 - _____ Perform systematic surface activity measurements.
 - _____ Perform systematic smear, surface and subsurface soil and media, sediment, surface water, and groundwater sampling, if appropriate for the site.
 - _____ Perform judgment direct measurements and sampling of elevated areas to provide data on the upper ranges of levels of the concentration of radioactive material.
 - _____ Document survey and sampling locations.
 - _____ Maintain chain of custody of samples when necessary.
- Note:* One category of radiological data (e.g., radionuclide concentration, direct radiation level, surface radioactivity) may be sufficient to determine the extent of residual radioactive material; other measurements may not be necessary (e.g., removable surface radioactive material, exposure rate measurements).
- Note:* Measuring and sampling techniques should be commensurate with the intended use of the data, because characterization survey data may be used to supplement FSS data.

Evaluating Survey Results

- _____ Compare survey results with DCGLs. Differentiate surfaces or areas as exceeding DCGLs, not exceeding DCGLs, or not affected.
- _____ Evaluate all locations of elevated direct measurements and determine the need for additional measurements or samples.
- _____ Prepare site characterization survey report.

5.2.3 Remedial Action Support Surveys

RAS surveys are conducted to (1) support remediation activities, (2) determine when a site or survey unit is ready for the FSS, and (3) provide updated estimates of site-specific parameters to use for planning the FSS. This manual does not discuss the routine operational surveys

(e.g., air sampling, dose rate measurements, environmental sampling) conducted for health and safety purposes to support remediation activities.

A RAS survey serves to monitor the effectiveness of remediation efforts to reduce residual radioactive material to acceptable levels. The RAS survey also ensures that remediation is targeted to only those areas requiring remediation, which in turn ensures a cost-effective remediation. This type of survey guides the cleanup in a real-time mode. The RAS survey typically relies on a simple radiological parameter, such as direct radiation near the surface, as an indicator of effectiveness. The investigation level for the RAS survey (established as the DCGL) is determined and used for immediate, in-field decisions (**Section 5.3.8**).

Such a survey is intended for expediency and cost-effectiveness and does not provide thorough or accurate data describing the radiological status of the site. Note that this survey typically does not provide information that can be used to demonstrate compliance with the DCGLs; rather, it is an interim step in the compliance demonstration process. Areas that are determined likely to satisfy the DCGLs on the basis of the RAS survey will then be surveyed in detail by the FSS. Alternatively, the RAS survey can be designed to meet the objectives of an FSS as described in **Section 5.3**.

Remedial activities result in changes to the distribution of residual radioactive material within a survey unit. The site-specific parameters used during FSS planning (e.g., variability in the radionuclide concentration within a survey unit, the probability of small areas of elevated activity) will change during remediation. For most survey units, values for these parameters will need to be re-established following remediation. Obtaining updated values for these critical planning parameters should be considered when designing a RAS survey.

5.2.3.1 *Survey Design*

The objective of the RAS survey is to determine whether remediation was adequate to remove radioactive material to levels at or below the DCGL criteria. Although the presence of small areas of elevated concentrations of radioactive material may satisfy the elevated measurement criteria, it may be more efficient to design the RAS survey to identify residual radioactive material at the radionuclide-specific release limit based on the spatial distribution of the radionuclide within a survey unit (DCGL for average concentrations over a wide area [DCGL_w]) and to remediate small areas of elevated concentrations of radioactive material that may potentially satisfy the release criteria. Survey instrumentation and techniques are therefore selected based on the instrumentation capabilities for the known or suspected radionuclides and DCGLs to be achieved.

There will be radionuclides and media that cannot be evaluated at the DCGL_w using field monitoring techniques. For these cases, it may be feasible to collect and analyze samples by methods that are quicker and less costly than radionuclide-specific laboratory procedures. Field laboratories and screening techniques may be acceptable alternatives to more expensive analyses. Reviewing remediation plans may be required to get an indication of the location and amount of residual radioactive material remaining following remediation.

5.2.3.2 *Conducting Surveys*

Field survey instruments and procedures are selected based on their ability to detect and quantify the expected radionuclides. Survey methods typically include scans of surfaces followed by direct measurements to identify residual radioactive material. The surface activity

levels are compared to the investigation levels, and a determination is made on the need for further remediation efforts.

Survey activities for soil excavations include surface scans using field instrumentation sensitive to beta and gamma activity. Because it can be difficult to correlate scanning results to radionuclide concentrations in soil, judgment should be exercised carefully when using scan results to guide the cleanup efforts. Field laboratories and screening techniques may provide a better approach for determining whether further soil remediation is necessary.

5.2.3.3 *Evaluating Survey Results*

Survey data (e.g., surface activity levels and radionuclide concentrations in various media) are converted to standard units and compared to the DCGLs (**Section 6.7**). If results of these survey activities indicate that remediation has been successful in meeting the DCGLs, remedial actions are ceased, and FSS activities are initiated. Alternatively, further remediation may be needed if results indicate the presence of residual radioactive material in excess of the DCGLs.

DCGLs may be recalculated based on the results of the remediation process as the regulatory program allows or permits.

5.2.3.4 *Documentation*

The RAS survey should guide the cleanup and alert those performing remedial activities that (1) additional remediation is needed or (2) the site may be ready to initiate an FSS. Data that indicate an area has been successfully remediated could be used to estimate the variance for the survey units in that area. Information identifying areas of elevated activity that existed before remediation may be useful for planning FSSs. **Example 5-3** presents an example of a RAS survey checklist, including survey design, conduct of surveys, and evaluation of survey results.

Example 5-3: Example Remedial Action Support Survey Checklist

Survey Design

_____ Enumerate Data Quality Objectives and Measurement Quality Objectives: State the objectives of the survey; survey instrumentation capabilities should be appropriate for the specific survey objective.

_____ Document the survey plan (e.g., Quality Assurance Project Plan, standard operating procedures).

_____ Review the remediation plans.

_____ Determine applicability of monitoring surfaces/soils for the radionuclides of concern.

Note: Remedial action support surveys may not be feasible for residual radioactive materials with very low-energy beta emitters or for soils or media containing pure alpha emitters.

_____ Select simple radiological parameters (e.g., surface activity) that can be used to make immediate in-field decisions on the effectiveness of the remedial action.

Conducting Surveys

- _____ Select instrumentation based on its capabilities for measuring the expected radionuclides.
- _____ Perform scanning and surface activity measurements near the surface being remediated.
- _____ Survey soil excavations and perform field evaluation of samples (e.g., gamma spectrometry of undried/non-homogenized soil) as remedial actions progress.

Evaluating Survey Results

- _____ Compare survey results with derived concentration guideline levels using survey data as a field decision tool to guide the remedial actions in a real-time mode.
- _____ Document survey results.

5.3 Final Status Surveys

An FSS is performed to demonstrate that residual radioactive material in each survey unit satisfies the predetermined criteria for release for unrestricted use or, where appropriate, for use with designated limitations. The survey provides data to demonstrate that all radiological parameters do not exceed the established DCGLs. For these reasons, more detailed information is provided for this category of survey. For the FSS, survey units represent the fundamental elements for demonstrating that the property meets the release criteria by using a combination of direct measurements or sampling and scanning (see **Sections 5.3.3–5.3.5**) or by a site-specific scanning survey of the property (if warranted by the scanning instrumentation detection capability and measurement uncertainty; see **Section 5.3.6**). The percentage of the area scanned is dependent upon the classification of the property or survey units within the site as well as the relative shift for the survey unit. The documentation specified in the following sections helps ensure a consistent approach among different organizations and regulatory agencies. This allows for comparisons of survey results among sites or facilities.

The MARSSIM approach recognizes that alternative methods may be acceptable to different regulatory agencies. This section includes flow diagrams and a checklist to assist the user in planning a survey.

Figure 5-4 through **Figure 5-6** illustrate the process of designing an FSS. This process begins with development of DQOs and MQOs. The first decision after developing the DQOs and MQOs is to establish whether a site-specific scanning survey or traditional MARSSIM approach (scanning with direct measurements and/or samples) will be used. Based on these objectives and the known or anticipated radiological conditions at the site, the numbers and locations of measurement and sampling points used and amount of scanning to demonstrate compliance with the release criteria are then determined. Finally, survey techniques appropriate to develop adequate data (see **Chapters 6 and 7**) are selected and implemented.

The elements of an FSS discussed in **Section 5.3** consist of the following subsections:

- selecting either Scenario A or Scenario B as a basis of the survey design (**Section 5.3.1**)
- selecting the appropriate statistical test based on whether radionuclides of concern are present in the background (**Section 5.3.2**)
- determining the appropriate number of data points for statistical tests when residual radioactive materials are present in the background (**Section 5.3.3**)
- determining the appropriate number of data points for statistical tests when residual radioactive materials are not present in the background (**Section 5.3.4**)
- establishing procedures for determining the number of data points for small areas of elevated concentration of radioactive material (**Section 5.3.5**)
- determining the scan area (**Section 5.3.6**)
- determining the survey locations (**Section 5.3.7**)
- establishing the appropriate investigation level for a survey (**Section 5.3.8**)
- developing an integrated survey design (**Section 5.3.9**)
- evaluating the survey results (**Section 5.3.10**)
- documenting the results (**Section 5.3.11**)

Another important consideration during planning for an FSS is the performance of confirmatory surveys. Planning for the FSS should include early discussions with the regulatory agency concerning logistics for confirmatory or verification surveys. A confirmatory survey (also known as an independent verification survey) may be performed by the regulatory agency or by an independent third party (e.g., a party contracted by the regulatory agency) to provide data to substantiate results of the FSS. Additional field measurements and sampling may be performed.

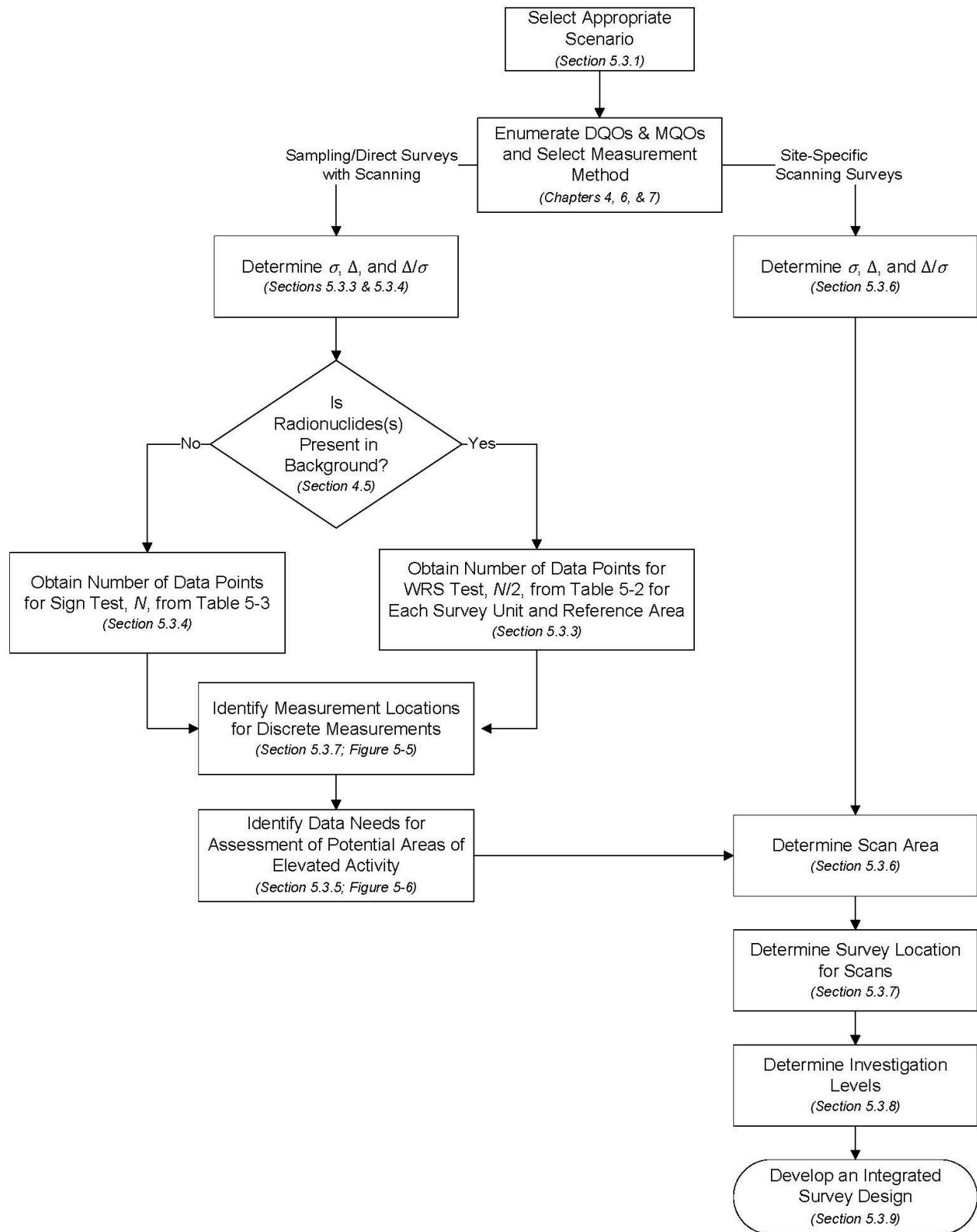


Figure 5-4 Process for Designing an Integrated Survey Plan for an FSS

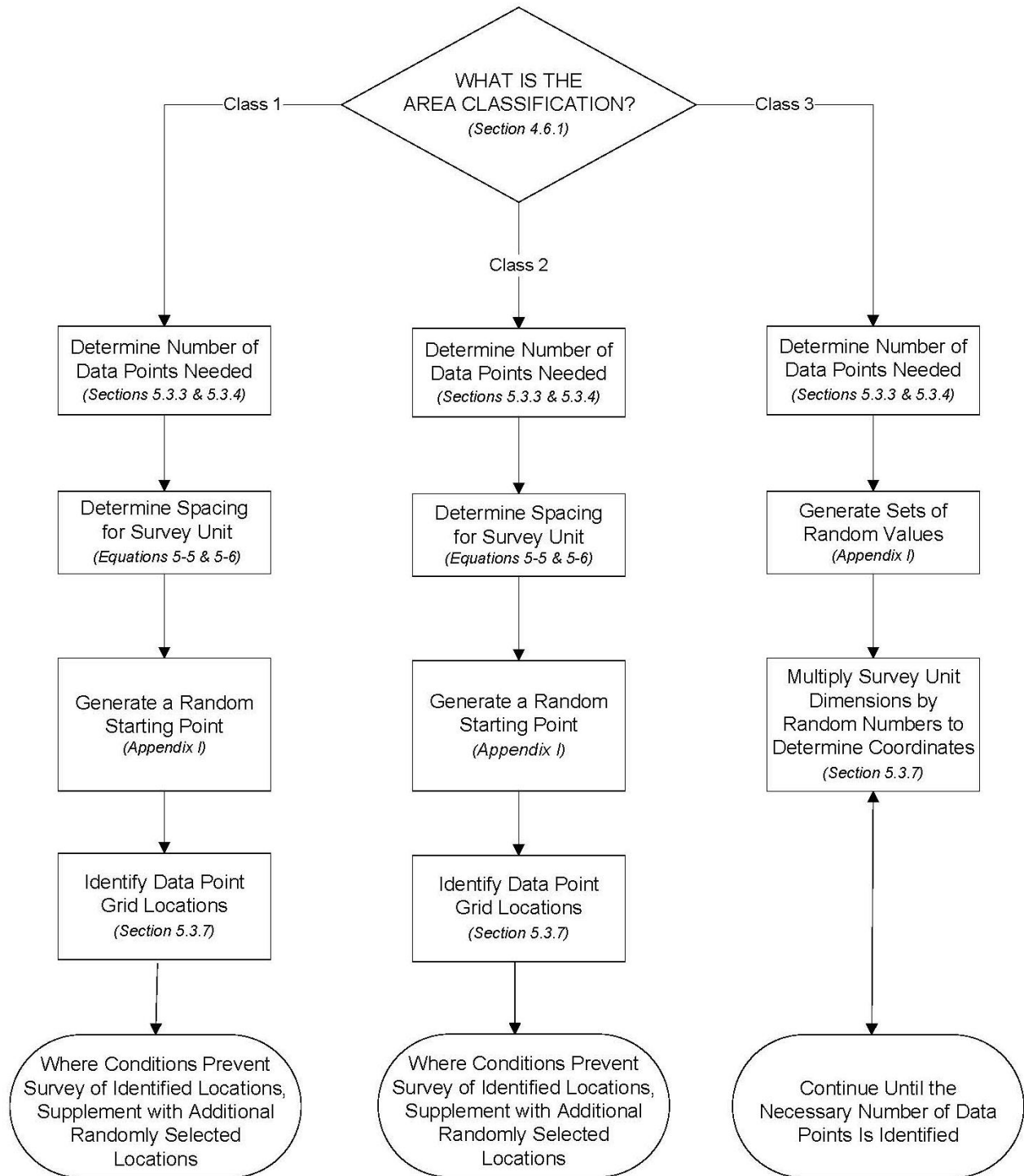


Figure 5-5 Process for Identifying Discrete Measurement Locations Based on Area Classification

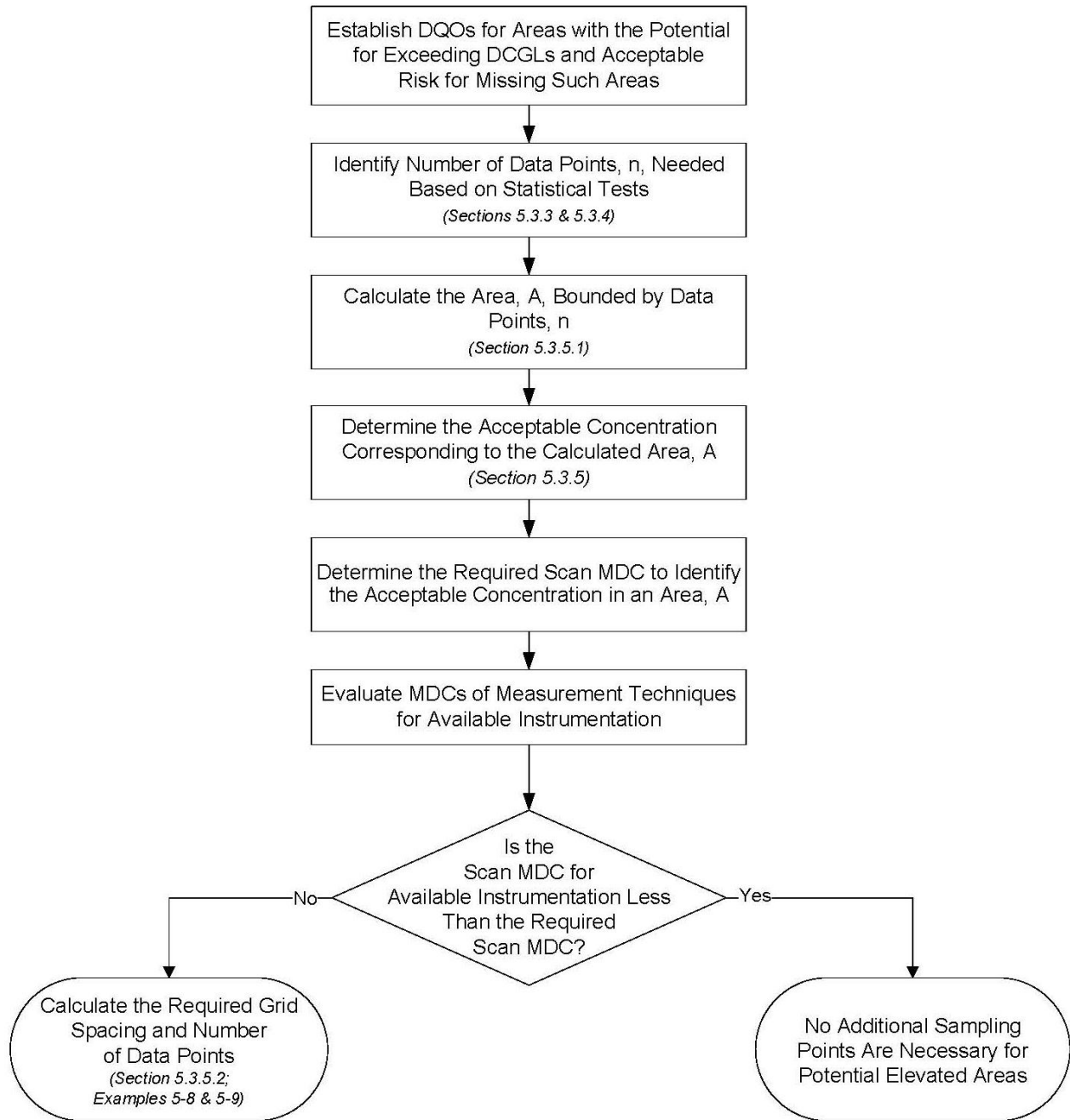


Figure 5-6 Identifying Data Needs for Assessment of Potential Areas of Elevated Activity in Class 1 Survey Units

Independent confirmatory survey activities are usually limited in scope to spot-checking conditions at selected locations, comparing findings with those of the FSS, and performing independent statistical evaluations of the data developed from the confirmatory survey and the FSS. Another purpose of the confirmatory activities may be to identify any deficiencies in the FSS documentation based on a thorough review of survey procedures and results. Finally, reviewing the results of confirmatory surveys performed on other survey units or other sites may

provide insight into possible survey deficiencies, which can then be corrected before the FSS is performed (Bailey 2008).

5.3.1 Selecting the Appropriate Scenario

The DQO process, as it is applied to FSSs, is described in more detail in **Appendix D** to this manual and in EPA and NRC guidance documents (EPA 1987b, 1987c, 2006c; NRC 1998a). As part of this process, the objective of the survey and the null and alternative hypotheses should be clearly stated. The objective of FSSs is typically to demonstrate that residual radioactive material levels meet the release criteria. One of two approaches is used to demonstrate that this objective is met; the two approaches differ in the selection of the null hypothesis (i.e., what is assumed to be the true state of nature in the absence of sufficient evidence to the contrary), as summarized in **Table 5-1**.

Table 5-1 Null and Alternative Hypothesis for Scenarios A and B

Scenario	Null Hypothesis (H_0)	Alternative Hypothesis (H_1)
A	The concentration of residual radioactive material is equal to or exceeds the release criteria.	The concentration of residual radioactive material is less than the release criteria.
B	The concentration of residual radioactive material is equal to or less than the release criteria.	The concentration of residual radioactive material exceeds the release criteria.

Historically, MARSSIM recommended the use of Scenario A, which put the burden of proof that the survey unit met the release criteria on the individuals designing the survey. However, Scenario A requires that survey designers choose a discrimination limit (DL), the lower bound of the gray region (LBGR), at some radioactive material concentration less than the $DCGL_w$. This is effectively impossible when the action level (AL) corresponding to the release criteria is “zero residual radioactive material” or “zero residual radioactive material above background.” The only way to design a survey for these kinds of release criteria is to establish a DL at some radioactive material concentration greater than the AL.

In Scenario B, the burden of proof is no longer on the individuals designing the survey and, thus, should be used with caution and only in those situations for which Scenario A is not an effective alternative. The consequence of inadequate power is an increased Type II decision error (β) rate. For Scenario A, this means that a survey unit that does meet the release criteria has a higher probability of being incorrectly determined not to meet the release criteria. For Scenario B, this means that a survey unit that does not meet the release criteria has a higher probability of being incorrectly determined to meet the release criteria. For this reason, individuals designing a MARSSIM survey using Scenario B should make conservative assumptions for the estimate of the standard deviation (σ) (see **Section 5.3.3.2**) so that even if the variability in the survey unit is higher than expected, the power of the resulting survey ($1-\beta$) (see **Section 5.3.2**) will still be sufficient to ensure that survey units with residual radioactive material in excess of the AL will be discovered with a probability of $1-\beta$. As a result, a retrospective power analysis needs to be performed following the completion of Scenario B MARSSIM surveys indicating that regulatory agency requirements on β at the DL were met. **Chapter 8** and **Appendix M** contain more information on performing a retrospective power analysis.

5.3.2 Selecting the Appropriate Statistical Test

The choice of statistical test(s) used to evaluate data for FSSs in which direct measurements or sampling and analysis are performed depends on the scenario selected. For radionuclides that are present in background, the Wilcoxon Rank Sum (WRS) test is typically used in Scenario A. In Scenario B, two nonparametric statistical tests are performed: the WRS test and the Quantile test. The WRS and Quantile tests are both used because each test detects different residual radioactive material patterns in the survey unit. When radionuclides of concern are not present in background, the Sign test is used for both scenarios. For site-specific scanning surveys, a comparison to an upper confidence limit is performed. The Sign, WRS, upper confidence limit, and Quantile tests are discussed in **Chapter 8**.

To determine data needs for these tests, the acceptable probability of making Type I decision errors (α) and Type II decision errors (β) should be established (see **Appendix D, Section D.1.6**). The acceptable decision error rates are defined at the LBGR and the DCGL_W for Scenario A and the AL and the DL for Scenario B. Acceptable decision error rates are determined during survey planning using the DQO process.

The final step of the DQO process includes selecting a survey design that satisfies the DQOs. For some sites or survey units, the information provided in this section may result in a survey design that cannot be accomplished with the available resources. For these situations, the planning team may be able to relax one or more of the constraints used to develop the survey design as described in **Appendix D**. For example, the planners may do one of the following:

- increase the decision error rates, considering the risks associated with making an incorrect decision
- increase the width of the gray region, as long as the LBGR is not set lower than the estimate of the residual radioactive material remaining in the survey unit in Scenario A
- change the boundaries in order to reduce measurement costs by changing or eliminating survey units that may require different decisions

5.3.3 Determining Numbers of Data Points for Statistical Tests for Residual Radioactive Material Present in Background

The comparison of measurements from the reference area and survey unit is made using the WRS test, which is usually conducted for each survey unit. In addition, the elevated measurement comparison (EMC) may need to be performed against each measurement to ensure that the measurement result does not exceed a specified investigation level. If any measurement in the remediated survey unit exceeds the specified investigation level, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactive material is uniformly present throughout a survey unit. The test is designed to detect whether the median concentration exceeds the DCGL_W. The advantage of this nonparametric test is that it does not assume the data are normally or log-normally distributed. The WRS test also allows for “less than” measurements to be present in the reference area and the survey units. This test can generally be used with up to 40 percent “less than” measurements in either the reference area or the survey unit. However, the use of “less than” values in data reporting is not recommended (NRC

2004). Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

This section introduces several terms and statistical parameters that will be used to determine the number of data points needed to apply the nonparametric tests. An example is provided below to better illustrate the application of these statistical concepts.

5.3.3.1 Define the Gray Region

In Scenario A, the upper bound of the gray region (UBGR) is equal to the $DCGL_W$. The gray region is defined as the interval between the LBGR and the $DCGL_W$ (**Figure 5-7**).

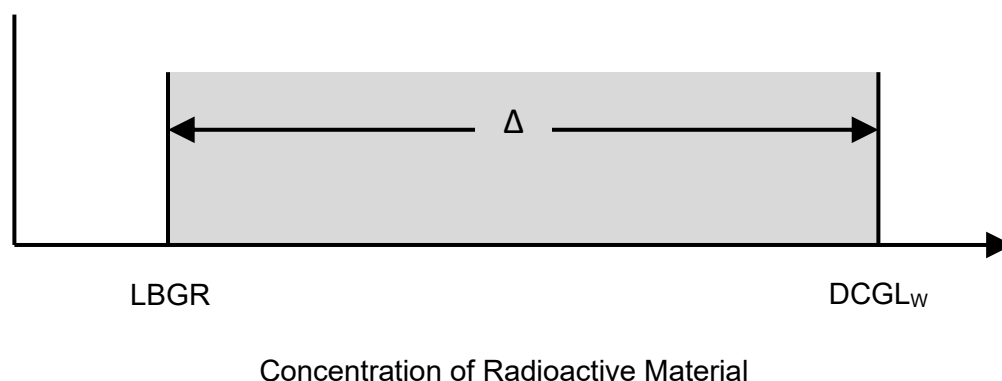


Figure 5-7 Gray Region for Scenario A

In Scenario A, the LBGR is the concentration at which the Type II error rate (β) is set. It is less than the $DCGL_W$ and is chosen by the survey designer at or above an estimate of the concentration of residual radioactive material in the survey unit. Ideally, the LBGR should be easily distinguishable from the $DCGL_W$, otherwise, the number of measurements required for the survey may be very large.

Choosing the LBGR is an iterative process, illustrated in **Example 5-4**, that starts with setting the LBGR at or above the median or mean concentration of residual radioactive material estimated to be remaining in the survey unit. If the true, but unknown, concentration in the survey unit is in the grey region, there will be difficulty in determining whether the survey unit concentration is less than the $DCGL_W$. The following should be taken into account when choosing the LBGR:

- variability of the concentrations in the survey unit (determined from prior surveys of the survey unit)
- variability in the measurements due to instrumentation at the candidate values for the LBGR
- probability that a survey unit could fail even though the concentration of residual radioactive material is, in fact, less than the $DCGL_W$

- costs of measurements at the sensitivities needed to measure the candidate values for the LBGR

The trade-offs between increased instrument sensitivity, costs, and the number of data points needed should be optimized. Setting the LBGR so the relative shift (Image) is between 1.0 and 3.0 will often result in a survey design that is adequate and cost effective (refer to **Section 5.3.3.2** for more information).

When no other information is available, MARSSIM suggests a default value for the LBGR equal to half the $DCGL_W$. After doing so, the iterative process should begin as more information about the survey unit becomes available.

Example 5-4: Determining and Using the LBGR

A Class 2 survey unit has only cesium-137 residual radioactive material. Following scoping and characterization surveys, the information in the table was generated to support hypothesis testing and sampling size.

Data-Generated Results	Project Criteria
Mean = 12.0 pCi/g	$DCGL_W = 15$ pCi/g
Median = 9.5 pCi/g	Beta (Type II error) = 0.25
$\sigma = 5.0$ pCi/g	Alpha (Type I error) = 0.05
Mode = 10	LBGR = ?

What LBGR would you recommend to the project team, and how many samples would be collected in the survey unit to satisfy the project criteria?

Determine LBGR:

Based on characterization survey information in the table, set the LBGR value to 9.5 picocuries per gram (pCi/g) (the median).

Determine Relative Shift (Δ/σ):

$$\Delta = DCGLW - LBGR = 15 \text{ pCi/g} - 9.5 \text{ pCi/g} = 5.5 \text{ pCi/g}$$

$$(\Delta/\sigma) = 5.5 \text{ pCi/g} / 5.0 \text{ pCi/g} = 1.1$$

In Scenario B, the UBGR is equal to the DL, and the LBGR is equal to the AL. The gray region is defined as the interval between the AL and the DL (**Figure 5-8**).⁵ The AL is the concentration of radioactive material that causes a decision-maker to choose one of the alternative actions, such as releasing a survey unit or requiring additional investigation. The planning team also chooses the DL. The DL is the concentration of radioactive material or level of radioactivity that can be reliably distinguished from the AL by performing measurements with the devices selected for the survey (e.g., direct measurements, scans, in situ measurements, samples with laboratory analyses) and defines the rigor of the survey. It is determined through negotiations with the regulator, and, in some cases, the DL will be set equal to a regulatory limit (e.g., Title 10 of the *Code of Federal Regulations* [10 CFR] 36.57, “Radiation Surveys,” and DOE 2011c). The DL and the AL should be reported in the same units. The selection of the appropriate null hypothesis is further discussed in **Chapter 8** and **Appendix D**.

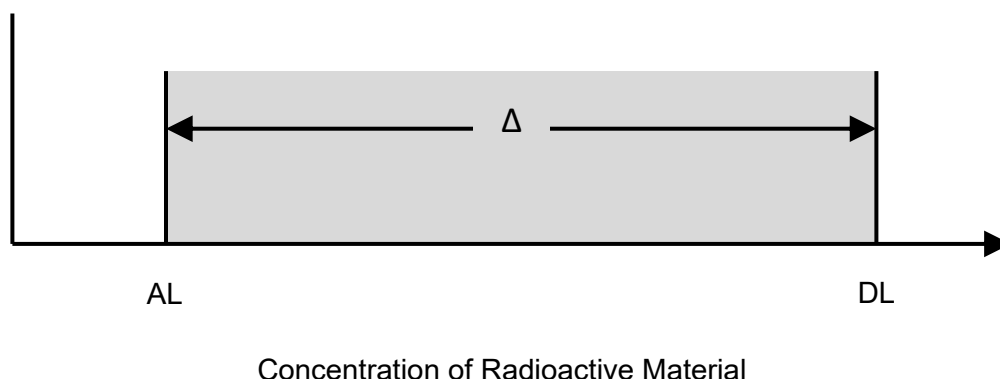


Figure 5-8 Gray Region for Scenario B

When Scenario B is being used, the variability in the data may be such that a decision may be “too close to call” when the true but unknown value of the residual radioactivity concentration is very near the DL. In this situation, consultation with the appropriate regulator may be required to determine the AL and DL. As an example, the NRC discusses methods in NUREG-1505, Revision 1, Chapter 13, to establish the gray region and a concentration level that is considered indistinguishable from background when the WRS test is used.⁶

5.3.3.2 Calculate the Relative Shift

The width of the gray region is a parameter that is essential for planning all statistical tests; it is also referred to as the shift, Δ . In Scenario A, the shift is the difference between the LBGR and the DCGL_W ($\Delta = \text{DCGL}_W - \text{LBGR}$). In Scenario B, the shift is the difference between the AL and the DL ($\Delta = \text{DL} - \text{AL}$). The absolute size of the shift is less important than the relative shift, Δ/σ , where σ is an estimate of the standard deviation of the measured values in the survey unit. This

⁵ This description of Scenario B is based on information contained in the Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME) (NRC 2009) and the Multi-Agency Radiation Laboratory Analytical Protocols Manual (MARLAP) (NRC 2004) and is fundamentally different from the description of Scenario B found in NUREG-1505, Revision 1, “A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys: Interim Draft Report for Use and Comment,” issued June 1998 (NRC 1998a).

⁶ Chapter 8 in NUREG-1505, Revision 1, provides additional information on the WRS test.

estimate of σ includes both the real spatial variability in the quantity being measured and the uncertainty of the chosen measurement method. The relative shift is an expression of the resolution of the measurements in units of measurement uncertainty.

The shift and the estimated standard deviation in the measurements of the radioactive material in the survey unit (σ_s) and reference area (σ_r) are used to calculate the relative shift (Δ/σ) (see **Appendix D, Section D.1.6.3**). The standard deviations in the radionuclide level will likely be available from previous systematic and non-judgment survey data (e.g., scoping or characterization survey data for unremediated survey units or RAS surveys for remediated survey units). If they are not available, it may be necessary to (1) perform some limited preliminary measurements (about 5–20) to estimate the distributions or (2) make a reasonable estimate based on available site knowledge. If the first approach above is used, the scoping or characterization survey data or preliminary measurements used to estimate the standard deviation should use the same technique as the FSS will. When preliminary data are not obtained, it may be reasonable to assume a coefficient of variation (CV) on the order of 30 percent, based on experience. The CV is a measure of the dispersion of the data and is defined by the ratio of the standard deviation to the mean.

The value selected as an estimate of σ for a survey unit may be based on data collected only from within that survey unit or from data collected from a much larger area of the site. Note that survey units are not finalized until the planning stage of the FSS. This means that there may be some difficulty in determining which individual measurements from a preliminary survey may later represent a particular survey unit. For many sites, the most practical solution is to estimate σ for each area classification (i.e., Class 1, Class 2, and Class 3) for both interior and exterior survey units. This will result in all exterior Class 3 survey units using the same estimate of σ , all exterior Class 2 survey units using a second estimate for σ , and all exterior Class 1 survey units using a third estimate for σ . If there are multiple types of surfaces within an area classification, additional estimates of σ may be required. For example, a Class 2 concrete floor may require a different estimate of σ than a Class 2 cinder block wall, or a Class 3 unpaved parking area may require a different estimate of σ than a Class 3 lawn. In addition, a separate estimate of σ should be obtained for every reference area.

The importance of choosing appropriate values for σ_r and σ_s must be emphasized. If the value is grossly underestimated, the number of data points will be too few to obtain the desired power level for the test, and a resurvey may be recommended (see **Chapter 8**). If, on the other hand, the value is overestimated, the number of data points determined will be unnecessarily large.

Values for the relative shift that are less than 1 will result in a large number of measurements needed to demonstrate compliance. The number of data points will also increase as Δ becomes smaller. Because the DCGL is fixed, this means that the LBGR also has a significant effect on the estimated number of measurements needed to demonstrate compliance in Scenario A. The DL selected during the DQO process will have a similar effect in Scenario B. When the estimated standard deviations in the reference area and survey units are different, the larger value should be used to calculate the relative shift (Δ/σ). There is little benefit, in terms of reduced number of measurements, for relative shift values greater than 3. Because of this and the large number of measurements resulting from relative shift values less than 1, in Scenario A, the LBGR may be adjusted to ensure the relative shift is greater than 1, as long as the LBGR is not set lower than the estimate of the residual radioactive material remaining in the survey unit. For Scenario B, the planning team may wish to adjust the DL to achieve a similar effect with approval from the regulator. However, it is extremely important that such adjustments

be supported by data. Additional considerations related to adjusting the relative shift are provided in **Appendix D, Section D.1.6.3**.

In practice, the DQO process is used to obtain a proper balance among the use of various measurement techniques. In general, there is an inverse correlation between the cost of a specific measurement method and the detection levels being sought. Depending on the survey objectives, there are many important considerations when selecting a measurement method that will ultimately affect both the survey costs and the statistical power of the sampling design. Statistical power is defined as the probability that a statistical test will correctly reject the null hypothesis when it is not true (i.e., under Scenario A, rejecting that a survey unit does not meet the release criteria when it truly does, and under Scenario B, rejecting that a survey unit does meet the release criteria when it truly does not). A general example approach that might be undertaken for a Scenario A planning session is discussed below.

N is the total number of data points for each survey unit/reference area combination. The N data points are divided between the survey unit, n , and the reference area, m . The simplest method for distributing the N data points is to assign half the data points to the survey unit and half to the reference area, so $n = m = N/2$. This means that $N/2$ measurements are performed in each survey unit, and $N/2$ measurements are performed in each reference area. If more than one survey unit is associated with a particular reference area, $N/2$ measurements should be performed in each survey unit, and $N/2$ measurements should be performed in the reference area.

Table 5-2 provides a list of the number of data points needed to demonstrate compliance using the WRS test for selected values of α , β , and Δ/σ . The values listed in **Table 5-2** represent the number of measurements to be performed in each survey unit and in the corresponding reference area. These values were calculated using **Equation N-1** in **Appendix N** and increased by 20 percent to account for missing or unusable data and uncertainty in the calculated value of N . If the calculated value falls in between two lines on the table, the lower number should be used to be conservative. In addition, if values above 3.0 are calculated, the line for 3.0 can be used to determine the number of measurements because the numbers do not change significantly above 3. **Example 5-5** illustrates the use of the WRS test under Scenario A.

Example 5-5: Use of WRS Test under Scenario A

A site has 14 survey units and 1 reference area in a building, and the same measurement method is used to perform measurements in each survey unit and the reference area. The radionuclide has a $DCGL_w$ of 400 Bq/m² (240 disintegrations per minute [dpm]/100 square centimeters [cm²]). The radionuclide is present in background at a level of 100 ± 15 Bq/m² (1σ). The standard deviation of the radionuclide in the survey area is ± 40 Bq/m² (24 dpm/100 cm²), based on previous survey results for the same or similar radionuclide distribution. When the estimated standard deviation in the reference area and the survey units is different, the larger value, 40 Bq/m² in this example, is used to calculate the relative shift. During the DQO process, Scenario A is selected. The LBGR is selected to be 240 Bq/m². This is based on a conservative estimate of the concentration of residual radioactive material in the survey unit. Type I and Type II error values (α and β) of 0.05 are selected. Determine the number of data points to be obtained from the reference area and from each of the survey units for the statistical tests.

The value of the relative shift for the survey unit, Δ/σ , is $(400 - 240)/40$, or 4.0. The number of data points can be obtained directly from **Table 5-2**. For $\alpha = 0.05$, $\beta = 0.05$, and $\Delta/\sigma = 4.0$, a value of 10 is obtained for $N/2$. The table value has already been increased by 20 percent to account for missing or unusable data.

Example 5-6 illustrates the use of the WRS test under Scenario B.

Example 5-6: Use of WRS Test under Scenario B

A site has 14 survey units and 1 reference area in a building, and the same measurement method is used to perform measurements in each survey unit and the reference area. The radionuclide is present in background at a level of $100 \pm 15 \text{ Bq/m}^2$ (1σ). The standard deviation of the radionuclide in the survey area is 40 Bq/m^2 , based on previous survey results for the same or similar radionuclide distribution. When the estimated standard deviation in the reference area and the survey units is different, the larger value, 40 Bq/m^2 in this example, should be used to calculate the relative shift. During the DQO process, Scenario B is selected because the release criterion for the site is no residual radioactive material above background. The discrimination limit is selected to be 220 Bq/m^2 as a stakeholder agreed-upon starting point for developing an acceptable survey design, and Type I and Type II error values (α and β) of 0.05 are selected. Determine the number of data points to be obtained from the reference area and from each of the survey units for the statistical tests.

The value of the relative shift for the reference area, Δ/σ , is $(220 - 100)/40$, or 3.0. The number of data points can be obtained directly from **Table 5-2**. For $\alpha = 0.05$, $\beta = 0.05$, and $\Delta/\sigma = 3.0$, a value of 10 is obtained for $N/2$. The table value has already been increased by 20 percent to account for missing or unusable data.

Table 5-2 Values of $N/2$ for Use with the WRS Test

Δ/σ	$\alpha = 0.01$					$\alpha = 0.025$					$\alpha = 0.05$					$\alpha = 0.10$					$\alpha = 0.25$				
	β					β					β					β					β				
	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25
0.1	5,452	4,627	3,972	3,278	2,268	4,627	3,870	3,273	2,646	1,748	3,972	3,273	2,726	2,157	1,355	3,278	2,646	2,157	1,655	964	2,268	1,748	1,355	964	459
0.2	1,370	1,163	998	824	570	1,163	973	823	665	440	998	823	685	542	341	824	665	542	416	243	570	440	341	243	116
0.3	614	521	448	370	256	521	436	369	298	197	448	369	307	243	153	370	298	243	187	109	256	197	153	109	52
0.4	350	297	255	211	146	297	248	210	170	112	255	210	175	139	87	211	170	139	106	62	146	112	87	62	30
0.5	227	193	166	137	95	193	162	137	111	73	166	137	114	90	57	137	111	90	69	41	95	73	57	41	20
0.6	161	137	117	97	67	137	114	97	78	52	117	97	81	64	40	97	78	64	49	29	67	52	40	29	14
0.7	121	103	88	73	51	103	86	73	59	39	88	73	61	48	30	73	59	48	37	22	51	39	30	22	11
0.8	95	81	69	57	40	81	68	57	46	31	69	57	48	38	24	57	46	38	29	17	40	31	24	17	8
0.9	77	66	56	47	32	66	55	46	38	25	56	46	39	31	20	47	38	31	24	14	32	25	20	14	7
1.0	64	55	47	39	27	55	46	39	32	21	47	39	32	26	16	39	32	26	20	12	27	21	16	12	6
1.1	55	47	40	33	23	47	39	33	27	18	40	33	28	22	14	33	27	22	17	10	23	18	14	10	5
1.2	48	41	35	29	20	41	34	29	24	16	35	29	24	19	12	29	24	19	15	9	20	16	12	9	4
1.3	43	36	31	26	18	36	30	26	21	14	31	26	22	17	11	26	21	17	13	8	18	14	11	8	4
1.4	38	32	28	23	16	32	27	23	19	13	28	23	19	15	10	23	19	15	12	7	16	13	10	7	4
1.5	35	30	25	21	15	30	25	21	17	11	25	21	18	14	9	21	17	14	11	7	15	11	9	7	3
1.6	32	27	23	19	14	27	23	19	16	11	23	19	16	13	8	19	16	13	10	6	14	11	8	6	3
1.7	30	25	22	18	13	25	21	18	15	10	22	18	15	12	8	18	15	12	9	6	13	10	8	6	3
1.8	28	24	20	17	12	24	20	17	14	9	20	17	14	11	7	17	14	11	9	5	12	9	7	5	3
1.9	26	22	19	16	11	22	19	16	13	9	19	16	13	11	7	16	13	11	8	5	11	9	7	5	3
2.0	25	21	18	15	11	21	18	15	12	8	18	15	13	10	7	15	12	10	8	5	11	8	7	5	3
2.25	22	19	16	14	10	19	16	14	11	8	16	14	11	9	6	14	11	9	7	4	10	8	6	4	2
2.5	21	18	15	13	9	18	15	13	10	7	15	13	11	9	6	13	10	9	7	4	9	7	6	4	2
2.75	20	17	15	12	9	17	14	12	10	7	15	12	10	8	5	12	10	8	6	4	9	7	5	4	2
3.0	19	16	14	12	8	16	14	12	10	6	14	12	10	8	5	12	10	8	6	4	8	6	5	4	2

Notes:

1. In Scenario B, the sample size for the WRS test is also used for the Quantile test.
2. The values were calculated using **Equation N-1** and increased by 20 percent for the reasons discussed in **Appendix N**.

5.3.4 Determining Numbers of Data Points for Statistical Tests for Residual Radioactive Material Not Present in Background

If the residual radioactive material is not present in background or is present at such a small fraction of the $DCGL_W$ as to be considered insignificant, a background reference area is not necessary. Instead, the radionuclide levels are compared directly with the DCGL value. The general approach closely parallels that used for the situation when the radionuclide is present in background as described in **Section 5.3.3**. However, the statistical tests differ. The Sign test replaces the WRS test described above. **Sections 5.3.3.1** and **5.3.3.2** describe how to define the gray region and calculate the relative shift, respectively.

Table 5-3 provides a list of the number of data points needed to demonstrate compliance using the Sign test for selected values of α , β , and Δ/σ . The values listed in **Table 5-3** represent the number of measurements to be performed in each survey unit. These values were calculated using **Equation N-2** in **Appendix N** and increased by 20 percent to account for missing or unusable data and uncertainty in the calculated value of N . **Example 5-7** illustrates the use of the Sign test under Scenario A. **Section N.3** of **Appendix N** provides additional information on the Sign test.

Example 5-7: Use of Sign Test Under Scenario A

A site has one survey unit. The $DCGL_W$ for the radionuclide of interest is 140 Bq/kg (3.9 pCi/g) in soil. The radionuclide is not present in background; data from previous investigations indicate average residual radioactive material at the survey unit of 110 ± 3.7 (1σ) Bq/kg (3.7 ± 0.1 pCi/g). Using Scenario A, the LBGR was selected to be 110 Bq/kg. A value of 0.05 is next selected for the probability of Type I decision errors (α), and a value of 0.01 is selected for the probability of Type II decision errors (β) based on the survey objectives. Determine the number of data points to be obtained from the survey unit for the statistical tests.

The value of the relative shift, Δ/σ , is $(140 - 110)/3.7$, or 8.1. The number of data points can be obtained directly from **Table 5-3**. For $\alpha = 0.05$, $\beta = 0.01$, and $\Delta/\sigma > 3.0$, a value of 20 is obtained for N . The table value has already been increased by 20 percent to account for missing or unusable data and uncertainty in the calculated value of N .

Table 5-3 Values of N for Use with the Sign Test

Δ/σ	$\alpha = 0.01$					$\alpha = 0.025$					$\alpha = 0.05$					$\alpha = 0.10$					$\alpha = 0.25$				
	β					β					β					β					β				
	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25	0.01	0.025	0.05	0.10	0.25
0.1	4,095	3,476	2,984	2,463	1,704	3,476	2,907	2,459	1,989	1,313	2,984	2,459	2,048	1,620	1,018	2,463	1,989	1,620	1,244	725	1,704	1,313	1,018	725	345
0.2	1,035	879	754	623	431	879	735	622	503	333	754	622	518	410	258	623	503	410	315	184	431	333	258	184	88
0.3	468	398	341	282	195	398	333	281	227	150	341	281	234	185	117	282	227	185	143	83	195	150	117	83	40
0.4	270	230	197	162	113	230	1921	162	131	87	197	162	136	107	68	162	131	107	82	48	113	87	68	48	23
0.5	178	152	130	107	75	152	126	107	87	58	130	107	89	71	45	107	87	71	54	33	75	58	45	33	16
0.6	129	110	94	77	54	110	92	77	63	42	94	77	65	52	33	77	63	52	40	23	54	42	33	23	11
0.7	99	83	72	59	41	83	70	59	48	33	72	59	50	40	26	59	48	40	30	18	41	33	26	18	9
0.8	80	68	58	48	34	68	57	48	39	26	58	48	40	32	21	48	39	32	24	15	34	26	21	15	8
0.9	66	57	48	40	28	57	47	40	33	22	48	40	34	27	17	40	33	27	21	12	28	22	17	12	6
1.0	57	48	41	34	24	48	40	34	28	18	41	34	29	23	15	34	28	23	18	11	24	18	15	11	5
1.1	50	42	36	30	21	42	35	30	24	17	36	30	26	21	14	30	24	21	16	10	21	17	14	10	5
1.2	45	38	33	27	20	38	32	27	22	15	33	27	23	18	12	27	22	18	15	9	20	15	12	9	5
1.3	41	35	30	26	17	35	29	24	21	14	30	24	21	17	11	26	21	17	14	8	17	14	11	8	4
1.4	38	33	28	23	16	33	27	23	18	12	28	23	20	16	10	23	18	16	12	8	16	12	10	8	4
1.5	35	30	27	22	15	30	26	22	17	12	27	22	18	15	10	22	17	15	11	8	15	12	10	8	4
1.6	34	29	24	21	15	29	24	21	17	11	24	21	17	14	9	21	17	14	11	6	15	11	9	6	4
1.7	33	28	24	20	14	28	23	20	16	11	24	20	17	14	9	20	16	14	10	6	14	11	9	6	4
1.8	32	27	23	20	14	27	22	20	16	11	23	20	16	12	9	20	16	12	10	6	14	11	9	6	4
1.9	30	26	22	18	14	26	22	18	15	10	22	18	16	12	9	18	15	12	10	6	14	10	9	6	4
2.0	29	26	22	18	12	26	21	18	15	10	22	18	15	12	8	18	15	12	10	6	12	10	8	6	3
2.5	28	23	21	17	12	23	20	17	14	10	21	17	15	11	8	17	14	11	9	5	12	10	8	5	3
3.0	27	23	20	17	12	23	20	17	14	9	20	17	14	11	8	17	14	11	9	5	12	9	8	5	3

Notes:

1. The values were calculated using **Equation N-2** and increased by 20 percent for the reasons discussed in **Appendix N**.

5.3.5 Determining the Number of Discrete Data Points for Small Areas of Elevated Activity

As described in **Section 4.5.2**, the treatment of areas with elevated concentrations of radioactive material is determined strictly based on the requirements of the regulatory agencies and is beyond the scope of MARSSIM. A technically sound approach should be used to derive the values of the DCGL for the EMC (DCGL_{EMC}). The methodology presented in MARSSIM of using the unity rule to consider the combined impact of each elevated area is one conservative approach to assess areas of elevated radioactive materials. **Figure 5-6** summarizes the data needs for areas of elevated activity.

The statistical tests described throughout **Sections 5.3.3** and **5.3.4** (see also **Chapter 8**) evaluate whether the concentration of residual radioactive material in an area exceeds the DCGL_W for radionuclide concentrations that are approximately uniform across the survey unit. In addition, there should be a reasonable level of assurance that the FSS will not miss any small areas of elevated concentrations of residual radioactive material that could be significant relative to the DCGL_{EMC}. The statistical tests introduced in the previous sections may not successfully detect small areas of elevated concentrations of radioactive material. Instead, systematic measurements or samples are made at locations defined by a systematic grid, in conjunction with surface scanning. These results are used to obtain adequate assurance that small areas of elevated concentrations of radioactive material are below the DCGL_{EMC} and the release criteria are met. The procedure is applicable for all radionuclides, regardless of whether they are present in background, and is implemented for Class 1 survey units.

5.3.5.1 Determine Whether Additional Data Points Are Needed

The investigator should identify the number of survey data points needed for the statistical tests discussed in **Section 5.3.3** or **Section 5.3.4** (the appropriate section is determined by whether the radionuclide is present in background). These data points are then positioned throughout the survey unit by randomly selecting a start point and establishing a systematic pattern. This systematic sampling grid may be either triangular or rectangular/square. The triangular grid is generally more efficient for locating small areas of elevated activity. **Appendix D** includes a brief discussion on the efficiency of triangular and rectangular grids for locating areas of elevated activity. EPA guidance offers a more detailed discussion (EPA 1994b).

The number of calculated survey locations, n , and the total area of the survey unit, A , are used to determine the grid spacing, L , of the systematic sampling pattern, using **Equation 5-1** and **Equation 5-2**:

$$L = \sqrt{\frac{A \text{ (total area of survey unit)}}{0.866 n}} \text{ for a triangular grid} \quad \text{Equation 5-1}$$

$$L = \sqrt{\frac{A}{n}} \text{ for a rectangular grid} \quad \text{Equation 5-2}$$

The grid area that is bounded by these survey locations is given by **Equation 5-3** and **Equation 5-4**:

$$A \text{ (grid area)} = 0.866 L^2 \text{ for a triangular grid} \quad \text{Equation 5-3}$$

$$A \text{ (grid area)} = L^2 \text{ for a rectangular grid} \quad \text{Equation 5-4}$$

The risk of not sampling a circular area—equal to A (grid area)—of elevated activity by use of a random-start grid pattern is illustrated in **Figure D-3** in **Appendix D**.

The $DCGL_{EMC}$ that corresponds to this size of the area of elevated activity (A_{EA}) is obtained from specific regulatory agency guidance. After using the grid area calculated in **Equation 5-3** or **Equation 5-4** to determine the $DCGL_{EMC}$ for a specific radionuclide, the required minimum detectable concentration (MDC) of the scan procedure needed to detect an area of elevated activity is given by **Equation 5-5**:

$$\text{Scan MDC (required)} = DCGL_{EMC} \quad \text{Equation 5-5}$$

The actual scan MDCs of scanning techniques are then determined for the available instrumentation (see **Sections 6.3.2** and **6.6**). The actual scan MDC of the selected scanning technique is compared to the required scan MDC. If the actual scan MDC is less than the required scan MDC, no additional sampling points are necessary for the assessment of small areas of elevated activity. In other words, the scanning technique exhibits adequate detection capability to detect small areas of elevated activity.

Revisions 0 and 1 of MARSSIM (NRC 1998b and NRC 2000, respectively) included the calculation of an area factor⁷ as an intermediate step in the determination of the required scan MDC. The use of an area factor is not necessary if the $DCGL_{EMC}$ is tabulated directly as a function of the area of radioactive material. To simplify the determination of the required scan MDC, this revision of MARSSIM does not include the use of the area factor as an intermediate calculation.

5.3.5.2 Calculate the Required Grid Spacing and Number of Data Points

If the actual scan MDC is greater than the required scan MDC (i.e., the available scan detection capability is not sufficient to detect small areas of elevated activity), then it is necessary to decrease the size of the area of elevated activity (A_{EA}), thereby increasing the $DCGL_{EMC}$ that corresponds to this new area of elevated activity (A_{EA}), until the new $DCGL_{EMC}$ satisfies the inequality in **Equation 5-6**:

$$DCGL_{EMC} \geq \text{Scan MDC (actual)} \quad \text{Equation 5-6}$$

The size of the new area of elevated activity (A_{EA}) that corresponds to this new $DCGL_{EMC}$ is then obtained from specific regulatory agency guidance. The new number of data points required for assessing small areas of elevated activity (n_{EA}) can then be determined by dividing this new area of elevated activity (A_{EA}) into the survey unit area using **Equation 5-7**:

⁷ The area factor, as used in MARSSIM Revisions 0 and 1 represented the ratio of the $DCGL_{EMC}$ to the $DCGL_W$ as a function of the grid area and relates the required scan MDC to the $DCGL_W$ using this equation:

$$\text{Scan MDC (required)} = A_m \times DCGL_W$$

For a well-defined $DCGL_{EMC}$, the approach in MARSSIM Revisions 0 and 1 will produce essentially the same results for determining the required scanning and sampling requirements.

$$n_{EA} = \frac{A \text{ (survey unit)}}{A_{EA} \text{ (grid unit)}} \quad \text{Equation 5-7}$$

The calculated number of measurement or sampling locations, n_{EA} , is used to determine a revised spacing, L_{EA} , of the systematic pattern, using **Equation 5-8** and **Equation 5-9**:

$$L_{EA} = \sqrt{\frac{A \text{ (survey unit)}}{0.866 n_{EA}}} \text{ for a triangular grid} \quad \text{Equation 5-8}$$

$$L_{EA} = \sqrt{\frac{A \text{ (survey unit)}}{n_{EA}}} \text{ for a rectangular grid} \quad \text{Equation 5-9}$$

The distance between measurement/sampling locations should generally be rounded *down* to the nearest distance that can be conveniently measured in the field. This value of L_{EA} is then used to determine the measurement locations as described in **Section 5.3.7**. The Sign, WRS, and Quantile tests are performed using the larger number of data points, n_{EA} . **Figure 5-6** provides a concise overview of the procedure used to identify data needs for the assessment of small areas of elevated activity.

If residual radioactive material is found in an isolated area of elevated activity, in addition to residual radioactive material distributed relatively uniformly across the survey unit, the information in **Section 8.6.2** can be used to ensure that the total dose or risk does not exceed the release criteria. If there is more than one area of elevated activity, a conservative method is to include a separate term in the formula for each; however, this method may violate assumptions used in the pathway modeling process if adjustments are not made to the modeling. Specifically, if a receptor is assumed to be located directly above one area of elevated activity for the full occupancy period, that same receptor cannot realistically also be assumed to be located directly above a separate area of elevated activity for the full occupancy period associated with the exposure scenario.⁸ As an alternative, the dose or risk due to the actual residual radioactive material can be modeled if there is an appropriate exposure pathway model available. Note that these considerations generally apply only to Class 1 survey units, since areas of elevated activity should not exist in Class 2 or Class 3 survey units.

When the detection limit of the scanning technique is very large relative to the $DCGL_{EMC}$, the number of measurements needed to demonstrate compliance using the statistical tests may become unreasonably large. In this situation, the investigator should evaluate the survey objectives and considerations. These considerations may include the survey design and measurement methodology, exposure pathway modeling assumptions and parameter values used to determine the DCGLs, HSA conclusions concerning source terms and radionuclide distributions, and the results of scoping and characterization surveys. In most cases, the result of this evaluation is not expected to justify an unreasonably large number of measurements. **Example 5-8** shows how to determine whether additional data points are required to ensure the actual scan MDC is less than or equal to the required scan MDC.

⁸ By default, RESRAD assumes that the receptor spends 50 percent of the time indoors and 25 percent of the time outdoors; without further adjustment, and if two areas are considered, the receptor would spend 100 percent of the time indoors and another 50 percent of the time outdoors for a total time of 150 percent of what would typically be assumed for the exposure scenario.

Example 5-8: Example Determination Whether Additional Data Points Are Required

A Class 1 land area survey unit of 1,500 m² is potentially affected by residual radioactive material consisting of cobalt-60 (⁶⁰Co). The DCGL_W for ⁶⁰Co is 110 Bq/kg (3 Ci/g), and the scan detection capability for this radionuclide has been determined to be 150 Bq/kg (4 pCi/g). The table below provides the DCGL_{EMC} for different grid areas.

Grid Area (m ²)	DCGL _{EMC} (Bq/kg)
1	1,070
3	480
10	230
30	160
100	130
300	120
1,000	120
3,000	110
10,000	110

Calculations indicate that 27 data points are needed for statistical testing. The distance between measurement locations for this number of data points and the given land area is 8 m, as illustrated in the application of **Equation 5-1**:

$$L = \sqrt{\frac{A \text{ (survey unit)}}{0.866 n}} = \sqrt{\frac{1,500 \text{ m}^2}{0.866 \times 27}} = 8.0 \text{ m for a triangular grid}$$

The grid area encompassed by a triangular sampling pattern of 8 m is approximately 55.4 m² as calculated using **Equation 5-3**:

$$A \text{ (grid area)} = 0.866 L^2 = 0.866 (8.0 \text{ m})^2 = 55.4 \text{ m}^2$$

The DCGL_{EMC} for a grid area of 55.4 m² is determined by interpolation to be 150 Bq/kg:

$$160 \text{ Bq/kg} + \left(\frac{55.4 \text{ m}^2 - 30 \text{ m}^2}{100 \text{ m}^2 - 30 \text{ m}^2} \right) (130 \text{ Bq/kg} - 160 \text{ Bq/kg}) = 150 \text{ Bq/kg}$$

The acceptable MDC of the scan procedure needed to detect an area of elevated activity in a 55.4 m² area is therefore calculated using **Equation 5-5**:

$$\text{Scan MDC (required)} = \text{DCGL}_{\text{EMC}} = 150 \text{ Bq/kg}$$

Because the detection capability of the procedure to be used (150 Bq/kg) is equal to or less than the required scan MDC, no additional data points are needed to demonstrate compliance with the EMC criteria.

Example 5-9 also shows how to determine whether additional data points are required to ensure the actual scan MDC is less than or equal to the required scan MDC, including how to calculate the number of required data points when the actual scan MDC is greater than the required scan MDC.

Example 5-9: Example Determination Whether Additional Data Points Are Required

A Class 1 land area survey unit of 1,500 m² is potentially affected by residual radioactive material consisting of ⁶⁰Co. The DCGL_W for ⁶⁰Co is 110 Bq/kg (3 pCi/g). The table below provides the DCGL_{EMC} for different grid areas:

Grid Area (m ²)	DCGL _{EMC} (Bq/kg)
1	1,070
3	480
10	230
30	160
100	130
300	120
1,000	120
3,000	110
10,000	110

In contrast to **Example 5-8**, the scan detection capability for this radionuclide has been determined to be 170 Bq/kg (4.6 pCi/g). Calculations indicate that 15 data points are needed for statistical testing. The distance between measurement locations for this number of data points and the given land area is 10 m, as illustrated using **Equation 5-1**:

$$L = \sqrt{\frac{A \text{ (survey unit)}}{0.866 n}} = \sqrt{\frac{1,500 \text{ m}^2}{0.866 \times 15}} = 10.7 \text{ m for a triangular grid}$$

The grid area encompassed by a triangular sampling pattern of 10 m is approximately 99.1 m², as calculated using **Equation 5-3**:

$$A \text{ (grid area)} = 0.866 L^2 = 0.866 (10.7 \text{ m})^2 = 99.1 \text{ m}^2$$

The DCGL_{EMC} for a grid area of 99.1 m² is determined by interpolation to be 130 Bq/kg:

$$160 \text{ Bq/kg} + \frac{99.1 \text{ m}^2 - 30 \text{ m}^2}{100 \text{ m}^2 - 30 \text{ m}^2} (130 \text{ Bq/kg} - 160 \text{ Bq/kg}) = 130 \text{ Bq/kg}$$

The required scan MDC for that grid area is therefore also 130 Bq/kg:

$$\text{Scan MDC (required)} = \text{DCGL}_{\text{EMC}} = 130 \text{ Bq/kg}$$

Because the actual scan MDC of the procedure to be used (170 Bq/kg) is greater than the required scan MDC, the data points obtained for the statistical testing may not be sufficient to demonstrate compliance using the EMC. The grid area corresponding to a DCGL_{EMC} of 170 Bq/kg is determined by interpolation to be 27 m²:

$$30 \text{ m}^2 + \left(\frac{170 \text{ Bq/kg} - 160 \text{ Bq/kg}}{230 \text{ Bq/kg} - 160 \text{ Bq/kg}} \right) (10 \text{ m}^2 - 30 \text{ m}^2) = 27 \text{ m}^2$$

The number of samples required to account for areas of elevated activity (n_{EA}) is calculated using **Equation 5-7**:

$$n_{EA} = \frac{A \text{ (survey unit)}}{A_{EA} \text{ (grid unit)}} = \frac{1,500 \text{ m}^2}{27 \text{ m}^2} = 56 \text{ measurements}$$

The triangular grid spacing required to account for areas of elevated activity (L_{EA}) is calculated using **Equation 5-8**:

$$L_{EA} = \sqrt{\frac{A \text{ (survey unit)}}{0.866 n_{EA}}} = \sqrt{\frac{1500 \text{ m}^2}{0.866 \times 56}} = 5.5 \text{ m for a triangular grid}$$

The number of data points required increased from 15 to 56, and the grid spacing decreased from 10.7 m to 5.5 m.

5.3.6 Determining the Scanning Area

The use of direct measurements or sampling in combination with separate scans of the area is necessary when the scanning instrument and technique have sufficient detection capability to identify areas of elevated concentrations of radioactive material, but insufficient detection capability to quantify the average concentration of radioactive material in the survey unit.

Section 5.3.9 summarizes the recommended survey coverage for structures and land areas. If the measurement method has sufficient detection capability to meet the MQOs to both quantify the average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material, a site-specific scanning survey can be considered. Similar in principle to a site-specific scanning survey is a series of direct measurements that have the detection capability to meet the MQOs to both quantify the average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material.

5.3.6.1 Site-Specific Scanning Surveys

During site-specific scanning surveys, many discrete scanning measurements are taken and analyzed; this approach is greatly facilitated by the use of scanning systems that automatically record scan measurements and their locations. These systems typically use GPS or other position determinations in conjunction with radiological measurements, with both the radiological and locational data being automatically recorded. These techniques permit the convenient accumulation, storage, and display of hundreds or thousands of scan data points for a survey unit.

Site-specific scanning surveys will likely require site-specific validation samples to ensure that the method can reliably detect concentrations at the DCGL_w under the conditions expected at the site. This validation can be accomplished at any point in the RSSI process (after remediation, if remediation is performed). Validation samples should include both rescanning and static measurements, especially for areas where scan measurements may be elevated relative to the area in general. Any area with multiple scan measurements above established investigation levels should be subjected to verification measurements (rescanning, static, and physical samples with quantitative analysis). Investigators should consult with their regulator for guidance on the level of effort needed to validate site-specific scanning surveys.

Site-specific scanning surveys generally cover a much larger portion of the survey unit than traditional discrete sampling or measurement. Consider the collection of 20 to 30 measurements

(static or samples) at discrete locations for a Class 1 survey unit versus 100 percent scan coverage. A similar concept is found in a series of direct measurements, where the field of view of the direct measurements covers a statistically significant portion of the survey unit (i.e., 10 percent or more).⁹

However, a site-specific scanning approach should be used only for circumstances where the measurement method has sufficient detection capability to meet the MQOs to both quantify the average concentration of radioactive material in the survey unit and identify areas of elevated concentrations of radioactive material. To ensure that this is the case, the scan MDC (for the scan system) should be less than 50 percent¹⁰ of the DCGL_W. The site-specific scanning methodology will require validation, which likely requires collecting some percentage of samples for laboratory analysis to compare with results from the same location. Other MQOs should be met as well, including the MQO for measurement method uncertainty at the DCGL_W.

In general, when using a site-specific scanning survey approach, the anticipated measurement method uncertainty is expected to be higher than traditional scan and sampling procedures. Therefore, a maximum scan coverage (e.g., 100 percent) should always be achieved in Class 1 areas when using this approach. The percentage of Class 2 or Class 3 areas that should be scanned is 10 percent or the result using **Equation 5-10**, whichever is larger:

$$\% \text{ of Scan Area} = \frac{(10 - \Delta/\sigma)}{10} \times 100\% \quad \text{Equation 5-10}$$

For Class 3 areas, scanning can be lower than 10 percent if sampling or direct measurements, or both, are taken in areas judged to have the highest potential for residual radioactive material. Scanning a greater percentage than that calculated above is always acceptable. When performing site-specific scanning surveys, the following must be considered and addressed in survey plans:

- Perform quality control procedures, such as evaluating measurement method uncertainty by performing replicate scans over a prescribed portion of the site and performing reference standard checks at a prescribed frequency.
- Evaluate the extent to which alpha and beta radiation in the surface may impact site-specific scanning survey results.
- Determine the number and type of validation samples to establish a correlation between site-specific scanning and laboratory results.

5.3.6.2 *Scanning and Sampling*

When scanning is done in combination with direct measurements or sampling, the scanning measurement technique must have detection capabilities that meet the MQOs for identifying areas of elevated concentrations of radioactive material. This differs from the requirements for site-specific scanning surveys that must have detection capabilities to both identify areas of

⁹ The MARSAME Manual refers to a direct measurement survey covering a statistically significant portion of the survey unit as an “in situ” survey type; in MARSSIM, this survey type is incorporated into site-specific scanning surveys.

¹⁰ **Section 2.3.1** discusses detection capability.

elevated concentrations of radioactive material and quantify the average concentration of radioactive material in the survey unit.

The percentage of the area that needs to be scanned depends on the classification of the survey unit. For Class 1 survey units, 100 percent of the area should be scanned. The percentage of Class 2 or Class 3 areas that should be scanned is 10 percent or the result using **Equation 5-10**, whichever is larger. For Class 3 areas, scanning can be lower than 10 percent if sampling or direct measurements, or both, are taken in areas judged to have the highest potential for residual radioactive material. Scanning a greater percentage than that calculated above for Class 2 or Class 3 survey units is always acceptable.

The detection capability for scanning techniques used in Class 2 and Class 3 survey units is not tied to the area between measurement locations like it is in a Class 1 survey unit (refer to **Section 5.3.5**). The scanning techniques selected should represent the best reasonable effort based on the survey objectives. Structure surfaces are generally scanned for alpha-, beta-, and gamma-emitting radionuclides. In contrast, scanning for alpha or beta emitters in land-area survey units is generally not considered effective because of problems with attenuation and media interferences. If one can reasonably expect to find any residual radioactive material, it is prudent to perform a judgment scanning survey.

5.3.7 Determining Survey Locations

Like the required scanning percentages, the determination of discrete survey locations for the direct measurements or the collection of samples depends on the classification of the survey unit. The method for determining survey locations for land areas and structure surfaces is described below.

5.3.7.1 *Survey Locations for Discrete Measurements and Samples*

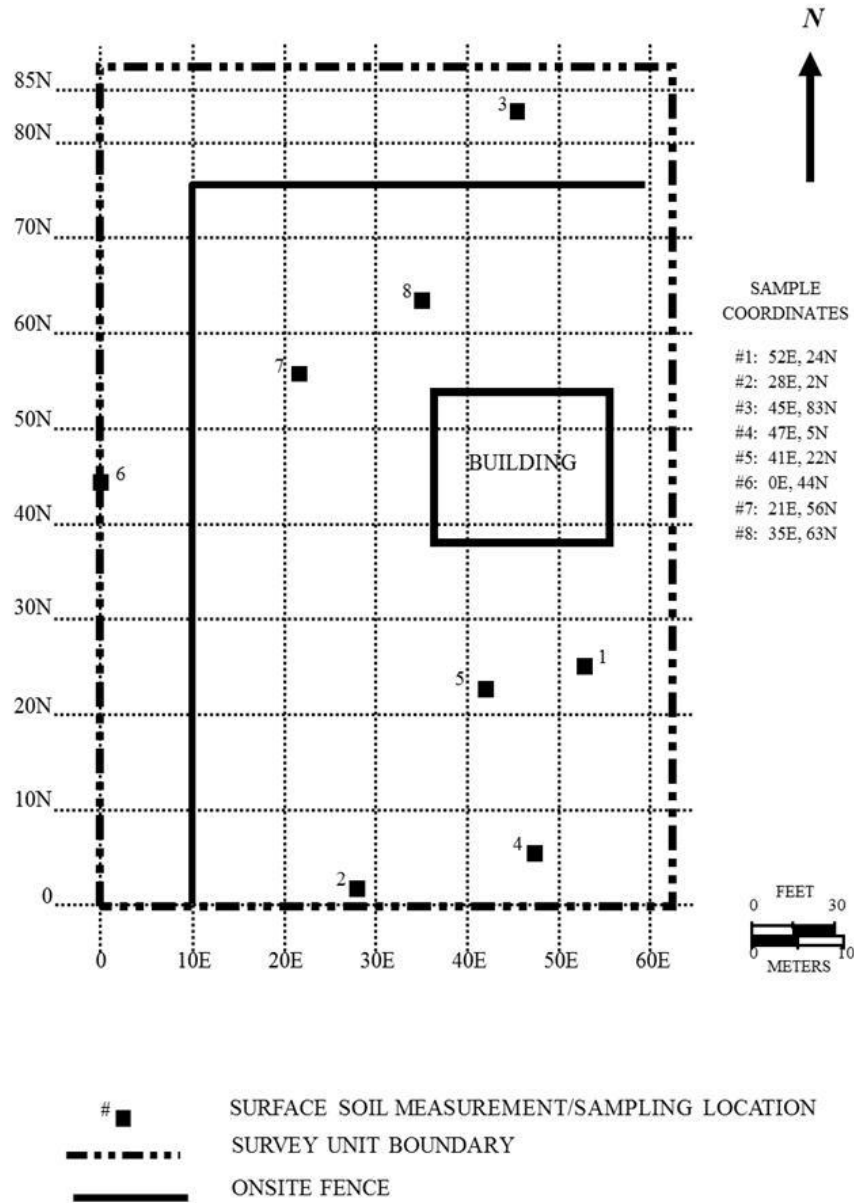
A scale drawing of the survey unit is prepared, along with the overlying planar reference coordinate system or grid system. Any location within the survey area is thus identifiable by a unique set of coordinates. The maximum dimensions for length, X, and width, Y, of the survey unit are then determined. The step of identifying and documenting a specific location for each measurement performed is an important part of an FSS to ensure that measurements can be reproduced if necessary. The reference coordinate system described in **Section 4.9.5** provides a method for relating measurements to a specific location within a survey unit. Systems using GPS technology and data logging software are widely available to identify and track survey dimensions, sampling locations, and locations associated with specific scan results.

5.3.7.1.1 Land Areas

Measurements and samples in Class 3 survey units and reference areas are usually taken at random locations. These locations are determined by generating sets of random numbers (two values, representing the X-axis and Y-axis distances). Random numbers can be obtained from mathematical tables, including **Table I-13** in **Appendix I**, or generated by calculator or computer. Sufficient sets of numbers will be needed to identify the total number of survey locations established for the survey unit. Each set of random numbers is multiplied by the appropriate survey unit dimension to provide coordinates, relative to the origin of the survey unit reference grid pattern. Coordinates identified in this manner that do not fall within the survey unit area or that cannot be surveyed because of site conditions are replaced with other survey points determined in the same manner. **Example 5-10** provides an example of a random sampling pattern.

Example 5-10: Random Sampling Pattern

In this example, eight data points were identified using the appropriate table (**Table 5-2** or **Table 5-3**). The locations of these points were determined using the table of random numbers found in **Appendix I, Table I-13**.



Class 2 areas are surveyed on a random-start systematic pattern. The number of calculated survey locations, n , based on the statistical tests, is used to determine the spacing, L , of a systematic pattern as specified in **Equation 5-1** and **Equation 5-2**.

After L is determined, a random start location is identified, as described previously in this section, for a survey pattern starting location. Beginning at the random start location, a row of points is identified parallel to the X-axis at intervals of L .

For a triangular grid, a second row of points is then developed, parallel to the first row, at a distance of $0.866L$ from the first row. Survey points along that second row are midway (on the X-axis) between the points on the first row. This process is repeated to identify a pattern of survey locations throughout the affected survey unit. If identified points fall outside the survey unit or at locations that cannot be surveyed, additional points are determined using the random process described above until the desired total number of points is identified.

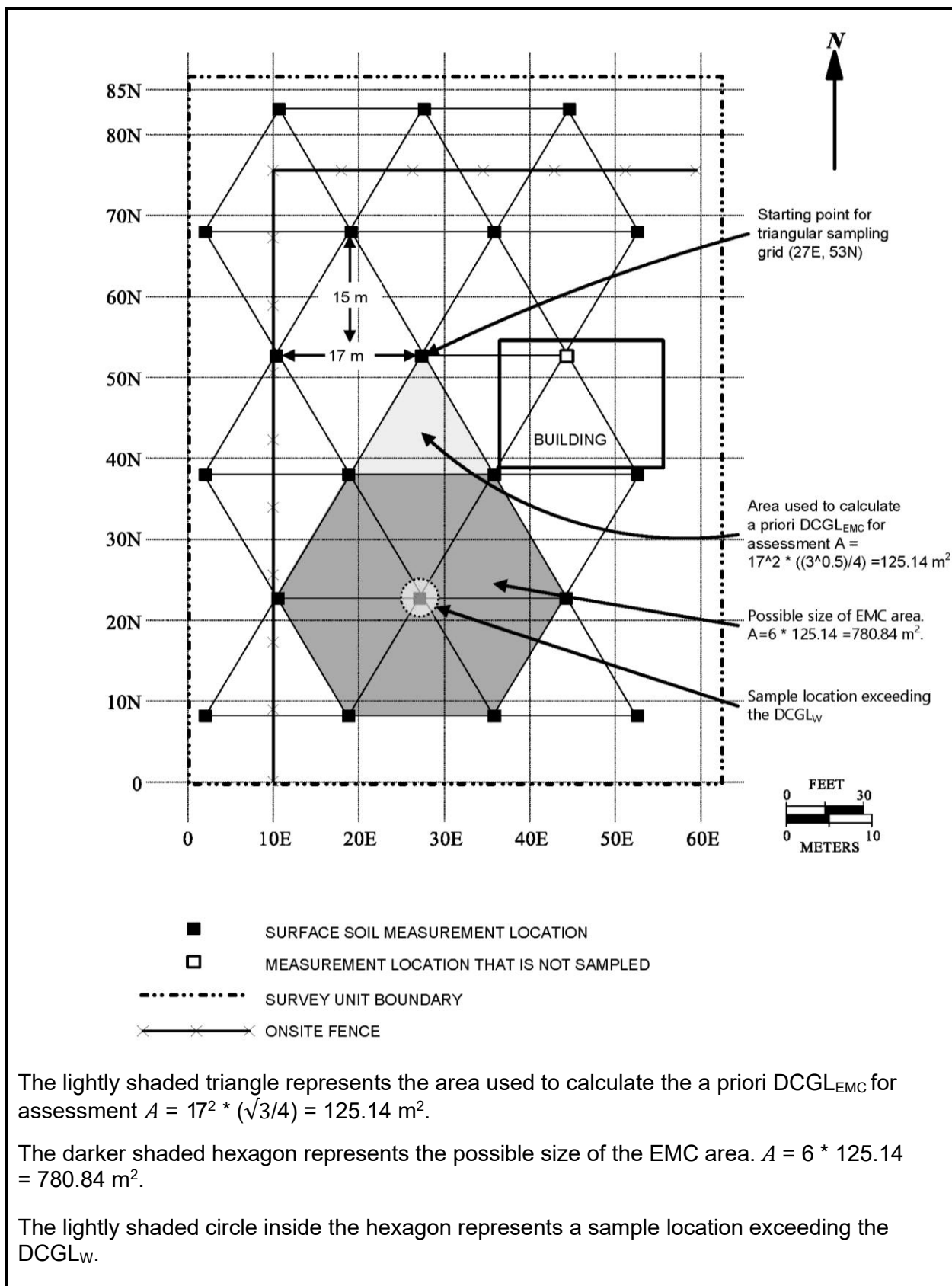
For Class 1 areas, a systematic pattern having the dimensions determined in **Section 5.3.6** is installed on the survey unit. The starting point for this pattern is selected at random, as described above for Class 2 areas. The same process as described above for Class 2 areas applies to Class 1. **Example 5-11** provides an illustration of a triangular systematic pattern in an outdoor Class 2 survey unit.

Example 5-11: Illustration of a Triangular Systematic Pattern in an Outdoor Class 2 Survey Unit

In this example, the statistical test calculations estimated that 20 samples are needed (**Table 5-3**, $\alpha = 0.01$, $\beta = 0.05$, $\Delta/\sigma > 3.0$). The random-start coordinates were 27E, 53N. The grid spacing (L) was calculated using **Equation 5-8**:

$$L = \sqrt{\frac{5,100 \text{ m}^2}{0.866 \times 20}} = 17 \text{ m}$$

Two points were identified on a row parallel to the X-axis, each 17 m from the starting point. The subsequent rows were positioned $0.866 \times L$, or 15 m, from the initial row. This random-start triangular sampling process resulted in 21 sampling locations, one of which was difficult to assess because of the building location, which yields the desired number of data points.



The shading indicates that when a grid point is exceeding the $DCGL_{EMC}$ (lightly shaded circle), the elevated area could be as large as that. The $DCGL_{EMC}$ is calculated on the basis of the grid area, since this is about the same as the largest circular area that has some chance of being missed when sampling on the grid.

When a measurement is found to exceed the $DCGL_{EMC}$, there is more work to be done before the question of compliance can be answered. An individual elevated measurement on a systematic grid could conceivably represent an area three to four times as large as the systematic grid area used to define the $DCGL_{EMC}$. The elevated area might also be smaller than the grid area. Since the allowable concentration generally increases as the elevated area decreases in size, further investigation is necessary to determine both the actual area and average concentration.

5.3.7.1.2 Structure Surfaces

All structure surfaces for a specific survey unit are included on a single reference grid system for the purpose of identifying survey locations. The same methods as described above for land areas are then used to locate survey points for all survey units, regardless of class.

In addition to the survey locations identified for statistical evaluations and EMCs, data may be obtained from judgment locations that are selected because of their unusual appearance, location relative to areas affected by residual radioactive material, high potential for residual radioactive material, general supplemental information, or other factors. Data points selected based on professional judgment are not included with the data points from the random-start triangular grid for statistical evaluations; instead, they are compared individually with the established DCGLs and conditions. Measurement locations selected through professional judgment cannot be considered representative of the survey unit, a necessary condition if the statistical tests described in **Chapter 8** are used.

5.3.7.2 Survey Locations for Scans

Like the determination of the location of discrete measurements or samples, the determination of survey locations for scans depends on the classification of the survey unit.

5.3.7.2.1 Class 1 Survey Units

For Class 1 survey units, scans are intended to detect small areas of elevated concentration of residual radioactive material that are not detected by the measurements using the systematic pattern (refer to **Section 5.3.5**). This is the reason for recommending 100 percent coverage for the scanning survey. Coverage of 100 percent means that the entire accessible surface area of the survey unit is covered by the field of view of the scanning instrument. If the field of view is 2 m wide, the survey instrument can be moved along parallel paths 2 m apart to provide 100 percent coverage. If the field of view of the detector is 5 centimeters (cm), the parallel paths should be 5 cm apart.

5.3.7.2.2 Class 2 Survey Units

Class 2 survey units have a lower probability than Class 1 survey units for areas of elevated concentration of residual radioactive material, but some portions of the survey unit may have a higher potential than others. Judgment scanning surveys focus on the portions of the survey unit

with the highest probability for areas of elevated concentration of residual radioactive material. If the entire survey unit has an equal probability for areas of elevated activity, or the judgment scans do not cover at the required scanning percentage of the area, systematic scans along transects of the survey unit or scanning surveys of randomly selected grid blocks should be performed.

5.3.7.2.3 Class 3 Survey Units

Class 3 survey units may be uniformly scanned for radiation emitted from the radionuclides of interest, or the scanning may be performed in areas with the greatest potential for residual radioactive material (e.g., corners, ditches, and drains) based on professional judgment and the objectives of the survey. Such recommendations are typically provided by a health physics professional with radiation survey experience. This provides a qualitative level of confidence that no areas of elevated activity were missed by the random measurements or that there were no errors made in the classification of the area. In some cases, a combination of these approaches may be the most appropriate.

5.3.8 Determining Investigation Levels

An important aspect of the FSS is the design and implementation of investigation levels. Investigation levels are radionuclide-specific levels of radioactive material used to indicate when additional investigations may be necessary. Investigation levels also serve as a quality control check to determine when a measurement process begins to get out of control. For example, a measurement that exceeds the investigation level may indicate that the survey unit has been improperly classified (see **Section 4.6**), or it may indicate a failing instrument. Typically, investigation levels are set as part of the DQO process.

When an investigation level is exceeded, the first step is to confirm that the initial measurement or sample actually exceeds the particular investigation level. This may involve taking further measurements to determine that the area and level of the elevated residual radioactive material are such that the resulting dose or risk meets the release criteria. Rather than—or in addition to—taking further measurements, the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs, as well as the consistency of the results obtained with the HSA and the scoping, characterization, and RAS surveys. Depending on the results of the investigation actions, the survey unit may require reclassification, remediation, or resurvey. **Table 5-4** illustrates an example of how investigation levels can be developed.

Table 5-4 Example FSS Investigation Levels

Survey Unit Classification	Flag Direct Measurement or Sample Result When...	Flag Scanning Measurement Result When...
Class 1	> DCGL _{EMC} or > DCGL _W and > a statistical parameter-based value	> DCGL _{EMC} for the area bounded by four adjacent systematic grid measurement points to determine the DCGL _{EMC} (when a traditional MARSSIM approach is used), or for the area bounded by an acceptable elevated area size (when a site-specific scanning approach is used)
Class 2	> DCGL _W	> DCGL _W or > scan MDC
Class 3	> fraction of DCGL _W	> DCGL _W or > scan MDC

When determining an investigation level using a statistical-based parameter (e.g., standard deviation), one should consider survey objectives and underlying radionuclide distributions, and have an understanding of corresponding types (e.g., normal, lognormal, nonparametric), descriptors (e.g., standard deviation, mean, median), population stratifications (i.e., subgroups), and other prior survey and historical information. For example, a level might be arbitrarily established at the mean + 3s, where s is the standard deviation of the survey unit's residual radioactive material concentrations, assuming a normal distribution. A higher value might be used if locating discrete sources of higher activity was a primary survey objective. By the time the FSS is conducted, survey units should be defined. Estimates of the mean, variance, and standard deviation of the radionuclide activity levels within the survey units should also be available.

For a Class 1 survey unit, measurements above the $DCGL_W$ are not necessarily unexpected. However, a measurement above the $DCGL_W$ at one of the discrete measurement locations might be considered unusual if it were much higher than all the other discrete measurements. Thus, further investigation should be performed for any discrete measurement that is both above the $DCGL_W$ and above the statistically based parameter for the measurements. Any measurement, either at a discrete location or from a scan that is above the $DCGL_{EMC}$, should also be flagged for further investigation. When using a traditional MARSSIM approach (scanning with direct measurements or samples, or both), the $DCGL_{EMC}$ should be established for the largest (worst case) potential elevated measurement area (the area bounded by four sampling grid measurement points). This largest potential elevated area is also the survey unit area divided by the number of measurements or samples (for the systematic sampling grid). When using a site-specific scanning approach, it is important to establish an appropriate size for a potential elevated area and associated $DCGL_{EMC}$ as a part of the DQO process and in agreement with the regulator.

In Class 2 or Class 3 areas, neither measurements above the $DCGL_W$ nor areas of elevated activity are expected. Any measurement at a discrete location exceeding the $DCGL_W$ in these areas should be flagged for further investigation. Because the survey design for Class 2 and Class 3 survey units is not driven by the EMC, the scan MDC might exceed the $DCGL_W$. In this case, any indication of residual radioactive material during the scan would warrant further investigation.

When it is not feasible to obtain a scan MDC below the $DCGL_W$, the basis for using the $DCGL_{EMC}$ or an investigation level above the $DCGL_W$ in **Table 5-4** for Class 2 and Class 3 areas may be necessary but should be justified in survey planning documents. For example, where there is high uncertainty in the reported scan MDC, more conservative criteria would be warranted.

Similarly, data quality assessment (DQA) for scanning may warrant a more conservative flag, as would greater uncertainty from the HSA or other surveys on the size of potential areas of elevated activity. In some cases, it may even be necessary to agree in advance with the regulatory agency on which site-specific investigation will be used if other than those presented in **Table 5-4**.

Because there is a low expectation for the presence of residual radioactive material in a Class 3 area, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The level selected in these situations should be commensurate with the potential exposures at the site, the radionuclides of concern, and the measurement and scanning methods chosen. This level should be set using the DQO process during the survey design.

phase of the data life cycle. In some cases, the investigator may also wish to follow this procedure for Class 2 and even Class 1 survey units.

5.3.9 Developing an Integrated Survey Strategy

The final step in survey design is to integrate the survey techniques (**Chapter 6**), including the number of measurements and measurement spacing, with the amount of scanning determined earlier in this chapter. This integration, along with the information provided in other portions of this manual, produces an overall strategy for performing the survey. The survey design may consist of site-specific scanning, or a combination of scans with sampling or direct measurements. **Table 5-5** summarizes the recommended survey coverage for structures and land areas. This survey coverage for different areas is the subject of this section.

Table 5-5 Recommended Survey Coverage for Structures and Land Areas

Area Classification	Scanning and Direct Measurements and/or Sampling Survey		Site-Specific Scanning Survey Scanning
	Scanning	Direct Measurements or Samples	
Class 1	100%	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4); additional measurements may be necessary for small areas of elevated activity (Section 5.3.5)	100%
Class 2	10–100% Systematic and Judgment “Scan Area” = $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4)	10–100% Systematic and Judgment “Scan Area” = 10% or $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$ whichever is larger
Class 3	Judgment “Scan Area” = $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$	Number of data points from statistical tests (Sections 5.3.3 and 5.3.4)	10–100% ^a Judgment “Scan Area” = 10% or $\frac{(10 - \Delta/\sigma)}{10} \times 100\%$ whichever is larger

Note: Δ/σ represents the relative shift.

^a For surveys using sampling or direct measurements (or both), this percentage can be lower than 10 percent judgmental.

For surveys in which discrete measurements or samples are taken, random measurement patterns are generally used for Class 3 survey units to ensure that the measurements are independent and support the assumptions of the statistical tests. Systematic grids are used for Class 2 survey units because there is an increased probability of small areas of elevated activity. The use of a systematic grid allows the decision-maker to draw conclusions about the size of the potential areas of elevated activity based on the area between measurement locations. The random starting point of the grid provides an unbiased method for obtaining measurement locations to be used in the statistical tests. Class 1 survey units have the highest potential for small areas of elevated activity, so the areas between measurement locations might need to be adjusted to ensure that these areas can be detected by scanning techniques.

MARSSIM allows the use of both sampling (where a sample is collected and sent to an onsite or offsite analytical laboratory) and direct measurements (e.g., fixed measurement taken in the field by an in situ gamma spectroscopy or beta scintillation meter). It is important to consider the required MQOs for the survey and ensure that the measurement method chosen meets those criteria. Some direct measurement methods may not be appropriate for some radionuclides in land areas.

The objectives of the scanning surveys are different. Scanning is used to identify locations within the survey unit that exceed the investigation level. These locations are marked and/or receive additional investigations to determine the concentration, area, and extent of the residual radioactive material.

Scanning measurements can also be used in place of the sampling or direct measurements when the detection capability is sufficient and many discrete scan measurements are taken and analyzed; this approach is greatly facilitated by the use of scan systems that automatically record scan measurements and location. These systems typically use GPS or other position determinations in conjunction with radiological measurements, with both the radiological and locational data recorded automatically. These techniques permit the convenient accumulation, storage, and display of hundreds or thousands of scan data points for a survey unit. However, a site-specific scanning approach should only be used if the scan MDC (for the scan system) is less than 50 percent of the $DCGL_W$ and other MQOs, such as requirements for measurement method uncertainty, can be met. For site-specific scanning surveys of Class 2 or Class 3 survey units where less than 100 percent of the area is scanned, the survey must be designed so that the average concentration of radioactive material calculated from the survey data is an unbiased representative estimate of the true mean concentration in the survey unit. If the site-specific scanning survey option is feasible for a site or survey unit, the sampling function of the FSS would not be applicable.

Measurements or sampling, or both, independent from the FSS may be necessary at numerous other locations besides the building and land surface areas described above. Examples include items of equipment and furnishings, building fixtures, drains, ducts, and piping. Many of these items or locations have both internal and external surfaces with potential residual radioactive material. The MARSAME Manual (NRC 2009) includes an approach for conducting or evaluating these types of surveys. Subsurface measurements or sampling may also be necessary.

Special situations may be evaluated using judgment sampling and measurements. Data from such surveys should be compared directly with a limit developed for the specific situation and approved by the regulator.

Quality control measurements are recommended for all surveys, as described in **Sections 4.8, 6.2, and 7.2**. For site-specific scanning surveys, replicate quality control scans should be performed using an independent surveyor and measurement instrumentation. Also, some regulatory programs require removable activity measurements (e.g., U.S. Department of Energy (DOE) requirements in DOE Order 458.1, "Radiation Protection of the Public and the Environment," issued February 2011 [DOE 2011c]; 10 CFR Part 835, "Occupational Radiation Protection"). These additional measurements should be considered during survey planning.

5.3.9.1 *Class 1 Survey Units*

For Class 1 survey units, scanning surveys are designed to detect small areas of elevated activity above the $DCGL_W$ that are not detected by the measurements using the systematic pattern (**Section 5.3.7**). For this reason, the measurement locations and the number of measurements may need to be adjusted based on the sensitivity of the scanning technique (**Section 5.3.5.1**). This is also the reason for recommending 100 percent coverage for the scanning survey.

As discussed in **Section 5.3.6.1**, scanning techniques can be used in lieu of discrete samples or direct measurements when the scan MDC is less than 50 percent of the $DCGL_W$ and the scan coverage is 100 percent. Note that, in a statistical sense, a scan of 100 percent of a survey unit constitutes a sample of 100 percent of the survey unit. Other MQOs need to be met, as well, including the MQO for required measurement method uncertainty.

Locations of direct radiation above an investigation level are identified and evaluated. Results of initial and follow-up direct measurements and sampling at these locations are recorded and documented in the FSS report. For structure surfaces, measurements of total and (when applicable) removable radioactive material are performed at locations identified by scans and at previously determined locations (**Section 5.3.7**). Soil sampling or direct measurements are also performed at locations identified by scans and at previously determined locations (**Section 5.3.7**).

The development of direct measurement or sample investigation levels for Class 1 areas should establish a course of action for individual measurements that exceed the investigation level. Because measurements above the $DCGL_W$ are not necessarily unexpected in a Class 1 survey unit, additional investigation levels may be established to identify discrete measurements that are much higher than the other measurements. Any discrete measurement that both is above the $DCGL_W$ and exceeds a statistically based parameter (e.g., three standard deviations above the mean) should be investigated further (**Section 5.3.8**). Any measurement (direct measurement, sample, or scan) that exceeds the $DCGL_{EMC}$ should be flagged for further investigation.

The results of the investigation and any additional remediation that was performed should be included in the FSS report. Data are reviewed as described in **Section 8.2.2**, additional data are collected as necessary, and the final complete dataset evaluated as described in **Section 8.3** and **Section 8.4**.

5.3.9.2 *Class 2 Survey Units*

Scanning surveys in Class 2 survey units are also primarily performed to find areas of elevated activity not detected by the measurements using the systematic pattern. However, the number and location of measurements are not adjusted based on sensitivity of the scanning technique, and scanning is performed in portions of the survey unit. The level of scanning effort should be

proportional to the potential for finding areas of elevated activity based on the conceptual site model developed and refined from **Section 3.6.4**. In other words, the farther the expected residual radioactive material in the survey unit is from the $DCGL_W$ in units of uncertainty (i.e., the larger the Δ/σ), the less scanning is needed. Surface scans are performed over 10–100 percent of structure surfaces or open land surfaces, as calculated in **Equation 5-10**. A larger portion of the survey unit would be scanned in Class 2 survey units that have residual radioactive material close to the release criteria, but for survey units that are closer to background scanning results, scanning a smaller portion of the survey unit may be appropriate.

As discussed in **Section 5.3.6.1**, scanning techniques for Class 2 survey units might be used in lieu of discrete samples or direct measurements when the scan MDC is less than 50 percent of the $DCGL_W$ and the scan coverage is between 10 and 100 percent. Note that, in a statistical sense, a scan of 10–100 percent of a survey unit constitutes a sample of 10–100 percent of the survey unit. Other MQOs need to be met, as well, including the MQO for required measurement method uncertainty. The area scanned should be selected in an unbiased manner.

Locations of scanning survey results greater than the investigation level are identified and investigated. If small areas of elevated activity are confirmed by this investigation, all or part of the survey unit should be reclassified as Class 1 and the survey strategy for that survey unit redesigned accordingly. Investigation levels for Class 2 areas should be established for investigation of individual measurements close to but less than the $DCGL_W$. Investigation levels for Class 2 areas should also lead to a course of action for individual measurements that exceed or approach the $DCGL_W$. The FSS report should include the results of the investigation of the positive measurements and basis for reclassifying all or part of the survey unit as Class 1.

The results of the investigation should be included in the FSS report. Data are reviewed as described in **Section 8.2.2**, additional data are collected as necessary, and the final complete dataset evaluated as described in **Section 8.3** and **Section 8.4**.

5.3.9.3 *Class 3 Survey Units*

Class 3 survey units have the lowest potential for areas of elevated activity. Locations exceeding the scanning survey investigation level should be flagged for further investigation. If the presence of residual radioactive material occurring at concentrations greater than a small fraction of the $DCGL_W$ is identified, the classification of the survey unit should be reevaluated.

As discussed in **Section 5.3.6.1**, scanning techniques for Class 3 survey units can be used in lieu of sampling and statistical testing when the scan MDC is less than 50 percent of the $DCGL_W$. Other MQOs need to be met, as well, including the MQO for required measurement method uncertainty.

Sampling or direct measurements are performed at randomly selected locations (**Section 5.3.7**). Survey results are tested for compliance with DCGLs, and additional data are collected and tested as necessary. For structure surfaces, measurements of total and (when applicable) removable radioactive material are performed at the locations identified by the scans and at the randomly selected locations that are chosen in accordance with **Section 5.3.7**.

Investigation levels for Class 3 areas should be established to identify areas of elevated activity that may indicate the presence of residual radioactive material. Because there is a low expectation for residual radioactive material in a Class 3 survey unit, it may be prudent to investigate any measurement exceeding even a fraction of the $DCGL_W$. The investigation level selected will depend on the site, the radionuclides of concern, and the measurement and

scanning methods chosen. This level should be commensurate with the potential exposures and should be determined using the DQO process during survey planning. In some cases, the user may wish to follow this procedure for Class 2 survey units.

The data are tested relative to the preestablished criteria. If additional data are needed, they should be collected and evaluated as part of the entire dataset. Identification of residual radioactive material suggests that the area may be incorrectly classified. If so, the Class 3 area classification should be reevaluated and, if appropriate, all or part of the survey unit should be resurveyed as a Class 1 or Class 2 survey unit.

The FSS report should include the results of the investigation of the measurements that exceed the investigation level and the basis for reclassifying all or part of the survey unit as Class 1 or Class 2.

As discussed in **Section 5.3.8**, investigation levels are determined and used to indicate when additional investigations may be necessary or when a measurement process begins to get out of control. The results of all investigations should be documented in the FSS report, including the results of scan surveys that may have potentially identified areas of elevated direct radiation.

5.3.10 Evaluating Survey Results

Chapter 8 describes detailed procedures for evaluating survey results. After data are converted to the same units as the DCGLs, the process of comparing the results to the DCGLs and objectives begins. Individual measurements and sample concentrations are first compared to DCGL levels for evidence of small areas of elevated activity and not to determine whether reclassification is necessary. Additional data or further remediation and resurveying may be necessary. Data are then evaluated using statistical methods to determine whether they exceed the release criteria. If the release criteria have been exceeded or if results indicate the need for additional data points, the site management and the regulatory agency will determine appropriate further actions. The scope of further actions should be agreed upon and developed as part of the DQO process before the survey begins (**Appendix D**). Finally, the results of the survey are compared with the DQOs established during the planning phase of the project. Note that DQOs may identify a need for a report of the evaluation of removable radioactive material resulting from the analysis of smears. These results may be used to satisfy regulatory requirements.

5.3.11 Documentation

Documentation of the FSS should provide a complete and unambiguous record of the radiological status of the survey unit relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent re-creation and evaluation at some future time. Much of the information in the FSS report will be available from other site remediation documents; however, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. The report should be independently reviewed (see **Section 8.7**) and should be approved by a designated person (or persons) who is capable of evaluating all aspects of the report before release, publication, or distribution. **Example 5-12** includes an example of an FSS checklist, including survey preparations, survey design, conduct of surveys, and evaluation of survey results.

Example 5-12: Example FSS Checklist

Survey Preparations

- _____ Ensure that residual radioactive material limits have been determined for the radionuclides present at the site, typically performed during earlier surveys associated with the release process.
- _____ Identify the radionuclides of concern. Determine whether the radionuclides of concern exist in background.
- _____ Segregate the site into Class 1, Class 2, and Class 3 areas, based on the presence of potential residual radioactive material.
- _____ Identify the survey units.
- _____ Select representative reference (background) areas for both indoor and outdoor survey areas. Reference areas are selected from non-impacted areas and—
 - _____ are free of residual radioactive material from site operations
 - _____ exhibit similar physical, chemical, and biological characteristics of the survey area
 - _____ have similar construction, but have no history of radioactive operations
- _____ Select measurement method, based on the required Measurement Quality Objectives (MQOs).
 - _____ Determine minimum detectable concentrations (MDCs) (select instrumentation based on the radionuclides present) and match between instrumentation and derived concentration guideline levels (DCGLs)—the selected instruments should be capable of detecting the radionuclides of concern at less than 50 percent of the DCGLs.
 - _____ Determine measurement method uncertainty and compare to the required measurement method uncertainty.
 - _____ Determine ruggedness, specificity, and range and compare to requirements.
- _____ Prepare the area if necessary—clear and provide access to areas to be surveyed.
- _____ Establish reference coordinate systems (as appropriate).

Survey Design

- _____ Enumerate Data Quality Objectives (DQOs) and MQOs: State the objective of the survey, state the null and alternative hypotheses, specify the acceptable decision error rates (Type I [α] and Type II [β]) and requirements for MDC, measurement method uncertainty, ruggedness, specificity, and range.

- _____ Specify sample collection and analysis procedures.
- _____ Determine numbers of data points for statistical tests, depending on whether the radionuclide is present in background. Alternatively, design a site-specific scanning survey using automated equipment recording both data and location.
 - _____ Specify the number of samples/measurements to be obtained, if applicable.
 - _____ Evaluate the power of the statistical tests to determine whether the number of samples is appropriate.
 - _____ Ensure that the sample size is sufficient for detecting areas of elevated activity.
 - _____ Add additional samples/measurements for quality control and to allow for possible loss.
 - _____ Establish the percentage of the survey unit to be surveyed by scanning.
- _____ Specify sampling locations, if appropriate.
- _____ Specify areas and percentage of areas subject to scanning survey.
- _____ Provide information on the survey measurement method.
- _____ Specify methods of data reduction and comparison of survey units to reference areas.
- _____ Provide quality control procedures and a Quality Assurance Project Plan (QAPP) for ensuring the validity of survey data:
 - _____ properly calibrated instrumentation
 - _____ necessary replicate, reference, and blank measurements
 - _____ comparison of field measurement results to laboratory sample analyses
- _____ Document the survey plan (e.g., QAPP, standard operating procedures [SOPs]).

Conducting Surveys

- _____ Perform reference (background) area measurements and sampling.
- _____ Conduct survey activities:
 - _____ Perform surface scans of the Class 1, Class 2, and Class 3 survey units.
 - _____ Conduct surface activity measurements and sampling at previously selected sampling locations, if applicable.
 - _____ Conduct additional direct measurements and sampling at locations based on professional judgment.

- _____ Perform and document any necessary investigation activities, including survey unit reclassification, remediation, and resurvey.
- _____ Document measurement and sample locations; provide information on measurement system MDC and measurement method uncertainty.
- _____ Document any observations, abnormalities, and deviations from the QAPP or SOPs.

Evaluating Survey Results

- _____ Review DQOs and MQOs.
- _____ Perform data reduction on the survey results.
- _____ Conduct a preliminary data review.
- _____ Select the statistical test(s).
- _____ Verify the assumptions of statistical test(s).
- _____ Compare survey results with regulatory DCGLs:
 - _____ Conduct an elevated measurement comparison, if appropriate.
 - _____ Determine the area-weighted average, if appropriate.
 - _____ Conduct Wilcoxon Rank Sum or Sign tests, if appropriate.
 - _____ Conduct a Quantile test or retrospective power analysis, if appropriate.
 - _____ Conduct upper confidence limit comparison, if appropriate.
- _____ Prepare the FSS report.
- _____ Obtain an independent review of the report.

6 FIELD MEASUREMENT METHODS AND INSTRUMENTATION

6.1 Introduction

“Measurement” is used in the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) to mean (1) the act of using a detector and associated recording system to determine the level or quantity of radioactive material on a surface or in a sample of material removed from a medium being evaluated, or (2) the quantity obtained by the act of measuring. Three methods are available for collecting radiation data while performing a survey: direct measurements, scanning, and sampling. This chapter discusses direct measurement methods, scanning, and instrumentation. **Chapter 7** presents the collection and analysis of media samples, while **Appendix H** provides information on the operation and use of individual field and laboratory instruments.

Total surface activities, removable surface activities, and radionuclide concentrations in various environmental media are the radiological parameters typically determined using field measurements and laboratory analyses. Certain radionuclides or radionuclide mixtures may necessitate the measurement of alpha, beta, and gamma radiations. In addition to assessing the whole integrated survey unit area, the planning team should¹ identify (to the extent practicable) any small areas of elevated activity and determine their extent and levels of activity. Due to numerous detector requirements, multiple measurement methods (survey technique and instrument combination) may be needed to adequately measure all of the parameters required to satisfy the release criteria or meet all the objectives of a survey.

Selecting an appropriate measurement method requires evaluation of both Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs) (refer to **Section 2.3.1**). Instruments should be stable and reliable under the environmental and physical conditions where they are used, and their physical characteristics (size and weight) should be compatible with the intended application. Numerous commercial firms offer a wide variety of instruments appropriate for the radiation measurements described in this manual. These firms can provide thorough information regarding capabilities, operating characteristics, limitations, and other aspects of specific equipment.

If the available field measurement methods do not achieve the MQOs, laboratory methods discussed in **Chapter 7** are typically used. In certain cases, a combination of field and laboratory measurements is necessary. Certain radionuclides are difficult to measure at some derived concentration guideline levels (DCGLs)² typically encountered in situ using current state-of-the-art instrumentation and techniques because of the types, energies, and abundances of their radiations. Examples of such radionuclides include very low-energy, pure beta emitters such as lead-210, tritium, strontium-90 (⁹⁰Sr), technetium-99 (⁹⁹Tc), iodine-129, and nickel-63 and low-energy photon emitters such as iron-55 and iodine-125. Pure alpha emitters dispersed in soil or covered with some absorbing layer may not be measurable, because alpha radiation will not penetrate through the media or covering to reach the detector.

¹ MARSSIM uses the word “should” as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM’s survey planning documentation will address how to apply the process on a site-specific basis.

² Throughout this chapter, if the scenario is not explicitly stated, the default terms “derived guideline concentration level” or “DCGL” and “lower bound of the gray region” or “LBGR” will be used. If using Scenario B, please substitute “action level” or “AL” and “upper bound of the gray region” or “UBGR” (i.e., “discrimination limit” or “DL”) for these terms, respectively.

A common example of such a condition would be thorium-230 (^{230}Th) surface contamination covered by paint, dust, oil, or moisture. The U.S. Nuclear Regulatory Commission (NRC) report NUREG-1507, Revision 1, “Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions,” issued August 2020 (NRC 2020), provides information on the extent to which these surface conditions, as well as other environmental conditions, may affect detection capability. In such circumstances, the survey design will usually rely on sampling and laboratory analysis to measure residual activity levels.

Section 6.2 includes a discussion of DQOs and MQOs. Two important MQOs, detection capability and measurement uncertainty, are covered in more detail in **Section 6.3** and **Section 6.4**, respectively. **Section 6.5** discusses the selection of a service provider to perform field data collection activities. The selection of a measurement method is outlined in **Section 6.6**. **Section 6.7** contains information on the data conversion needed to make comparisons with the applicable DCGLs. Radon measurements are considered in **Section 6.8**. **Section 6.9** addresses special equipment.

6.2 Data Quality Objectives

The third step of the DQO process (EPA 2006c) (refer to **Section 2.3.1**) involves identifying the data needs for a survey. One decision that can be made at this step is the selection of field measurement methods that meet the MQOs or determining that sample collection and subsequent laboratory analysis are required.

6.2.1 Identifying Data Needs for Field Measurement Methods

The decision-maker and the survey planning team need to identify the data needs for the survey being performed, including the following:

- type of measurements to be performed (**Chapter 5**)
- radionuclide(s) of interest (**Section 4.5**)
- number of direct measurements to be performed (**Sections 5.3.3–5.3.5**)
- area of survey coverage for surface scans based on survey unit classification (**Section 5.3.6**)
- type and frequency of field quality control (QC) measurements to be performed (**Section 4.8**)
- standard operating procedures (SOPs) to be followed or developed (**Chapter 6**)
- detection capability for each radionuclide of interest (**Section 6.3**)
- measurement method uncertainties (**Section 6.4**)
- cost of the measurement methods being evaluated (both cost per measurement and total cost) (**Appendix H**)
- necessary turnaround time (a potential health and safety concern for situations involving excavations)

- background for the specific radionuclides of interest (**Section 4.5**)
- DCGL for each radionuclide of interest (**Section 4.5**)
- measurement documentation requirements (**Section 5.3.11**)
- measurement tracking requirements (**Section 7.8**)

Some of this information will be supplied by subsequent steps in the DQO process, and several iterations of the process may be necessary to identify the data needs. Consultation with a health physicist or radiochemist may be called for to properly evaluate the information before deciding between field measurement methods or sampling followed by laboratory analytical methods to perform the survey. Many surveys will involve a combination of field measurements and sampling methods to demonstrate compliance with the release criteria.

6.2.2 Measurement Performance Indicators

Measurement performance indicators are used to evaluate the performance of the measurement method. These indicators describe how the measurement method is performing to ensure the survey results are of sufficient quality to meet the survey objectives.

6.2.2.1 Background Measurements/Blanks

Background measurements are direct measurements or scans of materials with little or no radioactive material, other than that present in the natural background of the material. Background measurements include observing the response of the instrument to ambient radiation when the instrument is moved away from the surface being surveyed. These measurements are performed to determine whether the measurement process introduces any increase in instrument signal rate that could impact the measurement method detection capability. Background measurements should be representative of all measurements performed using a specific measurement method (i.e., combination of instrumentation and measurement technique). When practical, the background measurements should be conducted on unimpacted similar or equivalent location(s) as the area being surveyed, with a similar contribution from cosmic radiation. In urban areas, finding similar or equivalent locations may be challenging due to the variety of materials of different origins present in upper soil layers.

Background measurements typically are performed before and after a series of measurements to demonstrate the measurement method was performing adequately throughout the survey. At a minimum, background measurements should be performed at the beginning and end of each shift. When large quantities of data are collected (e.g., scanning measurements) or there is an increased potential for radionuclide contamination of the instrument (e.g., removable or airborne radionuclides), background measurements may be performed more frequently. In general, background measurements should be performed before too many measurements have been performed, since it may not be practical to repeat those measurements if a problem is identified.

A sudden change in the measured background indicates a condition requiring immediate attention. Sudden changes can be caused by the introduction of a radionuclide, a change in ambient background (including a change in cosmic radiation), instrument instability, or contamination of the detector. For radon measurements, such changes can be caused by seasonal, diurnal, or weather-related variabilities. Gradual changes in the measured background indicate a need to inspect all survey areas for sources of radioactive material. Gradual buildup of removable radionuclides over time or instrument drift and deterioration can

result in slowly increasing background measurements. High variability in background measurements can result from instrument instability or improper classification of areas (i.e., high-activity and low-activity areas combined into a single survey unit). It is important to correct any problems with blanks to ensure that the detection capability (refer to **Section 6.3**) is not compromised. For radon measurements, some instruments need to allow for decay of internally built-up radionuclides between samplings; some need to be purged by clean air before measurements.

If smears or swipes, described in more detail in **Section 6.6.1.4**, are used to estimate the amount of removable radioactive material on the surface, then measurement of an unused smear, or blank, provides a background measurement of the instrument used to test the smears.

Currie 1968 defines the blank as the signal resulting from a sample that is identical, in principle, to the sample of interest, except that the residual activity is absent. This determination must be made under the same geometry and counting conditions as used for the sample (Brodsky and Gallagher 1991). In radon measurements, blanks are a type of QC check that quantifies detector response due to factors other than the measurement environment itself (i.e., effects caused during storage, shipping, handling, and transport) (ANSI/AARST 2023).

6.2.2.2 *Replicate/Duplicate Measurements*

Replicate measurements are two or more measurements performed at the same location or on the same sample that are performed primarily to provide an estimate of the random uncertainty for the measurement method. The reproducibility of measurement results should be evaluated by replicates to establish this component of measurement uncertainty (refer to **Section 6.4**).

Replicates typically are performed at specified intervals during a survey (e.g., 5 percent of all measurements or once per day) and should be employed to evaluate each batch of data used to support a decision (e.g., one replicate per survey unit). For site-specific scanning surveys, in which decisions are made based on logged and geolocated measurements, typically 5 percent of all measurements are replicated (i.e., 5 percent of the scanned area is scanned twice).

Estimates of random uncertainty exhibit a range of values and depend in part on the surface being measured and the activity level. Small changes in the random uncertainty are expected, and the acceptable range of variability should be established before initiating data collection activities. The main causes for high random uncertainty include irregular surfaces, the type of surface being measured, counting statistics when the activity levels are low, and instrument contamination.

In radon measurements, duplicate measurements are collocated, simultaneous measurements conducted with instruments or devices that are identical for the purposes of assessing and monitoring the measurement system uncertainty.

6.2.2.3 *Spikes and Standards*

Spikes and standards are materials with known composition and amounts of radioactive material; they are used to evaluate bias in the measurement method and are typically performed periodically during a survey (e.g., 5 percent of all measurements or once per day). When spikes and standards are available, they should be used to evaluate each batch of data supporting a release decision (i.e., at least one spike or standard per survey unit). In radon measurements, spikes are devices or materials that are exposed in a Standard Test Atmosphere for Radon

(STAR) to known radon concentrations for the duration or integrated exposure normally encountered in field measurements (ANSI/AARST 2023).

Tracking the results of measurements with known activity can indicate the magnitude of the systematic uncertainty or drift of the measurement system. In general, activity levels near the DCGLs (or discrimination limits in Scenario B) will provide adequate information on the performance of the measurement system.

6.2.3 Instrument Performance Indicators

Evaluating instrument performance indicators provides information on the operation of the instruments and how they are performing. **Appendix H** contains more information about specific instruments.

6.2.3.1 Performance Tests

Performance tests should be carried out periodically and after any maintenance to ensure that the instruments continue to meet performance requirements for measurements. An example of a performance test is a test for response time. In radon measurements, a performance test is a blind spike in which the radon concentration reported by the device user or laboratory is compared by an independent party, such as a chamber or proficiency program. Performance requirements should be met as specified in the applicable sections of the American National Standards Institute (ANSI) publications ANSI N323AB-2013, “American National Standard for Radiation Instrumentation Test and Calibration, Portable Survey Instruments” (ANSI 2013), ANSI N42.17A-2003, “American National Standard Performance Specifications for Health Physics Instrumentation—Portable Instrumentation for Use in Normal Environmental Conditions” (ANSI 2004), ANSI N42.17C, “American National Standard Performance Specifications for Health Physics Instrumentation—Portable Instrumentation for Use in Extreme Environmental Conditions,” dated March 28, 1990 (ANSI 1990); and ANSI/American Association of Radon Scientists and Technologists (AARST) MS-QA-2023, “Radon Measurement Systems Quality Assurance” (ANSI/AARST 2023). These tests may be conducted as part of the calibration procedure.

6.2.3.2 Functional Tests

Functional tests should be performed before initial use of an instrument and after periods when the instrument was stored for a relatively long time or transported over a long distance. These functional tests should include the following:

- general condition
- battery condition
- verification of current calibration (i.e., check to see that the date due for calibration has not passed)
- source and background response checks (and other tests as applicable to the instrument)
- consistency check

The effects of environmental conditions (e.g., temperature, humidity) and interfering radiation on an instrument should be established before use. The performance of functional tests should be appropriately documented. This may be as simple as a checklist on a survey sheet, or it may include more detailed statistical evaluation, such as a chi-square test (Gilbert 1987).

6.2.3.3 *Instrument Background*

All radiation detection instruments have a background response, even in the absence of a sample or radiation source. In radon measurements, effects on the measurement devices caused by anything outside the environment tested (i.e., during storage, shipping, handling, and transport of measurement devices) should be accounted for by collecting a blank measurement. Inappropriate background correction will result in measurement error and increase the uncertainty of data interpretation.

6.2.3.4 *Efficiency Calibrations*

Knowing the detection efficiency is critical for converting the instrument response to activity (refer to **Section 6.7**, Section 7.8.2.2 of the Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME) (NRC 2009), and Chapter 16 of the Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP) (NRC 2004). Routine performance checks may be used to demonstrate that the system's operational parameters are within acceptable limits, and these measurements typically are included in the assessment of systematic uncertainty. The system's operational parameters may be tracked using control charts.

6.2.3.5 *Energy Calibrations (Spectrometry Systems)*

Spectrometry systems identify radionuclides based on the energy of the detected radiations. A correct energy calibration is critical to accurately identify radionuclides. An incorrect energy calibration may result in misidentification of peaks or failure to identify the radionuclides present.

6.2.3.6 *Peak Resolution and Tailing (Spectrometry Systems)*

The shape of the full energy peak is important for identifying radionuclides and quantifying their activity with spectrometry systems. Poor peak resolution and peak tailing may result in larger measurement uncertainty or in failure to identify the presence of peaks based on shape. Consistent problems with peak resolution indicate the presence of an analytical bias.

6.2.3.7 *Voltage Plateaus (Proportional Counters, Geiger-Mueller Detectors)*

The accuracy of results using a proportional counter or Geiger-Mueller (GM) detector can be affected if the system is not operated with its detector's high voltage adjusted such that it is on a stable portion of the operating plateau.

6.2.3.8 *Self-Absorption, Backscatter, and Crosstalk*

Alpha and beta measurement results can be affected by self-absorption and backscatter. Measurement systems using an electronic discriminator (e.g., gas flow proportional detectors) that simultaneously detect alpha and beta particles can be affected by crosstalk (i.e., overlap of counting pulse height or pulse shape between the alpha signal and the beta signal when the two signals are counted simultaneously, causing the identification of alpha particles as beta particles and vice versa). Accurate differentiation between alpha and beta activity depends on the

assessment and maintenance of information on self-absorption and crosstalk. Accounting for crosstalk in the appropriate channel is needed for accurate activity determinations, and self-absorption needs to be included in measurement method efficiency calculations.

6.3 Detection Capability

The detection capability (sometimes referred to as sensitivity) of a measurement system refers to the net response level that can be expected to be seen using a detector with a fixed level of confidence. This quantity is a factor of both the instrumentation and the technique or procedure being used.

The primary parameters that affect a measurement system's detection capability are the background count rate, the instrument's detection efficiency, and the counting time interval. When making field measurements, the detection capability will usually be less than what can be achieved in a laboratory due to increased background and, often, significantly lower detection efficiency. It is often impossible to guarantee that pure alpha emitters can be detected in situ, because the weathering of aged surfaces will often completely absorb the alpha emissions. NUREG-1507, Revision 1, contains data on many of the parameters that affect detection efficiencies in situ, such as absorption, surface smoothness, and particulate radiation energy.

Measurement methods for materials and equipment are often similar to those that might be used for surface residual radioactive material indoors and out. MARSAME and Chapter 20 of MARLAP can be useful references.

6.3.1 Detection Capability for Direct Measurements

Before performing field measurements using scalers, an investigator must evaluate the detection capability of the equipment proposed for use to ensure that levels below the DCGL can be detected. After a direct measurement has been made, it is then necessary to determine whether the result can be distinguished from the instrument background response of the measurement system. This manual uses the following terms to define detection capability for field measurements and sample analyses:

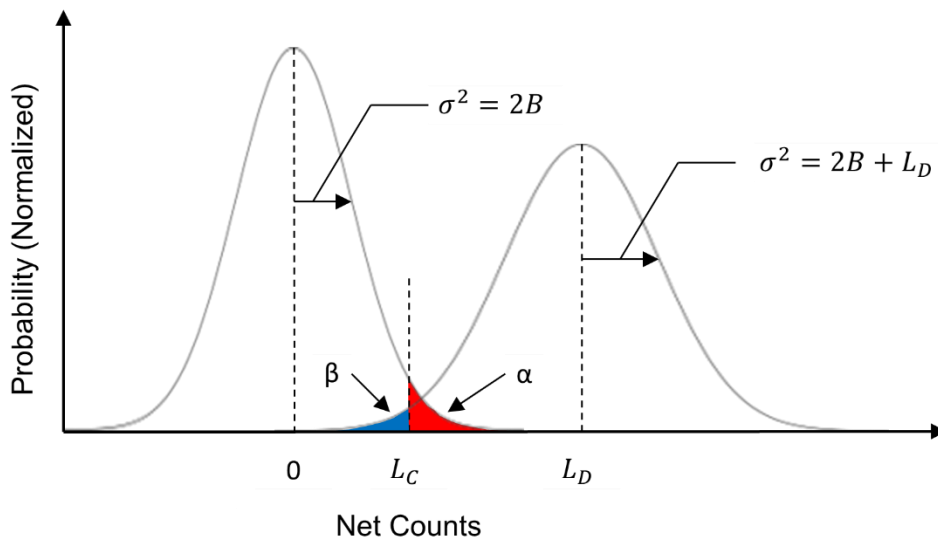
- *Critical level:* The critical level (L_C) is the level at which there is a statistical probability (with a predetermined confidence) of correctly identifying a background value as greater than background.
- *Detection limit:* The detection limit (L_D) is the net response level that can be expected to be seen with a detector with a fixed level of certainty.
- *Minimum detectable concentration:* The minimum detectable concentration (MDC) is the a priori activity concentration that a specific instrument and technique that has a specified probability (typically 95 percent) of producing a net count (or count rate) above the critical level. When stating the detection capability of an instrument, this value should be used. The MDC is the lower limit of detection multiplied by an appropriate conversion factor to give units of activity.

The following discussion provides an overview of the derivation contained in Currie 1968 and a description of how the resulting formulas should be used. Currie 1968 and Altshuler and Pasternack 1963 give details on the derivations involved. The two parameters of interest for a detector system with a background response greater than zero are as follows:

- (1) The critical level is the lower bound on the 95 percent detection interval defined for L_D and is the level at which there is a 5 percent chance of calling a background value “greater than background.” This value should be used when counting samples or making direct radiation measurements. Any net response above this level should be considered as above background (i.e., a net positive result). This will ensure 95 percent detection capability for L_D .
- (2) The detection limit is the net response level, in counts, that can be expected to be seen with a detector with a fixed level of certainty, which is assumed to be 95 percent.

Assuming that a system has a background response, and that random uncertainties and systematic uncertainties are accounted for separately, these parameters can be calculated using Poisson statistics. For these calculations, two types of decision errors should be considered. A Type I error (false positive) occurs when a detector response is considered to be above background when, in fact, only background radiation is present. A Type II error (false negative) occurs when a detector response is considered to be background when, in fact, radiation is present at levels above background. The probability of a Type I error is referred to as α (alpha) and is associated with L_C ; the probability of a Type II error is referred to as β (beta) and is associated with L_D . **Figure 6-1** graphically illustrates the relationship of these terms with respect to each other and to a typical background distribution.³

³ Note that the values of α and β chosen here are for the detection hypothesis test and are always chosen to be 5 percent for comparability purposes. These α and β values are separate and distinct from the values of α and β chosen by the planning team for use in designing site surveys.



- B = background counts (mean)
- L_C = critical level (net counts above background)
- L_D = detection limit (net counts above background)
- α = probability of Type I error
- β = probability of Type II error
- σ^2 = variance

Figure 6-1 Graphically Represented Probabilities for Type I and Type II Errors in Detection Capability for Instrumentation with a Background Response

If α and β are assumed to be equal, the variance (σ^2) of all counting values is assumed to be equal to the values themselves. If the background of the detection system is not well known, then the critical level and the detection limit can be calculated by using the following equations:

$$L_C = k\sqrt{2B} \quad \text{Equation 6-1}$$

$$L_D = k^2 + 2k\sqrt{2B} \quad \text{Equation 6-2}$$

where:

- L_C = critical level (counts)
- L_D = detection limit (counts)
- k = value of the standard normal deviate corresponding to a one-tailed probability level of $(1-\alpha)$ or $(1-\beta)$ where α and β are equal
- B = number of background counts expected to occur while performing an actual measurement

The curve to the left in **Figure 6-1** is the background distribution. The result is a Poisson distribution with a mean⁴ equal to the number of background counts, B , and a variance, σ^2 , equal to B . Note that this distribution accounts only for the expected statistical variation due to the stochastic nature of radioactive decay. Currie 1968 assumed “paired blanks” when deriving the above-stated relationships, which is interpreted to mean that the sample and background count times are the same.

If values of 0.05 for both α and β are selected as acceptable, then $k = 1.645$ (from **Appendix I, Table I-5**), and **Equation 6-1** and **Equation 6-2** can be written as follows:

$$L_C = 2.33\sqrt{B} \quad \text{Equation 6-3}$$

$$L_D = 3 + 4.65\sqrt{B} \quad \text{Equation 6-4}$$

Note: The derivation in Currie 1968 gave the constant factor of 3 in the L_D formula as 2.71, but since that time it has been shown (Brodsky 1992) and generally accepted that a constant of 3 is more appropriate.

Equation 6-3 and **Equation 6-4** apply to situation above in which the sample and background count times are the same. If the sample and background count times are not necessarily the same, if values of 0.05 for both α and β are selected as acceptable, then:

$$L_C = 1.645 \sqrt{B \left(\frac{t_S}{t_B} \right) \left(1 + \frac{t_S}{t_B} \right)} \quad \text{Equation 6-5}$$

$$L_D = 3 + 3.29 \sqrt{B \left(\frac{t_S}{t_B} \right) \left(1 + \frac{t_S}{t_B} \right)} \quad \text{Equation 6-6}$$

where t_S and t_B are the sample and background count times, respectively. Note that if the sample and background count times are equal, then **Equation 6-5** and **Equation 6-6** reduce to **Equation 6-3** and **Equation 6-4**, respectively.

The MDC value should be used when stating the detection capability of an instrument. Again, this value is calculated using the collected background measurement data before any survey unit measurements are made. (The term B can be estimated during planning but should be updated once determined from background measurements.) The MDC is used to estimate the level of activity that can be detected by a given measurement method.

For an integrated measurement over a preset time, the MDC can be obtained from **Equation 6-4** or **Equation 6-6** by multiplying by a factor C . This factor is used to convert from counts to concentration, using **Equation 6-7**:

$$\text{MDC} = C \times (3 + 4.65\sqrt{B}) \quad \text{Equation 6-7}$$

If the sample and background count times are not necessarily the same, and values of 0.05 for both α and β are selected as acceptable, **Equation 6-8** is used:

⁴ In MARSSIM, “average” and “mean” both refer to the arithmetic mean.

$$\text{MDC} = C \times \left[3 + 3.29 \sqrt{B \left(\frac{t_S}{t_B} \right) \left(1 + \frac{t_S}{t_B} \right)} \right] \quad \text{Equation 6-8}$$

The total detection efficiency and other constants or factors represented by C are usually not truly constants. It is likely that at least one of these factors will have an uncertainty associated with it. These varying factors combine into the single constant, C , by which the net count result will be multiplied when converting the final data. If the uncertainty in C varies significantly among measurements, then it might be best to select a value, C' , from the observed distribution of C values that represents a conservative estimate. For example, a value of C might be selected to ensure that at least 95 percent of the possible values of C are less than the chosen value, C' . The MDC calculated in this way helps ensure that the survey results will meet the DQOs. This approach for including uncertainties into the MDC calculation is recommended in both NUREG/CR-4007, "Lower Limit of Detection: Definition and Elaboration of a Proposed Position for Radiological Effluent and Environmental Measurements," issued September 1984 (NRC 1984), and Appendix A to ANSI/HPS N13.30, "Performance Criteria for Radiobioassay," dated January 1, 2011 (ANSI/HPS 2011). Underestimating an MDC can have adverse consequences, especially if activity is not detected but then later detected at a level above the stated MDC of the earlier measurement.

It is better to overestimate the MDC, so that when calculating the MDC and L_C , a measurement system background value should be selected that represents a conservative estimate of what is expected for a particular measurement method. For direct measurements, probes will be moved from point to point; as a result, it is expected that the average background will most likely vary significantly because of variations in background at different point locations, variation of source materials, and changes in geometry and shielding. Ideally, the MDC values should be calculated for each type of area, but again it may be simpler to select a conservative background value and use this in all calculations. However, an overly conservative MDC can result in unrealistically high values that do not reflect the actual measurement conditions. In some cases, the planning team may wish to consult with an expert in the measurement method used to help with developing the MDC.

Example 6-1 illustrates the calculation of an MDC in becquerels (Bq) per square meter (m^2) for an instrument with a 15 square centimeter (cm^2) probe area when the measurement and background counting times are each 1 minute.

Example 6-1: Calculation of the Critical Level (L_C), Detection Limit (L_D), and the MDC

This example illustrates the calculation of the critical level and the MDC in Bq/m² for an instrument with a probe area, W , of 15 cm² when the measurement and background counting times are each 1 minute. The average number of background counts, B , during the count time, T , is 40 counts.

The critical level, L_C , for this example is calculated from **Equation 6-3**:

$$L_C = 2.33\sqrt{B} = 2.33\sqrt{40} = 15 \text{ counts}$$

Only when the total number is greater than 55 counts (15 counts above the average number of background counts expected) is there sufficient evidence that number of counts observed is unlikely the result of natural fluctuations in the background, and therefore some radioactive material is present.

The detection limit, L_D , for this example is calculated from **Equation 6-4**:

$$L_D = 3 + 4.65\sqrt{B} = 3 + 4.65\sqrt{40} = 32 \text{ counts}$$

If the total efficiency (instrument and source), ε_t , is 20 percent (i.e., 0.20 counts per minute [cpm] per disintegrations per minute [dpm]), the conversion factor from cpm to concentration, C , is as shown in **Equation 6-9**:

$$\begin{aligned} C &= \frac{1}{\varepsilon_t \cdot T \cdot W} && \text{Equation 6-9} \\ &= \left[\frac{1}{(0.20 \text{ cpm dpm}^{-1})(1 \text{ minute})(15 \text{ cm}^2)} \right] \left(\frac{\text{Bq}}{60 \text{ dpm}} \right) \left(\frac{100 \text{ cm}^2}{1 \text{ m}^2} \right)^2 \\ &= 55.6 \text{ (Bq/m}^2\text{) (net count)}^{-1} \end{aligned}$$

If the total efficiency (instrument and source), ε_t , is 20 percent (i.e. 0.20 cpm/dpm), then the MDC is calculated from **Equation 6-7**:

$$\begin{aligned} \text{MDC} &= C \cdot [3 + 4.65\sqrt{B}] \\ &= [55.6 \text{ (Bq/m}^2\text{) (net count)}^{-1}] \cdot [32 \text{ counts}] \\ &= 1,800 \text{ Bq/m}^2 \text{ (1,080 dpm/100 cm}^2\text{)} \end{aligned}$$

Given the above scenario, if a person asked what level of residual radioactive material could be detected 95 percent of the time using this method, the answer would be 1,800 Bq/m² (1,080 dpm/100 cm²). When performing measurements using this method, any count yielding greater than 55 total counts, or greater than 15 net counts (55 – 40 = 15), during a period of 1 minute would be regarded as greater than background.

MDC values for other counting conditions may be derived from **Equation 6-5** and MARLAP Chapter 20, depending on the detector, radionuclides of concern, and differing background and sample count times. For example, it may be necessary to determine what level of residual radioactive material can be detected with any probe when the area is smaller than the probe

active area. **Table 6-1** lists several common field survey detectors with estimates of MDC values for uranium-238 (^{238}U) on a smooth, flat plane. As such, these represent minimum MDCs (i.e., MDC values that are lower than those actually achievable in practice). Appropriate site-specific MDC values should be determined using the DQO process.

Example 6-2 illustrates the calculation of an MDC in Bq/m^2 for an instrument with a 125 cm^2 probe area when the measurement and background counting times are not the same.

Example 6-2: This example illustrates the calculation of the following for a direct (static) surface activity concentration measurement when the measurement count time and background count time are not necessarily the same. The following values are determined:

- the critical value used to determine whether radioactive material above background is likely present
- the detection limit used to estimate the number of counts that can be reliably detected above background
- the minimum detectable surface activity concentration that can be reliably detected

For this example, the source efficiency of the radioactive material on the surface is 0.5. The area of the detector window on the survey probe is 125 cm^2 , and the instrument efficiency is $0.4037 \text{ counts per second (cps) Bq}^{-1}$. During a 2-minute measurement taken in the reference area, 595 counts were observed.

Using the expression for the critical value corresponding to a value of $\alpha = 0.05$ (i.e., there is no more than a 5 percent chance of incorrectly deciding there is radioactive material present when there is no radioactive material present), the critical value, L_C (i.e., the number of net counts observed above the expected number in the reference area), is as follows, using **Equation 6-5**:

$$L_C = 1.645 \sqrt{B \left(\frac{t_S}{t_B} \right) \left(1 + \frac{t_S}{t_B} \right)} = 1.645 \sqrt{\bar{R}_B t_S \left(1 + \frac{t_S}{t_B} \right)}$$

where:

- $\bar{R}_B$ = count rate for the background measurement made in the reference area
- t_B = count time for the background measurement made in the reference area
- t_S = count time for measurements in the survey unit

The product of the count rate and count time for the background measurement made in the reference area is equal to the number of counts observed:

$$\bar{R}_B t_B = \bar{n}_B = 595$$

The count times for measurements in the survey unit and the reference area are 30 seconds (s) and 120 seconds, respectively. The number of counts expected during a measurement in the survey unit when there is no radioactive material is present is as follows:

$$\bar{R}_B t_{S+B} = \frac{t_{S+B}}{t_B} \bar{n}_B = \left(\frac{30 \text{ s}}{120 \text{ s}} \right) (595 \text{ counts}) = 149 \text{ counts}$$

The critical value, L_C , is as follows:

$$L_C = 1.645 \sqrt{(149 \text{ counts}) \left(1 + \frac{30 \text{ s}}{120 \text{ s}}\right)} = 22 \text{ counts}$$

The critical value is 22 net counts or 171 total counts in a 30-second measurement.

Using the expression for the detection limit corresponding to a value of $\beta = 0.05$ (i.e., there is no more than a 5 percent chance of incorrectly deciding there is no radioactive material present when there is radioactive material present), the detection limit, L_D (i.e., the number of net counts observed above the expected number in the reference area), is as follows:

$$\begin{aligned} L_D &= 3 + 3.29 \sqrt{\bar{R}_B t_{S+B} \left(1 + \frac{t_{S+B}}{t_B}\right)} \\ &= 3 + 3.29 \sqrt{(149 \text{ counts}) \left(1 + \frac{30 \text{ s}}{120 \text{ s}}\right)} \\ &= 48 \text{ counts} \end{aligned}$$

The detection limit would be 48 net counts or 197 total counts. The MDC is shown in **Equation 6-10**:

$$\text{MDC} = \frac{L_D/t_S}{\varepsilon_s \cdot W \cdot \varepsilon_i} \quad \text{Equation 6-10}$$

where:

- ε_s = source efficiency of the radioactive material on the surface
- W = area of the detector window
- ε_i = instrument (i.e., detector probe) efficiency

Evaluating the MDC gives the following result:

$$\text{MDC} = \frac{(48 \text{ counts})/(30 \text{ s})}{(0.5)(1.25 \times 10^{-2} \text{ m}^2)(0.4074 \text{ cps Bq}^{-1})} = 628 \text{ Bq/m}^2$$

The MDC for a 30-second measurement in the survey unit is 628 Bq/m². The MDC should be used to estimate the smallest concentration of radioactive material that will result in a net reading above the critical level with a specified probability, when comparisons between net measurements and the critical level are used to determine whether radioactive material (above background) is present or not.

Table 6-1 provides examples of potential detection capabilities.

6.3.2 Detection Capability for Scans

The ability to identify a small area of elevated levels of radioactive material during surface scanning is dependent upon the surveyor's skill in recognizing an increase in the output of an

instrument. For notation purposes, this section uses the term “detection capability” (sometimes referred to as scanning sensitivity) to describe the ability of a surveyor to detect a predetermined level of residual radioactive material.

Table 6-1 Examples of Estimated Detection Capabilities for Alpha and Beta Survey Equipment (Static 1-Minute Counts for ^{238}U Calculated Using Equations 6-3, 6-4, and 6-5)

Option	Detector	Probe Area (cm ²)	Background (cpm)	Efficiency (cpm/dpm)	Approximate Detection Level		
					L_C (counts)	L_D (counts)	MDC (Bq/m ²) ^a
1	Alpha proportional	50	1	0.15	2	7	150
2	Alpha proportional	100	1	0.15	2	7	83
3	Alpha proportional	600	5	0.15	5	13	25
4	Alpha scintillation	50	1	0.15	2	7	150
5	Beta proportional	100	300	0.20	40	83	700
6	Beta proportional	600	1,500	0.20	90	183	250
7	Beta GM pancake	15	40	0.20	15	32	1,800

^a Assumes that the size of the area of radioactive material is at least as large as the probe area.

Many of the radiological instruments and monitoring techniques typically used for occupational health physics activities may not provide the detection capabilities necessary to detect activity at the action level and therefore cannot demonstrate compliance with release criteria. The detection capability for a given application can be improved (i.e., lower the MDC) to a point by (1) selecting an instrument with a higher detection efficiency or a lower background, (2) decreasing the scanning speed, or (3) increasing the size of the effective probe area.

Scanning is usually performed during radiological surveys to identify the presence of any areas of elevated activity. The probability of detecting residual radioactive material in the field not only depends on the detection capability of the survey instrumentation when used in the scanning mode of operation, but it also is affected by the surveyor’s ability (i.e., human factors). The surveyor must decide whether the signals represent only the background activity or residual radioactive material in excess of background. Lower levels of residual radioactive material can be detected by increasing the detection capability (i.e., detection of residual radioactive material is inversely proportional to the integrated detection capability). Accounting for these human factors represents a significant change from previous methods of estimating detection capabilities for scans.

An empirical method for evaluating the detection capability for surveys is by actual experimentation or by simulating an experimental setup using computer software. The following steps provide a simple example of how one can perform this empirical evaluation:

- (1) Select a desired radionuclide activity level.
- (2) Determine the response of the detector to be used for the selected radionuclide activity level.
- (3) Construct a test source that will give a detector count rate equivalent to the detector response, determined in Step 2. The count rate is equivalent to what would be expected from the detector when placed on an actual area with residual radioactive material equal in value to that selected in Step 1.
- (4) Move the detector of choice over the source at different scan rates until an acceptable speed is determined.

The most useful aspect of this approach is that the source can then be used to indicate what level of residual radioactive material can be identified with the scan. This can be used to demonstrate the expected response of the detector and how fast a survey can be performed while still enabling confidence about detecting the residual radioactive material at or less than the level of concern.

The remainder of this section provides information regarding the underlying processes involved when performing scanning surveys for alpha-, beta-, and gamma-emitting radionuclides. This information can be used for estimating realistic detection capabilities for scans.

6.3.2.1 *Scanning for Beta and Gamma Emitters*

The scan MDC depends on several factors:

- the intrinsic characteristics of the detector (e.g., efficiency, physical probe area)
- the nature (type and energy of emissions) and relative distribution of residual radioactive material (point versus distributed source and depth of residual radioactive material)
- scan rate
- environmental issues that may affect the surveyor's performance (e.g., fatigue, noise, level of training, experience)
- expectation about the presence of residual radioactive material (e.g., if a surveyor believes that the potential for residual radioactive material is very low, as in a Class 3 area, a relatively large signal may be required for the surveyor to conclude that residual radioactive material is present)

6.3.2.1.1 Signal Detection Theory

Personnel conducting radiological surveys for residual radioactive material at sites must interpret the audible output of a portable survey instrument to determine when the signal ("clicks") exceeds the background level by a margin sufficient to conclude that residual radioactive material is present. It is difficult to detect low levels of residual radioactive material, because both the signal and the background vary widely. Signal detection theory provides a framework for the task of deciding whether the audible output of the survey meter during scanning is due to background or signal plus background levels. An index of sensitivity (d') that represents the distance between the means of the background and background plus signal

(refer to **Figure 6-1** for determining L_D), in units of their common standard deviation, can be calculated for various decision errors (true positive detection and false positive rate).

As an example, for a true positive detection rate of 95 percent (complement of a false negative rate of 5 percent) and a false positive rate of 5 percent, d' is 3.28 (similar to the static MDC for the same decision error rates). The index of sensitivity is independent of human factors; therefore, the ability of an ideal observer (theoretical construct) may be used to determine the minimum d' that can be achieved for particular decision errors. The ideal observer makes optimal use of the available information to maximize the percent correct responses, providing an effective upper bound against which to compare actual surveyors. **Table 6-2** lists selected values of d' from Table 6.1 in NUREG-1507, Revision 1.

Table 6-2 Index of Sensitivity (d') Values for Selected True Positive and False Positive Proportions

False Positive Proportion	True Positive Proportion ¹							
	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
0.05	1.90	2.02	2.16	2.32	2.48	2.68	2.92	3.28
0.10	1.54	1.66	1.80	1.96	2.12	2.32	2.56	2.92
0.15	1.30	1.42	1.56	1.72	1.88	2.08	2.32	2.68
0.20	1.10	1.22	1.36	1.52	1.68	1.88	2.12	2.48
0.25	0.93	1.06	1.20	1.35	1.52	1.72	1.96	2.32
0.30	0.78	0.91	1.05	1.20	1.36	1.56	1.80	2.16
0.35	0.64	0.77	0.91	1.06	1.22	1.42	1.66	2.02
0.40	0.51	0.64	0.78	0.93	1.10	1.30	1.54	1.90
0.45	0.38	0.52	0.66	0.80	0.97	1.17	1.41	1.77
0.50	0.26	0.38	0.52	0.68	0.84	1.04	1.28	1.64
0.55	0.12	0.26	0.40	0.54	0.71	0.91	1.15	1.51
0.60	0.00	0.13	0.27	0.42	0.58	0.82	1.02	1.38

¹ $d' = k(\alpha) + k(\beta)$, where k values are from **Table I-1** (one-tailed confidence intervals).

6.3.2.1.2 Two Stages of Scanning

The framework for determining the scan MDC comes from NUREG-1507, Revision 1, and is based on the premise that there are two stages of scanning. That is, surveyors do not make decisions based on a single indication; rather, upon noting an increased number of counts, they pause briefly and then decide whether to move on or take further measurements. Thus, scanning consists of two components: continuous monitoring and stationary sampling. In the first component, characterized by continuous movement of the probe, the surveyor has only a brief “look” at potential sources, determined by the scan speed. The surveyor’s willingness to decide that a signal is present at this stage is likely to be liberal, in that the surveyor should respond positively on scant evidence, because the only “cost” of a false positive is a little time. The second component occurs only after a positive response was made at the first stage. This response is marked by the surveyor interrupting their scanning and holding the probe stationary for a period of time while comparing the instrument output signal during that time to the background counting rate. Owing to the longer observation interval, detection capability is

relatively high. For this decision, the criterion should be stricter, as the cost of a “yes” decision is to spend considerably more time taking a static measurement or a sample. Because scanning can be divided into two stages, it is necessary to consider the survey’s scan detection capability for each stage. Typically, the minimum detectable count rate (MDCR) associated with the first scanning stage will be greater due to the brief observation intervals of continuous monitoring—provided that the length of the pause during the second stage is significantly longer. Typically, observation intervals during the first stage are on the order of 1 or 2 seconds, while the second-stage pause may be several seconds longer. The greater value of MDCR from each of the scan stages is used to determine the detection capability.

6.3.2.1.3 Determination of Minimum Detectable Count Rate and Use of Surveyor Efficiency

The minimum detectable number of net source counts in the observation interval is given by s_i . Therefore, for an ideal observer, the number of source counts required for a specified level of performance can be arrived at by multiplying the square root of the number of background counts by the detectability value associated with the desired performance (as reflected in d') as shown in **Equation 6-11**:

$$s_i = d' \sqrt{b_i} \quad \text{Equation 6-11}$$

where the value of d' is selected from **Table 6-2** based on the required true positive and false positive rates, and b_i is the number of background counts in the observation interval. The MDCR can be calculated using **Equation 6-12**:

$$\text{MDCR} = \frac{s_i}{\Delta t_i} \quad \text{Equation 6-12}$$

where Δt_i is the observation interval (i.e., the amount of time the active area of the probe is over an assumed area of residual radioactivity.) **Example 6-3** illustrates the calculation of the MDCR for a probe with a background count rate of 1,500 cpm for a 1-second interval.

Example 6-3: Calculation of the MDCR for the First Stage of Scanning

Estimate the MDCR by scanning in an area with a background of 1,500 cpm. Note that the MDCR must be considered for both scan stages, and the more conservative value is selected as the minimum count rate that is detectable. It will be assumed that a typical source remains under the probe for 1 second during the first stage; therefore, the average number of background counts in the observation interval is as follows:

$$b_i = (1,500 \text{ cpm})(1 \text{ s}) \left(\frac{\text{minute}}{60 \text{ s}} \right) = 25 \text{ counts}$$

where b_i is the average number of background counts in an observation interval. Furthermore, it can be assumed that at the first scanning stage, a high rate (e.g., 95 percent) of true positive detections is required and that a correspondingly high rate of false positives (e.g., 60 percent) will be tolerated. From **Table 6-2**, the value of d' , representing this performance goal is 1.38. The net source counts needed to support the specified level of performance (assuming an ideal observer) will be estimated by multiplying 5 (the square root of 25) by 1.38. Thus, the net source counts, s_i , in interval Δt_i (in seconds) needed to yield

better than 95 percent detections with about 60 percent false positives is given using **Equation 6-11** as follows:

$$s_i = 1.38 \times \sqrt{25} = 6.9$$

The MDCR, in cpm, may be calculated using **Equation 6-12**:

$$\text{MDCR} = \frac{s_i}{\Delta t_i} = \left(\frac{6.9 \text{ counts}}{1 \text{ s}} \right) \left(\frac{60 \text{ s}}{\text{minute}} \right) = 414 \text{ cpm}$$

where s_i is the minimum detectable number of net source counts and is over the observation interval specified by t_i . For this example, the MDCR is equivalent to 414 cpm above a background of 1,500 cpm (1,914 cpm gross).

Example 6-4 illustrates the determination of the detection limit for the ideal observer (MDCR) at the first scanning stage for various background levels for a true positive proportion of 95 percent and false positive proportion of 60 percent.

Example 6-4: Determination of the Detection Limit for the Ideal Observer

The table below provides the MDCR and L_D for the ideal observer at the first scanning stage for various background levels, based on an index of sensitivity (d') of 1.38 for a true positive proportion of 95 percent (refer to **Table 6-2**), a false positive proportion of 60 percent, and a 2-second observation interval.

Detection Capability of the Ideal Observer for Various Background Levels

Background (cpm)	MDCR (net cpm)	Scan Sensitivity (gross cpm) ^a
45	50	95
60	60	120
260	120	380
300	130	430
350	140	490
400	150	550
1,000	240	1,240
3,000	410	3,410
4,000	480	4,480

^a The detection capability of the ideal observer during the first scanning stage is based on an index of sensitivity (d') of 1.38 and a 2-second observational interval.

The minimum number of source counts required to support a given level of performance for the final detection decision (second scan stage) can be estimated using the same method. As explained above, the performance goal at this stage will be more demanding. **Example 6-5**

illustrates the calculation of the MDCR for the probe from **Example 6-3** but with an interval of 4 seconds instead of 1 second.

Example 6-5: Calculation of the MDCR for the Second Stage of Scanning

The required rate of true positives remains high (e.g., 95 percent), but fewer false positives (e.g., 20 percent) can be tolerated, such that the index of sensitivity (d') (from **Table 6-2**) is now 2.48. One will assume that the surveyor typically stops the probe over a suspect location for about 4 seconds before making a decision, so that the average number of background counts in an observation interval is as follows:

$$b_i = (1,500 \text{ cpm})(4 \text{ s}) \left(\frac{\text{minute}}{60 \text{ s}} \right) = 100 \text{ counts}$$

where b_i is the average number of background counts in an observation interval. Therefore, the minimum detectable number of net source counts, s_i , is calculated using **Equation 6-11**:

$$s_i = d' \sqrt{b_i} = 2.48 \times \sqrt{100} = 24.8$$

The MDCR is calculated using **Equation 6-12**:

$$\text{MDCR} = \frac{s_i}{\Delta t_i} = \left(\frac{24.8 \text{ counts}}{4 \text{ s}} \right) \left(\frac{60 \text{ s}}{\text{minute}} \right) = 372 \text{ cpm}$$

where s_i is the minimum detectable number of net source counts and Δt_i is the observation interval. The MDCR is 372 cpm net, or 1,872 cpm gross. The value associated with the first scanning stage (**Example 6-3**: 414 cpm net or 1,914 cpm gross) will typically be greater, because of the relatively brief intervals assumed.

Laboratory studies using simulated sources and backgrounds were performed to assess the abilities of surveyors under controlled conditions. NUREG/CR-6364, "Human Performance in Radiation Survey Scanning," issued March 1998 (NRC 1998c), and NUREG-1507, Revision 1, describe the methodology and analysis of results for these studies, which clearly illustrate how differences between ideal conditions and practical application can affect detection capability. These differences can include signal detection (when relying on visual or audible detection) and other human factors, such as variability in scan speed and detector-source geometry. The surveyor's actual performance as compared with the ideal possible performance (using the ideal observer construct) gave an indication of the efficiency of the surveyors. Based on the results of the confidence rating experiment, this surveyor efficiency (p) was estimated to be between 0.5 and 0.75.

MARSSIM recommends assuming a surveyor efficiency value at the lower end of the observed range (i.e., 0.5) when making MDC estimates. Thus, the required number of net source counts, $\text{MDCR}_{\text{surveyor}}$, is determined by dividing the MDCR by the square root of p , as in **Equation 6-13**:

$$\text{MDCR}_{\text{surveyor}} = \frac{\text{MDCR}}{\sqrt{p}} \quad \text{Equation 6-13}$$

Example 6-6 shows the calculation of the surveyor MDCR for **Example 6-3**.

Example 6-6: Calculation of the Surveyor MDCR for Example 6-3

Using the data from **Example 6-1**, the surveyor MDCR is calculated using **Equation 6-13**:

$$\text{MDCR}_{\text{surveyor}} = \frac{\text{MDCR}}{\sqrt{p}} = \frac{414 \text{ cpm}}{\sqrt{0.5}} = 585 \text{ cpm}$$

The surveyor MDCR is 585 cpm net (2,085 cpm gross).

6.3.2.1.4 Scan Minimum Detectable Concentrations for Structure Surfaces and Land Areas

The survey design for determining the number of data points for areas of elevated activity (refer to **Section 5.3.5**) depends on the scan MDC for the selected instrumentation. In general, alpha or beta scans are performed on structure surfaces to satisfy the elevated activity measurements survey design, and gamma scans are performed for land areas. Because of low background levels for alpha emitters, the approach described here is not generally applied to determining scan MDCs for alpha emitters; rather, **Section 6.3.2.2** describes an appropriate method for determining alpha scan MDCs for building surfaces. In any case, the data requirements for assessing potential elevated areas of direct radiation depend on the scan MDC of the survey instrument (e.g., floor monitor, GM detector, sodium iodide [NaI] scintillation detector).

6.3.2.1.5 Scan Minimum Detectable Concentrations for Building/Structure Surfaces

The scan MDC is determined from the MDCR by applying conversion factors that account for detector and surface characteristics and surveyor efficiency.⁵ As discussed above, the MDCR accounts for the background level, performance criterion (d'), and observation interval. The observation interval during scanning is the actual time that the detector can respond to the source of residual radioactive material. This interval depends on the scan speed, detector size in the direction of the scan, and the dimensions of the area of elevated activity. Because the actual dimensions of potential areas of elevated activity in the field cannot be known a priori, MARSSIM recommends postulating a certain area (e.g., 50–200 cm²) and then selecting a scan rate that provides a reasonable observation interval.

Finally, the scan MDC in units of dpm/100 cm² for structure surfaces may be calculated using **Equation 6-14**:

$$\text{Scan MDC} = \frac{\text{MDCR}}{\sqrt{p} \varepsilon_i \varepsilon_s \frac{W}{100}} \quad \text{Equation 6-14}$$

where:

ε_i	=	instrument efficiency
ε_s	=	source efficiency
p	=	surveyor efficiency
W	=	physical probe area (cm ²)
100	=	a unit conversion from (cm ²) ⁻¹ to (100 cm ²) ⁻¹

⁵ **Section 6.6.4** provides more information on instrument and source efficiency.

Consideration may need to be given to the size of the detector probe relative to the size of the postulated hot spot size. For example, a large-area floor monitor with a probe area of approximately 600 cm² would fully cover the area of the postulated hot spot in the scenario presented above (i.e., 50–200 cm²). In this situation, a probe area correction is likely not appropriate. **Example 6-7** illustrates the calculation of the scan MDC for the probe in **Example 6-4** for ⁹⁹Tc.

Example 6-7: Calculation of the Scan MDC for the Probe in Example 6-4

As an example, the scan MDC (in dpm/100 cm²) for ⁹⁹Tc on a concrete surface may be determined for a background level of 300 cpm and a 2-second observation interval using a hand-held gas proportional detector (126 cm² probe area). For a specified level of performance at the first scanning stage of 95 percent true positive rate and 60 percent false positive rate (and assuming the second stage pause is long enough to ensure that the first stage is more limiting), d' equals 1.38 (**Table 6-2**) and the MDCR is 130 cpm (**Example 6-4**). Using a surveyor efficiency of 0.5, and assuming instrument and source efficiencies of 0.36 and 0.25, respectively, the scan MDC is calculated using **Equation 6-14**:

$$\text{Scan MDC} = \frac{\text{MDCR}}{\sqrt{p} \varepsilon_t \varepsilon_s \frac{W}{100}} = \frac{130 \text{ cpm}}{\sqrt{0.5} (0.36 \times 0.25 \text{ cpm/dpm}) \left(\frac{126 \text{ cm}^2}{100} \right)} = 1,640 \text{ dpm/100 cm}^2$$

The scan MDC for ⁹⁹Tc is 1,640 dpm/100 cm².

In some cases, planners may wish to use a conservative estimate for the efficiency to ensure that the calculated MDC is not too optimistic. NUREG-1507, Revision 1, contains additional examples for calculating the scan MDC.

6.3.2.1.6 Scan Minimum Detectable Concentrations for Land Areas

In addition to the MDCR and detector characteristics, the scan MDC for land areas is based on the area of elevated activity, depth of residual radioactive material, and the radionuclide (i.e., energy and yield of gamma emissions).

Thallium-activated NaI (NaI(Tl)) scintillation detectors are generally used for scanning land areas. Typically, the detectors are placed just above the surveyed area. By hand, this can be done by suspending the detector from the surveyor's hand by a rope. By mechanical means, the detector can be fixed from an automated device.

An overview of the approach used to determine scan MDCs for land areas follows. The NaI(Tl) scintillation detector background level and scan rate (observation interval) are postulated, and the MDCR for the ideal observer, for a given level of performance, is obtained. After a surveyor efficiency is selected, the ratio between the surveyor MDCR (MDCR_{surveyor}) and the radionuclide concentration in soil, in Bq/kilogram (kg) or picocuries (pCi)/gram (g) is determined. This correlation requires two steps: (1) the relationship between the detector's net count rate to net exposure rate (cpm per microrentgens [μR]/hour [h]) is established, and (2) the conversion factor between the concentration of residual radioactive material and exposure rate is determined (exposure rate [μR/h] per activity concentration [pCi/g or Bq/kg]).

For a particular gamma energy, the relationship of NaI(Tl) scintillation detector count rate and exposure rate may be determined analytically (in cpm per μR/h). NUREG-1507, Revision 1,

provides the approach used to determine the gamma fluence rate necessary to yield a fixed exposure rate (1 $\mu\text{R/h}$) as a function of gamma energy. The NaI(Tl) scintillation detector response (in cpm) is related to the fluence rate at specific energies, considering the detector's efficiency (probability of interaction) at each energy. From this, the values for NaI(Tl) detector count rate versus exposure rates for varying gamma energies are determined. After the relationship between the NaI(Tl) detector response and the exposure rate is established, the $\text{MDCR}_{\text{surveyor}}$ (in cpm) of the NaI(Tl) detector can be related to the minimum detectable exposure rate (MDER) using **Equation 6-15**:

$$\text{MDER} = \frac{\text{MDCR}_{\text{surveyor}}}{\text{Ratio of Count Rate to Exposure Rate}} \quad \text{Equation 6-15}$$

The MDER is used to determine the minimum detectable radionuclide concentration (i.e., the scan MDC) by modeling a specified small area of elevated activity and then dividing the MDER by the exposure rate conversion factor using **Equation 6-16**:

$$\text{Scan MDC} = \frac{\text{MDER}}{\text{Exposure Rate Conversion Factor}} \quad \text{Equation 6-16}$$

Example 6-8 illustrates the calculation of the scan MDC for cesium-137 (^{137}Cs) using a 38 millimeter (mm) by 32 mm (1.5 inch [in.] by 1.25 in.) NaI(Tl) scintillation detector.

Example 6-8: Calculation of a Scan MDC for ^{137}Cs

Modeling (using MicroShield 5.05™) of the small area of elevated activity (soil concentration) is used to determine the net exposure rate produced by a radionuclide concentration at a distance 10 centimeters (cm) above the source. This position is selected because it relates to the average height of the NaI(Tl) scintillation detector above the ground during scanning. The factors considered in the modeling include the following:

- radionuclide of interest (considering all gamma emitters for decay chains)
- expected concentration of the radionuclide of interest
- areal dimensions of the area of elevated activity
- depth of the area of elevated activity
- height of detector above the surface
- density and moisture content of soil

Modeling analyses are conducted by selecting a radionuclide (or radioactive material decay series) and then varying the concentration of the radionuclide. The other factors are held constant—the areal dimension of a cylindrical volume of soil containing elevated activity is 0.25 m² (radius of 28 cm), the depth of the area of elevated activity is 15 cm, the detector height is 10 cm above the surface, and the density of soil is 1.6 g per cubic centimeter. The soil was modeled as 50 percent aluminum and 50 percent carbon by weight. The objective is to determine the radionuclide concentration that is correlated to the minimum detectable net exposure rate.

The scan MDC for ^{137}Cs using a 38 mm by 32 mm (1.5 in. by 1.25 in.) NaI(Tl) scintillation detector is considered in detail. Assume that the background level is 4,000 cpm and that the desired level of performance, 95 percent true positive detections and 60 percent false positive rate, results in a d' of 1.38. The scan rate of 0.5 meter (m)/s provides an observation interval

of 1 second (based on a diameter of about 56 cm for the area of elevated activity). The $MDCR_{\text{surveyor}}$ may be calculated assuming a surveyor efficiency (p) of 0.5, as follows:

$$b_i = (4,000 \text{ cpm}) \times (1 \text{ s}) \times (1 \text{ min}/60 \text{ s}) = 66.7 \text{ counts}$$

$$MDCR = d' \sqrt{b_i} \times (60 \text{ s}/1 \text{ min}) = (1.38) \times (\sqrt{66.7}) \times (60 \text{ s}/1 \text{ min}) = 680 \text{ cpm}$$

$$MDCR_{\text{surveyor}} = \frac{MDCR}{\sqrt{p}} = \frac{680 \text{ cpm}}{\sqrt{0.5}} = 960 \text{ cpm}$$

The corresponding MDER is determined for this detector and radionuclide. The manufacturer of this particular 38 mm by 32 mm (1.5 in. by 1.25 in.) NaI(Tl) scintillation detector quotes a count rate to exposure rate ratio for ^{137}Cs of 350 cpm per $\mu\text{R}/\text{h}$, which is equivalent to 1.36 cpm per picocoulomb (pC)/kg/h, which can be converted into $\mu\text{R}/\text{h}$. The MDER can be calculated by dividing the $MDCR_{\text{surveyor}}$ by the exposure rate ratio for ^{137}Cs , as shown below:

$$MDER = \frac{960 \text{ cpm}}{1.36 \text{ cpm}/(\text{pC}/\text{kg})/\text{h}} = 706 (\text{pC}/\text{kg})/\text{h} (2.74 \mu\text{R}/\text{h})$$

Both ^{137}Cs and its short-lived progeny, barium-137 ($^{137\text{m}}\text{Ba}$), are chosen from the MicroShield® library. The source activity and other modeling parameters are entered into the modeling code. The source activity is selected based on an arbitrary concentration of 185 Bq/kg (5 pCi/g). The modeling code performed the appropriate calculations and determined an exposure rate of 337 pC/kg/h (1.307 $\mu\text{R}/\text{h}$), which accounts for buildup.

Finally, the radionuclide concentrations of ^{137}Cs and $^{137\text{m}}\text{Ba}$ (scan MDC) necessary to yield the MDER of 706 pCi/kg/h (2.74 $\mu\text{R}/\text{h}$) may be calculated using the following formula:

$$\text{scan MDC} = \frac{706 \text{ pC}/\text{kg}/\text{h}}{\left(\frac{337 \text{ pC}/\text{kg}/\text{h}}{185 \text{ Bq}/\text{kg}} \right)} = 390 \text{ Bq}/\text{kg}$$

The scan MDC for ^{137}Cs using a 38 mm by 32 mm (1.5 in. by 1.25 in.) NaI(Tl) scintillation detector, rounded to the appropriate number of significant digits, is 390 Bq/kg (11 pCi/g).

It must be emphasized that although a single scan MDC value can be calculated for a given radionuclide, other scan MDC values may be equally justifiable, depending on the values chosen for the various factors, including the MDCR (background level, acceptable performance criteria, observation interval), surveyor efficiency, detector parameters, and the modeling conditions of the residual radioactive material (i.e., the dimensions of the volume of soil containing elevated activity.) It should also be noted that determination of the scan MDC for radioactive materials—such as uranium and thorium—must consider the gamma radiation emitted from the entire decay series. NUREG-1507, Revision 1, provides a detailed example of how the scan MDC can be determined for enriched uranium.

Example 6-8 uses ^{137}Cs as the radionuclide, which is the same radionuclide that is used to calibrate the instrument. When conducting gamma surveys for radionuclides other than ^{137}Cs —the most common instrument calibration source—instruments may underestimate or overestimate the source strength because of the different energies of the gamma rays that are

emitted. This uncertainty can be reduced or eliminated by cross calibrating the detector to energy-compensated detectors, such as pressurized ion chambers, or the instrument can be calibrated to the specific radionuclide of concern.

Table 6-3 provides scan MDCs for common radionuclides and radioactive materials in soil. It is important to note that the variables used in the above examples to determine the scan MDCs for the 38 mm by 32 mm (1.5 in. by 1.25 in.) NaI(Tl) scintillation detector (i.e., the $MDCR_{surveyor}$ detector parameters [e.g., cpm per $\mu R/h$], and the characteristics of the area of elevated activity) have all been held constant to facilitate the calculation of scan MDCs provided in **Table 6-3**. The benefit of this approach is that generally applicable scan MDCs are provided for different radionuclides. Additionally, the relative detectability of different radionuclides is evident because the only variable in **Table 6-3** is the nature of the radionuclide.

As noted above, the scan MDCs calculated using the approach in this section are dependent on several factors. One way to validate the appropriateness of the scan MDC is by tracking the levels of residual radioactive material (both surface activity and soil concentrations) identified during investigations performed as a result of scanning surveys. The measurements performed during these investigations may provide an a posteriori estimate of the scan MDC that can be used to validate the a priori scan MDC used to design the survey.

Table 6-3 NaI(Tl) Scintillation Detector Scan MDCs for Common Radionuclides and Radioactive Materials

Radionuclide/ Radioactive Material	1.25 in. by 1.5 in. NaI Detector ^a	1.25 in. by 1.5 in. NaI Detector ^a	2 in. by 2 in. NaI Detector ^a	2 in. by 2 in. NaI Detector ^a
	Scan MDC (Bq/kg)	Weighted cpm/ $\mu R/h$	Scan MDC (Bq/kg)	Weighted cpm/ $\mu R/h$
Americium-241	1,650	5,830	1,170	13,000
Cobalt-60	215	160	126	430
Cesium-137	385	350	237	900
Thorium-230	111,000	4,300	78,400	9,580
Radium-226 (Individual radionuclide, in equilibrium with progeny)	167	300	104	760
Thorium-232 decay series (Sum of all radionuclides in the thorium decay series)	1,050	340	677	830
Thorium-232 (Individual radionuclide, in equilibrium with progeny in decay series)	104	340	66.6	830
Depleted uranium ^b (0.34% uranium-235)	2,980	1,680	2,070	3,790

Radionuclide/ Radioactive Material	1.25 in. by 1.5 in. Nal Detector ^a Scan MDC (Bq/kg)	1.25 in. by 1.5 in. Nal Detector ^a Weighted cpm/μR/h	2 in. by 2 in. Nal Detector ^a Scan MDC (Bq/kg)	2 in. by 2 in. Nal Detector ^a Weighted cpm/μR/h
Uranium in natural isotopic abundance ^b	4,260	1,770	2,960	3,990
3% Enriched uranium ^b	5,070	2,010	3,540	4,520
20% Enriched uranium ^b	5,620	2,210	3,960	4,940
50% Enriched uranium ^b	6,220	2,240	4,370	5,010
75% Enriched uranium ^b	6,960	2,250	4,880	5,030

^a Refer to text for complete explanation of factors used to calculate scan MDCs. For example, the background level for the 1.25 in. by 1.5 in. Nal detector was assumed to be 4,000 cpm, and 10,000 cpm for the 2 in. by 2 in. Nal detector. The observation interval was 1 second, and the level of performance was selected to yield a performance criterion (d') of 1.38.

^b Scan MDC for uranium includes the sum of ²³⁸U, uranium-235 (²³⁵U), and uranium-234.

6.3.2.2 Scanning for Alpha Emitters

Scanning for alpha emitters differs significantly from scanning for beta and gamma emitters in that the expected background response of most alpha detectors is very close to zero. The following discussion covers scanning for alpha emitters and assumes that the surface being surveyed is similar in nature to the material on which the detector was calibrated. In this respect, the approach is purely theoretical. Surveying surfaces that are dirty, nonplanar, or weathered can significantly affect the detection efficiency and therefore introduce bias to the expected MDC for the scan. The use of reasonable detection efficiency values instead of optimistic values is highly recommended. **Appendix J** contains a complete derivation of the alpha scanning equations used in this section.

Because the time an area is under the probe varies and the background count rate of some alpha instruments is less than 1 cpm, it is not practical to determine a fixed MDC for scanning. Instead, it is more useful to determine the probability of detecting an area of residual radioactive material at a predetermined DCGL for given scan rates.

For alpha survey instrumentation with backgrounds ranging from less than 1 to 3 cpm, a single count provides a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha-emitting radioactive materials on a surface can be calculated by use of Poisson summation statistics.

Given a known scan rate and a DCGL for residual radioactive material on a surface, the probability of detecting a single count while passing over the area of residual radioactive material is calculated using **Equation 6-17**:

$$P(n \geq 1) = 1 - e^{\frac{-G\varepsilon_t d}{60v}} \quad \text{Equation 6-17}$$

where:

$P(n \geq 1)$ = probability of observing one or more counts
 G = activity in dpm
 ε_t = total detection efficiency (4π)

d = width of the detector in the direction of the scan in cm
 v = scan speed in cm/s

Equation 6-17 may be solved for a minimum detectable alpha concentration by assessing the probability of detection using Poisson summation statistics. Specifically, by defining a certain probability of detection, the alpha scan minimum detectable activity (MDA) may be estimated by solving **Equation 6-17** for G , as shown in **Equation 6-18**, where i is the observation interval (in seconds) that can be calculated as d / v from **Equation 6-17**:

$$\text{Alpha Scan MDA} = \frac{[-\ln(1-P(n \geq 1))] \times (60/i)}{\varepsilon_t} \quad \text{Equation 6-18}$$

The scan MDC calculation may be written to account for the probe area, as shown in **Equation 6-19**:

$$\text{Alpha Scan MDC} = \frac{[-\ln(1-P(n \geq 1))] \times (60/i)}{\varepsilon_t \times \frac{A}{100}} \quad \text{Equation 6-19}$$

where A is the physical probe area (cm²) and the alpha scan MDC is in units of dpm/100 cm².

Note: This evaluation is shown for the situation in which a surveyor is expected to respond to one single count and would become more complex for two or more counts. It is also necessary to define an acceptable probability of detection, which should be considered during the DQO process and may require consultation with the regulator.

After a count is recorded, if it is determined that the guideline level of residual radioactive material is present, the surveyor should stop and wait until the probability of getting another count is at least 90 percent. This time interval can be calculated by using **Equation 6-20**:

$$t = \frac{[-\ln(1-P(n \geq 1))] \times 60 \times 100}{C \times A \times \varepsilon_t} = \frac{13,800}{C \times A \times \varepsilon_t} \quad \text{Equation 6-20}$$

where:

t = time period for static count in seconds
 C = DCGL in dpm/100 cm²
 A = physical probe area (in cm²)
 ε_t = total detection efficiency (4π)

Many portable proportional counters have background count rates on the order of 5–10 cpm, and a single count should not cause a surveyor to investigate further. A counting period long enough to establish that a single count indicates an elevated level would be prohibitively inefficient. For these types of instruments, the surveyor usually will need to get at least two counts while passing over the area containing residual radioactive material before stopping for further investigation.

Assuming this to be a valid assumption, the probability of getting two or more counts can be calculated using **Equation 6-21**:

$$P(n \geq 2) = 1 - P(n = 0) - P(n = 1) \quad \text{Equation 6-21}$$

$$= 1 - \left(1 + \frac{(G\varepsilon_t + B)t}{60} \right) \left(e^{-\frac{(G\varepsilon_t + B)t}{60}} \right)$$

where:

- $P(n \geq 2)$ = probability of getting two or more counts during the observation interval t
 - $P(n = 0)$ = probability of not getting any counts during the observation interval t
 - $P(n = 1)$ = probability of getting exactly one count during the observation interval t
 - B = background count rate (cpm)
- All other variables are the same as in **Equation 6-17**.

Appendix J provides a complete derivation of **Equation 6-17** through **Equation 6-21** and a detailed discussion of the probability of detecting residual alpha-emitting radioactive material on surfaces for several different variables. Several probability charts are included at the end of **Appendix J** for common detector sizes. **Table 6-4** provides estimates of the probability of detecting 300 dpm/100 cm² for some commonly used alpha detectors.

Table 6-4 Probability of Detecting 300 dpm/100 cm² of Alpha Activity While Scanning with Alpha Detectors Using an Audible Output (Calculated Using Equation 6-21)

Detector Type	Detection Efficiency (cpm/dpm)	Probe Dimension in Direction of Scan (cm)	Scan Rate (cm/s)	Probability of Detecting 300 dpm/100 cm ²
Proportional	0.20	5	3	80%
Proportional	0.15	15	5	90%
Scintillation	0.15	5	3	70%
Scintillation	0.15	10	3	90%

6.3.3 Detection Capability for Continuously Collected Data Surveys

Continuously collected data (CCD) systems generally use one or more⁶ detectors (e.g., NaI or gas proportional) of varying sizes, and a data logger. CCD is typically collected at a constant scan speed determined as part of the DQO process in a preplanned area along a survey path, transect, or set of transects producing a roughly evenly spaced set of data points. For spectroscopic systems, the scan rate and the acquisition interval between gamma spectra should be determined using the DQO process. They are also influenced by the capabilities of the system. CCD systems display the data (e.g., spectra or count rate) on the system computer for potential real-time analysis, and data are saved for offline use and analysis. **Figure 6-2** through **Figure 6-6** show example CCD systems.

⁶ It is important to note that when using multiple detectors, detector results may be slightly different (e.g., due to age of the detector). Therefore, it is important to consider variability in detector response when processing the data.

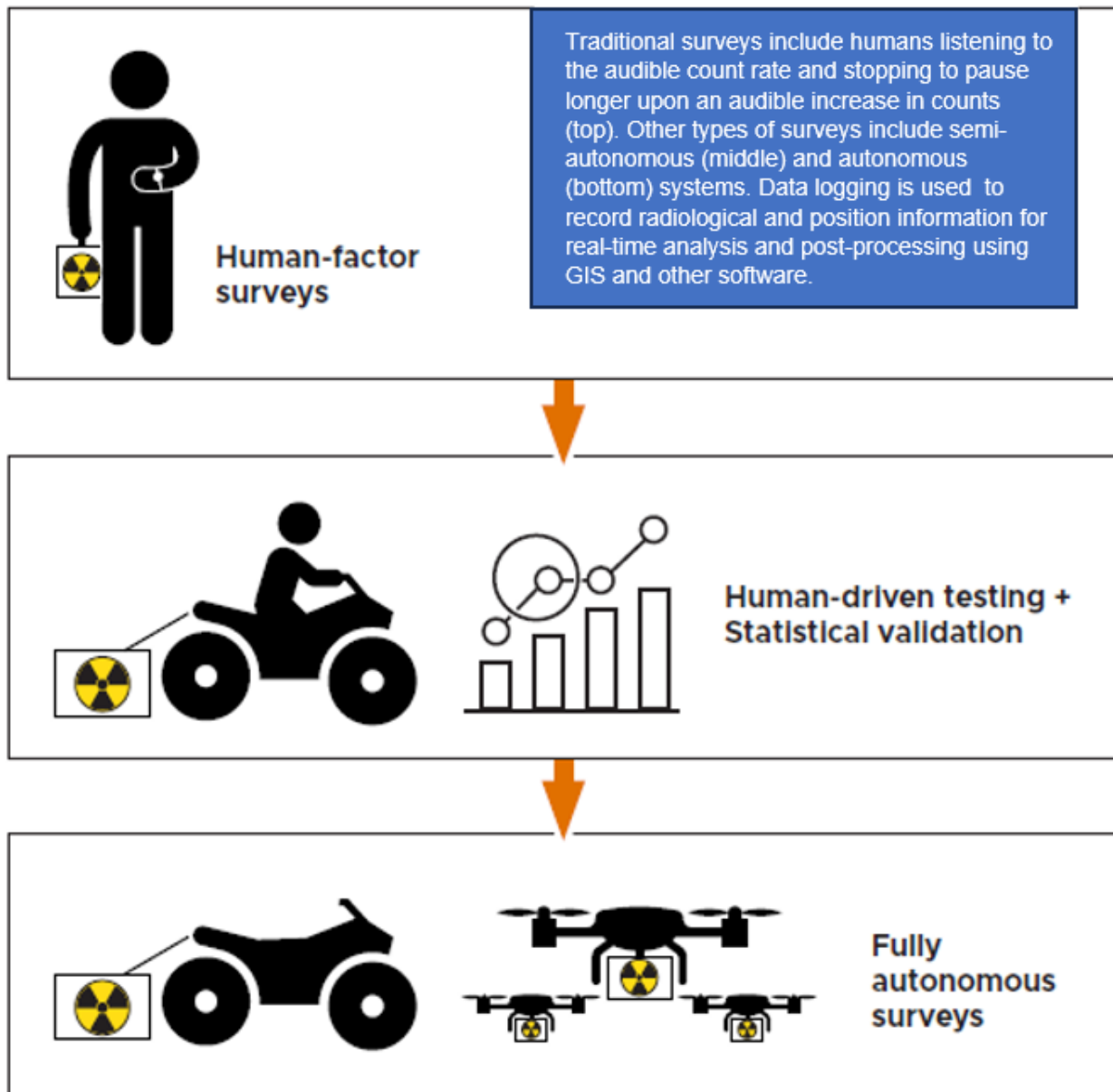


Figure 6-2 Types of CCD Systems (modified from PNNL 2020)



Figure 6-3 Various Human Manual and Pushed CCD Systems Used Indoors (a) and Outdoors (b)(c). (a) Gas proportional floor monitor survey using a total station for mapping indoor survey data, (b) a 2-in. by 2-in. Nal detectors integrated with Global Positioning System (GPS) equipment, (c) large-volume Nal detector integrated with GPS equipment. Image Credit: Oak Ridge Associated Universities



(a)



(b)

Figure 6-4 Human-Driven CCD System. (a) Off-road four-wheel drive truck with mounted crystal array on a sliding bed (b) and complementary detection systems with one array in the truck and another in the tow-behind trailer; both independently equipped with four 4x4x16 NaI detectors, associated data logger, and GPS equipment. Image Credit: U.S. Environmental Protection Agency (EPA) National Center for Radiation Field Operations, Las Vegas. Photos taken Las Vegas, Nevada, November 2024

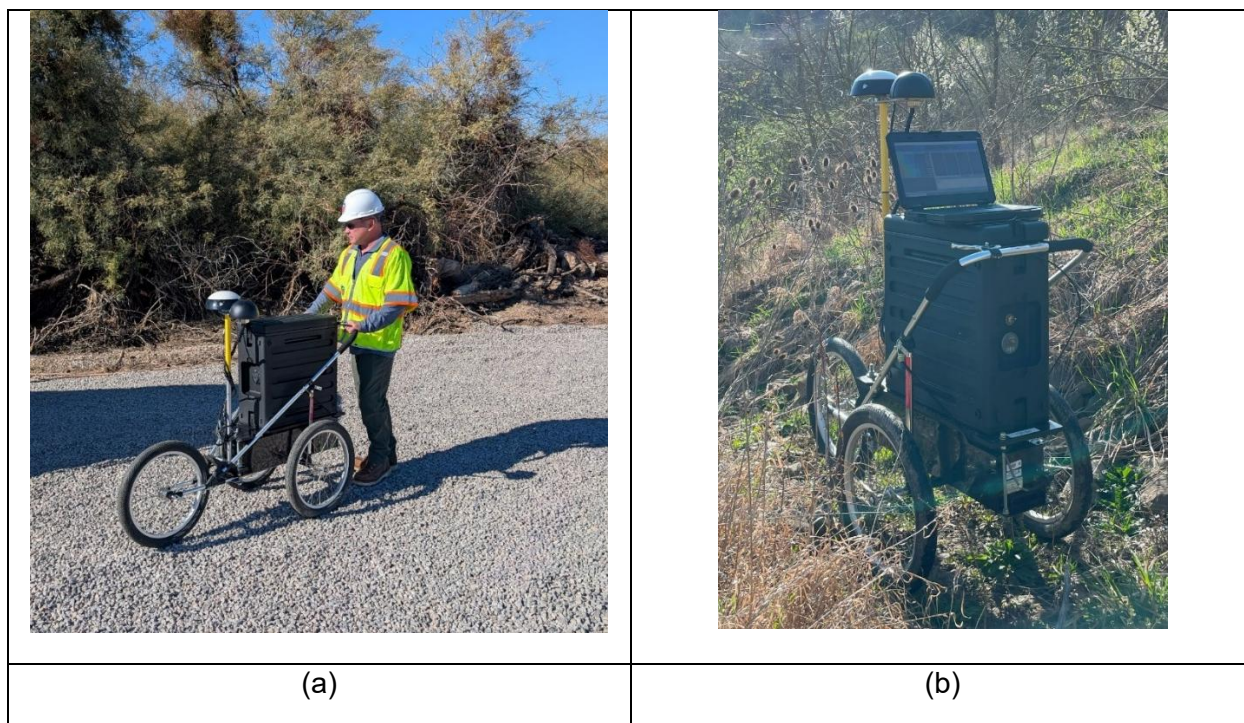


Figure 6-5 Human-Pushed CCD System (single 4x4x16 NaI detector mounted to the frame of a three-wheeled jogging stroller with associated data logger and GPS equipment). Image Credit: EPA National Center for Radiation Field Operations, Las Vegas. (a) photo taken Las Vegas, Nevada, November 2024, and (b) photo taken Fairmont, West Virginia, March 2024

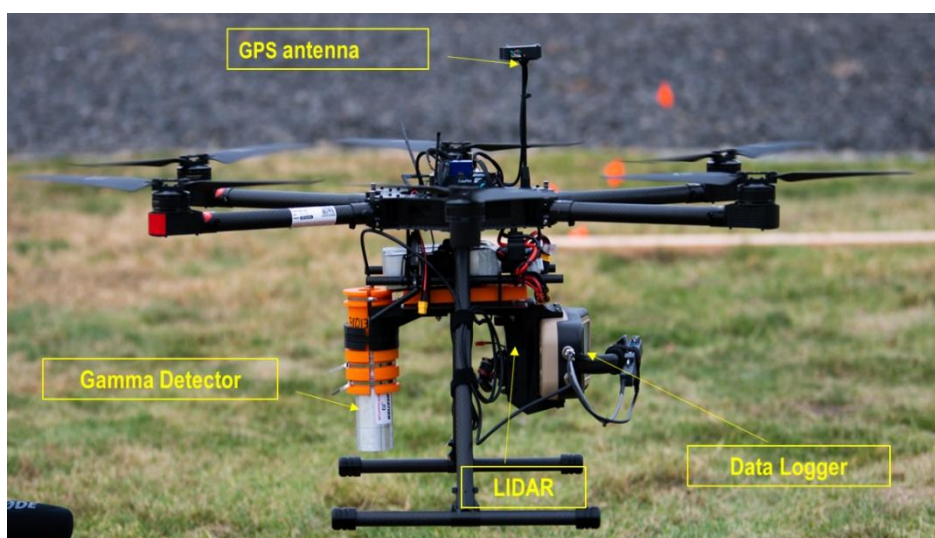


Figure 6-6 Autonomous or Unmanned Aerial Vehicle CCD system. Drone Equipped with NaI Detector, Light Detection and Ranging (LiDAR), and Data Logger. Image modified from Figure 3, Bunn et al. 2022

6.3.3.1 *Scan Minimum Detectable Concentration Calculations and Investigation Levels for Continuously Collected Data*

The a priori scan MDC calculations detailed in NUREG-1507, Revision 1, assume surveyor vigilance (i.e., pausing or stopping to investigate further when audio click data from a ratemeter indicate potential areas of concern). The scan MDC calculations include an index of sensitivity, surveyor efficiency, and observation interval for an assumed elevated area size and scan speed. These equations do not necessarily apply to the CCD gathered without audible surveyor vigilance, and depending on the elevated area size and scan speed, the detector output may not pick up the full response rate.⁷

Captured CCD are typically collected, processed, binned, and mapped with follow-up investigation decisions typically made after the fact (a posteriori). Recognizing the increasing use of CCD capture methods, NUREG-1507, Revision 1, also provides approaches that can be used to calculate a posteriori investigation levels for postprocessed data (IL_{PP}) for CCD (see Section 6.3 of NUREG-1507, Revision 1).

The proposed methods used to develop the IL_{PP} in NUREG-1507, Revision 1, are statistically or empirically based (or both). Statistically based methods employ commercially available statistical software (e.g., ProUCL) for evaluating data and setting an IL_{PP} relative to representative background populations. Several common statistical IL_{PP} values, above which anomaly investigations are performed, are considered, including the use of z-scores (normality assumed) or various background threshold value calculations, such as an upper tolerance limit (UTL) and upper simultaneous limit (USL). Because the USL typically returns the highest potential IL_{PP} , the USL can lead to an unacceptable false negative rates and should only be used when each of the following three statements is true:

- (1) The background dataset is free of outliers.
- (2) Background represents a single distribution.
- (3) Evaluation of the scanning equipment detection capability, considering uncertainty, confidently shows that the signal (based on the wide-area DCGL [$DCGL_W$] or DCGL for the elevated measurement comparison [$DCGL_{EMC}$]) plus background distribution is well outside the USL-calculated uppermost percentile of the background distribution.

Another important consideration is that the USL, which represents the upper boundary of the largest value, cannot be adjusted to control decision errors like the UTL can (with the UTL metric having the advantage of allowing an adjustment to the selection of the upper percentile to control decision error). Section 6.3 of NUREG-1507, Revision 1, provides an example using

⁷ For example, without pausing to count longer in the paradigm without surveyor audible vigilance, the ratemeter may not reach full scale if the observation interval over the elevated area is less than 2 to 4 seconds, which is equivalent to an area of 3 to 12 m² at a scan speed of 1 m/s (NRC 2020). Furthermore, Marianno et al. 2003 studied the impact of scan speed, depth of residual radioactivity, and selected response time on efficiency, with faster scan speeds, depth of residual radioactivity, and longer response times leading to lower efficiencies. Falkner and Marianno 2019 went on to develop a well-defined relationship between MDA and detector speed based on Monte Carlo N-Particle and model fits to modified four-parameter logistic function. Scan parameters and detector response time should be carefully selected as part of the DQO process and considered when calculating scan MDC. With data logging, another consideration is instrument dead time, such that during signal processing or data transfer, the instrument may not be capable of processing a signal from the detector. This is analogous to increased dead time created by increased count rate.

ProUCL to determine IL_{PP} values for various cpm to concentration ratios. Finally, the USL, like the UTL and z-score methods, relies on the assumption that observations are uncorrelated. Applying these methods to correlated observations likely to be observed in CCD but assuming they are uncorrelated could result in error rates that are higher than nominal levels.

Data capture tools coupled to GPS equipment can record the detector response in cpm along with the collection date, time, and x-y coordinates of each measurement. Geographic information systems (GIS) analysts typically analyze data by binning the data to show locations and levels of elevated residual radioactivity. Other techniques used to analyze the data include population outlier tests, count-rate-to-concentration correlation/threshold studies, an upper confidence/tolerance limit of background data, and other methods. Decommissioning projects should follow the DQO process and consider stakeholder requirements and resources to establish an acceptable IL_{PP} that balances the false positive rate with control of false negative decisions and thus provides confidence that the selected IL_{PP} will satisfy detection sensitivity requirements at the $DCGL_W$, $DCGL_{EMC}$, or other project-specific concentration-based limit.

6.3.3.2 *Postprocessing of Continuously Collected Data*

As discussed in **Section 6.3.3.1**, survey data are typically binned according to project-specific criteria, such as grouped by a certain standard deviation away from the mean background response value, or some other criterion. There are limitations to such approaches to determine areas for follow-up investigation when considering CCD. For example, a radionuclide could be present in an area that produces a small range of background response (e.g., 7,000 to 8,000 cpm) compared to an area that produces a broader range (larger variation) of response (e.g., 7,000 to 12,000 cpm). In the case of a broader range of background responses, when the background response is toward the lower end of that range, a radionuclide producing a relatively small response may not be detected with CCD and postprocessing. For example, whereas a surveyor listening to audible clicks in a with-vigilance data collection approach may notice, pause, and collect additional data in response to a 3,000-count jump compared to background, an analyst postprocessing CCD may not, depending on the magnitude above mean background used as the criterion for further investigation. In such cases, the elevated area may only be identified if one of the following is true:

- (1) The location happens to be selected for sampling.
- (2) The surveyor reports the anomaly.
- (3) The analyst notes the localized increase in counts suggesting the presence of contamination.

If the project limits investigations to an IL_{PP} based on some value near the upper end of the background distribution, relatively low contamination in areas near the low end of broad background ranges may be missed. Projects that make a posteriori decisions should, therefore, evaluate where the investigation level falls, considering the entire range of background, and the investigation level should be established using the DQO process. Alternative approaches to determining areas to be targeted for follow-up investigation may also be proposed.

Another issue with postprocessing CCD is related to the selection of background or reference areas. The following example demonstrates how the GIS technician may introduce the potential for false negative decisions by failing to set the IL_{PP} based on an appropriate set of background data. That is, if the standard deviation is estimated using the data population that includes detector responses from elevated areas (or gross contamination), the IL_{PP} may be set too high.

Figure 6-7 presents gamma walkover survey data from a staged survey performed in Oak Ridge, Tennessee. Several ^{137}Cs button sources were hidden from view, a survey was performed, and the data were delivered to an analyst for processing. The analyst was instructed to set a z-score = +3 as the IL_{PP} using a background dataset (from an area with no radiation sources), and to set a different z-score = +3 as the IL_{PP} using the data that included responses from the hidden sources. The figure on the right shows that, if the IL_{PP} was set using background data alone, the analyst would have identified all 10 hidden sources (note the two false positive results near the upper right corner—a few false positives are expected in a large dataset given that there is a statistical probability that 0.13 percent of the results would be expected to exceed the $z = 3$ value). However, the figure on the left shows that when the IL_{PP} was set using data that include responses from the hidden sources, the analyst would have identified only 5 of 10 hidden sources. Section 6.3.1 of NUREG-1507, Revision 1, provides several other examples showing the use of z-scores to establish investigation levels.

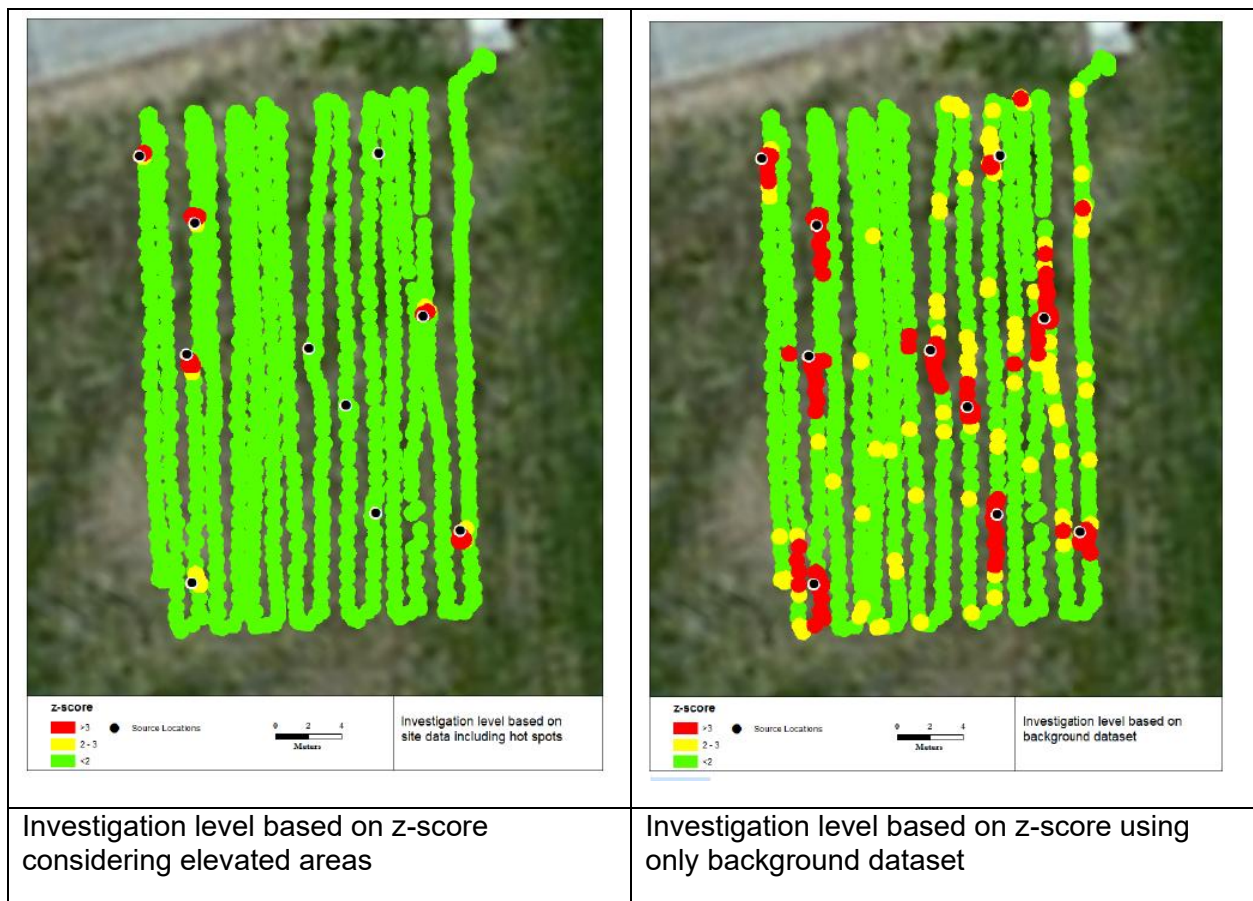


Figure 6-7 Example Use of GIS Software and Investigation Levels to Map and Color-Code CCD Based on Z-Scores (NRC 2020, Figure 6-14)

6.3.3.3 *Alternative Approaches to Calculation of Scan Minimum Detectable Concentration for Continuously Collected Data*

Alternative approaches to mitigating detection of elevated activity in low background areas have been proposed. Pacific Northwest National Laboratory (PNNL) expanded the concepts in NUREG-1507, Revision 1, by providing what is referred to as a “lag-k” method for a priori calculation of critical levels and detection limits (which can be converted to scan MDC), assuming surveys will be completed without audio vigilance (Fagan et al. 2024). The lag-k method can also be used after the survey has been completed (a posteriori) to process CCD and perform hypothesis testing to determine whether the data indicate the presence of potential elevated areas. The lag-k method presented in Fagan et al. 2024 addresses varying background rates, which present a challenge to scan survey interpretation. The lag-k method performs hypothesis testing by treating survey data as a linear time series and assessing differences between k consecutively collected data points before and after each observation to account for potentially changing background. Simulation studies show that the lag-k method is superior to traditional approaches in terms of meeting acceptable error probabilities when optimal values of k are selected and contamination is localized (as opposed to widespread). Fagan et al. 2024 presents several case studies to demonstrate the lag-k method.⁸

Chapter 7 of Fagan et al. 2024 summarizes the literature on the calculation of the scan MDC for CCD. Alecksen and Whicker 2016 and 2023 describe calculation of the scan MDC and retrospective analysis of CCD. Brogan and Brandl 2019 developed a Bayesian interaction model to analyze gross count measurements using five sequential measurements to inform detection decisions.

Other recent references include Electric Power Research Institute (EPRI) reports published in 2020 and 2022. EPRI Technical Report 3002018420, “Design and Demonstration of an Autonomous System for Radiological Characterization,” issued August 2020 (EPRI 2020), documents the use of an autonomous vehicle for land surveys for radiation. In October 2022, EPRI published Technical Report 3002023966, “Design and Demonstration of an Autonomous System for Radiological Characterization of Building Surfaces” (EPRI 2022), to demonstrate two industry prototype systems for autonomous survey of walls and floors at a decommissioning nuclear power plant. EPRI notes that the automation of repetitive radiation surveys of large areas has a strong potential to be successful and promises substantial benefit.

Fagan et al. 2024 also evaluated statistical and geostatistical tools to facilitate data importation and management, visualization, and analysis of CCD (without audible vigilance) for surface (two-dimensional) radiological surveys. A major finding of the report is that methods to account for spatial correlation should be implemented before hypothesis testing, as spatial correlation can result in reduced statistical power. Data quality assessment was also stressed as being important to ensure quality data to support decision-making.

As of 2024, methods for a priori calculation of scan MDC is an area of ongoing research, and tools to process CCD data are currently being developed. The NRC plans to update NUREG-1507, Revision 1, with additional a priori scan MDC calculational methods. Additionally, PNNL is updating the Visual Sample Plan computer code to include additional data visualization

⁸ The case studies presented in Fagan et al. 2024 use rate meter data as opposed to audio click data from surveys with audible vigilance. It is known, however, that there are differences between audio click data used in surveying with vigilance and data collected by the ratemeter when surveys are conducted without vigilance. The magnitude of differences between the audio and ratemeter data, and their subsequent impacts on scan MDC calculations, should be understood.

and analysis tools for CCD. The DQO process should be followed, and the appropriate regulatory authority should be contacted to discuss acceptable methods for planning and implementing CCD surveys.

6.4 Measurement Uncertainty

Uncertainty, as it is used in MARSSIM, is a parameter associated with the result of a measurement, x , that characterizes the dispersion of the values that could reasonably be attributed to the measurement of x . It is the estimated value of $\sigma(x)$ obtained from the propagation of uncertainty.

This section will cover methods for determining measurement uncertainty according to the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Guide 98, "Guide to the Expression of Uncertainty in Measurements," issued 1993 (ISO/IEC 1993), hereafter referred to as the "GUM." The GUM has become the universally accepted methodology for determining measurement uncertainty. National Institute of Standards and Technology (NIST) Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," issued September 1994 (NIST 1994), contains an excellent introduction to the GUM. ANSI, NIST, and numerous other national and international standards-setting organizations have endorsed the GUM. The GUM has become a globally accepted standard whose methods and nomenclature are understood and accepted for measurement uncertainty analysis.

Section 6.4.1 provides general information on measurement uncertainty, including the two types of uncertainty, historically referred to as systematic and random uncertainty and classified in the GUM as Type A and Type B uncertainties. **Section 6.4.2** describes a method for calculating statistical counting uncertainty. **Section 6.4.3** discusses how to combine this counting uncertainty with other uncertainties from the measurement process using uncertainty propagation. **Section 6.4.4** demonstrates how to use a tool such as the NIST Uncertainty Machine to perform uncertainty propagation. Finally, **Section 6.4.5** discusses setting and evaluating an MQO for required measurement method uncertainty.

6.4.1 Type A and Type B Uncertainties

Historically, measurement uncertainties were often broken into two subclasses: systematic uncertainty (e.g., methodical) and random uncertainty (e.g., stochastic). Systematic uncertainties derive from a lack of knowledge about the true distribution of values associated with a numerical parameter and result in data that are consistently higher or lower than the true value. An example of a systematic uncertainty would be the use of a fixed counting efficiency value without knowledge of the frequency, even though it is known that the efficiency varies from measurement to measurement. If the fixed counting efficiency value is higher than the true but unknown efficiency—as would be the case for an unrealistically optimistic value—then every measurement result calculated using that efficiency would be biased low. Random uncertainties refer to fluctuations associated with a known distribution of values. An example of a random uncertainty would be a well-documented chemical separation efficiency that is known to fluctuate with a regular pattern about a mean. A constant recovery value is used during calculations, but the true value is known to fluctuate from sample to sample with a fixed and known degree of variation.

The GUM does not use the terms “random” and “systematic” with regard to uncertainty or error. Rather, uncertainties are classified as Type A and Type B.⁹ In a Type A evaluation of uncertainty, knowledge about an input quantity x_i is inferred from independent repeated observations. In a Type B evaluation of uncertainty, knowledge about an input quantity x_i is inferred from scientific judgment or other information concerning the possible values of the quantity.

The focus of the GUM is uncertainty and not error.¹⁰ The exact error of a result of a measurement is, in general, unknown and unknowable, because the error is the difference between the measurement value and the “true” value, which is unknown and unknowable. While the approach based on “true” value and error yields the same numerical results as the approach taken by the GUM, the GUM’s concept of uncertainty eliminates the confusion between error and uncertainty. The GUM’s focus on the observed (or estimated) value of a quantity and the observed (or estimated) variability of that value makes any mention of error unnecessary.

The objective of a measurement is to determine the value of the measurand (i.e., the particular quantity to be measured). The mathematical model of the measurement transforms observations into the measurement result. In addition to the observations, the model generally includes various influence quantities that are inexactly known. This lack of knowledge contributes to the uncertainty of the measurement and any uncertainty associated with the mathematical model itself. The uncertainty of the measurement is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. The result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty.

Although the GUM provides a framework for assessing uncertainty, it cannot substitute for critical thinking, intellectual honesty, and professional skill. The evaluation of uncertainty is neither a routine task nor a purely mathematical one; rather, it depends on detailed knowledge of the nature of the measurand and of the measurement itself.¹¹

The quality of measurement data will be directly affected by the magnitude of the measurement uncertainty associated with it. Some uncertainties, such as statistical counting uncertainties, can be calculated easily from the count results using mathematical procedures. Evaluation of other sources of uncertainty requires more effort and in some cases is not possible. For example, if an alpha activity measurement is made on a porous concrete surface, the observed instrument response when converted to units of activity will probably not exactly equal the true activity under the probe. Variations in the absorption properties of the surface for particulate radiation will vary from point to point and therefore will create some level of variation in the expected detection efficiency. This variability in the expected detection efficiency results in uncertainty in the final reported result.

The measurement uncertainty should be reported for every measurement. This uncertainty, although not directly used for demonstrating compliance with the release criteria, is used for

⁹ These uncertainties, Type A and Type B, should not be confused with decision errors in hypothesis testing, Type I and Type II.

¹⁰ The GUM takes great care to distinguish between the terms “error” and “uncertainty.” They are not synonyms but rather represent completely different concepts; they should not be confused with one another or misused.

¹¹ The discussion above is largely drawn from material in the GUM itself.

survey planning and data assessment throughout the Radiation Survey and Site Investigation process. In addition, the uncertainty is used for evaluating the performance of measurement systems using QC measurement results. QC measurement results provide an estimate of random and systematic uncertainties associated with the measurement process. Uncertainty can also be used for comparing individual measurements to the DCGL or action level. This is especially important in the early stages of remediation (i.e., scoping, characterization, remedial action support), when decisions are made based on a limited number of measurements.

Finally, where controlling uncertainty is important, a required uncertainty can be specified, or a minimum quantifiable concentration can be defined. The minimum quantifiable concentration could, for example, be that concentration of residual radioactive material that can be quantified with a relative uncertainty no greater than some limit (e.g., 10 percent) at some specified concentration (e.g., the DCGL or action level).

The final status survey (FSS) data, which are used to document the final radiological status of a site, should state the uncertainties associated with the measurements. Conversely, detailing the uncertainties associated with measurements made during scoping or characterization surveys may or may not be of value, depending on the intended use of the data, as defined by the DQOs. From a practical standpoint, if the observed data are obviously greater than the DCGL or action level and will be cleaned up eventually, then the uncertainty may be relatively unimportant. Conversely, data collected during early phases of a site investigation that may eventually be used to show that the area complies with the release criteria, and therefore does not require any cleanup action, will need the same uncertainty evaluation as the FSS data. In summary, the level of effort needed to evaluate the uncertainty should match the intended use of the data.

To minimize the need for estimating potential sources of uncertainty, the sources of uncertainty themselves should be reduced to a minimal level by using such practices as the following:

- The detector used should minimize the potential uncertainty. For example, when making field surface activity measurements for ^{238}U on concrete, a beta detector—such as a thin-window GM “pancake” probe—may provide better quality data than an alpha detector, depending on the circumstances. Less random uncertainty would be expected between measurements with a beta detector, such as a pancake probe, because beta emissions from the uranium will be affected much less by thin, absorbent layers than the alpha emissions will.
- Calibration factors should accurately reflect the efficiency of the detection method used on the surface material being measured for the radionuclide or mixture of radionuclides of concern (see **Section 6.6.4**). For most field measurements, variations in the counting efficiency on different types of materials will introduce the largest amount of uncertainty in the final result.
- Uncertainties should be reduced or eliminated by using standardized measurement protocols (e.g., SOPs) when possible. Special effort should be made to reduce or eliminate systematic uncertainties, or uncertainties that are the same for every measurement simply due to an error in the process. If the systematic uncertainties are reduced to a negligible level, then the random uncertainties, or those uncertainties that occur on a somewhat statistical basis, can be dealt with more easily.

- Instrument operators should be trained and experienced with the instruments used to perform the measurements.
- Quality assurance and QC activities should be conducted.

Uncertainties that cannot be eliminated need to be evaluated such that the effect can be understood and properly propagated into the final data and uncertainty estimates. As previously stated in this section, nonstatistical uncertainties should be minimized as much as possible using good work practices.

Systematic uncertainty is derived from calibration errors, incorrect yields and efficiencies, nonrepresentative survey designs, and “blunders.” It is difficult—and sometimes impossible—to evaluate the systematic uncertainty for a measurement process, but bounds should always be estimated and made small compared to the random uncertainty, if possible. If no other information on systematic uncertainty is available, the NRC’s NUREG/CR-4007, “Lower Limit of Detection: Definition and Elaboration of a Proposed Position for Radiological Effluent and Environmental Measurements,” issued September 1984 (NRC 1984), recommends using 16 percent as an estimate for systematic uncertainties (1 percent for blanks, 5 percent for baseline, and 10 percent for calibration factors).

While MARLAP was written primarily for measurements in radiochemistry laboratories, much of the material on uncertainties applies equally well to field instruments and measurements. Chapter 19 of MARLAP discusses counting uncertainty in much greater detail.

6.4.2 Statistical Counting Uncertainty

Traditionally, for radiological counting data, the statistical uncertainty in the result is often the only source of uncertainty considered. This is typically reported as the “ 2σ ” Poisson counting uncertainty, where σ is taken to be the square root of the number of counts. As such, it is at best a minimum uncertainty in the reported result, and it is often an exaggeratedly optimistic underestimate. When performing an analysis with a radiation detector, the result will have an uncertainty associated with it because of the statistical nature of radioactive decay. To calculate the total uncertainty associated with the counting process, both the background measurement uncertainty and the sample measurement uncertainty must be taken into account. The standard deviation of the net count rate, or the statistical counting uncertainty, can be calculated using **Equation 6-22**:

$$\sigma_n = \sqrt{\frac{C_{s+b}}{t_{s+b}^2} + \frac{C_b}{t_b^2}} \quad \text{Equation 6-22}$$

where:

σ_n	=	standard deviation of the net count rate result
C_{s+b}	=	number of gross counts (sample)
t_{s+b}	=	gross count time
C_b	=	number of background counts
t_b	=	background count time

6.4.3 Uncertainty Propagation

Often, raw measurement data cannot be used directly. Instead, they will need to be included in a calculation to determine a final result in units that can be compared to a limit, such as an

action level or a DCGL. The equation used to perform the calculation is called the mathematical model of the measurement. The final result is called the measurand, and each variable in the mathematical model is known as an input quantity.

The total uncertainty associated with the final result, also referred to as the combined standard uncertainty (CSU), can be calculated. Assuming the individual uncertainties are relatively small, symmetric about zero, and independent of one another, then the total uncertainty for the final calculated result can be determined using the formula in **Equation 6-23**¹²:

$$u_c(y) = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 u^2(x_1) + \left(\frac{\partial f}{\partial x_2}\right)^2 u^2(x_2) + \cdots + \left(\frac{\partial f}{\partial x_n}\right)^2 u^2(x_n)} \quad \text{Equation 6-23}$$

where $y = f(x_1, x_2, \dots, x_n)$ defines the calculation of a final result as a function of the collected data. Each of the variables in this equation (i.e., $x_1, x_2, \dots, x_n$), other than numerical constants, are assumed to have an associated measurement uncertainty. $u_c(y)$ is the CSU associated with the final result y , and $u^2(x_1), u^2(x_2), \dots, u^2(x_n)$ are the standard deviations associated with the parameters $x_1, x_2, \dots, x_n$.

Chapter 8 of the GUM provides detailed instructions on how to carry out the general uncertainty calculation by breaking down the process into the following eight steps for evaluating and reporting the uncertainty of a measurement:

- (1) Identify the measurand, Y , and all the input quantities, X_i , for the mathematical model.
- (2) Determine an estimate, x_i , of the value of each input quantity, X_i .
- (3) Evaluate the standard uncertainty, $u(x_i)$, for each input estimate, x_i , using a Type A method, a Type B method, or a combination of both.
- (4) Evaluate the covariances, $u(x_i, x_j)$, for all pairs of input estimates with potentially significant correlations.
- (5) Calculate the estimate, y , of the measurand from the relationship $y = f(x_1, x_2, \dots, x_N)$.
- (6) Determine the CSU, $u_c(y)$, of the estimate, y .
- (7) Optionally, multiply $u_c(y)$ by a coverage factor k to obtain the expanded uncertainty, U .
- (8) Report the result as $y \pm U$ with the unit of measurement.

Sections 6.4.3.1 through 6.4.3.8 describe Steps 1–8 in more detail, respectively. **Example 6-9** demonstrates the eight-step process. As shown in **Figure 6-8**, Steps 5–7 can be done analytically by hand or numerically using a software tool such as the NIST Uncertainty Machine (<https://uncertainty.nist.gov/>).

¹² In some references, the symbol σ has been used for the uncertainties of the input quantities and the final result.

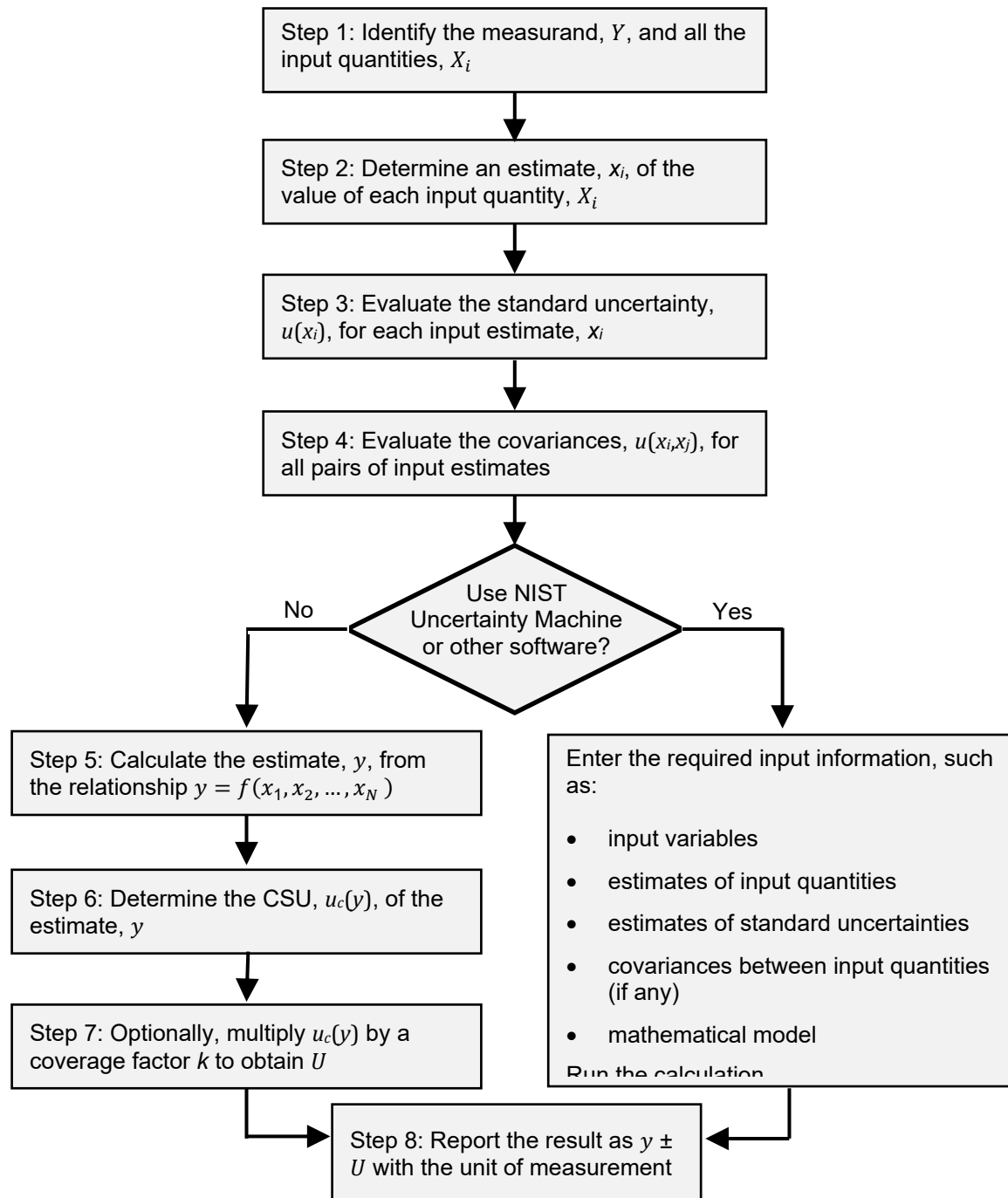


Figure 6-8 Flowchart for Evaluating Uncertainty

6.4.3.1 Identify the Measurand and Input Quantities for the Mathematical Model

Step 1 is to identify the measurand and all the input quantities for the mathematical measurement model. The procedure for assessing the uncertainty of a measurement begins with listing all significant sources of uncertainty in the measurement process. A good place to

begin is with the input quantities' mathematical model $Y = f(X_1, X_2, \dots, X_n)$. For example, one mathematical model for surface activity concentration, A_S , is given as **Equation 6-24**:

$$A_S = \frac{n_{s+b}/t_{s+b} - n_b/t_b}{\varepsilon_s \cdot W \cdot \varepsilon_i} \quad \text{Equation 6-24}$$

where:

n_{s+b}	=	number of counts from the source and background
t_{s+b}	=	count time for the source and background
n_b	=	number of background counts
t_b	=	background count time
ε_s	=	source efficiency of the radioactive material on the surface
ε_i	=	instrument (i.e., detector probe) efficiency
W	=	area of the detector window

The mathematical model may include additional inputs that affect the final result (e.g., pressure or temperature effects, effects due to the density of material being measured) as either corrections or correction factors. Corrections are added to or subtracted from the mathematical model. In some cases, they may have a value of zero, which would not change the final result, but they may have some uncertainty associated with them and therefore contribute to the measurement uncertainty. Similarly, correction factors multiply or divide the mathematical model. In some cases, they may have a value of 1, which does not change the final result, but they may have some variability associated with them and therefore also contribute to uncertainty. Including significant corrections and correction factors is important for getting a more accurate understanding of the uncertainty associated with the final result.

Example 6-9a: As part of a characterization survey, 10 direct measurements were made of the survey unit. The measurand ($\bar{A}_S$) is the average surface activity concentration in the survey unit. The following input quantities are needed to estimate the average surface activity concentration in the survey unit: the number of counts recorded in each survey unit measurement, the count time for the measurement, the number of background counts recorded, the count time for the background measurement, the source and instrument efficiency of the detector probe, and the area of the probe.

The mathematical measurement model from **Equation 6-24** is as follows:

$$\bar{A}_S = \frac{\bar{n}_{s+b}/t_{s+b} - n_b/t_b}{\varepsilon_s \cdot W \cdot \varepsilon_i}$$

where:

$\bar{n}_{s+b}$	=	average number of counts in the survey unit
t_{s+b}	=	count time for measurements in the survey unit
n_b	=	number of background counts*
t_b	=	count time for the background measurement
ε_s	=	source efficiency of the radioactive material on the surface
ε_i	=	instrument (i.e., detector probe) efficiency
W	=	area of the detector window

* This example uses a single background count to illustrate the use of Poisson statistics to estimate the evaluation of uncertainty from a single measurement. Taking measurements of the background at multiple locations provides a better estimate of any spatial or temporal variability in the concentration of radioactive material.

6.4.3.2 Determine an Estimate for Each Input Quantity

Step 2 is to determine an estimate of the value of each input quantity. This involves simply determining, for each measurement, the specific value, x_i , that should be substituted for the input quantity X_i in the mathematical relationship, $Y = f(X_1, X_2, \dots, X_N)$.

Example 6-9b: Continuing from **Example 6-9a**, the count time for the measurements in the survey unit is 30 seconds. The results for the 10 measurements are provided below:

1,438	1,371	1,089	1,521	1,589
1,492	1,015	1,037	1,065	1,626

The average for the number of counts observed in the survey unit is estimated as the experimental mean:

$$\bar{n}_{s+b} = \frac{1}{10} [1,438 + \dots + 1,626] = 1,324$$

A single background measurement was made observing 595 counts in 120 seconds.

According to technical specifications provided by the manufacturer, the area of the probe is approximately 125 cm², or 1.25×10⁻² m². The calibration record from the last time the instrument was calibrated (less than 1 year ago) indicated that the instrument efficiency (2π) was estimated to be (0.4074 ± 0.0104) cps Bq⁻¹ where the uncertainty is the standard uncertainty (1σ). Note that the efficiency of the detector probe might be provided on a calibration record for the instrument or measured previously using an appropriate calibration source.

6.4.3.3 Evaluate the Standard Uncertainty for each Input Estimate

Step 3 is to evaluate the standard uncertainty for each input estimate using either a Type A method of evaluation, a Type B method of evaluation, or some combination of the two. Both types of uncertainty (systematic and random) need to be taken into consideration. A Type A evaluation of an uncertainty uses a series of measurements to estimate the standard deviation empirically. Any other method of evaluating an uncertainty is a Type B method. A Type B evaluation of standard uncertainty is usually based on scientific judgment using all the relevant information available, which may include the following:

- previous measurement data
- experience with, or general knowledge of, the behavior and property of relevant materials and instruments
- manufacturer's specifications
- data provided in calibration and other reports
- uncertainties assigned to reference data taken from handbooks

The Type A standard uncertainty of the input estimate x_i may be defined to be the experimental standard deviation of the mean as in **Equation 6-25**:

$$u(x_i) = \frac{s(x_i)}{\sqrt{n}} = \sqrt{\frac{1}{n(n-1)} \sum_{k=1}^n (x_{i,k} - \bar{x}_i)^2} \quad \text{Equation 6-25}$$

There are other Type A methods, but all are based on repeated measurements.

Any evaluation of standard uncertainty that is not a Type A evaluation is a Type B evaluation. Sometimes a Type B evaluation of uncertainty involves making an estimation based on all available information and professional judgment. Despite the reluctance to make this kind of evaluation, it is almost always better to make an informed estimate of an uncertainty component than to ignore it completely.

There are many ways to perform Type B evaluations of standard uncertainty. One example of a Type B method is the estimation of counting uncertainty using the square root of the observed counts. If the observed count is x_i , when the Poisson approximation is used, the standard uncertainty of x_i may be evaluated using **Equation 6-26**:

$$u(x_i) = \sqrt{x_i} \quad \text{Equation 6-26}$$

Another Type B evaluation of an uncertainty $u(x_i)$ consists of estimating an upper bound, a , for the magnitude of the error of x_i based on professional judgment and the best available information. If nothing else is known about the distribution of the measured result, then after a is estimated, the standard uncertainty may be calculated using **Equation 6-27**:

$$u(x_i) = \frac{a}{\sqrt{3}} \quad \text{Equation 6-27}$$

which represents the standard deviation of a random variable uniformly distributed over the interval $(x_i - a, x_i + a)$. As shown in **Figure 6-9**, the variable a is called the half-width of the interval, with the area under any given probability distribution being equal to 1.

Given the same information on the range, if values near the middle of the range were considered more likely than those near the endpoint, a triangular distribution, as shown in **Figure 6-10**, may be more appropriate. The standard uncertainty for a triangular distribution is calculated using **Equation 6-28**:

$$u(x_i) = \frac{a}{\sqrt{6}} \quad \text{Equation 6-28}$$

which represents the standard deviation of a random variable with a triangular distribution over the interval $(x_i - a, x_i + a)$.

There are many distributions besides the ones described that might be selected based on the available information. For example, if there is known information about the uncertainty in the parameter value based on professional judgment, a normal or Weibull distribution may also be appropriate. When the estimate of an input quantity is taken from an external source, such as a book or a calibration certificate, the stated standard uncertainty can be used.

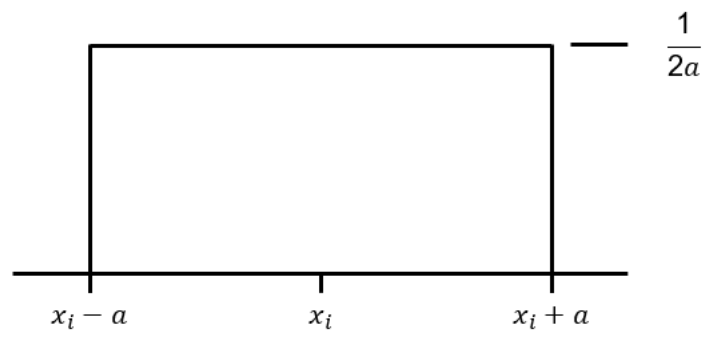


Figure 6-9 Uniform Probability Distribution

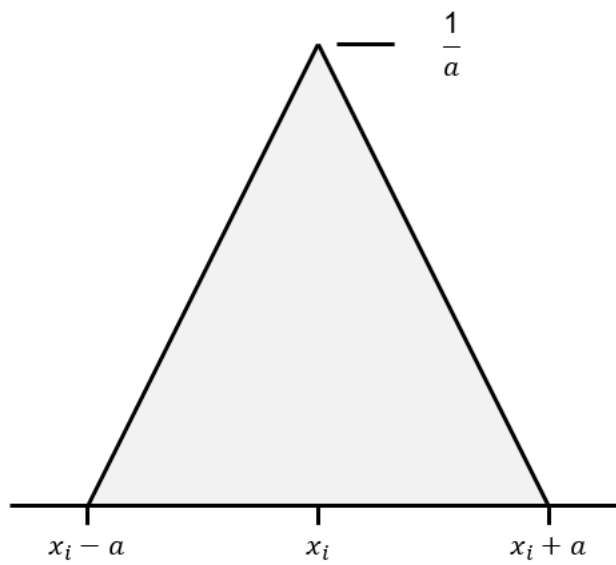


Figure 6-10 Triangular Probability Distribution

Example 6-9c: Continuing from **Example 6-9b**, the standard uncertainty in the average number of counts observed in the survey unit is estimated, using a Type A method of evaluation, as the standard error of the mean:

$$u(\bar{n}_{s+b}) = \sqrt{\frac{1}{10(10-1)} [(1,438 - 1,324)^2 + \dots + (1,626 - 1,324)^2]} = 78$$

Using a Type B method of evaluation, the distribution in the number of background counts is assumed to be approximated by a Poisson distribution, with a standard uncertainty in the number of background counts equal to the square root of the number of background counts:

$$u(\bar{n}_b) = \sqrt{595} = 24$$

When using digital scalers, the count times are assumed to be constant, and the standard uncertainties for the count times are therefore assumed to be negligible.

For the detector probe area, a uniform distribution between 124 and 126 cm² is assumed, giving the following estimated standard uncertainty:

$$u(W) = \frac{1 \text{ cm}^2}{\sqrt{3}} = 0.577 \text{ cm}^2 = 5.77 \times 10^{-5} \text{ m}^2$$

For the source efficiency, a symmetrical triangular distribution between 0.45 and 0.55 is assumed, giving the following estimated standard uncertainty:

$$u(\varepsilon_s) = \frac{0.05}{\sqrt{6}} = 0.0204$$

The standard uncertainty (1 σ) for the instrument efficiency, ε_i , is given on the instrument calibration as 0.0104 cps Bq⁻¹. **Table 6-5** provides the values, standard uncertainties, and methods of evaluation.

Table 6-5 Values, Standard Uncertainties, and Methods of Evaluation for Input Quantities Used in Example 6-9

Input Quantity	Value and 1 σ Standard Uncertainty	Method of Evaluation	Comments
$\bar{n}_{s+b}$	1,324 $\pm$ 78	Type A	Experimental standard deviation of the mean
$\bar{n}_b$	595 $\pm$ 24	Type B	Assumed Poisson distribution
t_{s+b}	30 s	N/A	Treated as a constant
t_b	120 s	N/A	Treated as a constant

Input Quantity	Value and 1 σ Standard Uncertainty	Method of Evaluation	Comments
ε_s	0.5 ± 0.0204	Type B	Estimated using NUREG-1507, Revision 1, and an assumed symmetrical triangular distribution
W	$(125 \pm 0.577) \text{ cm}^2$	Type B	Provided from an external source (manufacturer's technical specification) and uncertainty estimated using an uniform distribution.
ε_i	$(0.4074 \pm 0.0104) \text{ cps Bq}^{-1}$	Type B	Provided from an external source (e.g., calibration certificate)

6.4.3.4 Evaluate the Covariances for All Pairs of Input Estimates

Step 4 is to evaluate the covariances for all pairs of input estimates with potentially significant correlations. A Type A evaluation of the covariance of the input estimates x_i and x_j is given in **Equation 6-29**:

$$u(x_i, x_j) = \frac{1}{n(n-1)} \sum_{k=1}^n (x_{i,k} - \bar{x}_i)(x_{j,k} - \bar{x}_j) \quad \text{Equation 6-29}$$

An evaluation of variances and covariances of quantities determined by the method of least squares may also be a Type A evaluation. Evaluation of the covariance of two input estimates, x_i and x_j , whose uncertainties are evaluated by Type B methods may require expert judgment. In such cases, it may be simpler to estimate the correlation coefficient as in **Equation 6-30** first and then multiply it by the standard uncertainties, $u(x_i)$ and $u(x_j)$, to obtain the covariance, $u(x_i, x_j)$:

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i)u(x_j)} \quad \text{Equation 6-30}$$

Measured values obtained from two measurement processes may be correlated if some of the same input estimates are used to calculate output estimates in both models. If the two measured values are to be used as input quantities in a third model, their covariance should be estimated. Mathematical models with covariances between input estimates add significant complexity to uncertainty propagation calculations and will not be covered in detail in MARSSIM. MARLAP Section 19.4.4 and Example 19.11 contain more information on conducting uncertainty propagation with covariances.

Example 6-9d: Continuing from **Example 6-9c**, the input variables are determined to be independent, and correspondingly there are no correlations between any pairs of input estimates. As a result, this step may be skipped.

6.4.3.5 Estimate the Measurand

Step 5 is to calculate the estimate of the measurand from the mathematical measurement model determined in Step 1. This involves simply substituting, for the measurement at hand, the specific values of x_i for the input quantity X_i into the mathematical relationship $Y = f(X_1, X_2, \dots, X_N)$ and calculating the result $y = f(x_1, x_2, \dots, x_N)$.

Example 6-9e: Continuing from **Example 6-9d**, the average surface activity concentration in the survey unit, the surface activity concentration, $\bar{A}_S$, is calculated as follows:

$$\begin{aligned}\bar{A}_S &= \frac{\bar{n}_{s+b}/t_{s+b} - n_b/t_b}{\varepsilon_s \cdot W \cdot \varepsilon_i} \\ &= \frac{(1,324)/(30 \text{ s}) - (595)/(120 \text{ s})}{(0.5)(1.25 \times 10^{-2} \text{ m}^2)(0.4074 \text{ cps Bq}^{-1})} \\ &= 15,385 \text{ Bq m}^{-2}\end{aligned}$$

6.4.3.6 Determine the Combined Standard Uncertainty

Step 6 is to determine the CSU of the estimate of the measurand. The CSU of y is obtained using **Equation 6-31**:

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j) \quad \text{Equation 6-31}$$

where $u^2(x_i)$ denotes the estimated variance of x_i , or the square of its standard uncertainty; $u(x_i, x_j)$ denotes the estimated covariance of x_i and x_j ; $\partial f / \partial x_i$ (or $\partial y / \partial x_i$) denotes the partial derivative of f with respect to x_i evaluated at the measured values $x_1, x_2, \dots, x_N$; and $u_c^2(y)$ denotes the combined variance of y , whose positive square root, $u_c(y)$, is the CSU of y . The partial derivatives, $\partial f / \partial x_i$, are called sensitivity coefficients, usually denoted c_i . The sensitivity coefficient measures how much f changes when x_i changes. **Equation 6-31** is called the “law of propagation of uncertainty” in the GUM.

If the input estimates $x_1, x_2, \dots, x_N$ are uncorrelated, the uncertainty propagation formula reduces to **Equation 6-32**:

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \quad \text{Equation 6-32}$$

For example, the CSU of the net count rate, $u_c(A_S)$, as described in the mathematical model in **Equation 6-24**, is given by **Equation 6-33**:

$$u_c(A_S) = \sqrt{\left(\frac{1}{\varepsilon_s \cdot W \cdot \varepsilon_i} \right)^2 \left[\frac{u^2(n_{s+b})}{t_{s+b}^2} + \frac{u^2(n_b)}{t_b^2} \right] + A_S^2 \left[\frac{u^2(\varepsilon_s)}{\varepsilon_s^2} + \frac{u^2(W)}{W^2} + \frac{u^2(\varepsilon_i)}{\varepsilon_i^2} \right]} \quad \text{Equation 6-33}$$

Table 6-6 provides the CSUs for commonly used mathematical models in MARSSIM.

Table 6-6 CSUs for Commonly Used Mathematical Models in MARSSIM

Measurand (Mathematical Model)	CSU
$y = f(x_1, \dots, x_n)$	$u_c(y) = \sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) = \left(\frac{\partial f}{\partial x_1} \right)^2 u^2(x_1) + \dots + \left(\frac{\partial f}{\partial x_n} \right)^2 u^2(x_n)$
$R_S = \frac{n_{s+b}}{t_{s+b}} - \frac{n_b}{t_b}$	$u_c(R_S) = \sqrt{\frac{u^2(n_{s+b})}{t_{s+b}^2} + \frac{u^2(n_b)}{t_b^2}}$
$\varepsilon_t = \varepsilon_s \cdot \varepsilon_i$	$u_c(\varepsilon_t) = \varepsilon_t \sqrt{\varphi^2(\varepsilon_s) + \varphi^2(\varepsilon_i)}$
$A_S = \frac{n_{s+b}/t_{s+b} - n_b/t_b}{\varepsilon_s \cdot W \cdot \varepsilon_i}$	$u_c(A_S) = \sqrt{\left(\frac{1}{\varepsilon_s \cdot W \cdot \varepsilon_i} \right)^2 \left[\frac{u^2(n_{s+b})}{t_{s+b}^2} + \frac{u^2(n_b)}{t_b^2} \right] + A_S^2 [\varphi^2(\varepsilon_s) + \varphi^2(W) + \varphi^2(\varepsilon_i)]}$

Example 6-9f: Continuing from **Example 6-9e**, the CSU of the average surface activity concentration in the survey unit is given by the following equation:

$$u_c^2(\bar{A}_S) = \left(\frac{\partial \bar{A}_S}{\partial \bar{n}_{s+b}} \right)^2 u^2(\bar{n}_{s+b}) + \left(\frac{\partial \bar{A}_S}{\partial t_{s+b}} \right)^2 u^2(t_{s+b}) + \left(\frac{\partial \bar{A}_S}{\partial n_b} \right)^2 u^2(n_b) + \left(\frac{\partial \bar{A}_S}{\partial t_b} \right)^2 u^2(t_b) \\ + \left(\frac{\partial \bar{A}_S}{\partial \varepsilon_t} \right)^2 u^2(\varepsilon_s) + \left(\frac{\partial \bar{A}_S}{\partial W} \right)^2 u^2(W) + \left(\frac{\partial \bar{A}_S}{\partial \varepsilon_i} \right)^2 u^2(\varepsilon_i)$$

Evaluating the partial derivatives (sensitivity coefficients) and simplifying gives the following:

$$u_c(\bar{A}_S) = \sqrt{\left(\frac{1}{\varepsilon_s \cdot W \cdot \varepsilon_i} \right)^2 \left[\frac{u^2(\bar{n}_{s+b})}{t_{s+b}^2} + \frac{u^2(n_b)}{t_b^2} \right] + \bar{A}_S^2 \left[\frac{u^2(\varepsilon_s)}{\varepsilon_s^2} + \frac{u^2(W)}{W^2} + \frac{u^2(\varepsilon_i)}{\varepsilon_i^2} \right]} \\ = \left\{ \left[\frac{1}{(0.500)(1.25 \times 10^{-2} \text{ m}^2)(0.4074 \text{ cps Bq}^{-1})} \right]^2 \left[\frac{(78)^2}{(30 \text{ s})^2} + \frac{(24)^2}{(120 \text{ s})^2} \right] \right. \\ \left. + (15,385 \text{ Bq m}^{-2})^2 \left[\left(\frac{0.0204}{0.5000} \right)^2 + \left(\frac{5.77 \times 10^{-5} \text{ m}^2}{1.25 \times 10^{-2} \text{ m}^2} \right)^2 + \left(\frac{0.0104 \text{ cps Bq}^{-1}}{0.4074 \text{ cps Bq}^{-1}} \right)^2 \right] \right\}^{1/2} \\ = 1,266 \text{ Bq m}^{-2}$$

6.4.3.7 Multiply by a Coverage Factor to Obtain Expanded Uncertainty

Step 7 is to optionally multiply the CSU of the estimate of the measurand by a coverage factor, k , to obtain the expanded uncertainty to construct an interval that can be expected to contain the true value of the measurand with a specified (high) probability.

The interval $(y - U, y + U)$, constructed using the expanded uncertainty in **Equation 6-34**, can be expected to contain the value of the measurand with a specified probability, p :

$$U = k \cdot u_c(y) \quad \text{Equation 6-34}$$

The specified probability, p , is called the level of confidence or the coverage probability and generally is only an approximation of the true probability of coverage.

When the distribution of the measured result is approximately normal, the coverage factor often is chosen to be $k = 2$ for a coverage probability of approximately 95 percent. An expanded uncertainty calculated with $k = 2$ or 3 is sometimes informally called a two-sigma or three-sigma uncertainty, respectively. The GUM recommends the use of coverage factors in the range of 2 to 3 when the CSU represents a good estimate of the true standard deviation.

Example 6-9g: Continuing from **Example 6-9f**, a coverage factor of $k = 2$ is chosen to represent an approximate 95 percent level of confidence in the final result.

$$U = k \cdot u_c(y) \\ = (2)(1,266 \text{ Bq m}^{-2}) \\ = 2,532 \text{ Bq m}^{-2}$$

6.4.3.8 Report the Result with the Expanded Uncertainty and Coverage Factor

Step 8 is to report the result as the estimate of the measurand $\pm$ the expanded uncertainty, together with the unit of measurement, and, at a minimum, the coverage factor used to compute the expanded uncertainty and the estimated coverage probability. If Step 7 was not performed, a coverage factor of $k = 1$ should be reported, or the result should be reported as the CSU and not the expanded uncertainty.

The number of significant figures that should be reported for the result of a measurement depends on the uncertainty of the result. The common convention is to round the uncertainty (standard uncertainty or expanded uncertainty) to two significant figures and to report both the measured value and the uncertainty to the same number of decimal places.

Only final results should be rounded in this manner. Intermediate results in a series of calculation steps should be carried through all steps with additional figures to prevent unnecessary rounding errors. Additional figures are also recommended when the data are stored electronically. Rounding should be performed only when the result is reported. All results, whether positive, negative, or zero, should be reported as obtained, together with their uncertainties.

Example 6-9h: Continuing from **Example 6-9g**, $U = 2,532 \text{ Bq m}^{-2}$. Rounding the expanded uncertainty to two significant digits results in $U = 2,500 \text{ Bq m}^{-2} = 0.25 \times 10^4 \text{ Bq m}^{-2}$.

The estimated activity concentration can be reported as follows:

$$\bar{A}_S \pm U$$

Reporting the estimate of the measurand and the CSU to the same number of digits, the reported average surface activity concentration is $(1.54 \pm 0.25) \times 10^4 \text{ Bq m}^{-2}$ with a coverage factor of 2.

The interval expected to contain the value of the measurand with a 95 percent probability is $(1.29 \times 10^4 \text{ Bq m}^{-2}, 1.79 \times 10^4 \text{ Bq m}^{-2})$.

6.4.4 Using the NIST Uncertainty Machine

The estimate of the measurand and its associated uncertainty can also be calculated using the web-based NIST Uncertainty Machine (<https://uncertainty.nist.gov/>) or another software tool. To use the NIST Uncertainty Machine, complete the following steps:

- (1) Select the number of input quantities from the dropdown list.
- (2) Provide a unique name for each input quantity.
- (3) For each input quantity, select a distribution and provide the required distribution parameters.
- (4) If there are significant correlations between input quantities, enter the covariances.
- (5) Optionally, change the number of realizations run to estimate the uncertainty in the calculated output quantity.

- (6) Enter the formula for the mathematical model including all input quantities.
- (7) Click the “Run the computation” button to generate the results.

The output of the NIST Uncertainty Machine includes the following:

- summary statistics from the Monte Carlo method
- coverage intervals for different coverage factors
- analysis of variance (ANOVA)
- estimate of the measurand and CSU, along with the sensitivity coefficients and the percent contribution to the variance of the final result (CSU squared), using the GUM linear approximation

The numerical values of the sensitivity coefficients, described in **Section 6.4.3.6**, provide information about the effect of the input quantities on the value of measurand. If the sensitivity coefficients are positive, then the measurand, y , will increase if the value of the corresponding input quantity, x_i , increases. If the sensitivity coefficients are negative, then the measurand, y , will decrease if the value of the corresponding input quantity, x_i , increases. The larger the absolute value of the sensitivity coefficient, the larger the effect on the value of measurand.

The relative contribution of the i th input quantity, x_i , to the total uncertainty of the final result, y , can be estimated by dividing the variance (standard uncertainty squared) of the i th input quantity, x_i , by the variance (CSU squared) of the final result, y (i.e., $u^2(x_i)/u_c^2(y)$). Knowing the input quantities that most contribute to the uncertainty in the final result can be helpful to identify where efforts can best be focused to reduce the uncertainty.

Example 6-9i: As shown in **Figure 6-11**, the seven input quantities identified in Step 1 (**Example 6-9a**) and estimated in Step 2 (**Example 6-9b**) are entered in the appropriate fields, along with the required parameters of the input quantities identified in Step 3 (**Example 6-9c**). Finally, the mathematical model described in **Example 6-9a** is entered as a formula. Clicking the “Run the computation” button generates the output file shown in **Figure 6-12**.

The output text file provides the summary statistics, coverage intervals, ANOVA, and an estimate of the measurand and CSU, along with the sensitivity coefficients and the percent contribution to the variance of the final result (CSU squared), using the GUM linear approximation.

While ANOVA is not used as a part of the GUM methodology, it is provided by the NIST Uncertainty Machine as an additional tool. The sensitivity coefficients are the numerical values of the expressions provided in **Example 6-9f**. As shown in the output file, the three largest contributors to overall variance in the average surface activity concentration are the uncertainty in the average number of counts in the survey unit, the source efficiency, and the instrument efficiency, in order of decreasing contribution.

The estimates of the average surface activity concentration and its associated uncertainty calculated using the NIST Uncertainty Machine show good agreement with the results calculated in **Example 6-9a** through **Example 6-9g**.

NIST Uncertainty Machine

https://uncertainty.nist.gov

NIST

Version 1.6.2

About App

Introduction

The NIST Uncertainty Machine is a Web-based software application to evaluate the measurement uncertainty associated with an output quantity defined by a measurement model of the form $y = f(x_1, \dots, x_n)$.

User's manual available here.

Load examples

Drop configuration file here or click to upload

1. Select the number of input quantities

Number of input quantities: 7

2. Provide a unique name for each input quantity

Names of input quantities:

n_SB t_SB n_B t_B e_s W e_i

3. Select a distribution and provide the required parameters

n_SB	Gaussian (Mean, StdDev)	1324	78
t_SB	Constant (Value)	30	
n_B	Poisson (rate)	595	
t_B	Constant (Value)	120	
e_s	Triangular – Symmetric (Left Endpoint, Right Endpoint)	0.45	0.55
W	Rectangular (Left Endpoint, Right Endpoint)	0.0124	0.0126
e_i	Gaussian (Mean, StdDev)	0.4074	0.0104

4. Enter any covariances of input quantities

Correlations: ☐

5. Optionally, change the number of realizations of the output quantity

2. Choose Options

Number of realizations of the output quantity: 1000000

Random number generator seed: 51

Symmetrical coverage intervals: ☐

3. Write the Definition of Output Quantity

Definition of output quantity (R expression):

6. Enter the formula for the mathematical model

$(n\_SB/t\_SB - n\_B/t\_B) / (e\_s * W * e\_i)$

7. Click the "Run the computation" button to generate the results

Run the computation

Site Privacy Accessibility Privacy Program Copyright International Standards Institute Software Policy

Figure 6-11 Screen Shot of NIST Uncertainty Machine for Example 6-9

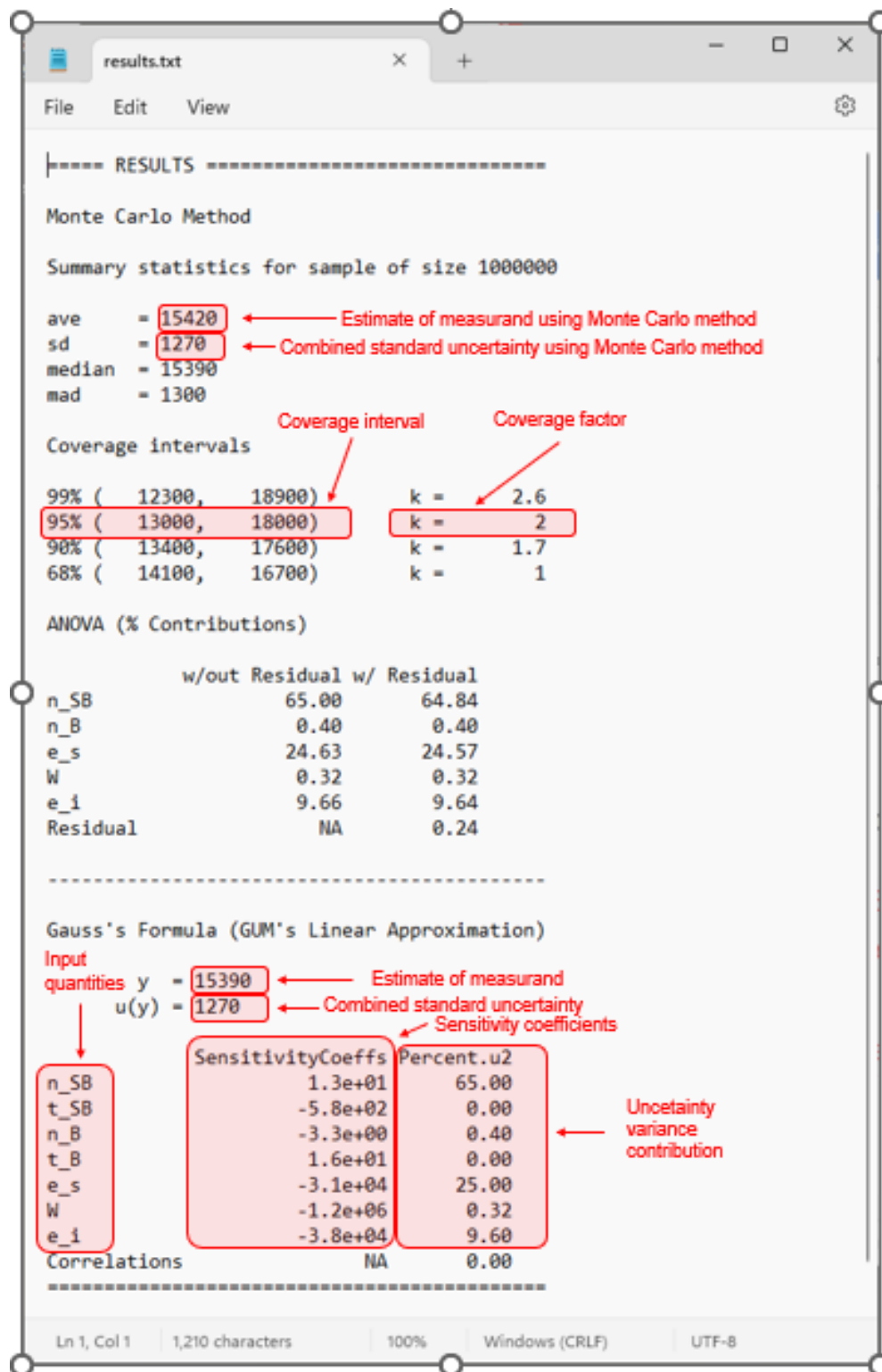


Figure 6-12 Text File with Results from the NIST Uncertainty Machine for Example 6-9

6.4.5 Required Measurement Method Uncertainty

One of the most important MQOs in any project is the required measurement method uncertainty, u_{MR} , at and below the upper bound of the gray region (UBGR) and the relative required measurement method uncertainty, ϕ_{MR} , at and above the UBGR.

Measurement method uncertainty refers to the predicted uncertainty of a measured value that would be calculated if the method were applied to a hypothetical sample with a specified radioactivity concentration or radiation level. Measurement method uncertainty is a characteristic of the measurement method and the measurement process. Measurement uncertainty, covered previously in **Section 6.4**, is a characteristic of an individual measurement.

The true measurement method standard deviation, σ_M , is a theoretical quantity and is never known exactly, but it may be estimated using the methods described in **Sections 6.4.3** and **6.4.4**. The estimate of σ_M will be denoted here by u_M and called the measurement method uncertainty. The measurement method uncertainty is the predicted value of the CSU of the measurement with concentration equal to the UBGR. The term “measurement method uncertainty” and its associated symbol u_M apply not just to the measurement method but also to the entire measurement process; that is, it should include uncertainties in how the measurement method is actually implemented. This definition of measurement method uncertainty is independent of the null hypothesis and applies to both Scenario A and Scenario B.

The true standard deviation of the measurement method, σ_M , is unknown, but the required measurement method uncertainty, σ_{MR} , is intended to be an upper bound for σ_M . In practice, σ_{MR} is actually used as an upper bound for the method uncertainty, u_M , which is an estimate of σ_M . Therefore, the value of σ_{MR} will be called the required measurement method uncertainty and denoted by u_{MR} .

6.4.5.1 Required Measurement Method Uncertainty at the Upper Bound of the Gray Region

This section provides the rationale and guidance for establishing project-specific MQOs for controlling σ_M . This control is achieved by establishing a desired maximum measurement method uncertainty, u_{MR} , at the UBGR. This control also will assist in both the measurement method selection process and in the evaluation of measurement data.

When making decisions about individual measurement results, as a rule-of-thumb, u_{MR} should be less than 0.3Δ , and when making decisions about the mean of several measurement results u_{MR} should be less than 0.1Δ , where Δ is the width of the gray region, $\Delta = \text{UBGR} - \text{LBGR}$, where LBGR refers to the lower bound of the gray region.

For a given width of the gray region, Δ , the relative shift, Δ/σ , can only be controlled by controlling σ . The overall standard deviation of the measurement results, σ , may have both a measurement component, σ_M , and a sampling component, σ_s . Classification may help in controlling σ_s (refer to **Section 4.6.1**) by ensuring that survey units contain areas with similar characteristics. Another method for controlling σ_s is to perform additional remediation to ensure that concentrations within the survey unit are more uniform by removing areas of elevated concentration.

However, it is often more cost effective to reduce the overall standard deviation by ensuring that σ_M is negligible in comparison to σ_s . σ_M can be considered negligible if it is no greater than $\sigma_s/3$.

If the sampling component of the uncertainty is effectively zero, as would be the case where single measurements are being compared directly to an investigation level, then assuming that the data are normally distributed, this works out to requiring that u_{MR} should be less than or equal to 0.3Δ .

When a decision is to be made about the mean of a sampled population, generally the average of a set of measurements for a survey unit is compared to the release criterion. The relative shift, Δ/σ , determines the number of measurements required to achieve the desired decision error rates α and β . Ideally, the target range for this ratio should be between 1 and 3 to keep the required number of measurements low, so the DQOs are aimed at establishing $\Delta/\sigma \approx 3$. The cost in terms of the number of measurements rises rapidly as the ratio Δ/σ falls below 1, but there is little benefit from increasing the ratio much above 3. Therefore, one of the main objectives in optimizing survey design is to achieve a relative shift, Δ/σ , of at least 1 and ideally around 3. Values of Δ/σ greater than 3, while desirable, should not be pursued at additional cost. If Δ/σ is 3 and σ_M is negligible in comparison to σ_s , then σ_M will be $\Delta/10$. Therefore, the recommendation is to keep $u_{MR} \leq \Delta/10$ when decisions are being made about the mean of a sampled population.

Example 6-10: Suppose the action level is 10,000 Bq/m² and the LBGR is 2,000 Bq/m². If decisions are to be made about survey units based on measurements at several locations, then the required measurement method uncertainty, u_{MR} , at 10,000 Bq/m² is as follows:

$$u_{MR} = \frac{\Delta}{10} = \frac{10,000 \text{ Bq/m}^2 - 2,000 \text{ Bq/m}^2}{10} = 800 \text{ Bq/m}^2$$

Example 6-11: Suppose the action level is 10,000 Bq/m², but this time the LBGR is 0 Bq/m². In this case, the required method measurement uncertainty, u_{MR} , at 10,000 Bq/m² is as follows:

$$u_{MR} = \frac{\Delta}{10} = \frac{10,000 \text{ Bq/m}^2 - 0 \text{ Bq/m}^2}{10} = 1,000 \text{ Bq/m}^2$$

The recommended values of u_{MR} are based on the assumption that any known bias in the measurement process has been corrected and that any remaining bias is well less than 10 percent of the shift, Δ , when a concentration near the gray region is measured.

Achieving a required measurement method uncertainty u_{MR} less than the recommended limits may be difficult in some situations. When the recommended requirement for u_{MR} is too difficult to meet, project planners may allow u_{MR} to be larger. In this case, project planners may choose σ_{MR} to be as large as $\Delta/3$ or any calculated value that allows the DQOs to be met at an acceptable level of effort. This may be possible if σ_s is believed to be less than $\Delta/10$ or if it is not difficult to make the additional measurements required by the larger overall data variance ($\sigma_M^2 + \sigma_s^2$).

Example 6-12: Suppose the uncertainty in **Example 6-10** of $u_{MR} = 800 \text{ Bq/m}^2$ cannot be achieved because of the variability in source efficiency with surface roughness. A required measurement method uncertainty, u_{MR} , as large as $\Delta/3 = 2,700 \text{ Bq/m}^2$ may be acceptable if σ_s is small or if more measurements are taken per survey unit.

6.4.5.2 *Required Measurement Method Uncertainty at Concentrations Other than the Upper Bound of the Gray Region*

The most important MQO for data evaluation is the one for measurement method uncertainty at a specified concentration. This MQO is expressed as the required measurement method uncertainty (u_{MR}) at the UBGR. However, to properly evaluate the data usability of measurement results at concentrations other than the UBGR, the implications of this requirement must be extended both above and below the UBGR.

When the concentration is less than or equal to the UBGR, the CSU, u_c , of a measured result should not exceed the required measurement method uncertainty, u_{MR} , specified at the UBGR. When the concentration is greater than the UBGR, the relative CSU, ϕ_{MR} , of a measured result should not exceed the required relative measurement method uncertainty at the UBGR, as shown in **Equation 6-35**:

$$\phi_{MR} = \frac{u_{MR}}{UBGR} \quad \text{Equation 6-35}$$

6.5 Select a Service Provider to Perform Field Data Collection Activities

Often, one of the first steps in designing a survey is to select a service provider to perform field data collection activities. MARSSIM recommends that this selection take place early in the planning process so that the service provider can provide information during survey planning and participate in the design of the survey. Service providers may include in-house experts in field measurements and sample collection, health physics companies, or environmental engineering firms, among others. **Section 6.8** and **Appendix H** contain important information concerning radon service providers.

Potential service providers should be evaluated to determine their ability to perform the necessary analyses. Consideration should be given to using a field survey company that is separate from the remediation company to preclude questions of independence and conflict of interest. For large or complex sites, this evaluation may take the form of a preaward audit. The results of this audit provide a written record of the decision to use a specific service provider. For less complex sites or facilities, a review of the potential service provider's qualifications is sufficient for the evaluation.

The following criteria should be reviewed during this evaluation:

- Does the service provider possess the validated SOPs, appropriate instrumentation, and trained personnel necessary to perform the field data collection activities, including radon/thoron measurements? Field data collection activities (e.g., scanning surveys, direct measurements, and sample collection) are defined by the data needs identified by the DQO process.
- Is the service provider experienced in performing the same or similar data collection activities?

- Does the service provider have satisfactory performance evaluationphysi or technical review results? The service provider should be able to provide a summary of quality assurance audits and QC measurement results to demonstrate proficiency. Equipment calibrations should be performed using NIST traceable reference radionuclide standards whenever possible.
- Is there adequate capacity to perform all field data collection activities within the desired timeframe? This criterion considers the number of trained personnel and quantity of calibrated equipment available to perform the specified tasks.
- Does the service provider conduct an internal QC review of all generated data that is independent of the data generators?
- Are there adequate protocols for method performance documentation, sample tracking and security (if necessary), and documentation of results?
- Is the service provider free of conflict of interest when serving regulatory and commercial entities?

Chapter 10 of MARLAP provides additional guidance related to field and sampling issues that affect laboratory measurements. Potential service providers should have an active and fully documented quality system in place. The quality management system is typically documented in a Quality Management Plan or Quality Assurance Manual. This system should enable compliance with the objectives determined by the DQO process in **Section 2.3** (refer also to EPA 2006c). The elements of a quality management system are discussed in **Appendix D** and EPA QA/G-5 (EPA 2002a).

6.6 Select a Measurement Method

The combination of a measurement technique with instrumentation, known as the measurement method, is selected to implement a radiological survey design based on the ability to meet the MQOs (see **Section 6.1**). Note that measurement techniques are separate from survey designs. A realistic determination of the measurement method uncertainty is critical to demonstrating a method meets the MQOs. Other considerations when selecting a measurement method include the following:

- health and safety concerns (**Section 4.10**)
- required detection capability (**Section 6.3**)
- required measurement method uncertainty or required measurement quantifiability (or both) (**Section 6.4**)
- DQOs for the project

Measurement techniques are discussed in **Section 6.6.1**. Instrumentation includes a combination of a radiation detector (**Section 6.6.2**) and a display, and it may also include data-logging tools (**Section 6.6.3**). Evaluation of a measurement method and comparison to MQOs also require an understanding of the instrument calibration (**Section 6.6.4**). Instrumentation for performing radiological measurements is varied and constantly being improved. **Section 6.6.5** provides an overview of some commonly used types of instruments and how they might be applied to FSSs. The purpose of the discussions on instrumentation is

not to give an exhaustive list of acceptable instruments, but instead to provide examples of how instrumentation and measurement techniques can be combined to meet the survey objectives. **Appendix H** contains additional information on instrumentation.

Section 6.6.6 covers the selection of a combination of measurement technique and instrumentation to provide a measurement method. The selected measurement method must meet the MQOs established during survey design. Selecting instrumentation can be an iterative process. Certain MQOs (e.g., MDC, required measurement method uncertainty) may not be attainable with some measurement methods. In some cases, selection of a different instrument may be all that is necessary, while in other cases, a different measurement technique or an entirely different measurement method will need to be considered. Finally, if the MQOs cannot be met with any available measurement methods, the regulator should be consulted for acceptable options.

6.6.1 Select a Measurement Technique

A measurement technique describes how a measurement is performed. The detector can be moved relative to the surface being measured (i.e., scanning) or used to perform static measurements at a specified location in the survey unit (i.e., in situ or direct measurements), or some representative portion of the survey unit is taken to a different location for laboratory analysis (i.e., sampling). These three measurement technique are described in **Section 6.6.1.1**, **Section 6.6.1.2**, and **Section 6.6.1.3**, respectively. Smears are a type of sampling in which a portion of the removable radioactive material is collected from the surface being investigated (**Section 6.6.1.4**).

6.6.1.1 Scanning Technique

Scanning techniques generally consist of moving portable radiation detectors at a specified distance relative to the physical surface of a survey unit at some specified speed to meet the MQOs. Scanning is used in surveys to locate radiation anomalies by searching for variations in readings, indicating gross activity levels that may require further investigation or action. Scanning techniques can more readily provide thorough coverage of a given survey unit and are often relatively quick and inexpensive to perform.

Scanning techniques can be used alone to demonstrate that concentrations of radioactive material do not exceed release criteria. These surveys, referred to as site-specific scanning surveys, are discussed in detail in **Section 5.3.6.1**. Important considerations include that the scan MDC and measurement method uncertainty are sufficient to meet MQOs to both quantify the average concentration of the radioactive material and identify areas of elevated activity.

Maintaining the specified distance and speed during scanning can be difficult, especially with hand-held instruments and irregularly shaped surfaces. Variations in source-to-detector distance and scan speed can result in increased total measurement method uncertainty. Determining a calibration function for situations other than surficial radionuclides uniformly distributed on a plane can be complicated and may also contribute to the total measurement method uncertainty.

The use of radiation measurement instruments with automated data capture tools (i.e., data logging) has numerous advantages over the normal user observation and manual data recording practice. Coupled with a location instrument, such as GPS and LiDAR units, these systems can also support data mapping and geospatial analyses. Recording detector position during scanning measurements enables the generation of two-dimensional (or

three-dimensional) maps of detector readout over the scanned surface, for example using GPS and GIS technologies.

Site-specific scanning surveys will require site-specific validation samples for establishing scanning detector response. This requires establishing the correlation of scanning measurements to the radionuclide(s) of concern to ensure that the method can reliably detect concentrations at a fraction of the $DCGL_W$ under the conditions expected at the site. This validation can be accomplished at any point in the Radiation Survey and Site Investigation process (after remediation if remediation is performed). During the FSS process, verification scanning measurements are needed, including selective rescanning (nominal 10 percent of the scan area) and static measurements, especially for areas where scanning measurements may be elevated relative to the area in general. Any area with multiple scanning measurements above established investigation levels should be subjected to verification measurements (i.e., rescanning, static, and physical samples with quantitative analysis). The regulator should be consulted for guidance on the level of effort needed to validate scan-based compliance surveys.

Section 4.8.3.1 contains guidance on conditions, including DQOs, for site-specific scanning surveys. Additional guidelines for performing site-specific scanning surveys include the following:

- Procedures covering the survey process, including validation steps, investigation levels, and correlation of sampling and laboratory analysis, are needed.
- A well-bounded correlation of scanning survey measurements to radionuclide concentration(s) (surface or soil levels) is needed. Selected measurements may be used to provide information of a qualitative nature to supplement other measurements. An example of such an application is in situ gamma spectrometry to demonstrate the absence (or presence) of specific radionuclides.
- Including a factor (reduction) for surveyor efficiency (p in the $MDCR_{\text{surveyor}}$) (**Section 6.3.2.1**) is not necessary for data-logging detection systems provided no user interface is required for meeting the MDC, as may be needed for alpha measurements (**Section 6.3.2.2**).
- Recorded data (by a data-logging system) should reflect total detections within a specified scan time period consistent with the MDC determination. Any influence by instrument signal processing (analog-to-digital conversion, instrument time constant) should be eliminated.
- A specified distance and speed during scanning should be maintained to minimize scanning measurement uncertainty. This feature is especially important when using hand-held instruments and irregularly shaped surfaces. Variations in source-to-detector distance and scan speed can result in increased total measurement method uncertainty.
- Signal processing issues, such as analog versus digital signal, instrument, instrument dead time correction, and response time constant, should be considered.
- The effect of field conditions, such as varying materials and backgrounds caused either by ambient radiation levels or changes in material composition, should be considered.

- Data integrity and security should be ensured by maintaining secured datasets, following the chain of custody, and tracking changes.

6.6.1.2 *Direct Measurements*

Direct measurements, also referred to as in situ measurements, are made by placing the instrument in a fixed position at a specified distance from the surface of a given survey unit and taking a discrete measurement for a predetermined time interval. Direct measurements may be combined with scanning measurements in an FSS design. In situ measurements are used generally to estimate the average radionuclide concentration or level of activity over a certain area or volume defined by the calibration function. In situ techniques are not typically used to identify or quantify small areas or volumes of elevated radionuclide concentration or activity, since such techniques integrate radioactivity measurements over relatively large volume or large area (e.g., several square or cubic meters).

Determining a calibration function and the associated MDA/MDC can be complicated and may increase the total measurement method uncertainty, especially for situations other than radionuclides uniformly distributed on a plane or through a regularly shaped volume (e.g., a disk or cylinder). Care must be taken to ensure MDCs and measurement uncertainties are sufficient to meet the MQOs.

However, in applicable situations and at the concurrence of the regulator, direct measurements may be substituted for laboratory analysis. For example, all or a fraction of the systematic soil samples may be measured in situ rather than through traditional laboratory analysis.

6.6.1.3 *Sampling*

Sampling consists of taking a representative portion of the survey unit for separate laboratory analysis. This measurement method generally has greater detection capability and less measurement uncertainty than techniques that may be implemented as scanning or direct measurements. **Chapter 7** discusses sampling in more detail.

6.6.1.4 *Smears*

Smears, sometimes referred to as smear tests, swipes, or wipes, are used to provide an estimate of removable radioactive material on the surface. Smears are a type of sample in which a filter paper or other substance is used to wipe a specified area of a surface. The filter paper or other substance is then tested for the presence of removable radioactive material. The amount of removable radioactive material transferred to the smear will depend on a number of factors, including the type of swipe or smear material, the method used, the physical and chemical nature of the surface being tested, the surface roughness, and the physical and chemical nature of the radioactive material. These factors result in the need to establish a removal factor that will be subject to some uncertainty. For this reason, although smears with detectable radioactive material provide a qualitative indication of removable radioactive material, caution should be exercised when using any quantitative results from smears.

EPA 600/R-11/122, "A Performance-Based Approach to the Use of Swipe Samples in Response to a Radiological or Nuclear Incident," issued October 2011 (EPA 2011), provides more detailed guidance on the use of smears.

6.6.2 Select Instrumentation—Radiation Detectors

The particular capabilities of a radiation detector will establish its potential applications in conducting a specific type of survey. Radiation detectors can be divided into four general classes based on the detector material or the application: (1) gas-filled detectors, (2) scintillation detectors, (3) solid-state detectors, and (4) passive integrating detectors. **Appendix H** contains more information on the detectors discussed in this section.

6.6.2.1 Gas-Filled Detectors

Radiation interacts with the fill gas, producing ion pairs that are collected by charged electrodes. Commonly used gas-filled detectors are categorized as ionization, proportional, or GM, referring to the region of gas amplification in which they are operated. The fill gas varies, but the most common are the following:

- air
- argon with a small amount of methane (usually 10 percent methane by mass, referred to as P-10 gas)
- a noble gas with a small amount of a halogen (e.g., chlorine or bromine)

Gas-filled detectors are available in a variety of shapes and sizes. The major differentiating factor between these different types is the applied voltage across the detector, which determines the type of response that the detector will register from an ionization event. For example, GM detectors can be used in hand-held probes attached to a survey instrument, while proportional counters can be used in larger planar area systems.

Ionization chambers exhibit a nearly uniform response to x-ray and gamma radiation over a wide range of energies and provide a reasonable overall estimate of the exposure or dose rates (or both). Pressurized ion chambers, while limited to the measurement of gamma radiation, can provide increased efficiency.

Proportional counters can be designed for the detection of both alpha and beta particles. Because the charge created in the proportional counter is proportional to the charge deposited by the particle in the detector, proportional counters can be used for charged particle spectroscopy and spectrometry, including pulse height discrimination between alpha and beta particles.

GM counters are well suited for detecting beta particles and alpha particles if the detector window is thin enough. Because pulse heights in a GM counter are the same regardless of the incident energy of the charged particle, they do not provide any spectroscopic information. GM counters can also detect gamma rays, either in the gas itself or more likely in the walls of the gas chamber. The efficiency of a GM counter for gamma rays is often much lower than for beta particles.

6.6.2.2 Scintillation Detectors

Radiation interacts with a solid or liquid medium, causing electronic transitions to excited states in a luminescent material. The excited states decay rapidly, emitting photons that, in turn, are captured by a photomultiplier tube. The ensuing electrical signal is proportional to the scintillator light output, which, under the right conditions, is proportional to the energy loss that produced

the scintillation. The most common scintillator materials are NaI(Tl), silver-activated zinc sulfide (ZnS(Ag)), cadmium tungstate (CdWO₄), thallium-activated cesium iodide (CsI(Tl)), lanthanum bromide (LaBr₃), and plastic scintillators. The most traditional radiation survey instruments are the NaI(Tl) detector used for gamma surveys and the ZnS(Ag) detector for alpha surveys.

Scintillators are available in a wide variety of sizes, thicknesses, and shapes, making them useful for the detection of alpha particles, beta particles, x-rays, and gamma rays. For example, inorganic scintillators can be used in smaller systems, such as hand-held survey instruments or drones, and in some cases in larger systems, such as ground vehicle-mounted systems. These inorganic scintillators can provide sufficient energy resolution for use in a gamma-ray spectroscopy or spectrometry system. One disadvantage of inorganic scintillators is their poorer energy resolution compared to solid-state detectors, described in **Section 6.6.2.3**. Advantages of inorganic scintillators include their ability to operate at room temperatures, higher efficiencies compared to some solid-state detectors, and availability in larger sizes. For the detection of x-rays and lower energy gamma rays, inorganic scintillators can be optimized to reduce the background rate while maintaining a high efficiency. One example is the Field Instrument for the Detection of Low-Energy Radiation (FIDLER).

Plastic scintillators are useful for the detection of beta particles. The inability of plastic scintillators to provide spectroscopic information is not an issue, as beta particles are emitted at a distribution of energies. Plastic scintillators can be made thin enough to minimize the background count rate while still detecting beta particles with high efficiency. Similar to the use of plastic scintillators for the detection of beta particles, a thin layer of ZnS(Ag) can be used for the detection of alpha particles. Pulse shape analysis can be used to determine which scintillator produced the signal. This allows the system to detect alpha and beta particles separately and simultaneously.

6.6.2.3 *Solid-State Detectors*

Radiation interacting with a semiconductor material creates electron-hole pairs that are collected by a charged electrode. The design and operating conditions of a specific solid-state detector determines the types of radiations (alpha, beta, or gamma) that can be measured, the detection limit of the measurements, and the ability of the detector to resolve the energies of the interacting radiations. The common semiconductor materials in use are high-purity germanium (HPGe), silicon, and cadmium zinc telluride (CZT).

These detectors can be made available in both n- and p-types in various configurations. The “n-type” contains a greater number of electrons compared to holes, and the “p-type” has more holes than electrons. Electrons from the n-type migrate across the junction between the two layers to fill the holes in the p-type, creating a depletion zone. This depletion zone acts like the detection area of an ion chamber. Radiation interacting with the atoms inside the depletion zone causes them to reionize, creating an electronic pulse that can be measured.

Spectrometric techniques using these detectors provide a marked increase in energy resolution in many situations. When a particular radionuclide contributes only a fraction of the total particle fluence, photon fluence, or both from all sources (natural or human-made background), gross measurements are inadequate and nuclide-specific measurements are necessary.

Spectrometry provides the means to discriminate among various radionuclides based on characteristic energies. Direct gamma spectrometry is particularly effective in field measurements because the penetrating nature of the radiation allows one to “see” beyond immediate radioactive materials on the surface. The availability of large, high-efficiency germanium detectors permits measurement of low-abundance gamma emitters, such as ²³⁸U.

6.6.2.4 *Passive Integrating Detectors*

An additional class of instruments consists of passive, integrating detectors and associated reading/analyzing instruments. The integrated ionization detector is read using a laboratory or hand-held reader. This class includes thermoluminescent dosimeters (TLDs), optically stimulated luminescence (OSL) dosimeters, and electret ion chambers (EICs). Because these detectors are passive and can be exposed for relatively long periods of time, they can provide better capability for measuring low activity levels for ongoing surveillance. The ability to read and present data on site is a useful feature, and such systems are comparable to direct-reading instruments.

For example, TLDs are used for measuring gamma, x-ray, and beta radiation exposures. They contain small chips of lithium fluoride, which absorb ionizing radiation energy and displace electrons from their ground state. The electrons then become trapped in a metastable state but can be restored to their original ground state by heating. When heated, the electrons return to their ground state and light is emitted. A TLD readout instrument is used to heat the chips and measure the emitted light. The amount of light emitted is related to the dose of radiation absorbed by the TLD and to the radiation exposure dose of the individual.

TLDs come in various shapes (thin rectangles, rods, and powder), sizes (0.08–0.6 cm [0.03–0.25 in.] on a side), and materials (manganese-doped calcium fluoride [$\text{CaF}_2\text{:Mn}$]; dysprosium-doped calcium sulfate [$\text{CaSO}_4\text{:Dy}$]; manganese-doped lithium-6 fluoride [$^6\text{LiF:Mn}$]; manganese-doped lithium-7 fluoride [$^7\text{LiF:Mn}$]; lithium borate [LiBO_4]; magnesium, copper, and phosphorous-doped lithium fluoride [LiF:Mg,Cu,P]; and carbon-doped aluminum oxide [$\text{Al}_2\text{O}_3\text{:C}$]).

OSL dosimeters are similar in principle to TLDs but use light instead of heat to release the free electrons and holes trapped when radiation is absorbed. Advantages of OSL dosimeters over TLDs include lower limits of detection and the fact that OSL dosimeters can be read multiple times and can be reread later, if necessary. Materials suitable for OSL are similar to those used in thermoluminescent dosimetry; that is, they are crystalline solids. In many cases, the same material can be used either as an OSL dosimeter or a TLD. Carbon-doped aluminum oxide ($\text{Al}_2\text{O}_3\text{:C}$) is a common crystalline solid used in commercially available OSLs.

The EIC consists of a very stable electret (a charged Teflon[®] disk) mounted inside a small chamber made of electrically charged plastic. The ions produced inside this air-filled chamber are collected onto the electret, causing a reduction of its surface charge. The reduction in charge is a function of the total ionization during a specific monitoring period and the specific chamber volume. This change in voltage is measured with a surface potential voltmeter. EICs are primarily used to measure radon concentration in indoor environments. For structures affected by residual radioactive material, the EIC is a good indicator of short-term and long-term radon concentrations. Electrets can also be configured as a passive integrating detector for measurements of alpha- or low-energy beta-emitting radionuclides on surfaces and in soils or gamma radiation dose in the environment.

6.6.3 **Display and Recording Equipment**

Radiation detectors are connected to electronic devices to (1) provide a source of power for detector operation and (2) enable measurement of the quantity or quality of the radiation interactions that are occurring in the detector. The quality of the radiation interaction refers to the amount of energy transferred to the detector. In many cases, radiation interacts with other material (e.g., air) before interacting with the detector or only partially interacts with the detector

(e.g., Compton scattering or pair production for photons). Because the energy recorded by the detector is affected, there is an increased probability of incorrectly identifying the radionuclide.

The most common recording or display device used for portable radiation measurement systems is a ratemeter. A ratemeter measures the counting rate of randomly arriving pulses, or the frequency of periodic signals, for example in the range of 0 to 107 cps (0 to 10 megahertz). This range of counting rates is typically covered with 18 different scales. The scales are typically arranged in a 25, 50, 100 sequence from 25 cps to 107 cps full scale. This device provides a display on either an analog meter representing the number of events occurring over some time period (e.g., cpm) or, in the case of digital ratemeters, on a digital display. The number of events can also be accumulated over a preset time period using a digital scaling device. The resulting information from a scaling device is the total number of events that occurred over a fixed period of time, while a ratemeter display varies with time and represents a short-term average of the event rate. Determining the average level on a ratemeter will require judgment by the user, especially when a low frequency of events results in significant variations in the meter reading. The use of a ratemeter, although acceptable for certain scanning applications, is discouraged for performing direct measurements (e.g., gross alpha/beta.)

Pulse height analyzers are specialized electronic devices designed to measure and record the number of pulses or events that occur at different pulse height levels at specific energies. These types of devices are used with detectors that produce output pulses proportional in height to the energy deposited within them by the interacting radiation. They can be used to record only those events occurring in a detector within a single band of energy, or they can simultaneously record the events in multiple energy ranges. In the former case, the equipment is known as a single-channel analyzer; the latter application is referred to as a multichannel analyzer. Both types of analyzers can quantify specific radionuclides.

6.6.4 Instrument Calibration

Calibration refers to the determination and adjustment of the instrument response in a particular radiation field of known intensity. Proper calibration procedures are essential for providing confidence in measurements made to demonstrate compliance with release criteria. Certain factors, such as energy dependence and environmental conditions, require consideration in the calibration process, depending on the conditions of instrument use in the field. Considerations for the use and calibration of instruments include the following:

- the radiation type for which the instrument is designed
- the radiation energies within the range of energies for which the instrument is designed
- the environmental conditions for which the instrument is designed
- the influencing factors, such as magnetic and electrostatic fields, for which the instrument is designed
- the orientation of the instrument, such that geotropic (gravity) effects are not a concern
- the manner in which the instrument is used, such that it will not be subject to mechanical or thermal stress beyond that for which it is designed

Routine calibration commonly involves the use of one or more sources of a specific radiation type and energy and of sufficient activity to provide adequate field intensities for calibration on all ranges of concern.

Actual field conditions under which the radiation detection instrument will be used may differ significantly from those present during routine calibration. Factors that may affect calibration validity include the following:

- The energies of radioactive sources used for routine calibration may differ significantly from those of radionuclides in the field.
- The source-detector geometry (e.g., point source or large-area distributed source) used for routine calibration may be different than that found in the field.
- The source-to-detector distance typically used for routine calibration may not always be achievable in the field.
- The condition and composition of the surface being monitored (e.g., sealed concrete, scabbled concrete, carbon steel, stainless steel, wood) and the presence of overlaying material (e.g., water, dust, oil, paint) may result in a decreased instrument response relative to that observed during routine calibration.

If the actual field conditions differ significantly from the calibration assumptions, a special calibration for specific field conditions may be required. Such an extensive calibration need only be done once to determine the effects of the range of field conditions that may be encountered at the site. If responses under routine calibration conditions and proposed use conditions are significantly different, a correction factor or chart should be supplied with the instrument for use under the proposed conditions.

As a minimum, each measurement system (detector/readout combination) should be calibrated annually and response checked with a source following calibration (ANSI 2013). Instruments may require more frequent calibration, if recommended by the manufacturer. Recalibration of field instruments is also required if an instrument fails a performance check or if it has undergone repair or any modification that could affect its response. The system should be calibrated to minimize potential errors during data transmission and retransmission. The user may decide to perform calibrations following industry-recognized procedures (ANSI 1997, NCRP 1978, NCRP 1985, NCRP 1991, ISO 1988, HPS 1994a, HPS 1994b), or the user can choose to obtain calibration by an outside service, such as a major instrument manufacturer or a health physics services organization. Instrument calibrations are typically performed using ANSI N323A, "Radiation Protection Instrumentation Test and Calibration—Portable Survey Instruments," dated December 31, 1997 (ANSI 1997), and radiation sources certified by NIST or traceable to NIST.

Calibration sources should be traceable to NIST standards. Where NIST-traceable standards are not available, standards obtained from an industry-recognized organization (e.g., the New Brunswick Laboratory for various uranium, thorium, and plutonium standards) may be used.

Instruments for measurement of residual radioactive material on surfaces should be calibrated such that a direct instrument response can be accurately converted to the 4π (total) emission rate from the source. An accurate determination of activity from a measurement of count rate above a surface in most cases is an extremely complex task because of the need to determine appropriate characteristics of the source, including decay scheme, geometry, energy, scatter,

and self-absorption. Proper calibration ensures that systematic errors in measurements are controlled to help ensure that the MQO for measurement method uncertainty is met.

The variables that affect instrument response should be understood. Therefore, the calibration should account for the following factors (where necessary):

- Calibrations for point and large-area source geometries may differ, and both may be necessary if areas of activity smaller than the probe area and regions of activity larger than the probe area are present.
- Calibration should either be performed with the radionuclide of concern or with appropriate correction factors developed for the radionuclide(s) present based on calibrations with nuclides emitting radiations similar to the radionuclide of concern.
- For portable instrumentation, calibrations should account for the substrate of concern (i.e., concrete, steel) or appropriate correction factors developed for the substrates relative to the actual calibration standard substrate. This is especially important for beta emitters because backscatter is significant and varies with the composition of the substrate. Conversion factors developed during the calibration process should be for the same counting geometry to be employed during the actual use of the detector.

For building-surface DCGLs, the level of residual radioactive material is typically expressed in terms of the activity per unit area, normally Bq/m² or dpm per 100 cm². In many facilities, residual radioactive material on the surface is assessed by converting the instrument response (in cpm) to surface activity using the overall total efficiency. The total efficiency may be considered to represent the product of two factors: the instrument (detector) efficiency and the source efficiency. Use of the total efficiency is not a problem, provided that the calibration source exhibits characteristics similar to the residual radioactive material on the surface (i.e., radiation energy, backscatter effects, source geometry, self-absorption). In practice, this is rarely the case; more likely, instrument efficiencies are determined with a clean, stainless-steel source, and then those efficiencies are used to determine the level of residual radioactive material on a dust-covered concrete surface. By separating the efficiency into two components, the surveyor has greater ability to consider the actual characteristics of the residual radioactive material on the surface.

The instrument efficiency is defined as the ratio of the net count rate of the instrument to the surface emission rate of a source for a specified geometry. The surface emission rate is defined as the number of particles of a given type above a given energy emerging from the front face of the source per unit time. The surface emission rate is the 2π particle fluence that embodies both the absorption and scattering processes that affect the radiation emitted from the source. Thus, the instrument efficiency is determined by the ratio of the net count rate and the surface emission rate. **Section 4.12.5** describes the correlation of instrument calibration efficiencies to survey results, especially where there is more than one radionuclide of concern.

The instrument efficiency is determined during calibration by obtaining a static count with the detector over a calibration source that has a traceable activity or surface emission rate. In many cases, a source emission rate is measured by the manufacturer and certified as NIST traceable. The source activity is then calculated from the surface emission rate based on assumed backscatter and self-absorption properties of the source. The maximum value of instrument efficiency is 1.

The source efficiency is defined as the ratio of the number of particles of a given type emerging from the front face of a source to the number of particles of the same type created or released within the source per unit time. The source efficiency takes into account the increased particle emission due to backscatter effects, as well as the decreased particle emission due to self-absorption losses. For an ideal source (i.e., no backscatter or self-absorption), the value of the source efficiency is 0.5. Many real sources will exhibit values less than 0.5, although values greater than 0.5 are possible, depending on the relative importance of the absorption and backscatter processes.

Source efficiencies may be determined experimentally. Alternatively, ISO-7503-1, "Measurement of radioactivity—Measurement and evaluation of surface contamination," Part 1, "General principles," issued 2016 (ISO 2016), makes recommendations for default source efficiencies. A source efficiency of 0.5 is recommended for beta emitters with maximum energies above 0.4 megaelectron volts (MeV). Alpha emitters and beta emitters with maximum beta energies between 0.15 and 0.4 MeV have a recommended source efficiency of 0.25. NUREG-1507, Revision 1, includes source efficiencies for some common surface materials and overlaying material.

Instrument efficiency may be affected by detector-related factors, such as detector size (probe surface area); window density thickness; geotropism; instrument response time; counting time (in static mode); scan rate (in scan mode); and ambient conditions, such as temperature, pressure, and humidity. Instrument efficiency also depends on solid angle effects, which include source-to-detector distance and source geometry.

Source efficiency may be affected by source-related factors, such as the type of radiation and its energy, source uniformity, surface roughness and coverings, and surface composition (e.g., wood, metal, concrete).

The calibration of gamma detectors for the measurement of photon radiation fields should also provide reasonable assurance of acceptable accuracy in field measurements. Use of these instruments to demonstrate compliance with release criteria is complicated by the fact that most radionuclides produce exposure rates of at most a few $\mu\text{R/h}$ at the levels of the DCGLs. Several of the portable survey instruments currently available in the United States for exposure rate measurements of about $1 \mu\text{R/h}$ (often referred to as micro-R meters) have full-scale intensities of about $3\text{--}5 \mu\text{R/h}$ on the first range. This is below the ambient background for most low-radiation areas and most calibration laboratories. A typical background exposure rate of 10 to $12 \mu\text{R/h}$ corresponds to a background dose rate approaching 100 millirem/year. Even on the second range, the ambient background in the calibration laboratory is normally a significant part of the range and must be taken into consideration during calibration. The instruments commonly are not energy compensated and are very sensitive to the scattered radiation that may be produced by the walls and floor of the room or additional shielding required to lower the ambient background.

Low-intensity sources and large distances between the source and detector can be used for low-level calibrations if the appropriate precautions are taken. Field characterization of low-level sources with traceable transfer standards can be difficult because of the poor signal-to-noise ratio. To achieve an adequate detector signal, the distance between the detector and the source generally will be as small as possible while still maintaining good geometry (5–7 detector diameters).

Corrections for scatter can be made using a shadow-shield technique, in which a shield of sufficient density and thickness is placed about midway between the source and the detector to

eliminate virtually all the primary radiation. The dimensions of the shield should be the minimum required to reduce the primary radiation intensity at the detector location to less than 2 percent of its unshielded value. The change in reading caused by the shield's removal is attributed to the primary field from the source at the detector position.

In some instruments that produce pulses (GM counters or scintillation counters), the detector can be separated electronically from the readout electronics, and the detector output can be simulated with a suitable pulser. Caution must be exercised to ensure that either the high voltage is properly blocked or that the pulser is designed for this application. If this can be accomplished, the instrument can first be calibrated on a higher range that is not affected by the ambient background and in a geometry where scatter is not a problem and, after disconnecting the detector, to provide the pulse-rate from the pulser, which will give the same instrument response. The pulse rate can then be related to field strength and reduced to give readings on lower ranges (with the detector disconnected) even below the ambient background. This technique does not account for inherent detector background independent of the external background.

Ionization chambers are commonly used to measure radiation fields at very low levels. To obtain the capability necessary to measure these radiation levels, the instruments are frequently very large and often pressurized. These instruments have some of the same calibration problems as the more portable micro-R meters described above. The same precautions (shadow shield) must be taken to separate the response of the instrument to the source from the response to scattered radiation. Generally, it is not possible to substitute an electronic pulser for the radiation field in these instruments.

For energy-dependent gamma scintillation instruments, such as NaI(Tl) detectors, calibration for the gamma energy spectrum at a specific site may be accomplished by comparing the instrument response to that of a pressurized ionization chamber, or equivalent detector, at different locations on the site. Multiple radionuclides with various photon energies may also be used to calibrate the system for the specific energy of interest.

In the interval between calibrations, the instrument should receive a daily performance check when in use. In some cases, a performance check following use may also provide valuable information. This calibration check is merely intended to establish whether the instrument is operating within certain specified, rather large, uncertainty limits. The initial performance check should be conducted following the calibration by placing the source in a fixed, reproducible location and recording the instrument reading. The source should be identified along with the instrument, and the same check source should be used daily in the same fashion to demonstrate the instrument's operability when the instrument is in use. Location and other specific conditions should be recorded as well (e.g., indoor, outdoor, inside trailer, inside vehicle, on the roof). For analog readout (count rate) instruments, a variation of ± 20 percent is usually considered acceptable. Optionally, instruments that integrate events and display the total on a digital readout typically provide an acceptable average response range of two or three standard deviations. This is achieved by performing a series of repetitive measurements (10 or more are suggested) of background and check source response and determining the average and standard deviation of those measurements. From a practical standpoint, a maximum deviation of ± 20 percent is usually adequate when compared with other uncertainties associated with the use of the equipment. The amount of uncertainty allowed in the response checks should be consistent with the level of uncertainty allowed in the final data. Ultimately, the decision-maker determines the acceptable level of uncertainty.

Instrument response, including both the background and check source response of the instrument, should be tested and recorded at a frequency that ensures the data collected with the equipment are reliable. For most portable radiation survey equipment, MARSSIM recommends performing a response check at least twice daily when the equipment is in use—typically before beginning the day’s measurements and again following the conclusion of measurements on that same day. Additional checks can be performed if warranted by the instrument and the conditions under which it is used. If the instrument response does not fall within the established range, the instrument is removed from use until the reason for the deviation can be resolved and an acceptable response again demonstrated. If the instrument fails the postsurvey source check, all data collected during that time period with the instrument must be carefully reviewed and possibly adjusted or discarded, depending on the cause of the failure. Ultimately, the frequency of response checks must be balanced with the stability of the equipment being used under field conditions, the quantity of data being collected, and the tolerance for potentially losing and needing to recollect data. For example, if the instrument experiences a sudden failure during the day’s work due to physical harm, such as a punctured probe, then the data collected up until that point are probably acceptable even though a postuse performance check cannot be performed. If no obvious failure occurred but the instrument failed the postuse response check, then the data collected with that instrument since the last response check should be viewed with great skepticism and possibly recollected or randomly checked with a different instrument. **Appendix D** presents additional corrective action alternatives. If recalibration is necessary, acceptable response ranges must be reestablished and documented.

Record-keeping requirements vary considerably and depend heavily on the needs of the user. Even though Federal and State regulatory agencies all specify requirements, the following records should be considered a minimum:

- laboratory QC
 - records documenting the traceability of radiological standards
 - records documenting the traceability of electronic test equipment
- record-keeping of instrument calibration files
 - date the instrument was received in the calibration laboratory
 - initial condition of the instrument, including mechanical condition (e.g., loose or broken parts, dents, punctures), electrical condition (e.g., switches, meter movement, batteries), and radiological condition (i.e., presence or absence of contamination)
 - calibrator’s records, including training records and signature on calibration records
 - calibration data, including model and serial number of instrument, date of calibration, recommended recalibration date, identification of source(s) used, NIST certificate or standard certificate from the industry-recognized organization (certificate must include the standard expiration date), “as found” calibration results, and final calibration results—“as returned” for use

In addition, records of instrument problems, failures, and maintenance can be included and are useful in assessing performance and identifying possible needs for altered calibration

frequencies for some instruments. Calibration records should be maintained as permanent records at the facility where the instruments are used, and they should be available either as hard copies or in safe computer storage.

6.6.5 Select Instrumentation Type—Radiation Survey Equipment

This section briefly describes the typical types of instrumentation that may be used to conduct radiological surveys. **Appendix H** contains more detailed information relevant to each type of instrument and measurement method.

6.6.5.1 Hand-Held Instruments

Hand-held instruments typically are composed of a detection probe (using a single detector) and an electronic instrument to power the detector and to interpret data from the detector to provide a measurement display. They may be used to perform scanning surveys or direct measurements. Hand-held measurements also allow the user the flexibility to constantly vary the source-to-detector geometry for obtaining data from difficult-to-measure areas.

6.6.5.2 Large-Area Detectors

Although hand-held instruments are very useful for making direct measurements and scanning small or difficult-to-measure areas, large-area detectors provide advantages when the survey unit includes large, easily accessible areas. These detectors may consist of either a single large detector or an array of detectors. Unlike most hand-held detectors, which can only measure the concentration in a small area (typically about 100 cm²), some detectors can measure the concentration in a much larger area.

6.6.5.3 In situ Gamma Spectroscopy

Some in situ gamma spectroscopy (ISGS) systems consist of a small, hand-held unit that incorporates the detector and counting electronics into a single package. Other ISGS systems consist of a semiconductor detector, a cryostat, a multichannel analyzer electronics package that provides amplification and analysis of the energy pulse heights, and a computer system for data collection and analysis. ISGS systems typically are applied to perform direct measurements, but they may be incorporated into innovative detection equipment setups to perform scanning surveys.

6.6.5.4 Laboratory Analysis

Laboratory analysis consists of analyzing a portion or sample of the surface soil or building surface. The laboratory will generally have recommendations or requirements concerning the amount and types of samples needed for the analysis of radionuclides or radiations. Communications should be established between the field team collecting the samples and the laboratory analyzing the samples. **Section 7.5** contains more information on sampling. Laboratory analyses can be developed for any radionuclide with any material, given sufficient resources. Laboratory analyses typically require more time to complete than field analyses. The laboratory may be located on site or off site. The quality of laboratory data typically is better than data collected in the field, because the laboratory instruments are of better resolution and detection, and the laboratories are able to control sources of measurement method uncertainty. The planning team should consider the resources available for laboratory analysis (e.g., time, cost), the sample collection requirements or recommendations, and the requirements for data

quality (e.g., MDC, required measurement method uncertainty) during discussions with the laboratory.

6.6.6 Select a Measurement Method

Table 6-7 illustrates the potential applications for combinations of the instrument and measurement techniques discussed in **Sections 6.6.1** and **6.6.5**, respectively, for the various radiations being emitted. Sampling followed by laboratory analysis is not included in these tables but is considered “GOOD” for all applications. The following qualifiers should be noted:

- GOOD: The measurement technique is well suited for performing this application.
- FAIR: The measurement technique can adequately perform this application.
- POOR: The measurement technique is poorly suited for performing this application.
- NA: The measurement technique cannot perform this application.
- Few: A relatively small number, usually three or less.
- Many: A relatively large number, usually more than three.

Table 6-8 illustrates that most measurement techniques can be applied to almost any area under investigation for the various types of radiation being detected. The size of the area to be surveyed becomes a major factor for the selection of measurement instruments described in this chapter. Facilities that conduct routine surveys may benefit financially from investing in measurement instruments and techniques that require less manual labor to conduct surveys. Use of such automated systems will also reduce the potential for ergonomic injuries and attendant costs associated with routine, repetitive surveys performed using hand-held instruments.

Hand-held surveying remains the more economical choice for a small area, but as the area increases, the cost of an automated system becomes an increasingly worthwhile investment to reduce manual labor costs associated with surveying. Note that alpha radiation has no survey design options that are described as “GOOD” in **Table 6-7**. The planning team should revisit earlier DQO selections to determine whether a different approach is more acceptable.

Each type of measurement technique has associated advantages and disadvantages, some of which are summarized in **Table 6-8**. All the measurement techniques described in this table include source-to-detector geometry and sampling variability as common disadvantages.

Table 6-7 Potential Applications for Instrumentation and Measurement Technique Combinations

Radiation Type	Hand-Held Instruments	ISGS
Direct Measurements		
Alpha	FAIR	NA
Beta	GOOD	NA
Photon	GOOD	GOOD
Scanning Surveys		
Alpha	POOR	NA
Beta	GOOD	NA
Photon	GOOD	GOOD

Note: The terms POOR, GOOD, and FAIR are subjective, and their use is intended to indicate relative usefulness for typical MARSSIM-type applications.

Table 6-8 Advantages and Disadvantages of Instrumentation and Measurement Technique Combinations

Instrument	Measurement Technique	Advantages	Disadvantages
Hand-Held Instruments	Direct	• Generally allows flexibility in media to be measured. • Detection equipment is usually portable. • Detectors are available to measure alpha, beta, gamma, and x-ray radiation. • Measurement equipment is relatively low cost. • May provide a good option for small areas.	• Requires a relatively large amount of manual labor as a surveying technique; may make surveying large areas labor intensive. • Detector windows may be fragile. • Most do not provide nuclide identification.
Hand-Held Instruments	Scanning	• Generally allows flexibility in media to be measured. • Detection equipment is usually portable. • Detectors are available to measure beta, gamma, and x-ray radiation. • Measurement equipment is relatively low cost. • May provide a good option for small areas.	• Requires a relatively large amount of manual labor as a surveying technique; may make surveying large areas labor intensive. • Detector windows may be fragile. • Most do not provide nuclide identification. • Incorporates more potential sources of uncertainty than most instrument and measurement technique combinations. • Potential ergonomic injuries and attendant costs are associated with repetitive surveys.
Hand-Held Instruments	Smear	• Easily transportable measurement technique for assessing removable radioactive material. • Removable radioactive material can be transferred and assessed in a low-background counting area.	• Instrument background may not be sufficiently low. • Detectors with a counting-sensitive region larger than the smear surface area may require counting adjustments to account for inherent backgrounds associated with other media located under the detector's sensitive region. • The results are not always reproducible and may not be considered quantitative.

Instrument	Measurement Technique	Advantages	Disadvantages
In Situ Gamma-Ray Spectrometer	Direct	- Provides quantitative measurements with flexible calibration. - Generally requires a moderate amount of labor. - May be cost-effective for measuring large areas. - Excellent peak resolution with HPGe detectors. - Good peak resolution for selected scintillators, such as cerium bromide and strontium iodide.	- Instrumentation may be expensive and difficult to set up and maintain. - May require liquid nitrogen supply (with ISGS semiconductor systems). - Size of detection equipment may discourage portability. - Poor peak resolution with NaI(Tl) detectors.
In Situ Gamma-Ray Spectrometer	Scanning	- Provides quantitative measurements with flexible calibration. - Improved MDCs (compared to gross scanning) for gamma-emitting radionuclides. - Generally requires a moderate amount of labor. - May be cost-effective for measuring large areas.	- Instrumentation may be expensive and difficult to set up and maintain. - May require liquid nitrogen supply (with ISGS semiconductor systems). - For semiconductor systems, size of detection equipment may discourage portability. - Resolution for scintillator detectors may not be able to distinguish target radionuclide peaks, leading to reduced MDAs.
Laboratory Analysis	Sampling	- Generally provides the lowest MDCs and measurement method uncertainties, even for difficult-to-measure radionuclides. - Allows positive identification of radionuclides without gammas.	- Most costly and time-consuming measurement technique. - May incur increased overhead costs while personnel are waiting for analytical results. - Great care must be taken to ensure samples are representative. - Detector windows may be fragile.

Instrument	Measurement Technique	Advantages	Disadvantages
Laboratory Analysis	Smear	- Only measurement technique for assessing radionuclide-specific gamma-emitting removable radioactive material. - Removable radioactive material can be transferred and assessed in a low-background counting area.	- Instrument background may not be sufficiently low. - Detectors with a counting sensitive region larger than the smear surface area may require counting adjustments to account for inherent backgrounds associated with other media located under the detector's sensitive region. - The results are not always reproducible and may not be considered quantitative.

6.7 Data Conversion

This section describes methods for converting survey data to appropriate units for comparison to radiological criteria. As stated in **Chapter 4**, conditions applicable to satisfying decommissioning requirements include determining that any residual radioactive material will not result in individuals being exposed to unacceptable levels of radiation or radioactive materials.

Radiation survey data are usually obtained in units that have no intrinsic meaning relative to DCGLs, such as the number of counts per unit time. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements should be converted to DCGL units. Alternatively, the DCGL can be converted into the same units used to record survey results.

6.7.1 **Surface Activity**

When measuring surface activity, it is important to account for the physical surface area assessed by the detector to make probe area corrections and report data in the proper units (i.e., Bq/m², dpm/100 cm²). This is termed the physical probe or active area. A common misuse is to make probe area corrections using the effective probe area, which accounts for the amount of the physical probe area covered by a protective screen. **Figure 6-13** illustrates the difference between the physical and effective probe areas. The physical probe area is used because the reduced detector response due to the screen is accounted for during instrument calibration as long as the screen is in place during calibration.

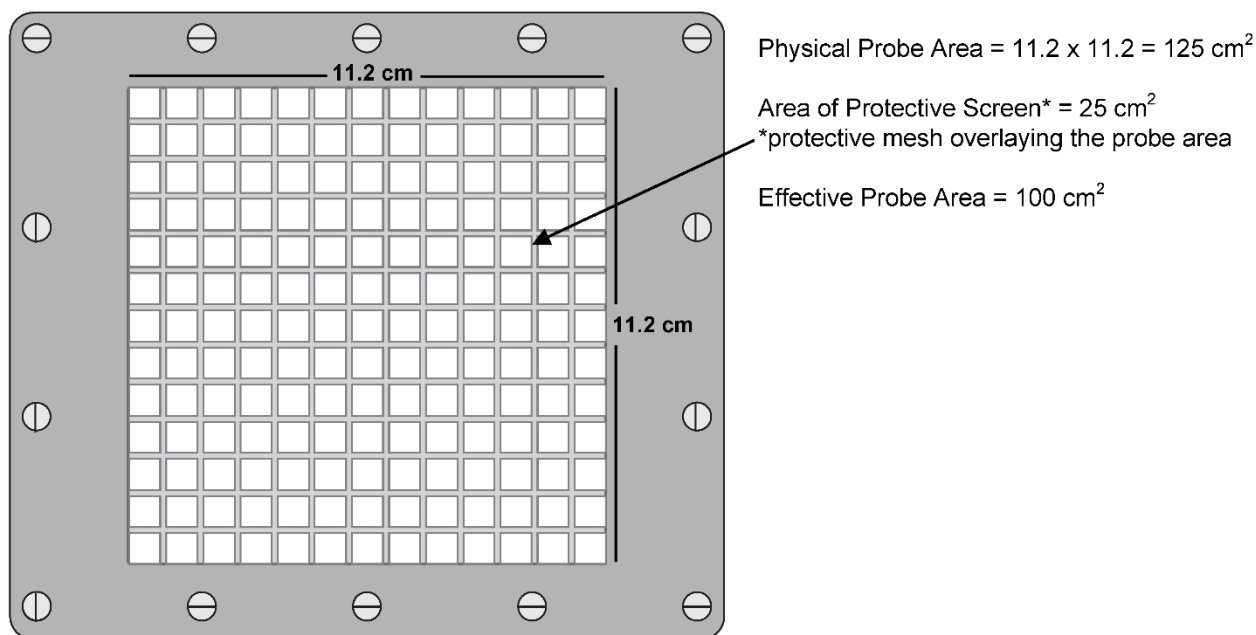


Figure 6-13 The Physical Probe Area of a Detector: Gas Flow Proportional Detector with Physical Probe Area of 125 cm^2

The conversion of instrument display of counts to surface activity in units of Bq/m^2 is obtained using **Equation 6-36**:

$$A_s = \frac{C_s/t_s}{\varepsilon_t \times W} \quad \text{Equation 6-36}$$

where:

- C_s = integrated counts recorded by the instrument
- t_s = time period over which the counts were recorded in seconds
- ε_t = total efficiency of the instrument in counts per disintegration, effectively the product of the instrument efficiency (ε_i) and the source efficiency (ε_s)
- W = physical probe area (m^2)

To convert instrument counts to conventional surface activity units of decays per minute per 100 cm^2 , **Equation 6-36** can be modified as shown in **Equation 6-37**:

$$A_s = \frac{C_s/t_s}{\varepsilon_t \times (W/100)} \quad \text{Equation 6-37}$$

where t_s is recorded in minutes instead of seconds, and W is recorded in 100 cm^2 instead of square meters.

Most instruments have background counts associated with the operation of the instrument. A correction for instrument background can be included in the data conversion calculation, as shown in **Equation 6-38**:

$$A_s = \frac{C_s/t_s - C_b/t_b}{\varepsilon_t \times W} \quad \text{Equation 6-38}$$

where C_b is the background counts recorded by the instrument, and t_b is the time period over which the background counts were recorded in minutes. Note that the instrument background is not the same as the measurements in the background reference area used to perform the statistical tests described in **Chapter 8**. **Equation 6-38** can be modified to provide conventional surface activity units of dpm per 100 cm², as shown in **Equation 6-39**:

$$A_s = \frac{C_s/t_s - C_b/t_b}{\varepsilon_t \times (W/100)} \quad \text{Equation 6-39}$$

where t_s and t_b are recorded in minutes instead of seconds, and W is recorded in square centimeters instead of square meters.

The presence of multiple radionuclides at a site calls for additional considerations for demonstrating compliance with a dose- or risk-based requirement. As demonstrated in **Section 4.5.3**, a gross activity DCGL should be determined. **Example 6-13** illustrates the calculation of a weighted efficiency for a gross activity DCGL.

Example 6-13: Calculation of a Weighted Efficiency for a Gross Activity DCGL

Consider a site with residual radioactive material containing ¹³⁷Cs and strontium/yttrium-90 (⁹⁰Sr/Y), with ¹³⁷Cs representing 60 percent of the total activity. The relative fractions are 0.6 for ¹³⁷Cs and 0.4 for ⁹⁰Sr/Y. If the DCGL for ¹³⁷Cs is 8,300 Bq/m² (5,000 dpm/100 cm²), and the DCGL for ⁹⁰Sr/Y is 12,000 Bq/m² (7,200 dpm/100 cm²), the gross activity DCGL is calculated using **Equation 4-10**, as shown below:

$$\begin{aligned} \text{DCGL}_{\text{gross}} &= \frac{1}{\frac{f_{\text{Cs}}}{\text{DCGL}_{\text{Cs}}} + \frac{f_{\text{Sr/Y}}}{\text{DCGL}_{\text{Sr/Y}}}} = \frac{1}{\frac{0.6}{8,300 \text{ Bq/m}^2} + \frac{0.4}{12,000 \text{ Bq/m}^2}} \\ &= 9,500 \text{ Bq/m}^2 \text{ (5,700 dpm/100 cm}^2\text{)} \end{aligned}$$

Note that because the half-lives of ¹³⁷Cs and ⁹⁰Sr are approximately the same, the relative fractions of the two radionuclides will not change because both decay at the same rate. For other radionuclides, the relative fractions will change over time from the decay of one radionuclide relative to the other.

It is important to use an appropriately weighted total efficiency to convert from instrument counts to surface activity units using **Equation 6-37** through **Equation 6-39**. In this example, the individual efficiencies for ¹³⁷Cs and ⁹⁰Sr/Y should first be evaluated independently. The maximum energies for beta particles for ¹³⁷Cs and ⁹⁰Sr/Y are 0.51 MeV and 2.28 MeV, respectively. The corresponding instrument efficiencies for ¹³⁷Cs and ⁹⁰Sr/Y are determined to be 0.38 and 0.45, respectively. The source efficiency of both nuclides is estimated to be 0.5.

The total efficiencies are calculated by multiplying the source efficiency by the instrument efficiency, as shown below (refer to **Section 4.12.5** for further explanation):

$$\varepsilon_{t,Cs} = \varepsilon_{s,Cs} \times \varepsilon_{i,Cs} = (0.5)(0.38) = 0.19$$

$$\varepsilon_{t,Sr/Y} = \varepsilon_{s,Sr/Y} \times \varepsilon_{i,Sr/Y} = (0.5)(0.45) = 0.22$$

The overall efficiency is then determined by weighting each individual radionuclide efficiency by the relative fraction of each radionuclide (**Equation 4-25**):

$$\varepsilon_t = f_{Cs}\varepsilon_{t,Cs} + f_{Sr/Y}\varepsilon_{t,Sr/Y} = (0.6)(0.19) + (0.4)(0.22) = 0.20$$

The overall efficiency is 0.20 (20 percent).

6.7.2 Soil Radionuclide Concentration and Exposure Rates

Analytical procedures, such as alpha and gamma spectrometry, are typically used to determine the radionuclide concentration in soil in units of Bq/kg. Net counts are converted to soil DCGL units by dividing by the time, efficiency, and mass or volume of the sample and by the fractional recovery or yield of the chemistry procedure (if applicable). **Chapter 7** includes examples of analytical procedures.

Instruments such as a pressurized ionization chamber or micro-R meter are used to measure exposure rate. Typically, exposure rates are read directly in millisieverts per hour (mSv/h) (International System of Units) or μ R/h. A gamma scintillation detector (e.g., NaI(Tl)) provides data in cpm, and conversion to mSv/h is accomplished by using site-specific calibration factors developed for the specific instrument (**Section 6.6.4**).

In situ gamma spectrometry data may require special analysis routines before the spectral data can be converted to soil concentration units or exposure rates. Commercially available measurement systems may use proprietary methods to convert instrument counts to the reported units. Although it is not always necessary to understand the conversion calculations, any deviations from assumptions included in the conversion must be accounted for in the estimate of total measurement uncertainty (**Section 6.4**). The manufacturer should be consulted to ensure the total measurement uncertainty is determined correctly.

6.8 Radon Measurements

There are three radon isotopes in nature: radon-222 (^{222}Rn) (radon) in the ^{238}U decay chain, radon-220 (^{220}Rn) (thoron) in the thorium-232 decay chain, and radon-219 (^{219}Rn) (actinon) in the ^{235}U decay chain. ^{219}Rn is the least abundant of these three isotopes, and because of its short half-life of 4 seconds, it has the least probability of emanating into the atmosphere before decaying. ^{222}Rn , with a 3.8-day half-life, and ^{220}Rn , with a 55-second half-life, are capable of migrating through soil or building material and reaching the atmosphere. Therefore, in most situations, ^{222}Rn and ^{220}Rn should be the predominant airborne radon isotopes. In other instances, thorium-containing building material or interior building structures where processed thorium ore is present can result in thoron becoming the predominant airborne radon isotope.

In some cases, radon may be detected within structures that do not contain residual radioactive material, and conversely, some structures that contain residual radioactive material may not

yield detectable radon or thoron. The regulator should be consulted for the applicability of radon or thoron measurements as part of a site survey.

This section contains an overview of information dealing with the measurement of radon and radon progeny. Many techniques have been developed over the years for measuring radon and radon progeny in air. In addition, the EPA gives considerable attention to the measurement of radon and radon progeny in homes (EPA 1992d). Radon and radon progeny emit alpha and beta particles and gamma rays. Therefore, numerous techniques can and have been developed for measuring these radionuclides based on detecting alpha particles, beta particles, or gamma rays, independently or in some combination. This discussion in this section focuses on the measurement of ^{222}Rn ; however, the information may be adapted for the measurement of ^{219}Rn and ^{220}Rn . There are commercial options for measurements of ^{220}Rn , but options for ^{219}Rn are limited. More consideration should be given to the two latter radon isotopes because of their short half-lives, which may prevent the shipment of the sample for offsite laboratory analyses, depending on the sampling and measurement methods.

The NRC's DUWP-ISG-01, "Evaluations of Uranium Recovery Facility Surveys of Radon and Radon Progeny in Air and Demonstrations of Compliance with 10 CFR 20.1301," issued June 2019 (NRC 2019), provides guidance on modeling and measurement methods to calculate dose and demonstrate compliance with dose-based limits for radon and radon progeny. The EPA website <https://www.epa.gov/radon/radon-standards-practice> includes a list of ANSI/AARST voluntary, consensus-based Radon Standards of Practice that the EPA considers pertinent to the measurement of radon in buildings and the environment. As a general principle, the Federal Government's reliance on privately developed voluntary consensus-based standards is to be preferred over the Federal Government developing such standards.

Radon in a building can come from radium content in nearby soil or bedrock, or in the structure or the utilities connected to the building. Many environmental factors and construction practices influence indoor radon concentrations. Environmental effects such as rainfall; snowfall; wind; barometric pressure; factors "capping" soil; stack and chimney effects; air-tightness of the structure; ventilation; heating, ventilation, and air conditioning [HVAC] ductworks; utility penetrations in foundations; and under-slab material density influence these concentrations. Indoor radon concentrations vary seasonally (usually highest in the winter) and diurnally (usually highest in the night). Radon concentrations within a fixed structure can vary significantly from one section of the building to another and can fluctuate over time. If a home has a basement, for instance, it is usually expected that a higher radon concentration will be found there. Radon primarily enters buildings that are at negative pressure with respect to the underlying foundation soils, where pressure-driven airflow from below-grade soils is the dominant entry mechanism. A small increase in the relative pressure between the soil and the inside of a structure can cause a significant increase in the amount of radon entering the building from the soil. Many factors play a role in these variations, but from a practical standpoint it is only necessary to recognize that temporal and spatial fluctuations, and diurnal and seasonal variations, of the indoor radon air concentration are expected and should be taken into account. Long-term measurement periods (91 days or more) are highly recommended to determine a mean concentration inside a structure; however, a mean may not be necessary to determine whether a risk-reduction strategy is required. It may also not be necessary if radon is being used as an indicator of nearby residual radioactive material. In the last case, for example, the entry points for radon gas into a building may be located within minutes or hours of sampling. Such sampling, however, would produce results with very high measurement uncertainties and would likely be considered as qualitative.

Two analytical end points are of interest when performing radon measurements. The first and most commonly used is radon concentration, which is stated in terms of activity per unit volume, in Bq per cubic meter (m^3) or picocuries per liter (pCi/L). Although this terminology is consistent with most Federal requirements, it only implies the potential dose equivalent associated with radon. The second analytical end point is the potential alpha energy concentration (PAEC) (or equilibrium equivalent concentration [EEC]) of the radon progeny. Radon progeny usually attach very quickly to charged aerosols in the air following creation. The fraction that remains unattached is usually quite small (i.e., 5–10 percent). Because most aerosol particles carry an electrical charge and are relatively massive (≥ 0.1 micrometer [μm]), they are capable of attaching to the surfaces of the bronchi and lung. Essentially all dose or risk from radon is associated with alpha decays from radon progeny deposited in the respiratory system. If an investigator is interested in accurately determining the potential dose or risk associated with radon in the air of a room, the radon progeny concentration must be known. It should be noted, however, that various processes remove radon progeny from a room. If mitigation measures significantly reduce the indoor air radon concentration, the risk from decay products will also be reduced significantly.

Radon progeny concentrations are usually reported in units of working levels, where one working level is equal to the potential alpha energy associated with the radon progeny in secular equilibrium with 100 pCi/L of radon. The short-lived progeny are rarely in equilibrium with their radon parent. One working level is defined as any combination of short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV/L of potential alpha energy. Given a known breathing rate and lung attachment probability, the expected mean lung dose from exposure to a known working level of radon progeny can be calculated.

Radon progeny are not usually found in secular equilibrium with radon indoors because of air exchange due to ventilation and the plating out of the charged aerosols onto walls, furniture, and other surfaces. Radiation dose models do not use measured radon gas concentration as input because the same radon gas concentrations can have different decay product concentrations under different environmental conditions. Instead, the radon EEC, which has the same PAEC as the original mixture, may be used. The equilibrium factor, F_{eq} , is defined as the ratio of EEC to the radon gas concentration. It can have values ranging from 0.1 to 1.0 in a wide range of buildings (Chen and Harley 2020) and from 0.3 to 0.63 in residences (EPA 1992e). If only the ^{222}Rn concentration is measured and it is not practical to measure the progeny concentrations, then general practice is to assume a progeny to ^{222}Rn equilibrium ratio for indoor areas. The appropriate regulatory agency should be consulted to determine the relevant equilibrium factor for a particular location. Usually, the equilibrium factor is higher inside industrial structures, especially abandoned buildings, than in occupied residential dwellings. This allows one to estimate the expected dose or risk associated with a given radon concentration.

In general, the following generic guidelines should be considered when performing radon measurements during site investigations:

- The radon measurement method used should be well understood, documented, and carried out in compliance with certification requirements as applicable. Measurements in buildings should conform to current radon standards of practice as required by the regulator.¹³

¹³ Contact AARST (<https://aarst.org>) for the most current radon standards of practice.

- Long-term measurements longer than 91 days are preferable.
- In nonresidential buildings, such as schools and commercial buildings, the impact of the HVAC system on radon entry should be considered, because radon levels may change significantly between occupied and nonoccupied periods.
- The impact of variable environmental conditions (e.g., humidity, temperature, dust loading, atmospheric pressure) on the measurement process should be accounted for when necessary. Consideration should be given to effects on both the air collection process and the counting system.
- The background response of the detection system should be taken into account.
- If measuring the PAEC directly is impractical, then the progeny activities can be estimated by assuming a specific equilibrium with radon. The concentrations of the radon progeny are then estimated by applying an equilibrium factor to the measured radon concentration. The appropriate regulatory agency should be consulted to determine the appropriate value of F_{eq} .
- Potential radon off-gassing from water and construction materials should be taken into account.

For a general overview, **Table 6-9** lists common radiation detectors with their usual applications during radon surveys. **Appendix H** describes specific equipment used for the measurement of radon.

The following provides a general overview of radon sampling and measurement concepts. This section is intended to give an overview of common methods and terminology.

6.8.1 Direct Radon Measurements

Direct radon measurements are performed by gathering radon into a chamber and measuring the ionizations or ion pairs produced. A variety of methods have been developed, each using the same fundamental mechanics but employing different measurement processes. The first step is to get the radon into a chamber without collecting any radon progeny from the ambient air. A filter is normally used to capture charged aerosols while allowing the radon gas to pass through. Most passive monitors rely on diffusion of the ambient radon in the air into the chamber to establish an equilibrium between the concentrations of radon in the air and in the chamber. Active monitors use some type of air pump system for the air exchange method.

Once inside the chamber, the radon decays by alpha emission to form polonium-218, which usually takes on a positive charge within thousandths of a second following formation. Some types of monitors collect these ionic molecules and subsequently measure the alpha particles emitted by the radon progeny. Others, such as the EIC, measure the ionization produced by the decay of radon and progeny in the air within the chamber by directly collecting the electrons produced inside the chamber. The electrets are influenced by the ambient gamma radiation level; therefore, correction factors based on the gamma radiation level must be established to adjust the radon results. Simple systems measure the cumulative radon during the exposure period based on the total alpha decays that occur. More sophisticated systems measure the individual pulse height distributions of the alpha or beta radiation emissions (or both) and derive the radon plus progeny isotopic concentration in the air volume.

Table 6-9 Radiation Detectors with Applications to Radon Surveys

System	Measures	Category	Description	Application	Collection Time	Remarks
Activated charcoal adsorption	^{222}Rn	Integrating/averaging methods	Activated charcoal is opened to the ambient air, then gamma counted on a gamma scintillator counter.	Measure radon concentration in indoor air.	2–7 days	MDC is 0.007–0.04 Bq/L (0.2–1.0 pCi/L). Must wait 3 hours after deployment ends to begin analysis. Not a true integrating device, as the absorbed radon will decay and partially desorb during the exposure. Must be returned to the laboratory promptly.
EIC	^{222}Rn ^{220}Rn Radon Flux	Integrating/averaging methods	A plastic vessel with an installed charged electret. Vessel opened to air. Voltage drop on electret caused by recombination of produced ions is measured.	Measure radon concentration in air.	2–7 days for short term 91–365 days for long term	Must correct reading for gamma radiation ambient level. Electret measurement sensitive to deformation of electrets caused by temperature and humidity differentials between readings. Reader is sensitive to temperature changes. The system is sensitive to air dust loading. MDC is 0.007–0.02 Bq/L (0.2–0.5 pCi/L) for a nominal 3-month measurement.
Alpha track detection	^{222}Rn ^{220}Rn Radon Flux	Integrating/averaging methods	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measure radon/thoron concentration in air.	91–365 days	MDC is 0.04 Bq/L-day (1 pCi/L-day). Typical deployment is a minimum of 90 days.

System	Measures	Category	Description	Application	Collection Time	Remarks
Filter/detector unit	²²² Rn Progeny ²²⁰ Rn Progeny	Integrating/averaging methods	Air pump and filtration unit with TLD chips or nuclear track detectors.	Measure progeny concentration in air.	1 day—a few weeks	MDC is 0.0002 working level for 1 week measurement.
Ionization chamber, scintillation detector, solid-state detector	²²² Rn ²²⁰ Rn	Continuous monitors	Measure radon/ thoron concentrations and log results in real time. May provide spectral data, depending on device.	Measure radon/thoron concentration in air; “sniffer” mode may be used to locate radon entry points in building.	Minutes to a few days	MDC is 0.004– 0.2 Bq/L (0.1– 5.0 pCi/L), depending on sample time.
Continuous radon progeny monitor	²²² Rn Decay Products ²²⁰ Rn Decay Products	Radon progeny measurements	Air pump and solid-state detector.	Measurement of PAEC. Can calculate equilibrium.	1 day– 1 week “grab samples” for some models	MDC is 20 nanojoules/m ³ (0.001 working level).
Large-area activated charcoal collector	²²² Rn	Short-term radon flux measurements/ thoron	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short-term radon flux measurements.	24 hours	MDC is 0.007 Bq/m ² /s (0.2 pCi/m ² /s).
EIC (8 and 24 hours)	²²² Rn	Short-term radon flux measurements/ thoron	Ion chamber has filtered outlets to prevent saturation.	Short-term radon flux measurements.	8–24 hours	Refer to remarks above for EIC. MDC is 0.003–0.009 Bq/m ² /s (0.08–0.24 pCi/m ² /s) for 24- and 8-hour measurements.

Care must be taken to accurately calibrate a system and to understand the effects of humidity, temperature, dust loading, air currents, and atmospheric pressure on the system. These conditions create a small adverse effect on some systems and a large influence on others.

6.8.1.1 Integrating/Averaging Methods

With integrating methods, measurements are made over a period of days, weeks, or months, and the device is subsequently read by an appropriate device for the detector media used. The most commonly used detectors are activated charcoal adsorbers (good for up to 1 week), EICs (good for days to weeks), and alpha track plastics (good for weeks to months). Short-term fluctuations are averaged out, thus making the measurement representative of average concentration. Results in the form of an average value provide no way to determine the fluctuations of the radon concentration over the measurement interval. Successive short-term measurements can be used in place of single long-term measurements to gain better insight into the seasonal dependence of the radon concentration. Continuous measurements can be used to get better insight into the time dependence of the radon concentration, which can be of particular importance in large buildings. Because charcoal allows continual adsorption and desorption of radon, the method does not give a true integrated measurement over the exposure time. Use of a diffusion barrier over the charcoal reduces the effects of drafts and high humidity.

6.8.1.2 Continuous Monitors

Devices that measure direct radon concentrations over successive time increments are generally called continuous radon monitors. These systems are more complex than integrating devices, in that they measure the radon concentration and log the results to a data recording device on a real-time basis. The monitor must take a reading at least once per hour to be considered a continuous monitor. Continuous radon measurement devices normally allow the noble gas radon to pass through a filter into a detection chamber, where the radon decays and the radon or the resulting progeny are measured. Common detectors used for real-time measurements are ion chambers, solid-state surface barrier detectors, and ZnS(Ag) scintillation detectors.

Monitors equipped with solid-state detectors perform an electrostatic collection of alpha emitters with spectral analysis. The electric field within the sample cell drives the positively charged ion to the detector, where it attaches. The detector converts alpha radiation directly to an electrical signal proportional in strength to the energy of the alpha particle. This alpha spectrometry makes it possible to tell exactly which isotope (e.g., polonium-218, polonium-214) produced the radiation and distinguish “old” radon/thoron from “new” radon/thoron, radon from thoron, and signal from noise. If operated in air with a relatively high radon concentration, these monitors need to be purged with filtered, fresh dry air with a normal radon concentration before taking the next series of measurements. Continuous methods offer the advantage of providing successive, short-term results over long periods of time. This allows the investigator not only to determine the average radon concentration, but also to analyze the fluctuations in the values over time. More complicated systems are available that measure the relative humidity and temperature at the measurement location and log the values along with the radon concentrations to the

data-logging device. This allows the investigator to adjust the resulting data, if necessary, before reporting the results.¹⁴

6.8.2 Radon Progeny Measurements

Radon progeny measurements are usually performed by collecting aerosols onto filter paper and subsequently counting the filter for attached progeny. Some systems pump air through a filter and then automatically count the filter for alpha or beta emissions. An equivalent but more labor-intensive method is to collect a sample using an air sampling pump and then count the filter in standalone alpha or beta counting systems. The measurement system may use any number of different techniques, ranging from full alpha and beta spectrometric analysis of the filters to simply counting the filter for total alpha and or beta emissions.

When performing total (gross) counting analyses, the assumption is usually made that the only radioisotopes in the air are due to ^{222}Rn and its progeny. This uncertainty, which is usually very small, can be essentially eliminated when performing manual sampling and analysis by performing a follow-up measurement of the filter after the radon progeny have decayed to a negligible level. This value can then be used as a background value for the air. Of course, such a simple approach is applicable only when ^{222}Rn is the isotope of concern. For ^{219}Rn or ^{220}Rn , other methods would have to be used.

Time is a significant element in radon progeny measurements. Given any initial equilibrium condition for the progeny isotopes, an investigator must be able to correlate the sampling and measurement technique back to the true concentration values. When collecting radon progeny, the buildup of total activity on the filter increases asymptotically until the activity on the filter becomes constant (after approximately 3 hours of sampling). At this point, the decay rate of the progeny atoms on the filter is equal to the collection rate of progeny atoms. This is an important parameter to consider when designing a radon and progeny sampling procedure. Depending on detection capability requirements, collection times can be as short as 5 minutes (Maiello and Hoover 2010). Although it is possible to sample for other time periods, the equations developed for the three major ^{222}Rn progeny concentrations are valid for sampling times of 5 minutes only. Samples should be shipped and analyzed as expeditiously as possible after sampling is concluded.

Note that the number of charged aerosol particles in the air can affect the results for radon progeny measurements. If there are few particles, as is possible when humidity is low and a room is very clean, then most of the progeny will not be attached and can plate out on room surfaces before reaching the sample filter.

6.8.3 Radon Flux Measurements

Sometimes it is desirable to characterize the source of radon in terms of the rate at which radon is emanating from a surface, such as soil, uranium mill tailings, or concrete. One method used for measuring radon flux is briefly described here.

The measurement of radon flux can be achieved by adsorption onto charcoal using a variety of methods, such as a charcoal canister or a large-area collector (e.g., 25 cm polyvinyl chloride [PVC] end cap). The collector is deployed by sealing the collection device onto the surface of

¹⁴ Depending on the device, these measurements would indicate unexpected disruptions when the device is used for radon testing. The theory is that opening windows or moving the device would cause a noticeable disruption in the measurement.

the material to be measured. After 24 hours of exposure, the activated charcoal is removed and transferred to plastic containers. The amount of radon adsorbed on the activated charcoal is determined by gamma spectroscopy. Because the area of the surface is well defined and the deployment period is known, the radon flux (in units of Bq/m²/s or pCi/m²/s) can be calculated.

This method is reliable for measuring radon flux in normal environmental situations. However, care should be taken if an extremely large source of radon is measured with this method. The collection time should be chosen carefully to avoid saturating the canister with radon. If saturation is approached, the charcoal loses its ability to absorb radon, and the collection rate decreases. Even transporting and handling of a canister that is saturated with radon can be a problem because of the dose rate from the gamma rays being emitted. One would rarely encounter a source of radon that is so large that this would become a problem; however, the potential for it should be recognized. Charcoal also can become saturated with water, which will affect the absorption of radon. This can occur in areas with high humidity.

An alternative method for making passive radon flux measurements has been developed recently using EICs. EIC technology has been widely used for indoor radon measurements. The passive EIC procedure is similar to the procedures used with large-area activated charcoal canisters. To provide the data for the background corrections, an additional EIC monitor is located side-by-side on a radon-impermeable membrane. These data are used to calculate the net radon flux. The Florida State Bureau of Radiation Protection has compared the results from measurements of several phosphogypsum flux beds using the charcoal canisters and EICs and has shown that the two methods give comparable results (EPA 1988c). The passive method seems to have overcome some of the limitations encountered in the use of charcoal. The measurement periods can be extended from hours to several days to obtain a better average, if needed. EIC flux measurements are not affected by such environmental conditions as temperature, humidity, and air flow. The measured detection capabilities are comparable to the charcoal method, but—unlike charcoal—EICs do not become saturated by humidity. Intermediate readings can be made if needed. In view of the low cost of the EIC reading and analysis equipment, the cost per measurement can be as much as 50 percent lower than the charcoal method, with additional savings in time. There are handling and storage requirements associated with these methods and detectors. The manufacturer and **Appendix H** should be consulted for more information.

6.9 Special Equipment

Various specialized systems have been developed that can be used during the performance of Radiation Surveys and Site Investigations. Many of these systems are used for CCD surveys, but the specialized equipment discussed here can be used to support other types of surveys as well. **Section 6.9.1** discusses surveys using GPS technologies. **Sections 6.9.2–6.9.4** provide information on various types of positioning systems. **Section 6.9.5** provides an introduction to radar, magnetometer, and electromagnetic systems, and, finally, **Section 6.9.6** gives an overview of aerial measurement systems. Advanced positioning technologies enhance survey capabilities by using GPS, laser, optical, and inertial technologies with application software and wireless communications. GPS is also more generally referred to as global navigation satellite system or satellite navigation system internationally.

6.9.1 Global Positioning System

This section refers to technology with associated software that may be linked to satellites for recording real-time geospatial data with the survey instrument output. In addition to exterior

GPS technologies, products are also available with three-dimensional mapping and positioning capabilities for surveys of a facility's interior. These typically hand-held devices can be used with commercial operating systems; this also allows the use of additional independent data-logging software when geospatial-related data recording is not feasible. The flexibility of this technology is that it permits use in many different applications and with a variety of radiation detection instruments.

6.9.2 Laser Positioning Systems

Laser positioning systems are available for monitoring positions in three dimensions. The newest systems use a reflectorless electronic technique to measure the distance to an object without actually accessing the object. Laser systems use the principles of phase shift and pulse (or time of flight), or a hybrid combination of these, to measure distance. This allows mapping of distant or inaccessible objects in hazardous areas. Using a reflector, or retroprism, to identify the location of a surveyor or detector allows the system to track the location of individual measurements. Laser systems are accurate to within a few millimeters at distances up to 1,000 meters. Laser systems require a clear line of sight between the object and the laser. Systems with multiple lasers at different locations can be used to minimize issues with line-of-sight interference.

6.9.3 Optical Positioning Systems

Another common sensor paired with radiation detection is LiDAR (which stands for “light detection and ranging” or “laser imaging, detection, and ranging”). LiDAR is an optical distant measurement sensor that uses light from a pulsed laser to measure ranges. Coupled with GPS and a radiation detector, LiDAR acts as a proximity sensor (altimeter), providing information about the distance between the surface and the height of the detector. With multiple LiDAR instruments, three-dimensional information can be collected. Since LiDAR can make measurements without connecting to satellites, which GPS requires, the three-dimensional information can provide precise mapping and positioning measurements for indoors, such as inside a building or confined space. LiDAR units are small and can be customized for multiple applications. Software outputs from the LiDAR unit are then synchronized with the radiation measurements, typically by matching time stamps in data feeds.

6.9.4 Inertial Positioning Systems

Inertial systems can determine position, orientation, and velocity using motion sensors (accelerometers and gyroscopes) and a computer. The systems can be used on land, under water, and in space. One advantage of this type of system is that after the initial position is determined, the systems do not require communication with satellites like other systems do (e.g., GPS).

6.9.5 Radar, Magnetometer, and Electromagnetic Sensors

The number of sensors and sensor systems applicable to the detection and location of buried waste has increased in terms of use and reliability in recent years. These systems are typically applicable to scoping and characterization surveys, where the identification of residual radioactive materials in the subsurface is a primary concern. However, the results of these surveys may be used during FSS planning to demonstrate that subsurface materials are not a concern for a particular site or survey unit. The following sections describe some of the major technologies.

6.9.5.1 *Ground-Penetrating Radar*

For most sites, ground-penetrating radar (GPR) is the only instrument capable of collecting images of buried objects in situ, as compared to magnetometers (**Section 6.9.5.2**) and electromagnetic sensors (**Section 6.9.5.3**), which detect the strength of signals as measured at the ground surface. Additionally, GPR is unique in its ability to detect both metallic and nonmetallic (e.g., plastic, glass) containers. GPR techniques are being studied to monitor the performance and stability of soil covers at uranium mill tailings sites and other land disposal sites with earthen covers (Necsoiu and Walter 2015).

Subsurface radar detection systems have been the focus of study for locating and identifying buried or submerged objects that otherwise could not be detected. There are two major categories of radar signals: (1) time domain and (2) frequency domain. Time-domain radar uses short impulses of radar-frequency energy directed into the ground being investigated. Reflections of this energy, based on changes in dielectric properties, are then received by the radar. Frequency-domain radar, on the other hand, uses a continuous transmission, and the frequency of the transmission can be varied either stepwise or continuously. The changes in the frequency characteristics due to effects from the ground are recorded. Signal processing, in both cases, converts this signal to represent the location of radar reflectors against the travel time of the return signal. Greater travel time corresponds to a greater distance beneath the surface.

Examples of existing GPR technologies currently being applied to subsurface investigations include the following:

- narrow-band radar
- ultra-wide-band radar
- synthetic aperture radar
- frequency modulated continuous radar
- polarized radar waves

The major limitation to GPR is the difficulty in interpreting the data, which is often provided in the form of hazy, “waterfall-patterned” data images requiring an experienced professional to interpret. Also, GPR can vary depending on the soil type—highly conductive clay soils often absorb a large amount of the radar energy and may even reflect the energy. GPR can be deployed using ground-based or airborne systems.

6.9.5.2 *Magnetometers*

Although soil affected by residual radioactive material and most radioactive waste possess no ferromagnetic properties, the containers commonly used to hold radioactive waste (e.g., 55-gallon drums) are made from steel. These containers possess significant magnetic susceptibility, making the containers detectable using magnetometry.

Magnetometers sense the pervasive magnetic field of the Earth. This field, when encountering an object with magnetic susceptibility, induces a secondary magnetic field in that object. This secondary field creates an increase or decrease in Earth's ambient magnetic field. Magnetometers measure these changes in the expected strength of the ambient magnetic field. Some magnetometers, called “vector magnetometers,” can sense both the direction and the magnitude of these changes. However, subsurface investigations use only the magnitude of the changes.

An alternative magnetometer survey can be performed using two magnetometers in a gradiometric configuration. This means that the first magnetometer is placed at the ground surface, and the second is mounted approximately 0.5 meter above the first. Data are recorded from both sensors and compared. If the readings from both detectors are nearly the same, this implies that there is no significant disturbance in the Earth's ambient magnetic field or that such disturbances are broad and far away from the gradiometer. When a secondary magnetic field is induced in an object, it affects one sensor more strongly than the other, producing a difference in the readings from the two magnetometers. This approach is similar to the use of a guard detector in anticoincidence mode in a low-background gas-flow proportional counter in a laboratory (see **Appendix H** for a description of gas-flow proportional counters). The gradiometric configuration filters out the Earth's ambient magnetic field, large-scale variations, and objects located far from the sensor to measure the effects of nearby objects, all without additional data processing. Fifty-five-gallon drums buried 5–7 meters below the surface may be detectable using a magnetometer. At many sites, multiple drums have been buried in trenches or pits, and detection is straightforward. A single operator carrying a magnetometer with the necessary electronics in a backpack can cover large areas in a relatively small amount of time.

The limitations on the system are related to the size of the objects and their depth below the surface. Objects that are too small or buried too deep will not provide a secondary magnetic field that can be detected at the ground surface.

6.9.5.3 *Electromagnetic Sensors*

Electromagnetic sensors emit an electromagnetic wave, in either a pulsed or continuous wave mode, and then receive the result of that transmission. The result of the transmission is two signals: quadrature and in phase. As the wave passes through some material other than air, it is slowed down by a resistive medium or sped up by a conductor through dielectric effects. This produces the quadrature signal. If the electromagnetic wave encounters a highly conductive object, it induces a magnetic field in the object. This induced electromagnetic field returns to the sensor as a reflection of the original electromagnetic wave and forms the in-phase signal.

The in-phase signal is indicative of the presence, size, and conductivity of nearby objects (e.g., 55-gallon drums), and the quadrature signal is a measure of the dielectric properties of the nearby objects, such as soil. This means that electromagnetic sensors can detect all metallic objects (including steel, brass, and aluminum), such as the metal in waste containers, and sample the soil for changes in properties, such as those caused by leaks of contents.

Depths of interest are largely determined by the spacing between the coil used to transmit the primary electromagnetic wave and the receiver used to receive that transmission. The rule of thumb is that the depth of interest is on the order of the distance between the transmitter and the receiver. A system designed with the transmitter and receiver placed tens of meters apart can detect signals from tens of meters below the surface. A system with the transmitter and receiver collocated can detect signals only from depths on the order of the size of the coil, which is typically about 1 meter. The limitations of electromagnetic sensors include a lack of clearly defined signals and decreasing signal resolution as the distance below the surface increases.

6.9.6 *Aerial Radiological Surveys*

Aerial radiological surveys have been used for geological exploration and mapping since the mid-1900s. Prospecting for rare metals, determining levels of background radiation over large areas, and assessing the impacts of radiological incidents and releases could all be accomplished to some extent using aerial radiological surveys (IAEA 2003). Some of the

biggest advantages of aerial surveys include the ability to measure large areas of land relatively quickly, over rough and difficult-to-access terrain, and to obtain measurements in areas where humans could not safely or easily travel (Sanada and Torii 2015). Disadvantages include the use of specialized equipment and expertise and challenges in quantification of survey results. Like other MARSSIM surveys, aerial radiological surveys only measure radiological material located on surface soils or building surfaces, but not in the subsurface.

Aerial radiological surveys historically were restricted to manned aerial vehicles (MAVs), such as fixed-wing and rotary-wing aircraft, which limited their use throughout most of the 20th century. However, with the increase in the use of unmanned aerial vehicles (UAVs, sometimes referred to as “drones”) in more recent years, combined with improvements in GIS capabilities for both MAVs and UAVs, aerial surveys are increasingly employed for radiological surveys of sites for a variety of uses, such as cleanup and emergency response. Some specific uses of aerial radiological surveys include the following:

- providing data to assist in the identification of residual radioactive material and its corresponding concentrations and spatial distributions
- characterizing the nature, extent, and impact of residual radioactive material

Aerial radiological surveys are usually more suitable for gamma-emitting radionuclides, due to the attenuation of beta and alpha radiation in the air (Bunn et al. 2022). Both gross gamma and gamma spectrometry surveys can be performed using aerial radiological surveys. Performing aerial radiological surveys over time can help assess the migration of radioactive materials in the environment and the effectiveness of remediation techniques (Sanada and Torii 2015).

6.9.6.1 *Benefits of Manned versus Unmanned Aerial Vehicle Surveys*

Both MAVs and UAVs offer unique advantages for conducting aerial surveys. In general, the basic trade-off is payload versus altitude and maneuverability, with each platform offering benefits and disadvantages (Beal 2023).

MAVs require specific support infrastructure, skilled pilots trained in flying for these types of surveys, and coordination with Federal Aviation Administration requirements. For fixed-wing aircraft, the minimum survey speed may be determined by the aircraft and flying conditions, whereas survey speed may be more flexible for a rotary-wing aircraft. MAVs typically operate at a higher altitude, which when combined with a higher speed leads to a larger area measured during each individual measurement and a much larger area surveyed overall per unit time. In many cases, MAV surveys are used to better focus follow-up ground-based surveys to locate smaller areas of elevated activity (National Security Technologies 2015). These are sometimes referred to as “ground-truthing surveys.” Their payload is also much higher, to accommodate a much larger detector array and accompanying electronics.

Advantages may include the following (Bunn et al. 2022):

- Higher payload accommodates greater flexibility in choosing detector arrays, electronics, and the possibility of carrying an on-board data analyst.
- Vehicles are sturdier and better able to accommodate instruments that are delicate, are under pressure, or require bulky support systems.
- Vehicles can operate under a broader range of weather conditions.

- Surveys measure a larger area in a relatively shorter timeframe.

UAVs typically fly at much lower speeds and altitudes than MAVs. In some cases, a UAV can take measurements at or below 1 meter above the ground surface. Many UAVs have the ability to hover or land and take-off again mid-survey, allowing them to take a fixed measurement at some distance above the ground surface, or land and take a fixed measurement from ground level if a particular location needs further investigation. The area included in a single measurement tends to be much smaller, and the overall survey area per time is also much smaller. This may allow for better delineation of smaller areas of elevated activity.

UAVs are widely commercially available, and there is growing expertise in the radiation survey community on their use. Several challenges must be overcome to use a UAV for a radiological survey, including, but not limited to, size and functional constraints on the instrumentation used, hardware configuration and testing requirements, maintenance requirements, relatively short time of flight, weather conditions under which surveys can be flown, collision avoidance systems, and permits and licensing requirements (Bunn et al. 2022). Compared to a human surveyor with a hand-held instrument, UAVs may be better able to access areas that are considered hazardous (e.g., unsafe buildings and terrain, high radiation areas, presence of unexploded ordnance), but they may also face challenges with thick vegetation or other obstacles (Ramos Pinto et al. 2021). UAVs may be better suited to survey areas with elements of steep terrain, such as riverbanks, gorges, natural or “urban” canyons, surveys of which may generate overestimated gamma exposure levels in MAV surveys (National Security Technologies, LLC, 2015).

Advantages may include the following (Bunn et al. 2022):

- Vehicles are widely available and require less infrastructure to operate.
- Vehicles can perform surveys in areas or structures hazardous to a human surveyor with a hand-held instrument.
- Surveys can better delineate smaller areas of elevated activity.
- Hovering and landing features allow for further investigation of an area of interest mid-survey.

6.9.6.2 *Aerial Surveys and Continuously Collected Data Surveys*

Aerial radiological surveys are often implemented as a form of CCD survey. **Section 6.9.1** contains more information on CCD surveys using GPS technology.

Geolocation of all aerial radiological survey measurements must be determined in three dimensions. For MAV surveys, this is typically accomplished using real-time differential GPS navigation and radar altimeter (IAEA 2003). Using a ground-based augmentation station can improve GPS navigation accuracy (Sinclair et al. 2016). The GPS location can be compared to the desired flight path and deviations communicated to the pilot so corrections can be made in real time (National Security Technologies 2015). For UAV surveys, a flight path may be programmed in three dimensions using GPS or other locational information and LiDAR, ultrasound, or other altimeter information (Bunn et al. 2022, Ramos Pinto et al. 2021).

Aerial radiological survey measurements should include correlated temperature and pressure data recorded by thermometer and barometer, respectively. These instrument readings together

help ascertain the density of the air and, when combined with the radar or other altimeter reading, can be used to correct the measurement for attenuation by the air column between the detector and the surface being measured (IAEA 2003).

Similar to other CCD surveys, aerial radiological surveys are often conducted as a series of parallel lines (sometimes referred to as flight lines) that cover some percentage of the survey unit. The effective field of view is considered to be a circle of diameter two times the height above ground surface (AGS), elongated by the distance traveled during the typically 1-second measurement (National Security Technologies 2016) (**Figure 6-14**). Data must be corrected to ensure that the corresponding integrated measurement is geolocated in the center of the field of view for that measurement. The width of the parallel line is determined by the planning team but should be chosen to ensure overall coverage of the survey unit meets the DQOs selected for the survey. **Figure 6-15** (EPA 2011) shows an example of the flight lines for an aerial radiological survey.

Nominal altitude for the aircraft is determined by the project planning team and is often 40–200 meters AGS (~120–600 feet AGS) for MAV surveys and much lower for UAV surveys, sometimes at 1 meter AGS (~3 feet AGS) or less. Gamma radiation attenuation by air decreases by altitude, so the lower the altitude of the survey, the smaller the effective field of view for the survey, and, consequently, the more flight time will be needed for the same areal coverage (IAEA 2003). The minimum height deemed acceptable for the survey may be affected by topography and structures within the survey unit, local regulations, and concerns that rotary-wing rotor wash (resulting from the vertical downwash of air generated by rotors) may affect the surface being measured at heights lower than 40 meters AGS (~120 feet AGS) (Sinclair et al. 2016). Radar or other altimeter readings can be used to correct data for deviations from the nominal altitude (National Security Technologies 2015).

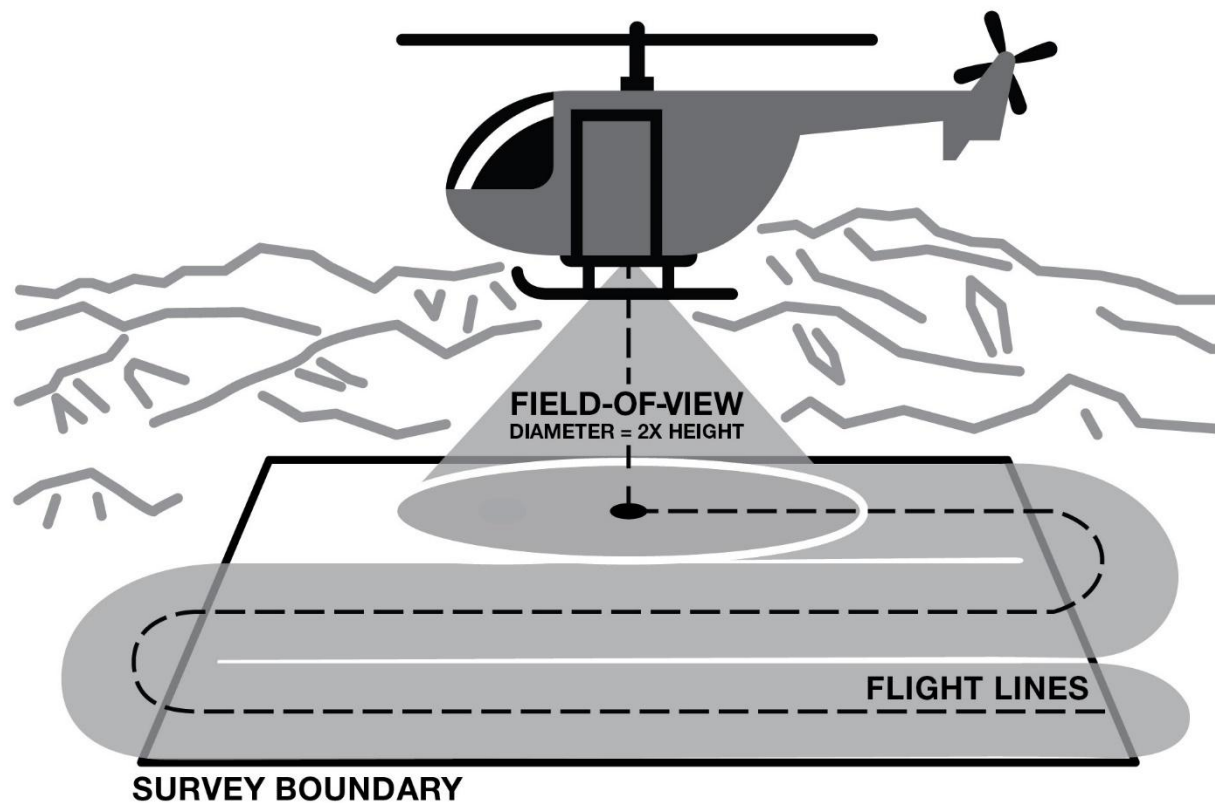


Figure 6-14 Detector Field of View for an Aerial Measurement (National Security Technologies 2016)



Figure 6-15 Example of Aerial Radiological Survey Flight Lines over a Site (EPA 2011)

6.9.6.3 Calibration of Aerial Measurements

Section 5.3 of International Atomic Energy Agency (IAEA) Technical Document 1363, “Guidelines for radioelement mapping using gamma ray spectrometry data,” issued July 2003 (IAEA 2003), provides a good summary of the corrections needed to calibrate aerial measurements to measure terrestrial activity. Empirically determined corrections will be needed for background, stripping, height, and sensitivity corrections, as described below.

Background correction—In order to calibrate measurements for sources of background radioactivity, calibration flights are often conducted in an area with low background, such as over a body of water that is sufficiently deep and sufficiently far from shore that it shields almost all terrestrial contribution to the measurements. The measurements would thus consist of background from cosmic rays and radiation from atmospheric radon and its progeny. This flight is sometimes referred to as a “water line.” To account for diurnal variations and variations due to changing weather on atmospheric radon, it may be necessary to repeat this flight several times each day that flight operations are conducted, for example, at the beginning and end of operations and after any major weather change (National Security Technologies 2015).

Stripping correction—If the survey consists of gamma spectrometry measurements of materials that contain background radioactivity concentrations of uranium, thorium, and potassium (such as surface soils or building materials such as concrete or brick), the measurement system should be calibrated empirically to correct each elemental window for the effects of other isotopes. Calibrations are often conducted by taking measurements of a series of four

ground-based sources: three consisting of known radioactivity concentrations of uranium, thorium, and potassium and one of source material background. One method uses four pads constructed of concrete with dimensions 1 meter x 1 meter x 0.3 meter, either with the aerial vehicle in place during the calibration or the instrumentation package placed directly on the pad. If the latter, then additional corrections will be needed to account for the thickness of the aircraft material (IAEA 2003).

Height Correction—As mentioned in **Section 6.9.6.2**, aerial radiological surveys will need to account for attenuation of the measurement due to the column of air between the surface being measured and the aircraft-mounted instrument. This height correction, known as an air or height attenuation coefficient, is determined empirically by flying over a “test line” located along relatively flat and homogenous terrain at multiple altitudes, sometimes referred to as an altitude spiral. For MAVs, one example of an altitude spiral used altitudes of 60–240 meters AGS (~180–720 feet AGS), conducted at 30-meter (~90-foot) intervals (IAEA 2003). The attenuation coefficient is determined by comparing the measurements at the same location but at different heights AGS.

Sensitivity Correction—At the same time an aerial measurement is collected over the test line, a ground-based instrument would collect comparable measurements of either natural background or check sources to help determine the sensitivity correction. The soil moisture and spectral profile of the test line, like all reference area measurements, should be as similar as possible to the survey area (National Security Technologies 2015). One best practice is to fly the test line at the nominal flight altitude and check measurements of both natural background and check sources at the beginning and end of each flight for consistency (e.g., with 10 percent of expected values) to look for possible equipment malfunction.

6.9.6.4 *Uses of Aerial Radiological Surveys*

Requirements for the use of aerial radiological surveys may vary depending on the regulator, location, and specific use. Aerial radiological surveys may be acceptable for some uses (scoping or characterization surveys, but not FSSs) or may be used to direct further ground-based surveys. Investigators should always check with local, State, and Federal laws governing aerial surveys at the site location and with the site regulator before planning an aerial radiological survey.

Assuming that these criteria are met, aerial radiological surveys may be used as scanning surveys in MARSSIM, provided that DQOs and MQOs can be met with the aerial survey. Aerial radiological surveys may be appropriate as site-specific scanning surveys or as generic scanning surveys. In many cases, aerial radiological surveys would constitute a form of CCD survey.

These surveys are typically only appropriate for gross gamma and gamma spectrometry measurements. Special care should be taken when using aerial radiological surveys in rough or uneven terrain; IAEA 2003 provides a good summary of the difficulties and ways to minimize the effects. Finally, assumptions about the size of elevated areas that can be delineated by an aerial radiological survey should be confirmed with follow-up ground-based measurements.

7 SAMPLING AND PREPARATION FOR LABORATORY MEASUREMENTS

7.1 Introduction

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides three methods for collecting radiation data while performing a survey: direct measurement, scanning, and sampling. A direct measurement is a radioactivity measurement obtained by placing the detector near the surface or media being surveyed for a prescribed amount of time. An indication of the resulting concentration of radioactive material is read out directly. Scanning is an evaluation technique performed by moving a portable radiation detection instrument at a constant speed and distance relative to the surface to detect radiation. These measurement techniques are discussed in **Chapter 6**. The third method of obtaining radiation data involves collecting a portion of a larger quantity of media for sample analysis using instrumentation in the field or in a laboratory (NRC 2004).

Chapter 7 discusses issues involved in collecting and preparing samples for analysis. Specifically, it provides guidance on the collection, treatment, and handling of solid and liquid samples in the field for subsequent shipment and analysis at a radiological laboratory. This information will assist in communications with the laboratory during survey planning.

Samples should¹ be collected and analyzed by qualified individuals using the appropriate equipment and procedures. MARSSIM assumes that the samples taken during the survey will be submitted to a qualified or certified laboratory for analysis. The laboratory should have written procedures that document its analytical capabilities for the radionuclides of interest and a quality assurance (QA)/quality control (QC) program that documents the compliance of the analytical process with established criteria. Certain agencies require the laboratory to be traceable to National Institute of Standards and Technology (NIST) standards in its QA/QC program. The method used to assay the radionuclides of concern should be recognized as a factor affecting analysis time.

Chapter 6 and **Appendix H** describe commonly used radiation detection and measuring equipment for radiological survey field applications. Many of these equipment types may also be used for laboratory analyses, usually under more controlled conditions that provide for lower detection limits and measurement method uncertainties and greater abilities to identify and quantify among radionuclides. Laboratory methods often involve combinations of both chemical and physical preparation and instrument techniques to quantify the low radionuclide concentration levels expected in the samples. This chapter provides guidance to assist the MARSSIM user in selecting appropriate procedures for collecting and handling samples for laboratory analysis. More detailed information is available in the Multi-Agency Radiological Laboratory Analytical Protocols Manual (MARLAP) (NRC 2004), specifically Chapter 3, "Key Analytical Planning Issues and Developing Analytical Protocol Specifications"; Chapter 5, "Obtaining Laboratory Services"; Chapter 6, "Selection and Application of an Analytical Method"; Chapter 7, "Evaluating Methods and Laboratories"; and Chapter 8, "Radiochemical Data Verification and Validation."

¹ MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

The development of Data Quality Objectives (DQOs) and Measurement Quality Objectives (MQOs) to define the data needs for a survey is described in **Section 7.2**. This includes making decisions regarding the need to collect samples, the appropriate sampling methods, and QC measurements implemented as part of the survey process. **Section 7.3** describes communication with laboratory personnel during survey planning, before and during sample collection, and during and after sample analysis. Collaborative communication with the laboratory is an important aspect of the sampling and analysis process that helps ensure that survey DQOs are met.

The selection of radiochemical laboratories based on their capability to meet technical, reporting, and other contractual requirements is described in **Section 7.4**. **Section 7.5** covers sample collection considerations to enhance the representativeness of the sample, and the establishment of field sample preparation and preservation criteria is included in **Section 7.6**.

Section 7.7 describes the selection of appropriate analytical methods to ensure that the residual radionuclides—either as individual radionuclides or as a total amount of radioactivity as identified in the DQOs and MQOs—can be detected at appropriate levels of sensitivity and that requirements for measurement uncertainties are met. Sample tracking from field activities through laboratory analysis and reporting is covered in **Section 7.8**. **Section 7.9** covers the packaging and shipping of samples containing radioactive material to minimize radiation exposure to the general public and meet applicable Federal and international requirements.

7.2 Data Quality Objectives and Measurement Quality Objectives

The survey design is developed and documented using the DQO process (refer to **Appendix D**). The third step of the DQO process involves identifying the data needs for a survey. One decision that can be made at this step is the selection of either a site-specific scanning survey, direct measurements in conjunction with scanning for performing a survey, or sampling and laboratory analysis in conjunction with scanning as the appropriate data collection strategy for the survey. This chapter addresses the sampling and laboratory analysis of samples.

DQOs apply to both sampling and analytical activities. From an analytical perspective, performance objectives are needed specifically for the analytical process of a project. Chapter 3 of MARLAP refers to these performance objectives as MQOs. An MQO is a quantitative or qualitative statement of a performance objective or requirement for a performance characteristic of a particular method. The MQOs can be viewed as the analytical portion of the overall project DQOs. In a performance-based approach, the MQOs are used initially for the selection and evaluation of analytical methods and protocols and are subsequently applied for the ongoing and final evaluation of the analytical data.

7.2.1 Identifying Data Needs

The decision-maker and the survey planning team need to identify the data needs for the survey being performed, including the following:

- type of samples to be collected or measurements to be performed (**Chapter 5**)
- radionuclide(s) of interest (**Section 4.5**)
- number of samples to be collected (**Sections 5.3.3–5.3.5**)

- type and frequency of field QC samples to be collected (**Section 4.8**)
- amount of material to be collected for each sample (**Section 4.8.3** and **Section 7.5**)
- sampling locations and frequencies (**Section 5.3.7**)
- standard operating procedures (SOPs) to be followed or developed
- measurement method uncertainty (**Section 6.4**)
- target detection capabilities for each radionuclide of interest (**Section 6.3**)
- cost of the methods being evaluated (cost per analysis and total cost)
- necessary turnaround time
- sample preservation and shipping requirements (**Section 7.6**)
- specific background for each radionuclide of interest (**Section 4.5**)
- derived concentration guideline level (DCGL)² for each radionuclide of interest (**Section 4.5**)
- measurement documentation requirements (**Section 5.3.11**)
- sample tracking requirements (**Section 7.8**)

Some of this information will be supplied by subsequent steps in the DQO process, and several iterations of the process may be needed to identify all the data needs. Consulting with a radiochemist or health physicist may be necessary to properly evaluate the information before deciding what combination of site-specific scanning, direct measurements and scanning, or sampling methods and scanning will be required to meet the DQOs. Surveys might require data from all three collection methods (i.e., sample analysis, direct measurements, and scans) to demonstrate compliance with the applicable regulations and DQOs for the project.

7.2.2 Data Quality Indicators

Precision, bias, representativeness, comparability, and completeness are some of the historical data quality indicators (DQIs) recommended for quantifying the amount of error in survey data (EPA 2002a). The first two of these DQIs represent different aspects of the measurement method uncertainty (**Section 6.4**), with *precision* representing that portion of the measurement method uncertainty due to random uncertainty and *bias* representing that portion of the measurement method uncertainty due to systematic uncertainty. Together, these DQIs should be considered when selecting a measurement technique (i.e., scanning, direct measurement, or sampling) or an analytical technique (e.g., radionuclide-specific analytical procedure). In some

² Throughout this chapter, if the scenario is not explicitly stated, the default terms “derived guideline concentration level” or “DCGL” and “lower bound of the gray region” or “LBGR” will be used. If using Scenario B, please substitute “action level” or “AL” and “upper bound of the gray region” or “UBGR” (i.e., “discrimination limit” or “DL”) for these terms, respectively.

instances, the DQI requirements will help in the selection of an analytical technique. In other cases, the analytical requirements will assist in the selection of appropriate levels for the DQIs.

7.2.2.1 Precision

Precision is a measure of agreement among replicate measurements of the same sampled object or property under prescribed similar conditions (ANSI/ASQ 2014). Precision is determined quantitatively based on the results of replicate measurements (equations are provided in EPA 1990). Several types of replicate analyses are available to determine the level of precision, and these replicates are typically distinguished by the point in the sample collection and analysis process at which the sample is divided:

- *Field replicates*³ are two or more separate samples collected at the same point in time and space (EPA 2002b). These samples, also known as collocated samples, are collected adjacent to the routine field sample to determine local variability of the radionuclide concentration. Typically, including for MARSSIM purposes, field replicates are collected about 0.5–3 feet away from the selected sample location. Analytical results from field replicates can be used to assess site variation, but only in the immediate sampling area. Field replicates should not be used to assess variability across a site and are not recommended for assessing error (EPA 1995). Field replicates can be non-blind, single-blind, or double-blind samples.
- *Field splits* are two or more representative portions taken from a single, usually homogenized, sample collected in the field (EPA 2002b). These portions are divided into separate containers and treated as separate samples throughout the remaining sample handling and analytical processes and are used to assess the uncertainty associated with sample heterogeneity, sample methodology, and analytical procedures. Field splits are used when determining total uncertainty for critical samples with residual radioactive material concentrations near the action level. A minimum of eight field split samples is recommended for valid statistical analysis (EPA 1995). Counting multiple split samples of a homogenized field sample will decrease the uncertainty of the sample, because the sample count times can be combined to derive the overall count time for the sample. In some cases, homogenization may not be possible (e.g., discrete [small] radioactive particles). Field split samples can be non-blind, single-blind, or double-blind and are recommended for determining the level of precision for a radiation survey or site investigation.
- An *analytical laboratory replicate* is two or more representative aliquots (portions of a homogeneous sample, removed for the purpose of analysis or other chemical treatment) whose independent measurements are used to determine the precision of laboratory preparation and analytical procedures (NRC 2004). It is used to determine method precision, but because it is a non-blind sample (i.e., it is known to the analyst), it can be used by the analyst only as an internal control tool and not as an unbiased estimate of analytical precision (EPA 1990).
- A *laboratory instrument replicate* is the repeated measurement of a sample that has been prepared for counting (i.e., laboratory sample preparation and radiochemical procedures have been completed). It is used to determine precision for the instrument (repeated measurements of the same sample using same instrument) and the

³ Some documents use the term “field replicates” to refer to what this guidance calls “field splits.”

instrument calibration (repeated measurements of the same sample using different instruments, such as two different germanium detectors with multichannel analyzers). A laboratory instrument replicate is generally performed as part of the laboratory QC program and is a non-blind sample. It is typically used as an internal control tool and not as an unbiased estimate of analytical precision.

Determining precision by replicating measurements with results at or near the detection limit of the measurement system is not recommended, because the measurement uncertainty is usually greater than the desired level of precision.

7.2.2.2 *Bias*

Bias is the systematic or persistent distortion of a measurement process that causes error in one direction (ANSI/ASQ 2014). Bias is determined quantitatively based on the analysis of samples with a known concentration. QC samples used to determine bias should be included as early in the analytical process as possible. There are several types of samples with known concentrations:

- *Reference materials* are one or more materials or substances with property values that are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method, or the assignment of values to materials (ISO 2008). A certified reference material is one for which each certified property value is accompanied by an uncertainty at a stated level of confidence. Radioactive reference materials may be available for certain radionuclides (e.g., uranium) in soil, but reference building materials may not be available. Because reference materials are prepared and homogenized as part of the certification process, they are rarely available as double-blind samples. When appropriate reference materials are available (i.e., proper matrix, proper radionuclide, and proper concentration range), they are recommended for use in determining the overall bias for a measurement system.
- *Performance evaluation samples* are used to evaluate the overall bias of the analytical laboratory and detect any error in the analytical method used. These samples are usually prepared by a third party, using a quantity of analyte(s) known to the preparer but unknown to the laboratory, and always undergo certification analysis. The analyte(s) used to prepare the performance evaluation sample is the same as the analyte(s) of interest. Laboratory procedural error is evaluated by the percentage of analyte identified in the performance evaluation sample (EPA 1995). These samples are recommended for use in determining overall bias for a measurement system when appropriate reference materials are not available. Performance evaluation samples are equivalent to matrix spikes prepared by a third party that undergo certification analysis and can be non-blind, single-blind, or double-blind samples.
- *Matrix spike samples* are environmental samples that are spiked in the laboratory with a known concentration of a target analyte(s) to verify percent recoveries. They are used primarily to check sample matrix interferences but can also be used to monitor laboratory performance. However, a dataset of at least three or more results is necessary to distinguish between laboratory performance and matrix interference (EPA 1995). Matrix spike samples are often replicated to monitor method performance and evaluate error due to laboratory bias and precision (when four or more pairs are

analyzed). These replicates are often collectively referred to as a matrix spike/matrix spike duplicate.

Several additional terms are applied to samples prepared by adding a known amount of the radionuclide of interest to the sample. The majority of these samples are designed to isolate individual sources of bias within a measurement system by preparing pre- and post-operation spikes. For example, the bias from the digestion phase of the measurement system can be determined by comparing the result from a pre-digestion spike to the result from a post-digestion spike.

Several types of samples are used to estimate bias caused by contamination during the sample collection or analytical process:

- *Background samples* are collected from a non-impacted area with similar characteristics (either on site or off site) where there is little or no chance of migration of the radionuclides of concern (EPA 1995). Background samples are collected from the background reference area (**Section 4.6.3**) to determine the natural composition and variability of the soil (especially important in areas with high concentrations of naturally occurring radionuclides). They provide a basis for comparison of radionuclide concentration levels with samples collected from the survey unit when the statistical tests described in **Chapter 8** are performed.
- *Field blanks* are samples prepared in the field using certified clean sand, soil, or water and then submitted to the laboratory for analysis (EPA 1995). A field blank is used to evaluate contamination error associated with sampling methodology and laboratory procedures. It also provides information about contaminants that may be introduced during sample collection, storage, and transport. Field blanks are recommended for determining bias resulting from contamination for a radiation survey or site investigation.
- *Method blanks* are analytical control samples used to demonstrate that reported analytical results are not the result of laboratory contamination (ATSDR 2005). A method blank contains distilled or deionized water and reagents and is carried through the entire analytical procedure (laboratory sample preparation, digestion, and analysis).⁴

7.2.2.3 Representativeness

Representativeness is a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point (ANS/IASQ 2014). Representativeness is a qualitative term that is reflected in the survey design through the selection of a measurement technique (e.g., direct measurement or sampling) and the size of a sample collected for analysis.

The results of sample collection and analysis are typically less representative of true radionuclide concentrations at a specific measurement location than the results of a direct measurement. This is because of the additional steps required in collecting and analyzing samples, such as sample collection, field sample preparation, laboratory sample preparation, and radiochemical analysis. However, direct measurement techniques with acceptable detection limits are not always available. When sampling is required as part of a survey design, it is critical

⁴ The method blank is also referred to as a reagent blank. The method blank is generally used as an internal control tool by the laboratory because it is a non-blind sample.

that the sample collection procedures consider representativeness. The location of the sample is determined as described in **Section 5.3.7**, but the size and content of the sample are usually determined as the sample is collected. Sample size and content are discussed in **Section 4.8.3** and **Section 7.5**. Sample collection procedures also need to be consistent with the development of the DCGLs when determining the representativeness of the samples.

7.2.2.4 Comparability

Comparability is a qualitative term that expresses the confidence that two datasets can contribute to a common analysis and interpolation. Generally, comparability is provided by using the same measurement system for all analyses of a specific radionuclide. In many cases, equivalent procedures used within a measurement system are acceptable. For example, including a liquid-liquid extraction purification step to determine the concentration of plutonium-238 (^{238}Pu) using alpha spectrometry may be equivalent to adding an ion-exchange column purification step. However, using a gross alpha measurement made with a gas proportional counting system would not be considered equivalent. Comparability is usually not an issue except if historical data have been collected and are being compared to current analytical results or when multiple laboratories are used to provide results as part of a single survey design and the analytical methods have not been clearly communicated to the laboratories.

7.2.2.5 Completeness

Completeness is a measure of the amount of valid data obtained from the measurement system, expressed as a percentage of the number of valid measurements that should have been collected. Valid data are all data that are usable for an intended purpose, including data with no validation qualifiers and data found to be estimated that are justifiable for use. For example, data below the DCGL for average concentrations over a wide area (DCGL_w) that are estimated with high bias would be considered usable data. Completeness is of greater concern for laboratory analyses than for direct measurements, because the consequence of having incomplete data is often the need to collect additional samples. Direct measurements can usually be repeated easily. The collection of additional samples generally requires a remobilization of sample collection personnel, which can be expensive. Conditions at the site may have changed, making it difficult or impossible to collect representative and comparable samples without repeating the entire survey. On the other hand, if it is simply an analytical problem and sufficient samples were originally collected, the analysis can be repeated using archived sample material. Samples collected on a grid to locate areas of elevated activity are also a concern for completeness. If one sample analysis result is not valid, the survey design may not be able to detect areas of elevated activity near or at the missing sample location.

7.2.2.6 Other Data Quality Indicators

Several additional DQIs that influence the final status survey (FSS) design are identified as DQOs and MQOs in **Section 2.3.1**. Many of these (e.g., selection and classification of survey units, decision error rates, variability in the contaminant concentration, lower bound of the gray region) are used to determine the number of measurements and are discussed in detail in **Section 5.3**. The required detection capability (**Section 6.3**) and measurement method uncertainties (**Section 6.4**) are directly related to the selection of a measurement method and a radionuclide-specific analytical technique.

Cost, time, best available technology, or other constraints may create situations in which the required detection capabilities or measurement method uncertainties are deemed impracticable.

Under these circumstances, different values may be acceptable. Although laboratories will state detection limits, these are usually based on ideal or optimistic situations and may not be achievable under actual measurement conditions. Detection limits and measurement method uncertainties are subject to variation from sample to sample, instrument to instrument, and procedure to procedure, depending on sample size, geometry, background, source and instrument efficiencies, chemical recovery, abundance of the radiations being measured, counting time, self-absorption in the prepared sample, and interferences from radionuclides or other materials present in the sample.

7.3 Communications with the Laboratory

Laboratory analyses of samples are generally performed by personnel not directly involved in the collection of the samples being analyzed. Samples are typically collected by one group working in the field and analyzed by a second group located in a laboratory. This separation of tasks can potentially lead to problems resulting from the lack of communication between the two groups. For this reason, communications among the project manager, field personnel, and laboratory personnel are vital to ensuring the success of a project. Section 11.2.1 of MARLAP provides more information on communications with a laboratory.

7.3.1 Communications During Survey Planning

The radioanalytical laboratory is a valuable resource during survey planning. It can readily provide information on available analytical techniques, measurement method uncertainty, method detection capability, required measurement uncertainties, analytical costs, and turnaround times. All this information is used to make the decision to perform direct measurements or collect samples for laboratory measurements. Additional information, such as required sample size/volume, type of sample container, preservative requirements, and shipping requirements—including the laboratory's availability for receipt of samples on weekends or holidays—can be obtained and factored into the survey plan.

Involving the radioanalytical laboratory during survey planning also provides the laboratory with site-specific information about the project. Information on the radionuclides of interest, possible chemical and physical forms of the residual radioactive material, and the mechanism for release of the residual radioactive material to the environment is used to modify or develop the analytical method for site-specific conditions, if required. The laboratory should also be provided with the site-specific action levels (i.e., DCGLs, investigation levels) early in the survey planning process.

In some cases, it is not practical to select a radioanalytical laboratory early in the survey process so that it can participate in survey planning activities. For example, Federal procurement procedures require development of a statement of work (SOW) identifying the tasks to be performed by the laboratory and specifying the analytical protocol before selecting a laboratory. Unfortunately, the details of the tasks for the laboratory to perform are developed during survey planning. This means that the information that would have been provided by the laboratory and used during survey planning will be obtained from another source, usually a radiochemist or health physicist trained in radiochemistry. The uncertainty associated with this information and subsequent decisions made based on this information increases. This may lead to increased costs if the SOW specifies an unnecessarily expensive analytical method, repeated sampling and analysis of samples that did not meet the required detection capabilities, or measurement method uncertainties because the specified analytical method was not sufficient. In addition, the laboratory may select unnecessary or inappropriate analytical methods because

site-specific information concerning the samples was not provided. The laboratory may be informally consulted as appropriate when scheduling the survey, particularly during the development of the specification for the analytical protocol, to ensure that the expected turnaround times can be met based on the projected laboratory workload.

7.3.2 Communications Before and During Sample Collection

In most situations, the laboratory supplies the sample collection and shipping containers; therefore, the laboratory should be notified well in advance of the sampling trip so that these items will be available to the sampling team during the survey.

The main purpose of communications with the laboratory during sample collection is to inform the laboratory of modifications to the survey design specified in the planning documents (e.g., Quality Assurance Project Plan [QAPP] and SOPs). The laboratory should have a copy of the survey design in its possession before samples are collected.

Modifications to the survey design are often minor deviations from the SOPs due to site-specific conditions and usually affect a small number of samples. For example, a rock outcropping covered by a thin layer of soil may restrict the depth of the surface soil sample to 5 centimeters (cm) (2 inches [in.]) instead of the 10 cm (4 in.) specified in the SOP. If the mass of the samples collected from this area of the site is one-half the expected sample mass, the laboratory needs to be informed of this deviation from the SOP. Also, the laboratory should be notified of the proper sample handling requirements (e.g., inform the laboratory of the proper handling of gravel in the samples, as some residual radioactive material could be present in the form of small gravel). Finally, the laboratory should be notified of the approximate activity concentrations to be expected in samples to ensure that the laboratory is licensed and equipped to handle samples with elevated activity concentrations. For the analysis of liquid samples, the laboratory should be informed of any field pretreatments on the sample, such as acidification and filtration, to document sample condition before reaching the laboratory.

In other situations, there may be an extensive modification to the number or types of samples collected at the site that will affect the analytical methods, detection capabilities, required measurement uncertainties, analytical costs, or even the assumptions used to develop the DCGL. For example, a large portion of the site may have been converted to a parking lot. A large pile of material that may represent the former surface soil will be sampled, as well as soil collected from beneath the parking lot surface. The number of samples to be analyzed has doubled compared to the original SOW.

If the expected timing of the receipt of samples at the laboratory changes because of deviations in the sample collection schedule, the laboratory should be notified. Most laboratories require prior notification for samples to be received on weekends.

7.3.3 Communications During Sample Analysis

The laboratory should communicate with the project manager and field personnel during sample analysis. The laboratory should provide a list of missing or damaged samples as soon as practical after the samples are received. This allows the project manager to determine whether resampling is required to replace the missing or damaged samples. The project manager may also request notification from the laboratory when samples are damaged or lost, or if any security seals are missing or broken. Preliminary reports of analytical results may be useful to help direct sampling activities and provide early indications of whether the survey objectives

defined by the DQOs and MQOs are being met. However, if preliminary results have not been verified or validated, their usefulness is limited.

7.3.4 Communications Following Sample Analysis

Following sample analysis, the laboratory will provide documentation of the analytical results as specified in the survey design, which should include the measurement result, measurement uncertainty, and quality control and chain-of-custody (COC) documentation. Laboratory personnel should be available to assist with interpretation, data verification, and data validation.

7.4 Selecting a Radioanalytical Laboratory

After the decision to perform sampling activities is made, the next step is to select the analytical methods and determine the data needs for these methods. It is advisable to select, or consult, a radiochemical laboratory as early as possible in the survey planning process so it may advise on the analytical methodology and the sampling activities. The laboratory provides information on personnel, capabilities, and current workload that are necessary inputs to the decision-making process. In addition, mobile laboratories can provide onsite analytical capability. Obtaining laboratory or other services may involve a specific procurement process. Federal procurement procedures may require additional considerations beyond the method described here.

The procurement of laboratory services usually starts with the development of a request for proposal (RFP) that includes an SOW describing the analytical services to be procured, including specification of the analytical protocol. Careful preparation of the SOW is essential to the selection of a laboratory capable of performing the required services in a technically competent and timely manner. Chapter 3 of MARLAP discusses this in detail.

The technical proposals received in response to the procurement RFP must be reviewed by personnel familiar with radioanalytical laboratory operations to select the most qualified offeror. For complicated sites with a large number of laboratory analyses, it is recommended that a portion of this evaluation take the form of a pre-award audit. The provision for this audit must be in the RFP. The results of this audit provide a written record of the decision to use a specific laboratory. Smaller sites or facilities may decide that a review of the laboratory's qualifications is sufficient for the evaluation.

Seven criteria should be reviewed during this evaluation:

- *Does the laboratory possess the appropriate, well-documented procedures, instrumentation, and trained personnel to perform the necessary analyses?* Necessary analyses are defined by the data needs (radionuclide[s] of interest, required measurement uncertainties, and target detection limits) identified by the DQO process.
- *Is the laboratory experienced in performing similar analyses?*
- *Does the laboratory have satisfactory performance evaluation results from formal monitoring or accreditation programs?* The laboratory should be able to provide a summary of QA audits and proof of participation in interlaboratory cross-check programs. Equipment calibrations should be performed using NIST-traceable reference radionuclide standards whenever possible.

- *Is there an adequate capacity to perform all analyses within the desired timeframe?* This criterion considers whether the laboratory possesses a radioactive materials handling license or permit for the samples to be analyzed. Very large survey designs may indicate that more than one analytical laboratory is necessary to meet the survey objectives. If several laboratories are performing analyses as part of the survey, the analytical methods used to perform the analyses should be similar to ensure comparability of results (refer to **Appendix D**).
- *Does the laboratory provide an internal QC review of all generated data that is independent of the data generators?*
- *Are there adequate protocols for method performance documentation and sample security?*

Providers of radioanalytical services should have an active and fully documented QA program in place, typically through one or more documents, such as a Quality Management Plan, Quality Assurance Manual, or QAPP. This program should comply with the objectives determined by the DQO process in **Section 2.3**.

Requirements for the QA program (e.g., QAPP), COC requirements, and the numbers of samples to be analyzed should be specified, communicated to the laboratory in writing, and agreed upon. The Sampling and Analysis Plan, analytical procedures, and documentation and reporting requirements should also be specified, communicated to the laboratory in writing, and agreed upon. The laboratory's accreditation, if required, should be confirmed by contacting the organization that provided the certification. These topics are discussed in detail in the following sections of this chapter. Chapter 5 of MARLAP contains additional guidance on obtaining laboratory services.

7.5 Sampling

This section provides guidance on developing appropriate sample collection procedures for surveys designed to demonstrate compliance with a dose- or risk-based regulation. Sample collection procedures are concerned mainly with ensuring that collected samples are representative of the sample media, are large enough to provide sufficient material to achieve the desired detection limit and required measurement uncertainties, and are consistent with assumptions used to develop the conceptual site model and the DCGLs. Additional considerations for sample collection activities are discussed in **Section 4.8.5**.

Commingled chemical and radioactive waste at a site can influence sample handling and laboratory requirements. Also, the external exposure rates or radioactivity concentration of a specific sample may limit the time that workers will be permitted to remain in intimate contact with the samples or may dictate that smaller samples be taken and special holding areas be provided for collected samples before shipment. These special handling considerations may conflict with the size specifications for the analytical method, normal sampling procedures, or equipment. There is a potential for biasing sampling programs by selecting samples that can be safely handled or legally shipped to support laboratories, which could be a concern for scoping, characterization, and Radiation Survey and Site Investigation samples.

7.5.1 Surface Soil

The purpose of surface soil sampling is to collect samples that accurately and precisely represent the radionuclides and their concentrations at the location being sampled. To do this

and plan for sampling, a decision must be made as to the survey design. The selection of a survey design is based on the Historical Site Assessment, results from preliminary surveys (i.e., scoping characterization, remedial action support), and the objectives of the survey developed using the DQO process. The selection between judgment, random, and systematic survey designs is discussed in **Section 5.3**.

7.5.1.1 Sample Volume

The sample collection procedure should specify the volume of soil to be collected. In most cases, surface soil samples range from 100 grams up to several kilograms if needed. In general, large volumes of soil are more representative than small volumes of soil. In addition, large samples provide sufficient material to ensure that required detection limits can be achieved and that sample reanalysis can be done if there is a problem. However, large samples may cause problems with shipping, storage, and disposal. All these issues should be discussed with the sample collection team and the analytical laboratory during development of sample collection procedures.

The sample collection procedure should also make clear if it is more important to meet the volume requirement of the survey design or the surface area the sample represents. Constant volume is related to comparability of the results, while surface area is more closely related to the representativeness of the results. Maintaining a constant surface area and depth for samples collected for a particular survey can eliminate problems associated with different depth profiles. The actual surface area included as part of the sample may be important for estimating the probability of locating areas of elevated concentration.

7.5.1.2 Sample Content

The material present in the field at the sample location may or may not provide a representative sample. Vegetative cover, soil particle size distribution, inaccessibility, and lack of sample material are examples of problems that may be identified during sample collection. All deviations from the survey design as documented in the SOPs should be recorded as part of the field sample documentation.

Sample content is generally defined by the assumptions used to develop the conceptual site model and the DCGLs. A typical agricultural scenario assumes that the top few centimeters of soil are available for resuspension in air; that the top 15 cm (6 in.) are homogenized by agricultural activities (e.g., plowing); that roots can extend down several meters to obtain water and nutrients, depending on the plant; and that external exposure is based on an assumed thickness of contaminated soil (usually at the surface). Depending on the dominant exposure pathways for each radionuclide, this can result in a complicated set of instructions for collecting representative samples. This situation can be further complicated by the fact that the site is not currently being used for agricultural purposes. For this situation, it is necessary to look at the analytical results from the preliminary surveys (i.e., scoping, characterization, remedial action support) to determine the expected depth of residual radioactive material.

In most situations, the vegetative cover is not considered part of the surface soil sample and is removed in the field. It is important that the sample collection procedure clearly indicates what is and what is not considered part of the sample.

7.5.1.3 Sampling Equipment

The selection of proper sampling equipment is important to ensure that samples are collected in a reproducible manner and to minimize the potential for cross-contamination. Sampling equipment generally consists of a tool to collect the sample and a container in which to place the collected sample. Sample tracking begins as soon as the sample is collected, so it may be necessary to consider the security of collected samples required to meet the objectives of the survey.

Sampling tools are selected based on the type of soil, sample depth, number of samples required, and training of available personnel. The selection of a sampling tool may also be based on the expected use of the results. For example, if a soil sample is collected to verify the depth profile used to develop the calibration for in situ gamma spectrometry, it is important to preserve the soil core. **Table 7-1** lists several examples of tools used for collecting soil samples, situations where they are applicable, and some advantages and disadvantages involved in their use.

Table 7-1 Soil Sampling Equipment⁵

Equipment	Application	Advantages	Disadvantages/ Considerations
Scoop, Trowel, or Post-Hole Digger	Soft surface soil	• Inexpensive • Easy to use and decontaminate	• Trowels with painted surfaces should be avoided.
Bulb Planter	Soft soil, 0–15 cm (0–6 in.)	• Easy to use • Uniform diameter and sample volume • Preserves soil core	• Limited depth capability • Can be difficult to decontaminate
Soil Coring Device	Soft soil, 0–60 cm (0–24 in.)	• Relatively easy to use • Preserves soil core	• Limited depth capability • Can be difficult to decontaminate
Thin-Wall Tube Sampler	Soft soil, 0–3 meters (0–10 feet)	• Easy to use • Preserves soil core • Easy to decontaminate	• Can be difficult to remove cores
Split Spoon Sampler	Soil, to bedrock	• Excellent depth range • Preserves soil core • Useful for hard soils	• Often used in conjunction with drill rig for obtaining deep cores
Shelby Tube Sampler	Soft soil, to bedrock	• Excellent depth range • Preserves soil core • Tube may be used for shipping core to lab	• May be used in conjunction with drill rig for obtaining deep cores
Bucket Auger	Soft soil, 7.5 cm–3 meters (3 in.–10 feet)	• Easy to use • Good depth range • Uniform diameter and sample volume	• May disrupt and mix soil horizons greater than 15 cm

⁵ Reproduced and adapted from EPA 1995.

Equipment	Application	Advantages	Disadvantages/ Considerations
Hand-Operated Power Auger	Soil, 15 cm–4.5 meters (6 in.–5 feet)	• Good depth range • Generally used in conjunction with bucket auger	• Destroys soil core • Requires two or more operators • Can be difficult to decontaminate

Samples collected below the surface are useful in establishing the extent of residual radioactive material in the vertical profile. Understanding the extent of residual radioactive material below the surface can be helpful in determining remediation alternatives and release criteria. Sample containers are generally not a major concern for collecting surface soil samples. Polyethylene bottles with screw caps and wide mouths are recommended and should be new or clean, dry, and checked for residual radioactive material before reuse. Polyethylene bags are acceptable, especially with heavy-gauge plastic to avoid sample spillage from tears in the bags. These containers are fairly economical, provide easy access for adding and removing samples, and resist chemicals, breakage, and temperature extremes. Glass containers are also acceptable, but they are fragile and tend to break during shipment. Metal containers are sometimes used, but sealing the container can present a problem, and corrosion can be an issue if the samples are stored for a significant length of time.

7.5.2 Building Surfaces

Because building surfaces tend to be relatively smooth, and the radioactive material is assumed to be on or near the surface, direct measurements are typically used to provide information on residual radioactive material concentrations. Sometimes, however, it is necessary to collect actual samples of the building material surface for analysis in a laboratory.

7.5.2.1 Sample Volume

The sample volume collected from building surfaces is usually a less significant DQO concern than the area from which the sample was collected. This is because building surface DCGLs are usually expressed in terms of activity per unit area. It is still necessary to consider the sample volume to account for sample matrix effects that may reduce the chemical recovery, which in turn affects the detection limit.

7.5.2.2 Sample Content

If residual radioactive material is covered by paint or some other treatment, the underlying surface and the coating itself may contain residual radioactive material. If the residual radioactive material is a pure alpha or low-energy beta emitter, measurements at the surface will probably not be representative of the actual residual activity level. In this case, the surface layer is removed from the known area, such as by using a commercial stripping agent or by physically abrading the surface. The removed coating material is analyzed for activity content and the level converted to appropriate units (i.e., becquerels [Bq] per square meter, disintegrations per minute [dpm]/100 cm²) for comparison with surface activity DCGLs. Direct measurements can be performed on the underlying surface after removal of the coating.

Residual radioactive material may be incorporated into building materials, such as pieces of concrete or other unusual matrices. Developing SOPs for collecting these types of samples may

involve consultation with the analytical laboratory to help ensure that the objectives of the survey are achieved.

The thickness of the layer of building surface to be removed as a sample should be consistent with the development of the conceptual site model and the DCGLs. For most sites, the surface layer will only be the first few millimeters of the material being sampled.

7.5.2.3 Sampling Equipment

Tools used to provide samples of building surfaces depend on the material to be sampled. Concrete may require chisels, hammers, drills, or other tools specifically designed to remove a thin layer of the surface. Wood surfaces may require using a sander or a saw to collect a sample. Paint may be chemically or physically stripped from the surface.

Sample containers for these samples are generally the same as those recommended for soil samples. If chemicals are used to strip paint or other surface materials, the chemical resistance of the container should be considered.

7.5.3 Other Media

Surface soil and building surfaces are the media addressed in MARSSIM during FSS design. Other media may be involved and may have been remediated. Data collection activities during preliminary surveys (i.e., scoping, characterization, remedial action support) may involve collecting samples of other media to support the FSS design. Examples of other media that may be sampled include the following:

- subsurface soil
- groundwater
- surface water
- sediments
- sewers and septic systems
- flora and fauna (plants and animals)
- airborne particulates
- air (gas)

Liquid samples typically are classified as aqueous, nonaqueous, or mixtures. Aqueous samples requiring analysis are likely to represent surface water, groundwater, drinking water, precipitation, tanks and lagoons, and runoff. Nonaqueous liquids may include a variety of solvents, oils, and other organic liquids. Mixtures of liquids represent a combination of aqueous and nonaqueous liquids or a solid suspended in either aqueous or nonaqueous liquids. Investigators should consider the potential impact of the collection process on sample integrity, such as the effects of dissolved gases (oxygen, carbon dioxide), which can react with certain dissolved metals and result in cross-contamination. Resources like APHA 2023, EPA 1985, 1987a, DOE 1997, and ASTM 2018b provide standardized liquid sampling procedures.

7.6 Field Sample Preparation and Preservation

Proper sample preparation and preservation are essential parts of any radioactive material sampling program. The sampling objectives should be specified before sampling activities begin. Precise records of sample collection and handling are necessary to ensure that data obtained from different locations or timeframes are correctly compared. The planning team

should discuss soil sample handling techniques with the analytical laboratory. For example, some laboratories sieve the samples to remove large objects before homogenization. Some of these large objects could be radioactive slags and should not be removed from the samples. As such, laboratories should scan any large objects removed from the samples before discarding them or homogenize the entire sample without discarding any large objects.

The appropriateness of sample preparation techniques is a function of the analysis to be performed (EPA 1992a, 1992b). Field sample preparation procedures are a function of the specified analysis and the objectives of the survey. It is essential that these objectives be clearly established and agreed on in the early stages of survey planning (refer to **Section 2.3**).

7.6.1 Surface Soil

Soil and sediment samples, in most protocols, require no field preparation and are not preserved. In some protocols (e.g., if the sample will be analyzed for both volatile organics and radionuclides), cooling of soil samples to 4 degrees Celsius is required during shipping and storage.

When replicate samples are prepared in the field, it is necessary to homogenize the sample before separation into replicates. There are standard procedures for homogenizing soil in the laboratory (ASTM 2010), but the equipment required for these procedures may not be available in the field. Simple field techniques, such as cone and quarter, or using a riffle splitter to divide the sample, may be appropriate if the sample can be dried (ASTM 2003, EPA 1995). If the sample contains significant amounts of residual water (e.g., forms clumps of soil) and there are no facilities for drying the sample, the homogenization and separation into replicates should be performed in a laboratory. It is preferable to use non-blind replicates, where the same laboratory prepares and analyzes the replicates, rather than use poorly homogenized or heterogeneous samples to prepare replicate samples.

7.6.2 Building Surfaces

Field preparation and preservation of building and associated materials, including smear samples, are not generally required. Homogenization of samples to prepare replicates is the same for building surface material and soil.

7.6.3 Other Media

Other media may have significant requirements related to field sample preparation and preservation. For example, water samples may need filtering and acidification. Storage at reduced temperatures (i.e., cooling or freezing) to reduce biological activity may be necessary for some samples. Adding chemical preservatives for specific radionuclides or media may also be required.

For liquids, the choice of sampling instrument or tool depends on the specific circumstances and the type of liquid being sampled. References for sampling liquids include Navy 1997; EPA 1982, 1984a, 1986b, 1987a; and DOI 1980.

The investigator should select appropriate sample containers based on the sample type and potential contaminants. Established guidelines for packaging liquid samples, such as those provided by EPA 1987a, should be followed. These typically involve placing each sample bottle in a sealed plastic bag, potentially within a metal can filled with vermiculite or other packing

material. Cans would then be placed upright in a cooler with a sealed drain plug and filled with packing material for cushioning.

Filtration is often necessary to separate dissolved contaminants from suspended particulates or sediment. The filtration method (e.g., gravity, syringe, vacuum pump, aspiration) depends on sample volume, particulate size and concentration, and available resources (NRC 2004). Preservation of liquid samples may be important to prevent degradation between collection and analysis. Appropriate preservatives should be selected based on compatibility with the radionuclides, analytical methods, and container materials.

Since it is volatile, radon-222 (^{222}Rn) requires special handling. Because radon is inert and nonpolar, it diffuses through plastic more rapidly than glass. The use of plastic scintillation vials, therefore, leads to a significant loss of radon in water (Whittaker et al. 1989, Hess and Beasley 1990). Samples may be collected in 23-milliliter (mL) glass scintillation vials with Teflon- or foil-lined caps to minimize radon loss. Investigators should employ a zero-headspace sampling protocol from a nonaerated faucet or spigot after allowing sufficient flow time for a representative sample.

Guidance on sample preparation and preservation in matrices not discussed above can be found in Chapter 10 of MARLAP.

7.7 Analytical Procedures

The appropriate radioanalytical methods are normally selected before the procurement of analytical services, and they are included in the SOW of the RFP. The SOW may dictate the use of specific methods or be performance based. Unless there is a regulatory requirement, such as conformance to the EPA drinking water methods (EPA 1980b), the specification of a performance-based methodology is encouraged. One reason for this is that a laboratory will usually perform better using the methods it routinely employs, rather than other methods with which it has less experience. The laboratory is also likely to have historical data on performance for methods routinely used by that laboratory. However, the methods employed in a laboratory should be derived from a reliable source.

This section briefly describes specific equipment and procedures to be used once the sample is prepared for analysis. The results of these analyses (i.e., the concentrations of radioactive material found in these samples) are the values used to determine the level of residual radioactive material at a site. In a decommissioning effort, the DCGLs are expressed in terms of the concentrations of certain radionuclides. It is of vital importance, therefore, that the analyses be accurate, have adequate sensitivity, and have adequate minimum measurement uncertainties for the radionuclides of concern. The selection of analytical procedures should be coordinated with the laboratory and specified in the survey plan.

Analytical methods should be adequate to meet the data needs identified in the DQO process. Consultation with the laboratory performing the analysis is recommended before selecting a course of action. MARSSIM is not intended to limit the selection of analytical procedures; rather, all applicable methods should be reviewed to provide results that meet the objectives of the survey. The decision-maker and survey planning team should decide whether routine methods will be used at the site or if nonroutine methods may be acceptable:

- Routine analytical methods are documented with information on minimum performance characteristics, such as detection limit, minimum measurement uncertainty, precision and accuracy, and useful range of radionuclide concentrations and sample sizes.

Routine methods may be issued by a recognized organization (e.g., Federal or State agency, professional organization), published in a refereed journal, or developed by an individual laboratory. The following are examples of sources for routine methods:

- *Methods of Air Sampling and Analysis*, issued 1988 (Lodge 1988)
- *Annual Book of ASTM Standards, Water and Environmental Technology*, Volume 11.05, “Environmental Assessment, Risk Management and Corrective Action, issued 2024 (ASTM 2024)
- *Standard Methods for the Examination of Water and Wastewater*, issued January 2023 (APHA 2023)
- HASL-300, “EML [Environmental Measurements Laboratory] Procedures Manual,” issued 1997 (DOE 1997)
- EPA/402-R-06-007, “Inventory of Radiological Methodologies For Sites Contaminated with Radioactive Materials,” issued October 2006 (EPA 2006d)
- EPA 520/5-84-006, “Eastern Environmental Radiation Facility: Radiochemistry Procedures Manual,” issued June 1984 (EPA 1984b)
- American National Standards Institute (ANSI)- American Association of Radon Scientists and Technologists (AARST) radon protocols and standards
 - MAH-2014, “Protocol for Conducting Measurements of Radon and Radon Decay Products in Homes,” issued 2014 (AARST 2014a)
 - MALB-2014, “Protocol for Conducting Measurements of Radon and Radon Decay Products in Schools and Large Buildings,” issued 2014 (AARST 2014b)
 - MAMF-2017, “Protocol for Conducting Measurements of Radon and Radon Decay Products in Multifamily Buildings,” issued 2017 (AARST 2017)
 - MS-PC-2015, “Performance Specifications for Instrumentation Systems Designed to Measure Radon Gas in Air,” issued 2015 (AARST 2015)
 - MS-QA-2023, “Radon Measurement Systems Quality Assurance,” issued 2023 (ANSIAARST 2023)
- Nonroutine methods address situations with unusual or problematic matrices; low detection limits; or new parameters, procedures, or techniques. Nonroutine methods include adjustments to routine methods, new techniques published in the refereed literature, and development of new methods.

References that provide information on radiochemical methodology and should be considered in the methods review and selection process are available from such organizations as the following:

- National Council on Radiation Protection and Measurements

- ASTM
- ANSI
- Radiological and Environmental Sciences Laboratory, Idaho Falls, Idaho (operated by the U.S. Department of Energy [DOE])
- National Urban Security Technology Laboratory, New York City, New York (operated by the U.S. Department of Homeland Security)

Equipment vendor literature, catalogs, and instrument manuals are often a source of useful information on the characteristics of radiation detection equipment. **Table 7-2** summarizes common laboratory methods and their estimated detection limits.

Analytical procedures in the laboratory consist of several parts that are assembled to produce an SOP for a specific project or sample type. These procedures may include all or only some of the following elements:

- laboratory sample preparation
- sample dissolution
- sample purification
- preparation for counting
- counting
- data reduction

7.7.1 Photon-Emitting Radionuclides

There is minimal special sample preparation required for counting samples using a germanium detector or a sodium iodide (NaI) detector beyond homogenizing and placing the sample in a known geometry for which the detector has been calibrated. The procedures to be followed to process a raw soil sample to obtain a representative subsample for analysis depend, to some extent, upon the size of the sample, the amount of processing already undertaken in the field, and—most importantly—the radionuclide of interest (NRC 2004). The samples can be measured as they arrive at the laboratory, or the sample can be dried, ground to a uniform particle size, and mixed to provide a more homogeneous sample if required by the SOPs. Guidance on the preparation of samples, including soil samples, can be found in Chapter 12 of MARLAP.

The samples are typically counted using a germanium detector with a multichannel analyzer or an NaI detector with a multichannel analyzer. Germanium detectors have better resolution and can identify peaks (and the associated radionuclides) at lower concentrations. NaI detectors often have a higher efficiency and are significantly less expensive than germanium detectors. Low-energy photons (i.e., x-rays and gamma rays below 50 kiloelectron volts) can be measured using specially designed detectors with an entrance window made from a very light metal, typically beryllium. **Appendix H** includes descriptions of germanium and NaI detectors.

Table 7-2 Typical Measurement Sensitivities for Laboratory Radiometric Procedures

Sample Type/ Radionuclides or Radiation Measured	Procedure	Approximate Detection Capability
Smears (Filter Paper)/ Gross alpha	Gas-flow proportional counter; 5 minute (min) count Alpha scintillation detector with scaler; 5 min count	0.08 Bq (5 dpm) 0.33 Bq (20 dpm)
Smears (Filter Paper)/ Gross beta	Gas-flow proportional counter; 5 min count End window Geiger-Mueller with scaler; 5 min count (unshielded detector)	0.17 Bq (10 dpm) 1.33 Bq (80 dpm)
Smears (Filter Paper)/ Low-energy beta (^3H , ^{14}C , ^{63}Ni)	Liquid scintillation spectrometer; 5 min count	0.50 Bq (30 dpm)
Soil Sediment/ ^{137}Cs , ^{60}Co , ^{226}Ra (^{214}Bi) ^a , ^{232}Th (^{228}Ac), ^{235}U	Germanium detector (25% relative efficiency) with multichannel analyzer; pulse height analyzer; 500 gram (g) sample; 15 min analysis	0.04–0.1 Bq/g (1–3 picocuries [pCi]/g)
Soil Sediment/ ^{234} , ^{235} , ^{238}U ; ^{238} , ^{239} , ^{240}Pu ; ^{227} , ^{228} , ^{230} , ^{232}Th ; other alpha emitters	Alpha spectroscopy with multichannel analyzer—pyrosulfate fusion and solvent extraction; surface barrier detector; pulse height analyzer; 1 g sample; 16 hour count	0.004–0.02 Bq/g (0.1–0.5 pCi/g)
Water/ Gross alpha	Gas-flow proportional counter; 100 mL sample, 200 min count	0.04 Bq/liter (L) (1 pCi/L)
Water/ Gross beta	Gas-flow proportional counter; 100 mL sample, 200 min count	0.04 Bq/L (1 pCi/L)
Water/ ^{137}Cs , ^{60}Co , ^{226}Ra (^{214}Bi), ^{232}Th (^{228}Ac), ^{235}U	Germanium detector (25% relative efficiency) with multichannel analyzer; pulse height analyzer; 3.5 L sample, 16 hour count	0.4 Bq/L (10 pCi/L)
Water/ ^{234} , ^{235} , ^{238}U ; ^{238} , ^{239} , ^{240}Pu ; ^{227} , ^{228} , ^{230} , ^{232}Th ; other alpha emitters	Alpha spectroscopy with multichannel analyzer—solvent extraction; surface barrier detector; pulse height analyzer; 100 mL sample, 30 min count	0.004–0.02 Bq/L (0.1–0.5 pCi/L)
Water/ ^3H	Liquid scintillation spectrometry; 5 mL sample, 30 min count	10 Bq/L (300 pCi/L)

^a Indicates that a member of the decay series is measured to determine the activity level of the parent radionuclide of primary interest.

Data reduction is usually the critical step in measuring photon-emitting radionuclides. Often several hundred individual gamma ray energies are detected within a single sample. Computer software is usually used to identify energy peaks and associate these peaks with their respective radionuclides. The software is also used to correct for the efficiency of the detector and the geometry of the sample and to provide results in terms of concentrations with the associated uncertainty. It is important that the software be either a well-documented commercial package or thoroughly evaluated and documented before use.

7.7.2 Beta-Emitting Radionuclides

Laboratory sample preparation is an important step in the analysis of surface soil and other solid samples for beta-emitting radionuclides. The laboratory will typically have a sample preparation procedure that involves drying the sample and grinding the soil so that all particles are smaller than a specified size to provide a homogeneous sample. A small portion of the homogenized sample is usually all that is required for the individual analysis.

Once the sample has been prepared, a small portion is dissolved, fused, or leached to provide a clear solution containing the radionuclide of interest. The only way to ensure that the sample is solubilized is to completely dissolve the sample. However, this can be an expensive and time-consuming step in the analysis. In some cases, leaching with strong acids can consistently provide greater than 80 percent recovery of the radionuclide of interest (NCRP 1976) and may be acceptable for certain applications. After dissolution, the sample is purified using a variety of chemical reactions to remove bulk chemical and radionuclide impurities. The objective is to provide a chemically and radiologically pure sample for measurement. Examples of purification techniques include precipitation, liquid-liquid extraction, ion-exchange chromatography, distillation, and electrodeposition. Gross beta measurements may also be performed on material that has not been purified.

After the sample is purified, it is prepared for counting. Beta-emitting radionuclides are usually prepared for a specific type of counter in a specified geometry. Some samples can be precipitated and collected on a filter in a circular geometry to provide a homogeneous sample. Other samples can be converted to the appropriate chemical form and diluted to a specified volume in preparation for counting.

Measurements of some samples may be performed using a gas-flow proportional counter. Because total beta activity is measured, it is important that the purification step be performed to remove any interfering radionuclides. Other samples can be added to a liquid scintillation cocktail and counted using a liquid scintillation spectrometer. Liquid scintillation spectrometers can be used for low-energy beta-emitting radionuclides, such as hydrogen-3 (^3H) and nickel-63 (^{63}Ni). Proper applications can decrease lower limits of detection for all nuclides; however, typical applications in many labs limit the minimum detectable activity to those that are higher than standard gas proportional counting. Gas-flow proportional counters have a very low background. **Appendix H** describes both the gas-flow proportional counter and the liquid scintillation spectrometer.

7.7.3 Alpha-Emitting Radionuclides

Laboratory sample preparation for alpha-emitting radionuclides is similar to that for beta-emitting radionuclides. Sample dissolution and purification tasks are also similar to those performed for beta-emitting radionuclides.

Because of the limited penetrating power of alpha particles, the preparation for counting is often a critical step. Gross alpha measurements can be made using small sample sizes with a gas-flow proportional counter, but self-absorption of the alpha particles results in a relatively high detection limit for this technique. Liquid scintillation spectrometers can also be used to measure alpha-emitting radionuclides, but the resolution limits the usefulness of this technique. Most alpha-emitting radionuclides are measured in a vacuum (to limit absorption by air) using alpha spectroscopy. This method requires that the sample be prepared as a virtually weightless mount in a specific geometry. Electrodeposition is the traditional method for preparing samples for counting. This technique provides the highest resolution, but it requires a significant amount of analyst training and expertise to produce a high-quality sample. Precipitation of the radionuclide of interest on the surface of a substrate is often used to prepare samples for alpha spectroscopy. While this technique generally produces a spectrum with lower resolution, the preparation time is relatively short compared to electrodeposition, and personnel can be trained to prepare acceptable samples relatively quickly.

Alpha-emitting radionuclides are typically measured using alpha spectroscopy. The data reduction requirements for alpha spectroscopy are greater than those for beta-emitting radionuclides and similar to those for photon-emitting radionuclides. Alpha spectroscopy produces a spectrum of alpha particles detected at different energies, but because the sample is purified before counting, all the alpha particles come from radionuclides of a single element. This simplifies the process of associating each peak with a specific radionuclide, but the lower resolution associated with alpha spectroscopy increases the difficulty of identifying the peaks. Although commercial software packages are available for interpreting alpha spectroscopy results, an experienced operator is required to ensure that the software is working properly.

7.8 Sample Tracking

Sample tracking refers to the identification of samples, their location, and the individuals responsible for their custody, storage, and transfer of the custody. This process covers the entire process from collection of the samples and remains intact through the analysis and final holding or disposal. It begins with taking a sample, including its identification and designation, which are critical to being able to relate the analytical result to a site location.

Tracking samples from collection to receipt at the analytical laboratory is normally done through a COC process and documented on a COC or tracking record. The purpose of the COC record is to ensure the security and legal defensibility of the sample throughout the process. When the laboratory receives the samples, internal tracking and COC procedures should be in place. These procedures should be documented through SOPs that ensure integrity of the samples. Documentation of changes in the custody of a sample is important. This is especially true for samples that may be used as evidence to establish compliance with release criteria. In such cases, there should be sufficient evidence to demonstrate that the integrity of the sample is not compromised from the time it is collected to the time it is analyzed. During this time, the sample should either be under the positive control of a responsible individual or secured and protected from any activity that could change the true value of the results or the nature of the sample. When this degree of sample handling or custody is necessary, written procedures should be developed for field operations and for interfacing between the field operations and the analytical laboratory. This ensures that a clear transfer of the custodial responsibility is well documented and that no questions exist as to who is responsible for the sample at any time.

7.8.1 Field Tracking Considerations

Suggestions for field sample tracking are given below:

- Field personnel are responsible for maintaining field logbooks with adequate information to relate the sample identifier (sample number) to its location and for recording other information necessary to adequately interpret the results of sample analytical data. Logbooks may use electronic records, provided information is stored in manner that is tamper proof and retrievable if electronic media fail.
- The sample collector is responsible for the care and custody of the samples until they are properly transferred or dispatched. This means that samples are in their possession, under constant observation, or secured. Samples may be secured in a sealed container, locked vehicle, locked room, or similar setting.
- Sample labels should be completed for each sample using waterproof ink or in a tamper-proof and recoverable electronic medium.
- The survey manager or designee determines whether or not proper custody procedures were followed during the field work and decides whether additional sampling is indicated.
- If photographs are included as part of the sampling documentation, the name of the photographer, date, time, site location, and site description should be entered sequentially in a logbook as the photos are taken. After the photographs are printed, the prints should be serially numbered. Alternatively, the information can be filed in a tamper-proof electronic form or database.

7.8.2 Transfer of Custody

Suggestions for transferring sample custody are given below:

- All samples leaving the site should be accompanied by a COC record. This record should be standardized and document sample custody transfer from the sampler, often through another person, to the laboratory. The sample collector is responsible for initiating the tracking record. The record should include a list, containing sample designation (number), of the samples in the shipping container and the analysis requested for each sample.
- Shipping containers should be sealed and include a tamper-indicating seal that will indicate if the container seal has been disturbed. The method of shipment, courier name, or other pertinent information should be listed in the COC record.
- The original COC record should accompany the samples. The individual or organization relinquishing the samples should retain a copy of the record. If a sample is to be split and distributed to more than one analytical laboratory, multiple forms will be needed to accompany sample sets.
- The custody objectives should be discussed with the shipper to ensure that the objectives are met. For example, if the samples are sent by mail and the originator of the sample requires a record that the shipment was delivered, the package should be registered with return receipt requested. If, on the other hand, the objective is to simply

provide a written record of the shipment, a certificate of mailing may be a less expensive and appropriate alternative.

- The individual receiving the samples should sign, date, and note the time of receipt on the record. The condition of the container and the tamper-indicating seal should be documented on the COC. Any problems with the individual samples, such as a broken container, should be noted on the record.
- COC procedures may use tamper-proof electronic media, as appropriate.

7.8.3 Radiochemical Holding Times

In some circumstances, sample holding times are particularly important. For example, liquid samples are usually analyzed as quickly as possible. This would also be true for radionuclides with short half-lives. Minimizing the holding times in these situations can reduce the measurement uncertainties and lower the minimum detectable concentrations.

For this reason, the SOW should contain the requirements for radiological holding and sample turnaround times. It is important that the laboratory reviews the specifications for radionuclides that have short half-lives (less than 30 days), because the method proposed by the laboratory may depend on the required radiological holding time. For very short-lived radionuclides, it is crucial to analyze the samples within the first two half-lives to meet the MQOs conveniently. Additionally, samples requiring parent decay or progeny ingrowth should be held for sufficient time before counting. Limits for minimum ingrowth and maximum or minimum decay times should be established for all analytical methods for which they are pertinent. For ingrowth, the limits should reflect the minimum time required to ensure that the radionuclides of interest have accumulated sufficiently to not adversely affect the detection limit or uncertainty (e.g., holding samples for radium-226 (^{226}Ra) analysis to permit ingrowth of ^{222}Rn). Alternatively, requirements for holding times may be set to ensure that interfering radionuclides have a chance to decay sufficiently. Conversely, the time for radioactive decay of the radionuclides of interest should be limited such that the decay factor does not elevate the minimum detectable concentration or adversely affect the measurement uncertainty (NRC 2004).

7.8.4 Laboratory Tracking

When the samples are received by the laboratory, they are prepared for radiochemical analyses; this includes dividing the sample into aliquots. The tracking and COC documentation within the laboratory become somewhat complicated because several portions of the original sample may exist in the laboratory at a given time. The term “tracking” refers to an accountability process that meets generally acceptable laboratory practices as described by accrediting bodies but is less stringent than a formal COC process. Similar to the COC process, tracking also develops a record of all individuals responsible for the custody and transfer of samples. The use of a computer-based laboratory information management system can greatly assist in tracking samples and fractions through the analytical system.

The minimal laboratory tracking process consists of the following:

- transfer of custody on receipt of the samples (original COC form is retained by the laboratory and submitted with the data package for the samples)
- documentation of sample storage (location and amount)

- documentation of removal and return of sample aliquots (amount, date and time, person removing or returning, and reason for removal)
- transfer of the samples and residues to the receiving authority (usually the site from which they were taken)
- tamper-proof electronic systems acceptable for laboratory tracking

The procedure for accomplishing the above varies from laboratory to laboratory, but the exact details of performing the operations of sample tracking should be contained in an SOP.

7.9 Packaging and Transporting Samples

All samples being shipped for radiochemical analysis should be properly packaged and labeled before transport off site or within the site. The primary concern is the possibility of spills, leaks, or breakage of the sample containers. In addition to resulting in the loss of samples and cross-contamination, the possible release of hazardous material poses a threat to the safety of persons handling and transporting the package.

The following are suggestions for packaging and shipping radioactive environmental samples:

- Review NRC requirements (Title 10 of the *Code of Federal Regulations* [10 CFR] Part 71) and U.S. Department of Transportation (DOT) requirements (49 CFR Parts 171–177) for packaging and shipping radioactive environmental samples.
- Visually inspect each sample container for indication of leaks or defects in the sample container.
 - Liquid samples should be shipped in plastic containers, if possible, and the caps on the containers should be secured with tape. One exception to the use of plastic bottles is samples collected for ^3H analyses, which may require glass containers.
 - Heavy plastic bags with sealable tops can be used to contain solid samples (e.g., soil, sediment, air filters). The zipper lock should be secured with tape. Heavy plastic lawn bags can be used to contain vegetation samples. The tops should be closed with a “tie” that is covered by tape to prevent it from loosening and slipping off.
- Wipe individual sample containers with a damp cloth or paper towel to remove any exterior contamination. The outer surfaces of containers holding samples collected in an area containing residual radioactive material should be surveyed with one or more hand-held instruments appropriate for the suspected type of radioactive material.
- If glass sample containers are used, place sample containers inside individual plastic bags and seal to contain the sample in case of breakage.
- Use packing material (e.g., paper, Styrofoam™, bubble wrap) to immobilize and isolate each sample container and buffer hard knocks on the outer container during shipping. This is especially important in cold weather, when plastic containers may become brittle and water samples may freeze.

- When liquid samples are shipped, include a sufficient quantity of an absorbent material (e.g., vermiculite) to absorb all liquid packed in the shipping container in case of breakage. This absorbent material also may suffice as the packing material.
- Include the original signed and dated COC form, identifying each sample in the package. It is good practice to place the COC form in a plastic bag to prevent it from becoming wet or contaminated in case of a spill during shipment. If possible, avoid having multiple packages of samples covered by a single COC form.
- Seal the package closed and apply COC tape in such a manner that it must be torn (broken) to open the package. The tape should carry the signature of the sender, and the date and time, so that it cannot be removed and replaced undetected.

In addition, the following should be noted:

- Ice chests constructed of metal or hard plastic make excellent shipping containers for radioactive environmental samples.
- Regulations may require specific labeling and markings on the external surface of each shipping container and that handling instructions and precautions be attached to the shipping container. Some information should be included on the package even if the regulations do not require it, such as the sender's and receiver's (consignee and consignor) names, addresses, and telephone numbers. When required by shipping regulation, proper handling instructions and precautions should be clearly marked on shipping containers.
- Shipments with dry ice or other hazardous packaging material are subject to requirements pertaining to the packaging, apart from the radioactive or hazardous contents.

If samples are sent off site for analysis, the shipper is responsible for complying with all applicable Federal, State, and local regulations. Applicable Federal regulations are briefly addressed in the subsections that follow. Any State or local regulation will very likely reflect a Federal regulation.

7.9.1 U.S. Nuclear Regulatory Commission Regulations

NRC regulations for packaging, preparation, and shipment of licensed material are contained in 10 CFR Part 71, "Packaging and Transportation of Radioactive Materials."

- Samples containing low levels of radioactive material are exempted as set forth in 10 CFR 71.10, "Public inspection of application."
- Low specific activity material is defined in 10 CFR 71.4, "Definitions." Samples classified as low specific activity need only meet the DOT requirements discussed below and the requirements of 10 CFR 71.88, "Air transport of plutonium." Most environmental samples will either fall into this category or be exempt from any DOT regulations.

7.9.2 U.S. Department of Transportation Regulations

The DOT provides regulations governing the transport of hazardous materials under the Hazardous Materials Transportation Act of 1975 (88 Stat. 2156, Public Law 93-633). Applicable

requirements of the regulations are found in 49 CFR Parts 107 and 171–177. Shippers of samples containing radioactive material should be aware of the current rules in the following areas:

- Accident reporting: 49 CFR Part 171
- Marking and labeling packages for shipment: 49 CFR Part 172
- Packaging: 49 CFR Part 173
- Placarding a package: 49 CFR Part 172
- Registration of a shipper/carrier: 49 CFR Part 107
- Shipper required training: 49 CFR Part 172
- Shipping papers and emergency information: 49 CFR Part 172
- Transport by air: 49 CFR Part 175
- Transport by rail: 49 CFR Part 174
- Transport by vessel: 49 CFR Part 176
- Transport on a public highway: 49 CFR Part 177

7.9.3 U.S. Postal Service Regulations

Any package containing radioactive materials may not be mailed if it is required to bear the DOT's Radioactive White-1 (49 CFR 172.436), Radioactive Yellow-II (49 CFR 172.438), or Radioactive Yellow-III (49 CFR 172.440) label, or if it contains quantities of radioactive material in excess of those authorized in Section 347.22 of U.S. Postal Service (USPS) Publication 52, "Hazardous, Restricted, and Perishable Mail" (USPS 2023).

7.9.4 International Atomic Energy Agency Regulations

If samples or other radioactive materials, such as calibration sources, are shipped outside the boundaries of the United States, the shipment of those materials must comply with International Atomic Energy Agency (IAEA) Technical Report Series 1, "Regulations for the Safe Transport of Radioactive Material," issued 2005 (IAEA 2005). The IAEA regulations address the following areas:

- activity limits and material restrictions
- requirements and controls for transport
- radioactive material package and packaging requirements
- test procedures
- administrative controls and requirements

8 INTERPRETATION OF SURVEY RESULTS

8.1 Introduction

This chapter discusses the interpretation of survey results, primarily those of the final status survey (FSS). Interpreting a survey's results is most straightforward when measurement data are entirely higher or lower than the derived concentration guideline level for average¹ concentrations over a wide area (DCGL_W).² In such cases, the decision that a survey unit meets or exceeds the release criteria requires little in terms of data analysis. However, formal statistical tests provide a valuable tool when a survey unit's measurements are neither clearly above nor exclusively below the DCGL_W. Nevertheless, the survey design always makes use of the statistical tests to help ensure that the number of sampling points and the measurement detectability and uncertainty are adequate, but not excessive, for the decision to be made. Although most statistical analysis is completed using statistical software packages, this chapter provides an explanation to facilitate the reader's understanding of the mechanics behind the calculations of these statistical tests.

Section 8.2 discusses the assessment of data quality. The remainder of **Chapter 8** deals with application of the statistical tests used in the decision-making process and the evaluation of the test results. In addition, an example checklist is provided to assist the user in obtaining the necessary information for interpreting the results of an FSS. **Section 8.3** discusses the application of the Sign test to survey data involving radionuclides that are not in the background. **Section 8.4** discusses the application of the Wilcoxon Rank Sum (WRS) test to survey data involving radionuclides that are in the background and, for Scenario B, the application of the Quantile test when the null hypothesis is not rejected. Comparisons of site-specific scanning results to an upper confidence limit (UCL) are discussed in **Section 8.5**. **Section 8.6** discusses the results, including the elevated measurement comparison (EMC), and interpretation of the statistical tests. **Section 8.7** discusses the documentation requirements.

8.2 Data Quality Assessment

Data Quality Assessment (DQA) is a scientific and statistical evaluation that determines whether the data are of the right type, quality, and quantity to support their intended use. An overview of the DQA process is presented in **Section 2.3** and **Appendix D**. The DQA process has five steps:

- (1) Review the Data Quality Objectives (DQOs), Measurement Quality Objectives (MQOs) and Survey Design (**Section 8.2.1**).
- (2) Conduct a preliminary data review (**Section 8.2.2**).
- (3) Select the statistical test (**Section 8.2.3**).

¹ In the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), "average" and "mean" both refer to the arithmetic mean.

² Throughout this chapter, if the scenario is not explicitly stated, the default terms "derived guideline concentration level" or "DCGL" and "lower bound of the gray region" or "LBGR" will be used. If using Scenario B, please substitute "action level" or "AL" and "upper bound of the gray region" or "UBGR" (i.e., "discrimination limit" or "DL") for these terms, respectively.

- (4) Verify the assumptions of the statistical test (**Section 8.2.4**).
- (5) Draw conclusions from the data (**Section 8.2.5**).

The effort applied to DQA should³ be consistent with the graded approach used to develop the survey design. More information on DQA can be found in the U.S. Environmental Protection Agency (EPA) documents EPA QA/G-9R, "Data Quality Assessment: A Reviewer's Guide," issued February 2006 (EPA 2006a), and EPA QA/G-9S, "Data Quality Assessment: Statistical Tools for Practitioners," issued February 2006 (EPA 2006b).

Data should be verified and validated as described in the Quality Assurance Project Plan (QAPP). Guidance on data verification and validation can be found in **Appendix D** of MARSSIM and Chapter 8 of the Multi-Agency Radiation Laboratory Analytical Protocols (MARLAP) manual (NRC 2004). Guidance on developing a QAPP is available in EPA QA/G-5, "Guidance for Quality Assurance Project Plans," issued December 2002 (EPA 2002a), and MARLAP Chapter 4.

8.2.1 Review the Data Quality Objectives, Measurement Quality Objectives, and Survey Design

The first step in the DQA evaluation is to review the DQO outputs to ensure that they are still applicable. The review of the DQOs and survey design should also include the MQOs (e.g., measurement uncertainty, detectability). For example, if the data suggest the survey unit was misclassified as Class 3 instead of Class 1 (i.e., because measurement results above the $DCGL_W$ were obtained), then the original DQOs should be redeveloped for the correct classification; or, for example, if the data show the measurement uncertainty exceeds the estimate used to design the survey, the DQOs and MQOs should be revisited.

The survey design and data collection documentation should be reviewed for consistency with the DQOs. For example, the reviewer should check that the calculated N number of samples was taken in the correct locations and that the samples were analyzed using measurement systems with the required detection capability and uncertainty. Example checklists for different types of surveys are given in **Chapter 5**.

Determining that the survey design provides adequate power is important to decision-making, particularly if the average levels of c are near the $DCGL_W$. This can be done both prospectively during survey design to test the efficacy of a proposed design and retrospectively during interpretation of survey results to determine that the objectives of the design are met.

Appendix M discusses the procedure for generating power curves for specific tests. Note that the accuracy of a prospective power curve depends on having good estimates of the data variability, σ , and the number of measurements. After the data are analyzed, a sample estimate of the data variability, namely the sample standard deviation (s), is calculated from the data, and the actual number of valid measurements will be known. While the Type I (α) decision error rate will always be achieved, the consequence of inadequate power is an increased Type II (β or false negative) decision error rate:

³ MARSSIM uses the word "should" as a recommendation, not as a requirement. Each recommendation in this manual is not intended to be taken literally and applied at every site. MARSSIM's survey planning documentation will address how to apply the process on a site-specific basis.

- For Scenario A, this means that a survey unit that actually meets the release criteria has a higher probability of being incorrectly deemed not to meet the release criteria.
- For Scenario B, this means that a survey unit that does not meet the release criteria has a higher probability of being incorrectly deemed to meet the release criteria.

Regulators are primarily concerned with errors that result from determining that a survey unit meets the release criteria when it does not. This incorrect decision is a Type I error under Scenario A and a Type II error under Scenario B. Site owners are also concerned with errors that result from determining that a survey unit does not meet the release criteria when it does. This incorrect decision is a Type II error under Scenario A and a Type I error under Scenario B.

8.2.2 Conduct a Preliminary Data Review

To learn about the structure and quality of the data—identifying patterns, relationships, or potential anomalies—it is recommended that the quality assurance and quality control reports be reviewed. Basic statistical quantities should be calculated and graphs of the data, or populations estimators, should be prepared so that objective evidence is provided to support conclusions about the dataset.

8.2.2.1 Data Evaluation and Conversion

Radiological survey data are usually obtained in units that have no intrinsic meaning relative to derived concentration guideline levels (DCGLs), such as the number of counts per unit time. For comparison of survey data to DCGLs, the survey data from field and laboratory measurements are converted to DCGL units. **Section 6.7** contains further information on instrument calibration and data conversion.

The following basic statistical quantities should be calculated for the sample dataset:

- sample mean
- sample standard deviation
- sample median⁴

The following other statistical quantities may also be calculated:

- the standard error for the mean
- the highest measurement
- the lowest measurement

The sample mean, $\bar{x}$, can be calculated using **Equation 8-1**:

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad \text{Equation 8-1}$$

⁴ The term “sample” here is a statistical term and should not be confused with laboratory samples. For the calculation of basic statistical quantities above, data may consist of scanning data, direct measurement data, or laboratory sample data. See also the **glossary** definition of *sample*.

where N is the number of samples, and x_i are the results of the individual samples. The sample standard deviation, s , can be calculated using **Equation 8-2**:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2} \quad \text{Equation 8-2}$$

The median is the middle value of the dataset when the number of data points is odd and is the average of the two middle values when the number of data points is even. Thus, 50 percent of the data points are above the median, and 50 percent are below the median. **Example 8-1** illustrates how to calculate the sample standard deviation.

Example 8-1: Calculate the Sample Standard Deviation

Suppose the following 20 concentration values are from a survey unit:

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

First, the sample mean of the data should be calculated:

$$\begin{aligned} \bar{x} &= \frac{1}{N} \sum_{i=1}^N x_i \\ &= \frac{1}{N} (90.7 + 83.5 + 86.4 + \dots + 92.4 + 75.5 + 80.5) \\ &= 83.5 \end{aligned}$$

The sample mean is 83.5. The sample standard deviation should also be calculated:

$$\begin{aligned} s &= \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2} \\ &= \sqrt{\frac{1}{20-1} [(90.7 - 83.5)^2 + (83.5 - 83.5)^2 + \dots + (75.5 - 83.5)^2 + (80.5 - 83.5)^2]} \\ &= 5.7 \end{aligned}$$

The sample standard deviation is 5.7.

For Scenario A, the mean concentration of the survey unit should always be compared to the $DCGL_W$. A mean concentration for the survey unit that is less than the $DCGL_W$ is a necessary, but not sufficient, requirement for the release of the survey unit if the radionuclide is not present in the background. Where remediation is inadequate, this comparison may readily reveal that a

survey unit contains excess residual radioactive material—even before applying statistical tests. For example, if the sample mean exceeds the DCGL_w and the radionuclide of interest does not appear in background, then the survey unit clearly does not meet the release criteria. On the other hand, if every measurement in the survey unit is below the DCGL_w, the survey unit clearly meets the release criteria.⁵

The value of the sample standard deviation is especially important. If the standard deviation is larger than that assumed during the survey design, this may indicate that an insufficient number of samples was collected to achieve the desired power of the statistical test. Again, inadequate power can lead to unnecessary failure to meet the release criteria for Scenario A (of particular interest to the regulated) or release of a site that does not meet the release criteria for Scenario B (of particular interest to the regulator).

Large differences between the mean and the median would be an indication of skewness in the data. This would also be evident in a histogram of the data. **Example 8-2** illustrates a comparison of the sample mean and median.

Example 8-2: Comparison of the Sample Mean and the Median

Using the data from the earlier example, take the 20 concentration values from the survey unit:

90.7, 83.5, 86.4, 88.5, 84.4, 74.2, 84.1, 87.6, 78.2, 77.6,
86.4, 76.3, 86.5, 77.4, 90.3, 90.1, 79.1, 92.4, 75.5, 80.5.

Sort and rank the data from lowest to highest:

1	2	3	4	5	6	7	8	9	10
74.2	75.5	76.3	77.4	77.6	78.2	79.1	80.5	83.5	84.1
11	12	13	14	15	16	17	18	19	20
84.4	86.4	86.4	86.5	87.6	88.5	90.1	90.3	90.7	92.4

For the example data above, the median is 84.25 (i.e., $(84.1 + 84.4)/2$). The difference between the median and the mean (i.e., $84.25 - 83.5 = 0.75$) is less than the sample standard deviation (i.e., 5.7). Thus, in this instance, the mean and median would not be considered significantly different.

Examining the minimum, maximum, and range of the data may provide additional useful information. The maximum is the value of the largest observed sample, the minimum is the value of the smallest observed sample, and the range is the difference between the maximum and minimum. When there are 30 or fewer data points, values of the range much larger than about four to five standard deviations would be unusual. For larger datasets, the range might be wider. **Example 8-3** illustrates how to determine the sample range.

⁵ It can be verified that if every measurement is below the DCGL_w, the conclusion from the statistical tests will always be that the survey unit does not exceed the release criteria.

Example 8-3: Determination of the Sample Range

The minimum in the previous example is 74.2 and the maximum is 92.4, so the range is 18.2 ($92.4 - 74.2 = 18.2$). Dividing the range by the standard deviation indicates how many standard deviations wide the sample data represent:

$$\frac{18.2}{5.7} = 3.2$$

This is only 3.2 standard deviations. Thus, the range is not unusually large.

8.2.2.2 Graphical Data Review

At a minimum, a graphical data review should consist of a posting plot and a histogram. Quantile plots are also useful diagnostic tools, particularly in the two-sample case, to compare the survey unit and reference area if the radionuclide is present in the background or measurements are not radionuclide specific. Quantile plots are discussed in **Appendix L, Section L.2**.

A posting plot is simply a map of the survey unit with the data values entered at the measurement locations. This potentially reveals heterogeneities in the data, especially possible areas of elevated residual radioactive material. (**Section 4.5.3.7** provides more information about requirements for small areas of elevated activity.) Even in a reference area, a posting plot can reveal spatial trends in background data that might affect the results of the statistical tests used when the radionuclide is present in the background or measurements are not radionuclide specific.

If the data given in the examples above were obtained using a triangular grid in a rectangular survey unit, the posting plot might resemble the display in **Figure 8-1**. In the figure, blue indicates data values in the 70s, green shows values in the 80s, and red is for values in the 90s. **Figures 8-1(a)** and **8-1(c)** show no unusual patterns in the data, whereas **Figures 8-1(b)** and **8-1(d)** show the exact same values (and therefore the same mean) but with a different distribution of residual radioactive material. **Figures 8-1(b)** and **8-1(d)** also reveal an obvious trend toward smaller values as one moves from left to right across the survey unit, which can be discerned only if spatial information is available and analyzed. The graphical display of data in a posting plot is beneficial to better understanding the distribution of residual radioactive material at a site.

If the posting plot reveals systematic spatial trends in the survey unit, the cause of the trends would need to be investigated. In some cases, such trends could be due to residual radioactive material, but they may also be due to inhomogeneities in the survey unit background. EPA 2006b discusses other diagnostic tools for examining spatial data trends. The use of geostatistical tools to evaluate spatial data trends may also be useful in some cases (EPA 1989b).

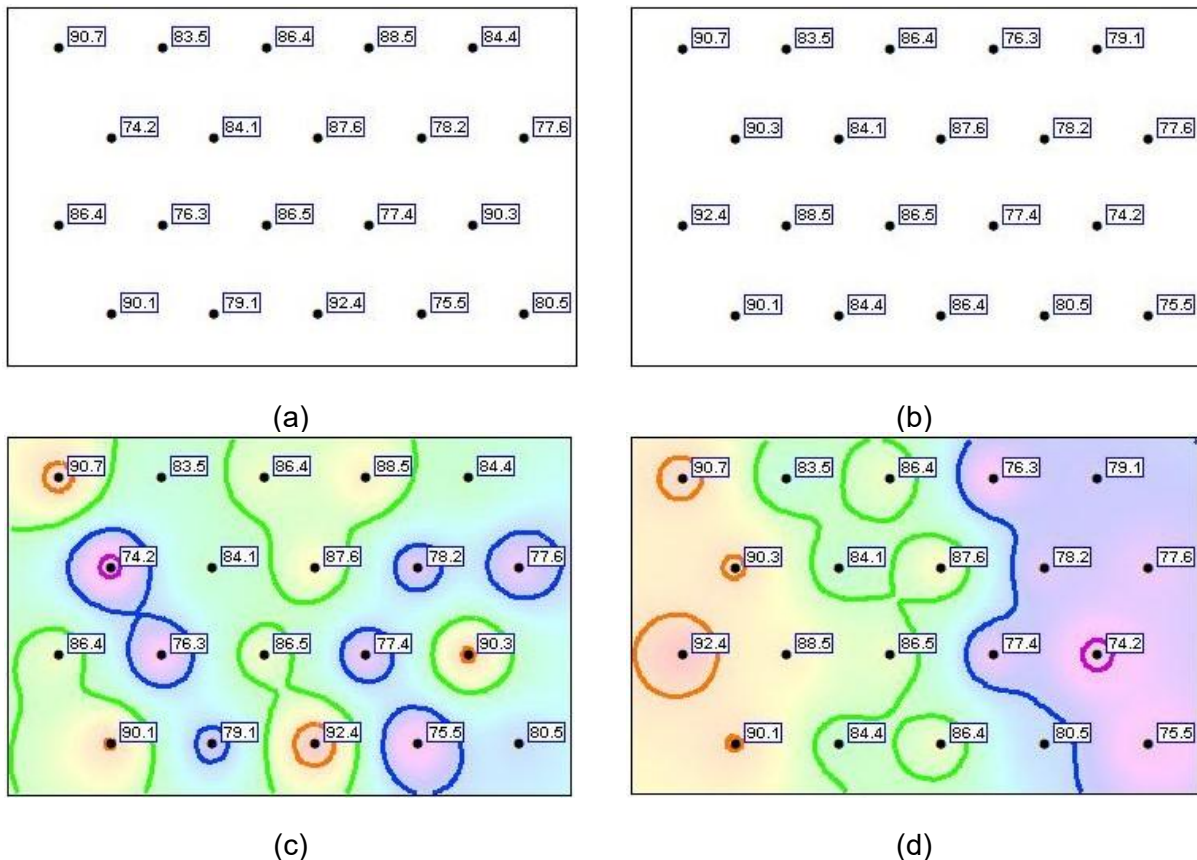


Figure 8-1 Examples of Posting Plots

Geographic information system (GIS) tools can also be used to help create conceptual models (e.g., provide spatial context and a better understanding of site features that may control or enhance radionuclide transport in the environment). Figures created with GIS tools can also assist with identifying relatively homogeneous areas of residual radioactivity for delineation of survey units. Features that can be captured on a figure using GIS tools include the following:

- study area and property boundary
- buildings where residual radioactivity may be present
- roads
- surface water features (streams, ponds, runoff basins, ditches, culverts)
- underground features (underground storage tanks, piping)
- topography, surface geology, and outcrop locations
- hydrostratigraphic surfaces and isopach maps
- water table and potentiometric surfaces
- sampling locations
- monitoring well locations
- contaminant distributions

Figure 8-2 is a sample GIS visualization. **Figure 8-2(a)** shows a map that includes the location of two hypothetical tanks. Leaks are known to have occurred near the tanks. GIS information on the location of important features and topography of surficial (or subsurface) structures can be

used to identify areas where residual radioactivity may be present and is more likely to have been transported (e.g., surface water runoff direction). GIS information and geostatistical tools can be helpful in designing survey plans and identifying areas most likely to be above risk-based thresholds. For example, the geostatistical tools available in such codes as Visual Sample Plan (VSP) and Spatial Analysis and Decision Assistance (SADA) can be used to analyze data and interpolate data for areas for which no data are available. **Figure 8-2** illustrates the use of SADA (Version 5) in creating a three-dimensional visualization of the volume of soil most likely to be affected based on sampling results and use of geostatistical tools available in the code. **Figure 8-2(b)** illustrates how geostatistical tools can be used to create a model to estimate the probability of exceeding a threshold following characterization.

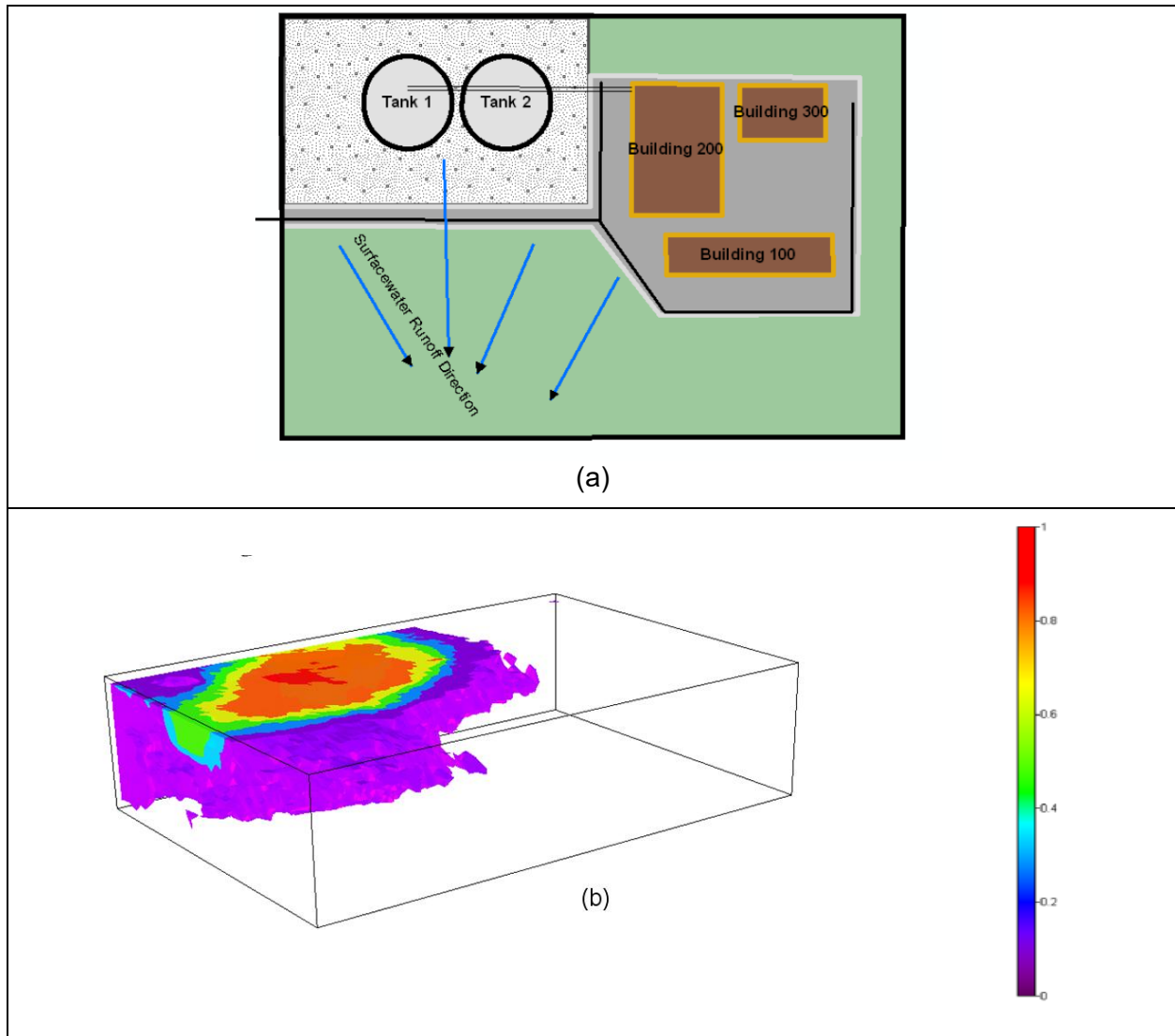


Figure 8-2 Sample GIS Visualization, Modified from Figures 3-4 and 7-8 in NUREG/CR-7021 (NRC 2012b)

A frequency plot (or a histogram) is a useful tool for examining the general shape of a data distribution. This plot is a bar chart of the number of data points within a certain range of values.

A frequency plot of the example data from **Figure 8-1** is shown in **Figure 8-3**. A simple method for generating a rough frequency plot is the stem-and-leaf display discussed in **Appendix L, Section L.1**. The frequency plot may reveal any obvious departures from symmetry, such as skewness or bimodality (two peaks), in the data distributions for the survey unit or reference area. The presence of two peaks in the survey unit frequency plot may indicate the existence of isolated areas of residual radioactive material, which may need to be further investigated as part of the EMC tests.

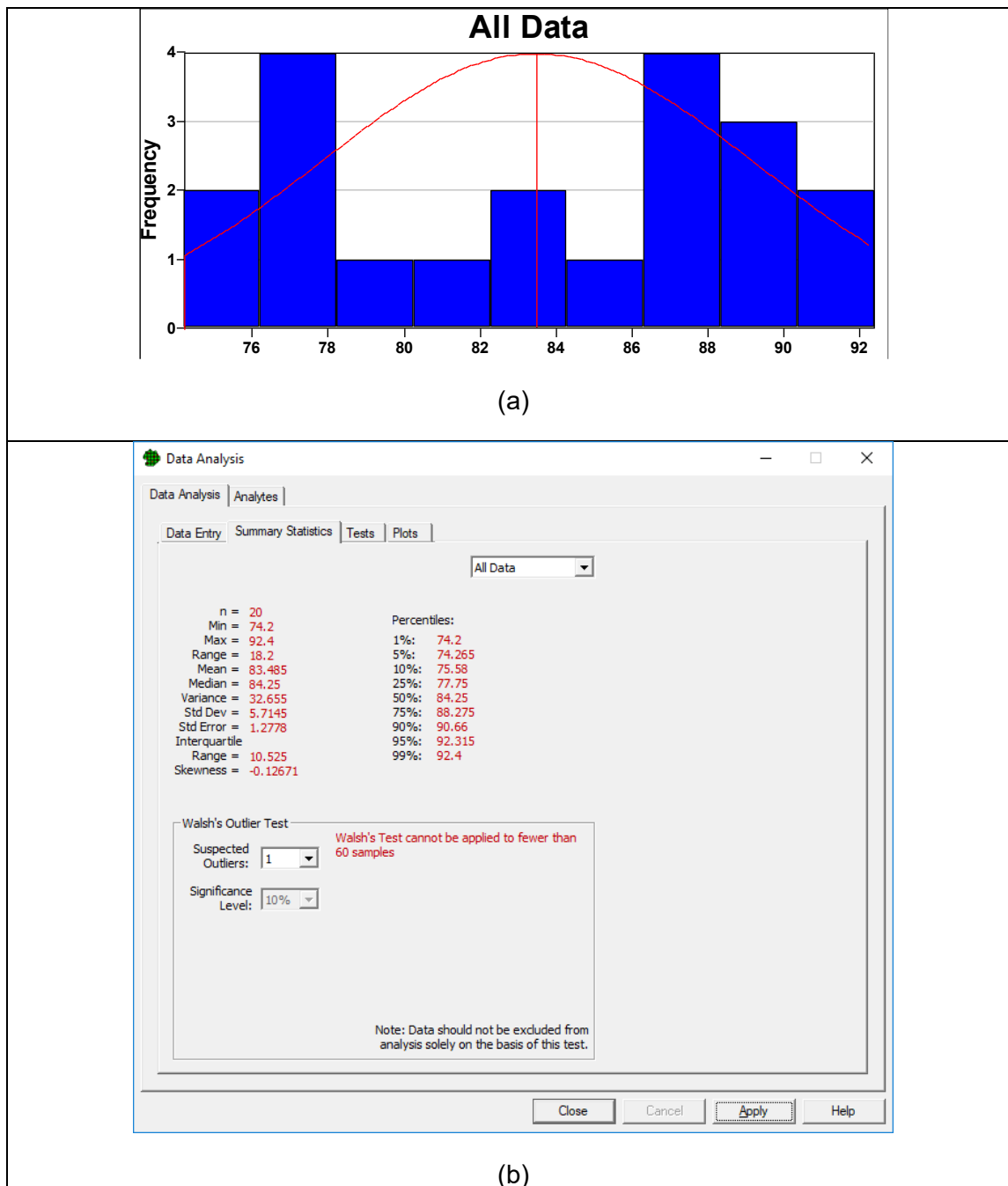


Figure 8-3 Example of a Frequency Plot (a) and Other Statistical Information Output from VSP Version 7 (b)

The presence of two peaks in the reference area or survey unit frequency plot may also indicate a mixture of background concentration distributions due to different soil types, construction materials, or similar factors, or it could indicate the presence of residual radioactivity in the reference area.⁶ The greater variability in the data due to the presence of such a mixture will reduce the power of the statistical tests to detect an adequately remediated survey unit that meets the release criteria for Scenario A or to detect a survey unit that does not meet the release criteria for Scenario B. These situations should be avoided whenever possible by carefully matching the background reference areas to the survey units and choosing more homogeneous survey units, as discussed in more detail in **Appendix D**. If relatively homogeneous survey units cannot be identified, consistent with the underlying assumptions in the DCGL_W derivation, then other approaches may need to be taken to evaluate the acceptability of the survey units for release (e.g., increased focus on evaluation of the risk of elevated areas). The regulator should be consulted for highly heterogeneous survey units.

Caution should be exercised when developing frequency plots (commonly referred to as histograms). The shape of a histogram can depend on the choice of the bin widths and ranges. If bins are too wide, features of the underlying distribution within the bin width may be missed. If bins are too narrow, the bin-to-bin variability can be mistaken as a feature of the underlying distribution. Additional caution should be exercised when interpreting histograms for small datasets where smaller features, such as a second smaller peak, may not be observed.

Skewness or other asymmetry can impact the accuracy of the statistical tests. When the underlying data distribution is highly skewed, it is often because there are a few elevated areas. Because the DCGL for the EMC (DCGL_{EMC}) is specifically used to evaluate the acceptability of elevated areas (i.e., the ability of a site with elevated areas of residual radioactivity material above the DCGL_W to meet release criteria), the limitations associated with the use of statistical tests based on the median or mean for nonhomogeneous residual radioactivity are mitigated. If highly heterogeneous residual radioactive material is present, care should be taken to ensure that the lateral extent of the elevated area is delineated and a DCGL_{EMC} is calculated consistent with the actual size of the elevated area. If a number of elevated areas are present, techniques can be used to evaluate the cumulative risk of the elevated areas dependent on the distribution of the elevated areas in the survey unit. Additional guidance on the application of DCGL_{EMCs} for multiple elevated areas can be found in Appendix I to NUREG-1757, "Consolidated Decommissioning Guidance," Volume 2, Revision 2, "Characterization, Survey, and Determination of Radiological Criteria," issued July 2022 (NRC 2022a).

8.2.2.3 *Good Practices for Post Processing of Continuously Collected Data*

As discussed in **Section 6.3.3**, continuously collected data (CCD) are typically analyzed using GIS software. This section lists good practices for processing and analysis of data using GIS software. These practices include recommendations for documenting conditions under which the survey was performed, ensuring the data collected are assigned to the correct geographic location, visual inspection of the data before analysis, performing exploratory spatial data analysis (ESDA), and choosing an analysis method. The goal is to ensure the quality of the data; provide traceable and reproduceable data collection, processing, and analysis methods; and produce defensible results that can aid in making decisions regarding the presence of elevated activity in a survey unit.

⁶ In some cases, it may be necessary to perform additional investigation to determine whether background reference areas were properly classified as non-impacted.

Some good practices, such as particular ESDA steps, may not apply to every situation, while others, such as steps taken to ensure the spatial accuracy of the data, are always a consideration. The following good practices appear in the order they are most likely to be implemented:

- For each separate data collection event, document the spatial data accuracy (Global Positioning System configuration, system capability), sensor sensitivity (minimum detection levels), and sensor accuracy (sensor capability, environmental factors). Determine whether the spatial accuracy of the data and sensor accuracy are adequate for their intended purpose.
- It is important to know the parameters of the coordinate system applied by both the data collection system and the GIS software used to process and analyze the data. This includes the units of measure, datum, spheroid (ellipsoid), and zone if applicable. If the coordinate system used in the GIS software differs from that of the collection system, it is important for the analyst to ensure the data are reprojected correctly, including by using an appropriate datum transformation, if necessary.
- When importing the data from the collection system into the GIS software, it is helpful to preserve any attributes such as autogenerated identification numbers and date/time stamps for individual survey points. If multiple units of equipment or multiple sensors are part of a single unit, preserving this information as additional attributes for each individual survey point can be helpful. This information can be compared with the data to help confirm the system is functioning correctly and aid in tracing any malfunctions back to a specific unit, sensor, or collection event. The time stamp can also help verify the data were collected within the acceptable speed tolerance.
- Recent high-resolution, orthorectified aerial imagery of a site (survey unit) is probably the single most valuable GIS reference layer. Other useful reference GIS data layers include historic aerial imagery, elevation, soils, geology, drainage, monitoring wells, prior surveys, buildings, transportation, surface cover, and historic locations of other human-made features.
- It is highly recommended that all imagery and other GIS reference layers for a project are reprojected to the same coordinate system used for the analysis of the data, being sure to apply the appropriate datum transformation for each layer. This is recommended even if the GIS software can reproject the layers “on the fly” for display purposes.
- Overlaying the survey data collected on the various reference layers can help ensure the data were properly georeferenced and any necessary reprojections of the data were performed correctly. It may also help identify anomalies, such as missing data, which might indicate possible flaws or malfunctioning of the data collection system.
- Displaying the survey data using a symbology scheme that distinguishes between high and low measurements may identify obvious patterns or trends in the spatial distribution of the data. For example, data collected on different days, or at different times of day, might exhibit significant value ranges, or there may be an abnormally high number of non-detects in data collected on a certain day. Note, the spatial distribution of the data should be visually inspected by individuals knowledgeable about the capabilities of the data collection system and the history of the site.

- Accessible color palettes (refer to EPA 2022) should be selected to aid in displaying the data for visually impaired individuals and to facilitate data interpretation.
- Analysts should be aware of how the GIS software represents the raw data (e.g., non-detects, null, 0, large negative number) and decide how to treat these values when processing the data.
- Performing ESDA on the dataset can help detect patterns, trends, and anomalies that visual inspection cannot detect. It is best to perform ESDA on the dataset from each separate collection event. Results of the ESDA should be compared among the datasets from each collection event. ESDA can include many of the following steps:
 - Apply graphical investigation methods such as box plots, histograms, and probability distributions.
 - Assess the statistical distribution of each dataset and generate summary statistics.
 - Search for local and global outliers.
 - Determine whether outliers represent real values or data collection errors.
 - Examine the spatial variability of the data, looking for clustering and spatial trends.
 - Perform tests for spatial dependency (autocorrelation) and spatial stationarity, especially if more advanced geostatistical analysis methods will be employed.
- Results of the ESDA, in conjunction with the requirements of the project (DQOs), can aid in choosing an analysis method or determining whether the characteristics of the data collected meet the requirements of a previously chosen method. In particular, ESDA can help do the following:
 - Decide whether nonspatial statistical analysis methods can be employed rather than spatial analysis methods. This may often be the case with CCD due to the dense nature of the data collection.
 - Determine whether additional data processing is necessary to make the data fit for the selected analysis method. This may include trend removal, declustering (less likely for CCD), statistical data transformation, and other methods.
- GIS analysis tools typically include options or parameter values. All parameter settings should be documented with sufficient detail to allow an analyst to reproduce the results, along with the basis for the parameter selection. When multiple analyses are performed using different parameter settings, or the software allows the user to enter a range of values for the parameters, the parameter selections and parameter ranges, as well as a basis for the selection, should be documented. A comparison of the results with the various parameter selections should be provided, along with a discussion about key differences in the results.
- If geospatial statistical analysis techniques will be used based on the assumption of spatial autocorrelation existing in the dataset, a multidisciplinary approach should be

taken to (1) help ensure a good conceptual understanding of the mechanisms leading to the spatial correlation in the data, and (2) help support parameter selections for the geospatial analysis.

The operator or licensee should contact the cognizant regulatory body to discuss whether the planned approaches for analysis of CCD are acceptable.

Additional references that can be consulted for information on good practices, including procedures for data collection, management, processing, visualization, and analysis methods, to promote transparency, repeatability, reproducibility, and replicability include EPA 2022 and EPA 2023.

8.2.2.4 *Draw Conclusions from the Preliminary Data Review*

In some instances, a preliminary review of the data may be sufficient to draw conclusions without performing the statistical tests described in **Section 8.2.3**. For example, under Scenario A, the sample mean of the survey unit data can be compared to the reference area sample mean and the $DCGL_W$ to get a preliminary indication of the survey unit status. If the difference of the survey unit sample mean and the reference area sample mean is greater than $DCGL_W$, then the survey unit cannot be released. Alternatively, significantly higher concentrations in the reference area compared to the survey unit may be an indicator that the reference area is not appropriate for the survey unit and warrants further investigation.

Table 8-3 through **Table 8-5** describe examples of other circumstances leading to specific conclusions based on a simple examination of the data without the need to perform certain statistical tests.

8.2.3 Select the Statistical Test

An overview of the statistical considerations important for FSSs appears in **Section 2.5** and **Appendix D**. The parameter of interest is the mean concentration in the survey unit. The nonparametric tests recommended in this manual, in their most general form, are tests of the median. For data that are from a skewed distribution, the mean could be significantly larger than the median. Therefore, the mean should be compared to the $DCGL_W$ to ensure that the mean is less than the $DCGL_W$, as indicated in **Section 8.2.2.4**. If the data are highly skewed because of the presence of elevated areas, the EMC test helps ensure that the site is acceptable for release.

If one assumes that the data are from a symmetric distribution where the median and the mean are effectively equal, these statistical evaluations are also tests of the mean. If the assumption of symmetry is violated, then nonparametric tests of the median approximately test the mean. Computer simulations (Hardin and Gilbert 1993) have shown that the approximation is a good one—that is, the correct decision will be made about whether the mean concentration exceeds the $DCGL_W$, even when the data come from a skewed distribution. In this regard, Hardin and Gilbert 1993 found the nonparametric tests to be correct more often than the commonly used Student's *t*-test. The robust performance of the Sign and WRS tests over a wide range of conditions is the reason that they are recommended in this manual.

When a given set of assumptions is true, a parametric test designed for exactly that set of conditions will have the highest power. For example, if the data are from a normal distribution, Student's *t*-test will have higher power than the nonparametric tests. It should be noted that for

large enough sample sizes (e.g., large number of measurements), Student's t -test is not a great deal more powerful than the nonparametric tests. On the other hand, when the assumption of normality is violated, the nonparametric tests can be much more powerful than the t -test. Therefore, any statistical test may be used, provided the data are consistent with the assumptions underlying their use. When these assumptions are violated, the prudent approach is to use the nonparametric tests, which generally involve fewer assumptions than their parametric equivalents.

The Sign test, described in **Section 5.3.4**, is typically used when the radionuclide is not present in background and radionuclide-specific measurements are made. The Sign test may also be used if the radionuclide is present in the background at such a small fraction of the $DCGL_W$ value as to be considered insignificant. In this case, background concentrations of the radionuclide are included with the residual radioactive material (i.e., the entire amount is attributed to facility operations). Thus, the total concentration of the radionuclide is compared to the release criteria. This option should be used only if one expects that ignoring the background concentration will not affect the outcome of the statistical tests. The advantage of ignoring a small background contribution is that no reference area is needed. This can simplify the FSS considerably. Some alternative statistical tests to the Sign test are described in Chapter 14 of NUREG-1505, Revision 1, "A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys," issued June 1998 (NRC 1998a), and in **Chapter 2**.

The Sign test (**Section 8.3.1**) evaluates whether the median of the data is above or below the $DCGL_W$. If the data distribution is symmetric, the median is equal to the mean. If the data are severely skewed, the mean may be above the $DCGL_W$, while the median is below the $DCGL_W$. In such cases, the survey unit does not meet the release criteria regardless of the result of the statistical tests. On the other hand, if the largest measurement is below the $DCGL_W$, the Sign test will always show that the survey unit meets the release criteria.

For FSSs, the WRS test discussed in **Section 5.3.3** can be used when the radionuclide of concern appears in background or if measurements used are not radionuclide specific. The WRS test (**Section 8.4.1**) assumes the reference area and survey unit data distributions are similar except for a possible shift in the medians. When the data are severely skewed, the value for the mean difference may be above the $DCGL_W$, while the median difference is below the $DCGL_W$. In such cases, the survey unit does not meet the release criteria regardless of the result of the statistical test. On the other hand, if the difference between the largest survey unit measurement and the smallest reference area measurement is less than the $DCGL_W$, the WRS test will always show that the survey unit meets the release criteria.

The use of paired observations for survey units with different backgrounds and some alternative statistical tests to the WRS test are described in Chapters 12 and 14, respectively, of NUREG-1505. If Scenario B was selected during the DQO process, the Quantile test is performed to test for skewness when the WRS test does not reject the null hypothesis.

If individual site-specific scanning survey results are recorded, a nonparametric confidence limit can be used to evaluate the results of the FSS. Similarly, a confidence limit can be used to evaluate a series of in situ measurements with overlapping fields of view. While measurements in overlapping fields of view are likely spatially dependent, the measurements themselves are independent. When calculating the average and UCL for the concentration of radioactive material using in situ measurements with or without overlapping fields of view, the spatial density of measurements should be constant throughout the survey unit. If not, the true

concentration of radioactive material may be overestimated or underestimated. If the spatial density of measurements differs throughout the survey unit, an unbiased estimate of the average concentration of radioactive material may be possible using a weighted average. A one-tailed version of Chebyshev's inequality, or a software tool (e.g., the EPA's ProUCL software), can be used to evaluate the probability of exceeding the upper bound of the grey region (UBGR) using a UCL. The use of a UCL applies to both Scenario A (where the UBGR equals the DCGL_w) and Scenario B (where the UBGR equals the discrimination limit [DL]).

The nonparametric Chebyshev UCL is one possible approach to calculating the UCL, but others include the normal Z-test and Chen's skewed *t*-test (Chen 1995). The Chebyshev UCL is already conservative and consistent with the Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (NRC 2009); however, there are some limitations to its use. For site-specific scanning surveys in which data are compared to a UCL, Chebyshev's inequality should be used with caution when there are very few points in the dataset (i.e., fewer than 30). This is because the population mean and standard deviation in the Chebyshev formula are being estimated by the sample mean and sample standard deviation. In a small dataset from a highly skewed distribution, the sample mean and sample standard deviation may be underestimated if the high concentration but low probability portion of the distribution is not captured in the sample dataset. It would be useful to compare the results to determine whether there would be different decisions made among these tests. Since there is generally a large number of data points in a data logging scanning survey, it is likely that the central limit theorem will be a good approximation and these three methods will give similar results.

Table 8-1 summarizes the statistical tests and evaluation methods discussed in this chapter. **Section 6.7** provides information on converting the instrument reading to the appropriate units for reporting the UCL.

Table 8-1 Summary of Statistical Tests and Evaluation Methods

Statistical Test or Evaluation Method	Applicability
Sign Test (see Section 8.3 and Table 8-3)	- Radionuclide not in background <u>and</u> nuclide-specific measurements - Scenario A or B
WRS Test (see Section 8.4 and Table 8-4)	- Radionuclide in background <u>or</u> non-nuclide specific measurements - Scenario A or B
Quantile Test (see Section 8.4)	- Test for non-uniform distribution of radioactive material - Combined with WRS test - Scenario B only
Comparison to UCL (see Section 8.5 and Table 8-5)	- Site-specific scanning surveys or in situ surveys - Scenario A or B

8.2.4 Verify the Assumptions of the Statistical Tests

An evaluation to determine that the data are consistent with the underlying assumptions made for the statistical procedures helps to validate the use of a test. One may also determine that

certain departures from these assumptions are acceptable when given the actual data and other information about the study.

For surveys consisting of a combination of scanning with samples or direct measurements, the nonparametric tests described in this chapter assume that the data from the reference area or survey unit consist of independent samples from each distribution. Spatial dependencies that potentially affect the assumptions can be assessed using posting plots (**Section 8.2.2.2**). More sophisticated tools for determining the extent of spatial dependencies are also available (e.g., EPA 2006b). These methods tend to be complex and are best used with guidance from a professional statistician.

Asymmetry in the data can be diagnosed with a stem-and-leaf display, a histogram, or a quantile plot.

One of the primary advantages of the nonparametric tests is that they involve fewer assumptions about the data than their parametric counterparts. If parametric tests are used, (e.g., Student's *t*-test), then any additional assumptions made in using them should be verified (e.g., testing for normality). EPA 2006b discusses these issues in detail.

One of the more important assumptions made in the survey designs described in **Sections 5.3.3** and **5.3.4** is that the sample sizes determined for the tests are sufficient to achieve the DQOs set for the Type I and Type II error rates. Verification of the power of the tests ($1-\beta$) correctly determines that a site that does not meet the release criteria is not released under Scenario B, regardless of what the test showed. This may be of particular interest to the regulator and is, therefore, required for surveys conducted under Scenario B. For Scenario A, verification of the power of the tests to correctly release a site that meets the release criteria, regardless of what the test determined, may be of particular interest to the site owner/operator. **Appendix M** discusses methods for assessing the power.

For these reasons, it is better to plan the surveys cautiously, including by doing the following:

- overestimating the potential data variability
- taking more than the minimum number of measurements
- overestimating minimum detectable concentrations (MDCs) and measurement method uncertainties

If one is unable to show that the DQOs and MQOs were met with reasonable assurance, a resurvey may be needed. **Table 8-2** summarizes some examples of assumptions and possible methods for their assessment.

Table 8-2 Methods for Checking the Assumptions of Statistical Tests

Assumption	Diagnostic
Spatial Independence	Posting Plot
Symmetry	Histogram, Quantile Plot
Data Variance	Sample Standard Deviation
Adequate Power	Retrospective Power Analysis

8.2.5 Draw Conclusions from the Data

The types of measurements that can be made in a survey unit are direct measurements, laboratory samples, and scans.

Specific details for conducting the statistical tests are given in **Section 8.3** (Sign test), **Section 8.4** (WRS test and Quantile test), and **Section 8.5** (UCL test). When the data clearly show that a survey unit meets or exceeds the release criteria ($DCGL_W$ for Scenario A and action level [AL] for Scenario B), the result is often obvious without performing the formal statistical analysis. The data still need to meet the assumptions for the statistical tests, (e.g., ensuring adequate power in Scenario B.) **Table 8-3** through **Table 8-5** display various survey results and their conclusions.

Table 8-3 Summary of Statistical Tests for Radionuclide Not in Background and Radionuclide-Specific Measurement

Scenario A Survey Result	Scenario A Conclusion
All measurements are less than $DCGL_W$.	Survey unit meets release criteria.
Sample mean is greater than $DCGL_W$.	Survey unit does not meet release criteria.
Any measurement is greater than $DCGL_W$, and the sample mean is less than $DCGL_W$.	Conduct Sign test and EMC.
Scenario B Survey Result	Scenario B Conclusion
All measurements are greater than AL.	Survey unit does not meet release criteria.
Any measurement is less than the AL.	Conduct Sign test, EMC, and retrospective power analysis.

Table 8-4 Summary of Statistical Tests for Radionuclide in Background or Radionuclide Non-Specific (Gross) Measurements

Scenario A Survey Result	Scenario A Conclusion
Difference between largest survey unit measurement and smallest reference area measurement is less than the $DCGL_W$.	Survey unit meets release criteria.
Difference between survey unit sample mean and reference area sample mean is greater than the $DCGL_W$.	Survey unit does not meet release criteria.
Difference between any survey unit measurement and any reference area measurement is greater than $DCGL_W$, and the difference between survey unit sample mean and reference area sample mean is less than the $DCGL_W$.	Conduct WRS test and EMC.

Scenario B Survey Result	Scenario B Conclusion
Difference between smallest survey unit measurement and largest reference area measurement is greater than the AL.	Survey unit does not meet release criteria.
Difference between any survey unit measurement and any reference area measurement is less than the AL.	Conduct WRS test, Quantile test, EMC, and retrospective power analysis.

Table 8-5 Summary of Results for Site-Specific Scanning Surveys

Scenario A Survey Result ^a	Scenario A Conclusion
UCL is less than DCGL _{LW} .	Survey unit meets average release criteria; conduct the EMC.
UCL is greater than DCGL _{LW} .	Survey unit does not meet release criteria.
Scenario B Survey Result	Scenario B Conclusion
UCL is less than DL.	Survey unit meets average release criteria; conduct the EMC.
UCL is greater than DL.	Survey unit does not meet release criteria.

^a **Section 8.5** contains additional details on calculating the UCL.

If applicable release criteria for elevated measurements exist, then both the measurements at discrete locations and the scans are also subject to the EMC. The result of comparing individual measurements, such as judgment measurements and samples, to the DCGL_{EMC} is not conclusive as to whether the survey unit meets or exceeds the release criteria, but it is a flag or trigger for further investigation. The investigation may involve taking further measurements to determine that the area and level of the elevated residual radioactive material are such that the resulting dose or risk meets the release criteria.⁷ The investigation should also provide adequate assurance, using the DQO process, that there are no undiscovered areas of elevated residual radioactive material in the survey unit that might otherwise result in a dose or risk exceeding the release criteria, when considered in conjunction with the dose or risk posed by the remainder of the survey unit. In some cases, this may lead to reclassifying all or part of a survey unit, unless the results of the investigation indicate that reclassification is not necessary. The investigation level appropriate for each class of survey unit and type of measurement is shown in **Table 5-4** and is described in **Section 5.3.8**. **Example 8-4** provides background information that will be used in **Example 8-5** through **Example 8-8**.

⁷ Rather than, or in addition to, taking further measurements, the investigation may involve assessing the adequacy of the exposure pathway model used to obtain the DCGLs. For example, additional data collected during the Radiation Survey and Site Investigation process may reveal that the DCGL_{EMC}s are too restrictive or support an updated site-specific analysis. The regulatory agency may approve alternative methods to assessing the risk of elevated areas and should be contacted.

Example 8-4: Illustrative Examples Background Information

This example provides the background for **Example 8-5 through Example 8-8**.

To illustrate the data interpretation process for Scenario A, consider an example facility with 14 survey units consisting of interior concrete surfaces, one interior survey unit with drywall surfaces, and two outdoor surface soil survey units. The radionuclide of concern is cobalt-60 (^{60}Co). The interior surfaces were measured with a gas-flow proportional counter (refer to **Appendix H**) with an active surface area of 100 square centimeters (cm^2) to determine gross beta activity. Because these measurements are not radionuclide specific, appropriate reference areas were chosen for comparison. The exterior surface soil was measured with a germanium spectrometer to provide radionuclide-specific results. A reference area is not needed because ^{60}Co does not have a significant background in soil.

To illustrate how the data interpretation changes when using Scenario B, at the same example facility, consider two outdoor surface soil survey units. The radionuclide of concern is radium-226. Exterior soil samples were collected and sent to a laboratory for analysis using gamma spectrometry (see **Appendix H**). A reference area was needed because radium-226 has a significant background in soil.

The exterior surface soil Class 3 survey unit incorporates areas that are not expected to contain residual radioactive material. The exterior surface soil Class 2 survey unit is similar to the Class 3 survey unit but is expected to contain concentrations of residual radioactive material below the DCGL_w . The exterior surface soil Class 1 survey unit is expected to contain small areas of elevated activity that may or may not exceed the DCGL_w . The Class 1 interior concrete survey units are expected to contain small areas of elevated activity that may or may not exceed the DCGL_w . The Class 2 interior drywall survey unit is similar to the Class 1 interior concrete survey unit, but the drywall is expected to have a lower background, less measurement variability, and a more uniform distribution of radioactive material. The Class 2 survey unit is not expected to contain areas of residual radioactive material above the DCGL_w . The survey design parameters and DQOs developed for these survey units under Scenario A are summarized in **Table 8-6** and under Scenario B are summarized in **Table 8-7**.

Table 8-7 provides survey design parameters and DQOs developed for two survey units under Scenario B where the lower bound of the gray region (LBGR) is zero or indistinguishable from background for a radionuclide that is in the natural background.

Table 8-6 FSS Parameters for Example Survey Units for Scenario A

Survey Unit	Type	DQO α	DQO β	LBGR	DCGL _W ^a	Estimated Standard Deviation, σ^b Survey Unit	Estimated Standard Deviation, σ^b Reference Area	Test/ Section
Exterior Surface Soil	Class 2	0.025	0.025	128 Bq/kg	140 Bq/kg	4.0 Bq/kg	N/A	Sign/ Example 8-5
Exterior Surface Soil	Class 3	0.025	0.01	128 Bq/kg	140 Bq/kg	4.0 Bq/kg	NA	Sign/ Example 8-6
Interior Concrete	Class 1	0.05	0.05	3,000 dpm/100 cm ²	5,000 dpm/100 cm ²	625 dpm/100 cm ²	220 dpm/100 cm ²	WRS/ Appendix A
Interior Drywall	Class 2	0.025	0.05	3,000 dpm/100 cm ²	5,000 dpm/100 cm ²	200 dpm/100 cm ²	200 dpm/100 cm ²	WRS/ Example 8-7

^a DCGL_W is given in units of becquerels (Bq) per kilogram (kg) or disintegrations per minute (dpm) per 100 cm².

^b Estimated standard deviation from scoping, characterization, and remedial action support surveys

Table 8-7 FSS Parameters for Example Survey Units for Scenario B

Survey Unit	Type	DQO α	DQO β	AL	DL ^a	Estimated Standard Deviation, σ^b Survey Unit	Estimated Standard Deviation, σ^b Reference Area	Test/ Section
Exterior Surface Soil	Class 1	0.05	0.05	0 Bq/kg	12 Bq/kg	6 Bq/kg	6 Bq/kg	WRS/ Example 8-8
Exterior Surface Soil ^c	Class 3	0.05	0.01	0 Bq/kg	12 Bq/kg	6 Bq/kg	6 Bq/kg	WRS/ Example 8-8

^a AL is zero.

^b Estimated standard deviation from scoping, characterization, and remedial action support surveys.

^c This survey unit is not worked out in further examples.

8.3 Radionuclide Not Present in Background

The statistical test discussed in this section, the Sign test, is used to compare each survey unit directly with the applicable release criteria. A reference area is not included because the measurement technique is radionuclide specific and the radionuclide of concern is not present in background (see **Section 8.2.3**). In this case, the concentrations of residual radioactive material are compared directly with the DCGL_W. The method in this section should be used only if the radionuclide is not present in background or is present at such a small fraction of the DCGL_W value as to be considered insignificant. In addition, the Sign test is applicable only if radionuclide-specific measurements are made to determine the concentrations. Otherwise, the WRS method discussed in **Section 8.4** is recommended.

Reference area samples are not needed when there is sufficient information to indicate that there is essentially no background concentration for the radionuclide being considered. With only a single set of survey unit samples, the statistical test used here is the Sign test.

Section 5.3.4 has further information appropriate to following the example and discussion presented here.

8.3.1 Sign Test

The Sign test is designed to detect failure of the survey unit to meet release criteria if the radioactive material is distributed across that survey unit. Although the parameter of interest is usually the mean concentration of residual radioactive material in the survey unit, the Sign test uses the median as an estimate of the mean. This test does not assume that the data follow any particular distribution, such as normal or lognormal.

In Scenario A, the hypothesis tested by the Sign test is as follows:

Null Hypothesis

H_0 : The median concentration of residual radioactive material in the survey unit is greater than or equal to the $DCGL_W$.

Versus

Alternative Hypothesis

H_1 : The median concentration of residual radioactive material in the survey unit is less than the $DCGL_W$.

The null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. For Scenario A, the null hypothesis states that the probability of a measurement less than the $DCGL_W$ is less than one-half; that is, the 50th percentile (or median) is greater than the $DCGL_W$.

Because the Sign test uses the median instead of the mean, the null hypothesis in Scenario A may be rejected if the median concentration is less than the $DCGL_W$, even if the mean concentration is greater than or equal to the $DCGL_W$. If the mean concentration is greater than or equal to the $DCGL_W$, the survey unit does not meet the release criteria (refer to **Table 8-3**). Furthermore, in addition to the Sign test, the $DCGL_{EMC}$ (refer to **Section 5.3.5**) is compared to each measurement to ensure none exceeds the $DCGL_{EMC}$. If a measurement exceeds the $DCGL_{EMC}$, then additional investigation is recommended, at least locally, to determine the actual areal extent of the elevated concentration.

In Scenario B, the hypothesis tested by the Sign test is as follows:

Null Hypothesis

H_0 : The median concentration of residual radioactive material in the survey unit is less than or equal to the AL.

Versus

Alternative Hypothesis

H_1 : The median concentration of residual radioactive material in the survey unit is greater than the AL.

Again, the null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. For Scenario B, the null hypothesis states that the probability of a measurement greater than the AL is less than one-half; that is, the 50th percentile (or median) is less than the AL.

When using the Sign test for both Scenario A and B, it is necessary to show that there are a sufficient number of measurements or samples with concentrations below the $DCGL_W$ or AL, respectively. Under Scenario A, when there are too many measurements or samples with concentrations above the $DCGL_W$, the investigator fails to reject the null hypothesis that the survey unit does not meet the release criteria. Under Scenario B, when there are too many measurements or samples with concentrations above the LBGR, the investigator rejects the null hypothesis that the survey unit does meet the release criteria.

When the values of α and β are selected in the DQO process, an important difference between Scenario A and Scenario B should be considered. For a fixed value of N , a lower value for α is more protective in Scenario A but is less protective in Scenario B. In both scenarios, a lower value for α requires a higher degree of evidence before the null hypothesis is rejected. In Scenario A, the null hypothesis is that the survey unit exceeds the release criteria, and a lower value for α makes it more difficult to reject this hypothesis. In Scenario B, the null hypothesis is that the survey unit meets the release criteria, and a lower value of α makes it more difficult to reject this hypothesis.

Note that some individual survey unit measurements may exceed the $DCGL_W$ even when the survey unit as a whole meets the release criteria. In fact, a survey unit sample mean that is close to the $DCGL_W$ might have almost half of its individual measurements greater than the $DCGL_W$. Such a survey unit may still not exceed the release criteria. The risk associated with any areas above the DCGL is evaluated by developing a $DCGL_{EMC}$ based on dose or risk modeling. The $DCGL_{EMC}$ is higher than the $DCGL_W$ and depends on the size of the elevated area. Concentrations above the $DCGL_{EMC}$ indicate that additional investigations or remediation (or both) may be needed. **Section 8.6.1** gives more details.

The assumption is that the survey unit measurements are independent random samples from a symmetric distribution. If the distribution of measurements is symmetric, the median and the mean are the same. If the distribution of measurements is highly skewed, then the efficacy of the statistical tests is reduced because of the underlying homogeneity assumptions inherent in the decision criteria (i.e., DCGL calculations).

The hypothesis specifies release criteria in terms of a $DCGL_W$. The test should have sufficient power ($1 - \beta$, as specified in the DQOs) to detect concentrations of residual radioactive material at the LBGR, which is less than the $DCGL_W$. If σ is the standard deviation of the measurements in the survey unit, then the relative shift (the width of the gray region, which is calculated by $DCGL_W - LBGR$, divided by the standard deviation [Δ/σ]) reflects the difference between the average concentration of radioactive material and the DCGL relative to measurement variability. **Sections 5.3.3.1** and **5.3.3.2** contain the procedures for selecting the LBGR and determining the relative shift (Δ/σ).

As stated above, the null hypothesis for Scenario B is that the median concentration of residual radioactive material in the survey unit is less than the LBGR (or AL). To use the Sign test with Scenario B, the concentration of radioactive material in background should be zero or insignificant compared to the LBGR (or AL). In some cases, the LBGR (or AL) may be set equal to zero (e.g., release criteria require that concentrations be indistinguishable from background

and the radionuclide is not present in background). In this case, results should be scattered about zero; therefore, if there are too many results with concentrations greater than zero, the null hypothesis should be rejected. Results less than zero are both possible and likely when the concentrations are truly equal to zero and measurements are subject to some random component of measurement method uncertainty.

In this case, the number of positive and negative results is expected to be the same, and the average of all the results is expected to be zero. When analyzing samples where the concentration is very small, the data analysis should be reviewed carefully, because even relatively small systematic errors can result in relatively large differences in the number of positive and negative results.

Some laboratories report results below the lower limit of detection as “< LLD” or below the minimum detectable activity as “< MDA”. Under Scenario A, the use of such results for the Sign test is usually not problematic, because the DL is required to be less than the DCGL_W, and any values less than the DL will also be less than the DCGL_W. However, under Scenario B, in which the DL is greater than the AL, it is difficult to determine whether the concentrations reported as “< LLD” or “< MDA” are greater than or less than the AL. For this reason, the Sign test should only be used for Scenario B when actual concentrations, no matter how small, are reported.

8.3.2 Applying the Sign Test

The Sign test is applied as outlined in the following five steps, and it is further illustrated by **Example 8-5** and **Example 8-6**. Separate instructions are given for Scenarios A and B.

Scenario A

- (1) List the survey unit measurements: $x_i, i = 1, 2, 3, \dots, N$.
- (2) Subtract each measurement, x_i , from the DCGL_W to obtain the differences:
 $D_i = \text{DCGL}_W - x_i, i = 1, 2, 3, \dots, N$.
- (3) Discard each difference that is exactly zero and reduce the sample size, N , by the number of such measurements exactly equal to the DCGL_W.
- (4) Count the number of positive differences. The result is the test statistic S^+ . (Note that a positive difference corresponds to a measurement below the DCGL_W and contributes evidence that the survey unit meets the release criteria.)
- (5) Large values of S^+ indicate that the null hypothesis is false. The value of S^+ is compared to the critical values in **Table I-4**. If S^+ is greater than the critical value, k , in that table, the null hypothesis is rejected.

Scenario B

- (1) List the survey unit measurements: $x_i, i = 1, 2, 3, \dots, N$.
- (2) Subtract the AL from each measurement, x_i , to obtain the differences:
 $D_i = x_i - \text{AL}, i = 1, 2, 3, \dots, N$.
- (3) Discard each difference that is exactly zero and reduce the sample size, N , by the number of such measurements exactly equal to the AL.

- (4) Count the number of positive differences. The result is the test statistic S^+ . (Note that a positive difference corresponds to a measurement above the AL and contributes evidence that the survey unit does not meet the release criteria.)
- (5) Large values of S^+ indicate that the null hypothesis is false. The value of S^+ is compared to the critical values in **Table I-4**. If S^+ is greater than the critical value, k , in that table, the null hypothesis is rejected.

Passing a survey unit without making a single calculation may seem an unconventional approach. However, the key is in the survey design, which is intended to ensure that enough measurements are made to satisfy the DQOs. After the data are collected, the conclusions and power of the test can be checked by constructing a retrospective power curve as outlined in **Appendix M**.

In addition to checking the power of the statistical test, it is also important to ensure that the uncertainty of the measurements has met the MQOs for required measurement uncertainty. One final consideration remains regarding the survey unit classification: "Was any definite amount of residual radioactive material found in the survey unit?" This will depend on the MDC of the measurement method. Generally, the MDC is at least three or four times the estimated measurement standard deviation. For example, in **Table 8-8**, the largest observation, 9.3 Bq/kg (0.25 picocuries/gram [pCi/g]), is less than three times the estimated measurement standard deviation of 3.8 Bq/kg (0.10 pCi/g). Thus, it is unlikely that any of the measurements could be considered indicative of positive residual radioactive material. This means that the Class 3 survey unit classification was appropriate.

Table 8-8 Sign Test Example Data for Class 3 Exterior Survey Unit

Sample Number	A Data (Bq/kg)	B DCGL _w – Data (Bq/kg)	C Sign
1	3.0	137.0	+
2	3.0	137.0	+
3	1.9	138.1	+
4	0.37	139.6	+
5	-0.37	140.4	+
6	6.3	133.7	+
7	-3.7	143.7	+
8	2.6	137.4	+
9	3.0	137.0	+
10	-4.1	144.1	+
11	3.0	137.0	+
12	3.7	136.3	+
13	2.6	137.4	+
14	4.4	135.6	+

Sample Number	A Data (Bq/kg)	B DCGL _w – Data (Bq/kg)	C Sign
15	-3.3	143.3	+
16	2.1	137.9	+
17	6.3	133.7	+
18	4.4	135.6	+
19	-0.37	140.4	+
20	4.1	135.9	+
21	-1.1	141.1	+
22	1.1	138.9	+
23	9.3	130.7	+

Number of positive differences $S^+ = 23$

Example 8-5 and **Example 8-6** illustrate how to use the Sign test on Class 2 and 3 exterior soil units.

Example 8-5: Sign Test for a Class 2 Exterior Soil Survey Unit

Example 8-4 contains the relevant background information. For the Class 2 exterior soil survey unit, the Sign test is appropriate, because the radionuclide of concern does not appear in background and radionuclide-specific measurements were made. Scenario A is selected.

Table 8-6 shows that the DQOs for this survey unit include $\alpha = 0.025$ and $\beta = 0.025$. The DCGL_w is 140 Bq/kg (3.8 pCi/g), and, based on site-specific measurements, the LBGR was selected to be 128 Bq/kg (3.5 pCi/g). The estimated standard deviation of the measurements is $\sigma = 4.0$ Bq/kg (0.11 pCi/g). The relative shift was calculated to be 3.0, as shown below:

$$\Delta/\sigma = \text{DCGLW} - \text{LBGR} / \sigma = \frac{140 \text{ Bq/kg} - 128 \text{ Bq/kg}}{4.0 \text{ Bq/kg}} = 3.0$$

Table 5-3 indicates the number of measurements (N) calculated as required for the Sign Test is 20 ($\alpha = 0.025$, $\beta = 0.025$, and $\Delta/\sigma = 3$). (**Table I-2** in **Appendix I** also lists the number of measurements needed for the Sign test.) This survey unit is Class 2, so the 20 measurements needed were made on a random-start triangular grid. When laying out the grid, 22 measurement locations were identified.

The 22 measurements taken on the exterior lawn Class 2 survey unit are shown in the first column of **Table 8-9**. The mean of these data is 129 Bq/kg (3.5 pCi/g), and the standard deviation is 11 Bq/kg (0.30 pCi/g). Since the number of measurements is even, the median of the data is the average of the two middle values $(126+128)/2 = 127$ Bq/kg (3.4 pCi/g). A quantile plot of the data is shown in **Appendix L, Figure L-3**.

Five measurements exceed the DCGL_w value of 140 Bq/kg: 142, 143, 145, 148, and 148. However, none exceed the mean of the data plus three standard deviations: $129 + (3 \times 11) = 162$ Bq/kg (4.3 pCi/g). Thus, these values appear to reflect the overall variability of the concentration measurements rather than to indicate an area of elevated activity—provided

that these measurements were scattered through the survey unit. However, if a posting plot demonstrates that the locations of these measurements are grouped together, then that portion of the survey unit containing these locations merits further investigation.

The middle column of **Table 8-9** contains the differences, $DCGL_W - \text{Data}$, and the last column contains the signs of the differences. The bottom row shows the number of measurements with positive differences, which is the test statistic S^+ . In this case, $S^+ = 17$.

The value of S^+ is compared to the appropriate critical value in **Table I-4** in **Appendix I**. In this case, for $N = 22$ and $\alpha = 0.025$, the critical value is 16. Because $S^+ = 17$ exceeds this value, the null hypothesis that the survey unit exceeds the release criteria is rejected.

Table 8-9 Example Sign Analysis: Class 2 Exterior Soil Survey Unit

Data (Bq/kg)	$DCGL_W - \text{Data}$ (Bq/kg)	Sign
121	19	+
143	-3	-
145	-5	-
112	28	+
125	15	+
132	8	+
122	18	+
114	26	+
123	17	+
148	-8	-
115	25	+
113	27	+
126	14	+
134	6	+
148	-8	-
130	10	+
119	21	+
136	4	+
128	12	+
125	15	+
142	-2	-
129	11	+

Number of positive differences $S^+ = 17$

Example 8-6: Sign Test for a Class 3 Exterior Soil Survey Unit

Example 8-4 contains the relevant background information. For the Class 3 exterior soil survey unit, the Sign test is again appropriate, because the radionuclide of concern does not appear in background and radionuclide-specific measurements were made. Scenario A is selected.

Table 8-6 shows that the DQOs for this survey unit include $\alpha = 0.025$ and $\beta = 0.01$. The $DCGL_W$ is 140 Bq/kg (3.8 pCi/g), and, based on site-specific measurements, the LBGR was selected to be 128 Bq/kg (3.5 pCi/g). The estimated standard deviation of the measurements is $\sigma = 4.0$ Bq/kg (0.11 pCi/g). The relative shift was calculated to be 3.0, as shown below:

$$\Delta/\sigma = DCGL_W - LBGR/\sigma = \frac{140 \text{ Bq/kg} - 128 \text{ Bq/kg}}{4.0 \text{ Bq/kg}} = 3.0$$

Table 5-3 indicates that the sample size estimated for the Sign test, N , is 23 ($\sigma = 0.235$, $\beta = 0.01$, and $\Delta/\sigma = 3$). This survey unit is Class 3, so the measurements were made at random locations within the survey unit. The 23 measurements taken on the exterior lawn are shown in the first column of **Table 8-8**. The mean of these data is 2.1 Bq/kg (0.057 pCi/g), and the standard deviation is 3.3 Bq/kg (0.089 pCi/g). None of the data exceed $2.1 \text{ Bq/kg} + (3 \times 3.3) \text{ Bq/kg} = 12.0 \text{ Bq/kg}$ (0.32 pCi/g). Because N is odd, the median is the middle (12th-highest) value, namely 2.6 Bq/kg (0.070 pCi/g).

An initial review of the data reveals that every data point is below the $DCGL_W$, so the survey unit meets the release criteria specified in **Table 8-3**. For purely illustrative purposes, the Sign test analysis is performed. The middle column of **Table 8-8** contains the quantity $DCGL_W - \text{Data}$. Because every data point is below the $DCGL_W$, the sign of $DCGL_W - \text{Data}$ is always positive. The number of positive differences is equal to the number of measurements, N , and so the Sign test statistic S^+ is 23. The null hypothesis will always be rejected at the maximum value of S^+ (which in this case is 23), and the survey unit passes. Thus, the application of the Sign test in such cases requires no calculations, and one need not consult a table for a critical value. If the survey is properly designed, the critical value must always be less than N .

Notice that some of the measurements in **Table 8-8** are negative (e.g., -0.37 for sample 5). This might occur if an analysis background (e.g., the Compton continuum under a spectrum peak) is subtracted to obtain the net concentration value. The data analysis is both easier and more accurate when numerical values are reported as obtained rather than reporting the results as “less than” or not detected.

If one determines that residual radioactive material is definitely present, this would indicate that the survey unit was initially misclassified. Ordinarily, MARSSIM recommends a resurvey using a Class 1 or Class 2 design. In some cases, the original survey may have met the requirements for the Class 1 or 2 design. **Section 8.6.3** includes additional discussion on the misclassification of survey units.

For example, if one determines that the survey unit is a Class 2, a resurvey might be avoided if the survey unit does not exceed the maximum size recommended for such a classification. In this case, the only difference in survey design would be whether the measurements were obtained on a random grid or on a triangular grid. Provided that the initial survey’s scanning

methodology has sufficient detection capability to detect areas at the $DCGL_W$ versus the higher $DCGL_{EMC}$, the scan would be able to compensate for differences in the survey grid sample locations, and those differences alone would not affect the outcome of the statistical analysis. Therefore, if the above conditions were met, a resurvey might not be necessary.

8.4 Radionuclide Present in Background

The statistical tests discussed in this section will be used to compare each survey unit with an appropriately chosen, site-specific reference area. Each reference area should be selected on the basis of its similarity to the survey unit, as discussed in **Section 4.6.3**.

8.4.1 Wilcoxon Rank Sum Test and Quantile Test

In Scenario A, measurements from the reference area and survey unit are compared using the WRS test. In Scenario B, the Quantile test should be used in addition to the WRS test to further evaluate survey units when the WRS test fails to reject the null hypothesis. The recommended tests should be conducted for each survey unit. In addition, the EMC is performed against each measurement to ensure that the measurement does not exceed a specified investigation level (e.g., $DCGL_{EMC}$ for Class 1 survey units). If any measurement in the remediated survey unit exceeds the specified investigation level, then additional investigation is recommended, at least locally, regardless of the outcome of the WRS test.

The WRS test is most effective when residual radioactive material is uniformly present throughout a survey unit. For Scenario A, the test is designed to detect whether this residual radioactive material exceeds the $DCGL_W$. For Scenario B, it is designed to detect whether this residual radioactive material exceeds the AL.

The advantage of the nonparametric WRS test is that it does not assume that the data are normally or lognormally distributed. The WRS test also allows “less than” measurements to be present in the reference area and the survey units. The WRS test can generally be used with up to 40 percent “less than” measurements in either the reference area or the survey unit. However, the use of “less than” values in data reporting is not recommended, as discussed in **Sections 2.3.5 and 8.3**. When possible, the actual result of a measurement should be reported together with its uncertainty.

The Quantile test is a statistical test for non-uniformity in the distribution of the residual radioactive material. The Quantile test was developed to detect differences between the survey unit and the reference area that consist of a shift to higher values in only a fraction of the survey unit. The Quantile test is performed only when Scenario B is used and only if the null hypothesis is not rejected for the WRS test. Using the Quantile test in tandem with the WRS test results in higher power to identify survey units that do not meet the release criteria than either test by itself.

Using the Quantile test in tandem with the WRS test also results in higher probability of Type I errors when the true concentration is equal to the AL. The probability of making a Type I error on at least one of the two tests is approximately $\alpha = \alpha_Q + \alpha_W$, where α_Q and α_W are the values of alpha selected for the Quantile and WRS tests, respectively. For this reason, when the Quantile test is performed in tandem with the WRS test α_Q and α_W should both be set equal to $\alpha/2$ so that when the true concentration is equal to the AL, the combined probability of a Type I error of the two tests is approximately α .

In Scenario A, the hypothesis tested by the WRS test is as follows:

Null Hypothesis

H_0 : The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by more than the $DCGL_W$.

Versus

Alternative Hypothesis

H_1 : The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by less than the $DCGL_W$.

In Scenario B, the hypothesis tested by the WRS test is as follows:

Null Hypothesis

H_0 : The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by less than the AL.

Versus

Alternative Hypothesis

H_1 : The median concentration of residual radioactive material in the survey unit exceeds that in the reference area by more than the AL.

Scenario B is used when the goal is that residual radioactive material in the survey unit be indistinguishable from background activity levels in the reference area (e.g., $AL = 0$) or when the AL is below the DL.

The difference between Scenario A and Scenario B discussed in **Section 8.3.1** should be considered when selecting the values of α and β in the DQO process, as illustrated in **Example 8-8** presented in **Section 8.4.3**.

In both scenarios, the null hypothesis is assumed to be true unless the statistical test indicates that it should be rejected in favor of the alternative. One assumes that any difference between the reference area and survey unit concentration distributions is due to a shift in the survey unit concentrations to higher values (i.e., due to the presence of residual radioactive material in addition to background). Note that some or all of the survey unit measurements may be larger than some reference area measurements while still meeting the release criteria. Indeed, some survey unit measurements may exceed some reference area measurements by more than the $DCGL_W$. The result of the hypothesis test determines whether the survey unit as a whole is deemed to meet the release criteria. The EMC is used to screen individual measurements. The actual size of the elevated area should also be delineated through scanning and direct measurement, and that area compared to a $DCGL_{EMC}$ derived for the actual size of the elevated area.

This test is based on two assumptions: (1) samples from the reference area and survey unit are independent, identically distributed random samples, and (2) each measurement is independent of every other measurement, regardless of the set of samples from which it came.

8.4.2 Applying the Wilcoxon Rank Sum Test

The WRS test is applied as outlined in the following six steps and further illustrated by the examples in **Section (6)** and **Appendix A**. Separate instructions are provided for Scenarios A and B.

Scenario A

- (1) Obtain the adjusted reference area measurements, z_i , by adding the DCGL_W to each reference area measurement, x_i : $z_i = x_i + \text{DCGL}_W$. The m adjusted reference sample measurements, z_i , from the reference area and the n sample measurements, y , from the survey unit are pooled and ranked in order of increasing size from 1 to N , where $N = m + n$.
- (2) If several measurements are tied (i.e., have the same value), all are assigned the average rank of that group of tied measurements.
- (3) If there are t “less than” values, all are given the average of the ranks from 1 to t . Therefore, they are all assigned the rank $t(t + 1)/(2t) = (t + 1)/2$, which is the average of the first t integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as “less than” values.⁸
- (4) Sum the ranks of the adjusted measurements from the reference area, W_r . Note that because the sum of the first N integers is $N(N + 1)/2$, one can equivalently sum the ranks of the measurements from the survey unit, W_s , and compute $W_r = N(N + 1)/2 - W_s$.
- (5) Compare W_r with the critical value given in **Table I-6** in **Appendix I** for the appropriate values of n , m , and α . If W_r is greater than the tabulated value, reject the hypothesis that the survey unit exceeds the release criteria.

Scenario B

- (1) Obtain the adjusted survey unit measurements, z_i , by subtracting the AL from each survey unit measurement, y_i : $z_i = y_i - \text{AL}$.
- (2) The m adjusted sample measurements, z_i , from the survey unit and the n reference measurements, x_i , from the reference area are pooled and ranked in order of increasing size from 1 to N , where $N = m + n$. (Note: When using **Table I-6** in **Appendix I** for Scenario B, the roles of m and n are reversed. That is, m is the number of survey measurements in Scenario B, while m is the number of reference area measurements in Scenario A.)
- (3) If several measurements are tied (i.e., have the same value), all are assigned the average rank of that group of tied measurements.

⁸ If more than 40 percent of the data from either the reference area or survey unit are “less than,” the WRS test *cannot* be used. Such a large proportion of non-detects suggest that the DQO process needs to be revisited for this survey to determine whether the survey unit was properly classified or the appropriate measurement method was used. As stated previously, the use of “less than” values in data reporting is not recommended. Wherever possible, the actual result of a measurement, together with its uncertainty, should be reported.

- (4) If there are t “less than” values, they are all given the average of the ranks from 1 to t . Therefore, all are assigned the rank $t(t + 1)/(2t) = (t + 1)/2$, which is the average of the first t integers. If there is more than one detection limit, all observations below the largest detection limit should be treated as “less than” values.
- (5) Sum the ranks of the adjusted measurements from the survey unit, W_s . Note that because the sum of the first N integers is $N(N + 1)/2$, one can equivalently sum the ranks of the measurements from the reference area, W_r , and compute $W_s = N(N + 1)/2 - W_r$.
- (6) Compare W_s with the critical value given in **Table I-6** in **Appendix I** for the appropriate values of n , m , and α . (Because the Quantile test is used in addition to the WRS test, $\alpha/2$ should be used rather than α .) If W_s is greater than the tabulated value, reject the null hypothesis that the survey unit does not exceed the release criteria.

Example 8-7 illustrates the WRS test in practice for a Class 2 interior drywall survey unit.

Example 8-7: WRS Test Example: Class 2 Interior Drywall Survey Unit

Example 8-4 contains the relevant background information. In this example, the gas-flow proportional counter measures gross beta activity (see **Appendix H**), and the measurements are not radionuclide specific. The WRS test is appropriate for the Class 2 interior drywall survey unit because background contributes to gross beta activity even though the radionuclide of interest does not appear in background. Scenario A is selected because the $DCGL_W$ is higher than the DL. As a result, the Quantile test will not be needed for this example.

Table 8-6 shows that the DQOs for this survey unit include $\alpha = 0.025$ and $\beta = 0.05$. The $DCGL_W$ is 8,300 Bq/m² (5,000 dpm/100 cm²), and, based on site-specific measurements, the LBGR was selected to be 5,000 Bq/m² (3,000 dpm/100 cm²). The estimated standard deviation, σ , of the measurements is about 830 Bq/m² (500 dpm/100 cm²). The relative shift was calculated to be 4.0, as shown below:

$$\Delta/\sigma = \frac{DCGL_W - LBGR}{\sigma} = \frac{8,300 \text{ Bq/m}^2 - 5,000 \text{ Bq/m}^2}{830 \text{ Bq/m}^2} = 4.0$$

In **Table 5-2**, one finds that the number of measurements calculated as required for the WRS test is 12 in each survey unit and 12 in each reference area ($\alpha = 0.025$, $\beta = 0.05$, and $\frac{\Delta}{\sigma} = 4$). (**Table I-3** in **Appendix I** also lists the number of measurements needed for the WRS test.)

Table 8-10 lists the data obtained from the gas-flow proportional counter in units of counts per minute (cpm). A reading of 160 cpm with this instrument corresponds to the $DCGL_W$ of 8,300 Bq/m² (5,000 dpm/100 cm²). Column A lists the measurement results as they were obtained. The sample mean and sample standard deviation of the reference area measurements are 44 and 4.4 cpm, respectively. The sample mean and sample standard deviation of the survey unit measurements are 98 and 5.3 cpm, respectively. In column B, the code “R” denotes a reference area measurement, and “S” denotes a survey unit measurement. Column C contains the adjusted data. The adjusted data are obtained by adding the $DCGL_W$ to the reference area measurements (refer to Step 1 at the beginning of this section). The ranks of the adjusted data appear in column D. They range from 1 to 22,

because there is a total of 11+11 measurements (refer to Step 2 at the beginning of this section).

Note that some adjusted measurements in **Table 8-10** have the same value, of 104 cpm and 205 cpm. Each tied measurement is always assigned the average of the ranks. Therefore, both measurements at 104 are assigned rank $\frac{9+10}{2} = 9.5$ (refer to Step 3 at the beginning of this section). Also note that the sum of all of the ranks is still $\frac{22(22+1)}{2} = 253$. Checking this value with the formula in Step 5 at the beginning of this section is recommended to guard against errors in the rankings.

Column E of **Table 8-10** contains only the ranks belonging to the reference area measurements. The total is 187. This is compared with the entry for the critical value of 156 in **Table I-6** in **Appendix I** for $\alpha = 0.025$, with $m = 11$ and $n = 11$. Because the sum of the reference area ranks is greater than the critical value, the null hypothesis (i.e., that the mean survey unit concentration exceeds the $DCGL_W$) is rejected.

If some of the values of the survey unit had been higher and had ranked above some of the reference unit samples, then the sum of the reference values would have been lower (because the survey values are not counted and would have displaced downward reference values). This then would move the sum closer to the critical value. If enough survey sample ranks had displaced reference rankings, then the sum would have been below the critical value and the null hypothesis would be accepted.

Table 8-10 WRS Test for Class 2 Interior Drywall Survey Unit in Example 8-7

	A	B	C	D	E
Sample Number	Data (cpm)	Survey Unit (S) or Reference Area (R)	Adjusted Data (cpm)	Ranks	Reference Area Ranks
1	49	R	209	22	22
2	35	R	195	12	12
3	45	R	205	17.5	17.5
4	45	R	205	17.5	17.5
5	41	R	201	14	14
6	44	R	204	16	16
7	48	R	208	21	21
8	37	R	197	13	13
9	46	R	206	19	19
10	42	R	202	15	15
11	47	R	207	20	20
12	104	S	104	9.5	0
13	94	S	94	4	0
14	98	S	98	6	0

	A	B	C	D	E
Sample Number	Data (cpm)	Survey Unit (S) or Reference Area (R)	Adjusted Data (cpm)	Ranks	Reference Area Ranks
15	99	S	99	7	0
16	90	S	90	1	0
17	104	S	104	9.5	0
18	95	S	95	5	0
19	105	S	105	11	0
20	93	S	93	3	0
21	101	S	101	8	0
22	92	S	92	2	0
			Sum	253	187

8.4.3 Applying the Quantile Test—Used Only in Scenario B

The Quantile test was developed to detect differences between the survey unit and the reference area that consist of a shift to higher values in only a fraction of the survey units. It should be noted that, in general, this shift is not necessarily the same as the shift used for the WRS test. The Quantile test is better at detecting situations in which only a portion of the survey unit contains excess residual radioactive material. The WRS test is better at detecting situations in which any excess residual radioactive material is uniform across the entire survey unit. The Quantile test is used only in Scenario B. The Quantile test is performed after the WRS test, if the null hypothesis for the WRS test has not been rejected. Using the Quantile test in tandem with the WRS test in Scenario B results in higher power to detect survey units that do not meet the release criteria than either test has by itself.

The Quantile test is outlined in the following six steps:

- (1) Calculate α_Q ($\alpha_Q = \alpha/2$).
- (2) Obtain the adjusted survey unit measurements, z_i , by subtracting the AL from each survey unit measurement, y_i : $z_i = y_i - AL$. If the $DCGL_W$ is equal to zero, then this step is unnecessary.
- (3) The n adjusted survey unit measurements, z_i , and the m reference area measurements, x_i , are pooled and ranked in order of increasing size from 1 to N , where $N = m + n$.
- (4) If several measurements are tied (i.e., have the same value), all are assigned the mean rank of that group of tied measurements.
- (5) Look up the values for r and k in **Tables I-9 through I-12 of Appendix I** to be based on the number of measurements in the survey unit (n), the number of measurements in the

reference area (m), and α_Q . The decision described in the next step is made using the values for r and k .⁹

- (6) If k or more of the r largest measurements in the combined ranked dataset are from the survey unit, the null hypothesis is rejected.

Example 8-8 through **Example 8-10** illustrate how certain tests can be used under a variety of testing scenarios.

Example 8-8: Class 2 Interior Survey Example Under Scenario B Using WRS and Quantile Tests

Example 8-4 contains the relevant background information. The data for an example WRS test using Scenario B are shown in column A of **Table 8-11**. In column B, the label “R” denotes a reference area measurement, and the label “S” denotes a survey unit measurement. Column C contains the adjusted data obtained by subtracting the LBGR of 142 cpm from just the survey unit measurements (the reference area measurements are not adjusted). The ranks of the adjusted data in column C are listed in column D. The ranks range from 1 to 24, because there are $12 + 12 = 24$ measurements. The sum of all the ranks is $N(N + 1)/2 = (24 \times 25)/2 = 300$. Column E contains only the ranks belonging to the adjusted survey unit measurements.

The sum of the ranks of the adjusted survey unit data is 194.5. From **Table I-6** in **Appendix I**, for $\alpha = 0.025$ and $n = m = 12$, the critical value is 184. Because the sum of the adjusted survey unit ranks, 194.5, is greater than the critical value, 184, the null hypothesis that the survey unit concentrations do not exceed the LBGR is rejected (i.e., the site is determined to be dirty). In Scenario B, the true concentration of radioactive material in the survey unit is judged to be in excess of 142 cpm above the background.

For the Quantile test, **Table I-9** in **Appendix I** provides the critical value, k , of the largest r measurements for different values of n , the number of measurements from the survey unit, and m , the number of measurements from the reference area. The same rankings in column D of **Table 8-11** for the WRS test can be used for the Quantile test. If k or more of the r largest measurements in the combined ranked dataset are from the survey unit, the null hypothesis is rejected. For a survey unit that has failed the WRS test, as was the case in this example, it is not usually necessary to also perform the Quantile test. However, the Quantile test is presented for illustrative purposes.

In **Table 8-11**, columns F and G show the sorted ranks of the adjusted data and the location associated with each rank (i.e., “R” for reference area and “S” for survey unit). In **Table I-10** of **Appendix I**, the closest entry to $n = m = 12$ is for $n = m = 10$. The values of $r = 7$, $k = 6$, and $\alpha = 0.029$ are found. Thus, the null hypothesis is rejected if six of the seven largest adjusted measurements come from the survey unit. **Table 8-11** shows that only five of the

⁹ While MARSSIM provides an approach (refer to **Appendix I, Tables I-9** through **I-12**) to determine r and k values for a specified α , n , and m , alternatively, the percentile of interest can be specified during the DQO process and r can be determined based on n and m . For example, a decision can be made during the DQO process whether the 80th or 90th percentile is of interest. Then, the value of r , and subsequently k , may be calculated based on the desired α . This alternative approach is implemented in VSP and provides greater flexibility beyond the approach laid out in MARSSIM and the tables in **Appendix I (Tables I-9** through **I-12)**.

seven largest adjusted measurements come from the survey unit, so the null hypothesis is not rejected based on the Quantile test. The values of n and m that were used are close to, but not equal to, the actual values, so the α value will be different from that listed in the table. It is prudent to check a few other entries in **Table I-10 of Appendix I** that are near the actual sample size. Additionally, Chapter 7 in NUREG-1505 provides equations to calculate exact and approximate values of the alpha error for the Quantile test as a function of n , m , k , and r .

Table 8-11 WRS and Quantile Test Under Scenario B for Class 2 Interior Drywall Survey Unit in Example 8-8

Sample Number	A Data (cpm)	B Survey Unit (S) or Reference Area (R)	C Adjusted Data (cpm)	D Ranks	E Survey Unit Ranks	F Sorted Ranks	G Location Associated with Sorted Ranks ^a
1	47	R	47	18	—	1	R
2	28	R	28	1	—	2	R
3	36	R	36	6	—	3	R
4	37	R	37	7	—	4.5	R
5	39	R	39	9.5	—	4.5	S
6	45	R	45	13	—	6	R
7	43	R	43	11	—	7	R
8	34	R	34	3	—	8	S
9	32	R	32	2	—	9.5	R
10	35	R	35	4.5	—	9.5	R
11	39	R	39	9.5	—	11	R
12	51	R	51	21	—	13	R
13	209	S	67	24	24	13	S
14	197	S	55	23	23	13	S
15	188	S	46	16	16	16	S
16	191	S	49	19	19	16	S
17	193	S	51	21	21	16	S
18	187	S	45	13	13	18	R
19	188	S	46	16	16	19	S
20	180	S	38	8	8	21	R
21	193	S	51	21	21	21	S
22	188	S	46	16	16	21	S
23	187	S	45	13	13	23	S
24	177	S	35	4.5	4.5	24	S
Sum				300	194.5	—	—

^a Measurements from the reference area and the survey unit are denoted by R and S, respectively. The adjusted data and data columns are identical when $AL = 0$.

8.4.4 Applying the Kruskal-Wallis Test (Optional)—Used Only in Scenario B

For sites where variations in mean background between potential reference areas may make performing a traditional MARSSIM survey difficult, the Kruskal-Wallis test or other similar test may be useful. NUREG-1505 provides guidance on optional alternative methods used to demonstrate indistinguishability from background when Scenario B is deemed appropriate to use (e.g., when the DCGL is close to background considering variability), and variations in mean background among the potential reference areas become comparable in magnitude to the width of the gray region. Because any difference in radioactivity between the reference area and survey unit is assumed to be due to residual radioactivity, and it is not possible to determine whether the difference is actually due to differences in background concentrations between the two areas, tests are available to determine the significance of background variability and how this variability can be considered in the statistical tests used to help identify whether the site is clean.

The Kruskal-Wallis test may be used to determine whether or not there is a statistically significant difference among the medians of three or more independent survey groups. The parametric F-test assumes a normal distribution, whereas the nonparametric Kruskal-Wallis test does not make an assumption regarding the underlying distribution; thus, the Kruskal-Wallis test can be used to determine whether variability between the means of potential reference areas is statistically significant. The Kruskal-Wallis test is less sensitive to outliers compared to the F-test because it does not assume normality (Daniel 1990). To perform the Kruskal-Wallis test, all of the measurements from the reference areas are pooled and ranked. If the distribution of measured concentrations in each reference area is the same, then the average rank for each reference area should also be about the same. The Kruskal-Wallis statistic is a weighted sum of the squares of these differences over all of the reference areas. NUREG-1505, Equation 13-3 (reproduced below as **Equation 8-3**), is used to calculate a Kruskal-Wallis statistic:

$$K = \frac{12}{N(N+1)} \left(\sum_{i=1}^k \frac{R_i^2}{n_i} \right) - 3(N+1) \quad \text{Equation 8-3}$$

where:

- N = total number of measurements in all the reference areas $i = 1$ to k
- n_i = number of measurements in a given reference area
- R_i = sum of the ranks of the measurements in a given reference area

Although the Kruskal-Wallis test (or F-test) is used to determine whether it is appropriate to consider reference area variability in applying Scenario B, NUREG-1505 also indicates that background variability could be given the benefit of the doubt, in which case the Kruskal-Wallis test (or F-test) need not be conducted. If it is determined that the variability between reference means should be considered, NUREG-1505, Equation 13-13, can be used to calculate the variance, $\hat{\omega}^2$, which can be used to determine the LBGR, or AL for Scenario B. As part of the DQO process, an agreed-upon value for the LBGR as a multiple of $\hat{\omega}$ can be selected.

NUREG-1505 provides an example in which the mean square between reference areas, s_b^2 , and mean square within reference areas, s_w^2 , calculated manually using Equation 13-13 or output from analysis of variance (ANOVA) testing can be used to compute $\hat{\omega}^2 = (s_b^2 - s_w^2)/n_0$, where n_0 is equal to the number of measurements per reference area when the number of

measurements in each reference area is the same (or refer to Equation 13-13 when the number of measurements in the reference areas is not the same).

Although a full treatment of methods for conducting the Kruskal-Wallis test is outside the scope of MARSSIM, NUREG-1505 contains full details.

Example 8-9: Using the NUREG-1505 Kruskal-Wallis Test to Determine Whether Background Variability Is Significant and Determine the AL for Scenario B

Suppose there are four reference areas under consideration, and 10 measurements are made in each. The data and ranks shown in **Table 8-12** are used to determine ranks of reference area measurements applied to perform the Kruskal-Wallis test using NUREG-1505, Equation 13-13 (reproduced as **Equation 8-3**).

The resulting test statistic of 14.0 is compared to the critical values provided in NUREG-1505, Table 13.1. In the example, the Kruskal-Wallis statistic of 14.0 is above the critical threshold for $4 - 1 = 3$ reference areas that range from 11.3 for an α value of 0.01 to 4.6 for an α value of 0.2. Therefore, the null hypothesis that the variability in the reference area means is zero can be rejected with high confidence (i.e., the null hypothesis is rejected even for very small α or false positive error rates).

Using the ANOVA output in **Table 8-13**—

$$\hat{\omega}^2 = \frac{s_b^2 - s_w^2}{n_0} = \frac{6.52 - 0.97}{10} = 0.55$$

As part of the DQO process, an agreed-upon value for the LBGR as a multiple of $\hat{\omega}$ can be selected. Note that the difference in means between reference areas 2 and 4 in NUREG-1505, Table 13.2, is 1.82, which is similar to the LBGR calculated based on $3\hat{\omega}$ ($\sqrt{0.55} \times 3 = 0.74 \times 3 = 2.22$), and so the value of $3\hat{\omega}$ will be used in this example.

NUREG-1505, Table 13.5, also provides information on the power of the F-test, which is used to approximate the power of the Kruskal-Wallis test, to help determine the number of reference areas and the number of measurements that should be taken in each reference area to perform the Kruskal-Wallis test and to estimate $\hat{\omega}$. In all cases, the regulatory authority should be consulted to determine the acceptability of using Scenario B, using the Kruskal-Wallis test, and determining appropriate values for the test parameters.

Table 8-12 Calculation of $\hat{\omega}^2$ for Example 8-9

Sample Number	Measurements				Measurement Ranks				Measurements Squared			
	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4	Area 1	Area 2	Area 3	Area 4
1	0.27	1.04	2.45	3.77	6	13	27	39	0.07	1.08	6.00	14.21
2	1.87	0.39	0.34	2.63	20	9	8	31	3.50	0.15	0.12	6.92
3	0.97	2.07	3.06	4.05	10	23	37	40	0.94	4.28	9.36	16.40
4	1.01	0.57	2.83	1.72	11	2	35	19	1.02	0.32	8.01	2.96
5	2.08	1.97	1.09	1.50	24	21	14	17	4.33	3.88	1.19	2.25
6	1.62	0.22	0.26	2.47	18	3	5	29	2.62	0.05	0.07	6.10
7	0.30	1.39	2.80	1.42	7	15	34	16	0.09	1.93	7.84	2.02
8	1.98	0.05	2.77	2.47	22	4	33	28	3.92	0.00	7.67	6.10
9	2.18	0.75	2.42	2.76	25	1	26	32	4.75	0.56	5.86	7.62
10	1.02	2.50	2.86	3.35	12	30	36	38	1.04	6.25	8.18	11.22
Sum	13.30	7.87	20.88	26.14	155	121	255	289	22.28	18.50	54.30	75.80
Average	1.33	0.79	2.09	2.61	—	—	—	—	—	—	—	—
Average Squared	1.77	0.62	4.36	6.83	—	—	—	—	—	—	—	—

Table 8-13 ANOVA Output for Example 8-9 Data

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Statistic
Between Groups	19.56	3	6.52	6.69
Within Groups	35.08	36	0.97	—
Total	54.65	39	—	—

Example 8-10: Class 1 Interior Concrete Survey Unit

As in the previous example, the gas-flow proportional counter measures gross beta activity (see **Appendix H**) and the measurements are not radionuclide specific. The nonparametric statistical test used when the radionuclide is present in background is appropriate for the Class 1 interior concrete survey unit because gross beta activity contributes to the overall background, even though the specific radionuclide of interest does not appear in background.

Appendix A provides a detailed description of the calculations for the Class 1 interior concrete survey unit.

8.4.5 Multiple Radionuclides

Section 4.4 discusses use of the unity rule when there is more than one radionuclide to be considered. **Example 8-11** and **Example 8-12** give example applications of the use of the unity rule.

Example 8-11: Application of the WRS Test to Multiple Radionuclides

Consider a site with both ^{60}Co and cesium-137 (^{137}Cs) contamination. ^{137}Cs appears in background from fallout at a typical concentration of about 37 Bq/kg (1 pCi/g). Assume that the DCGL_W for ^{60}Co is 74 Bq/kg (2 pCi/g) and for ^{137}Cs is 52 Bq/kg (1.4 pCi/g). In disturbed areas, the background concentration of ^{137}Cs can vary considerably. An estimated spatial standard deviation of 19 Bq/kg (0.5 pCi/g) for ^{137}Cs will be assumed. During remediation, it was found that the concentrations of the two radionuclides were not well correlated in the survey unit. ^{60}Co concentrations were more variable than the ^{137}Cs concentrations, and 26 Bq/kg (0.7 pCi/g) is estimated for its standard deviation. Measurement errors for both ^{60}Co and ^{137}Cs using gamma spectrometry will be small compared to this. For the comparison to the release criteria, the weighted sum of the concentrations of these radionuclides is computed from—

$$T = \frac{^{60}\text{Co concentration}}{^{60}\text{Co DCGL}} + \frac{^{137}\text{Cs concentration}}{^{137}\text{Cs DCGL}}$$

$$= \frac{^{60}\text{Co concentration}}{74 \text{ Bq/kg}} + \frac{^{137}\text{Cs concentration}}{52 \text{ Bq/kg}}$$

The variance of the weighted sum, assuming that the ^{60}Co and ^{137}Cs concentrations are spatially unrelated, is—

$$\sigma^2(T) = \left[\frac{\sigma(^{60}\text{Co concentration})}{^{60}\text{Co DCGL}} \right]^2 + \left[\frac{\sigma(^{137}\text{Cs concentration})}{^{137}\text{Cs DCGL}} \right]^2$$

$$= \left[\frac{26 \text{ Bq/kg}}{74 \text{ Bq/kg}} \right]^2 + \left[\frac{19 \text{ Bq/kg}}{52 \text{ Bq/kg}} \right]^2 = 0.26$$

Thus, $\sigma = 0.5$. The DCGL_W for the weighted sum is 1. The null hypothesis for Scenario A is that the survey unit exceeds the release criteria. During the DQO process, the LBGR was set at 0.5 as a conservative estimate of the mean weighted sum, so that $\Delta = \text{DCGL}_W - \text{LBGR} = 1.0 - 0.5 = 0.5$, and $\Delta/\sigma = 0.5/0.5 = 1.0$. The acceptable error rates chosen were $\alpha = \beta = 0.05$. To achieve this, 32 samples each are required in the survey unit and the reference area.

The weighted sums are computed for each measurement location in both the reference area and the survey unit. The WRS test is then performed on the weighted sum. **Table 8-14** shows the calculations for this example. The DCGL_W for the unity rule (i.e., 1.0) is added to the weighted sum for each location in the reference area. The ranks of the combined survey unit and adjusted reference area weighted sums are then computed. The sum of the ranks of the adjusted reference area weighted sums is then compared to the critical value for $n = m = 32$, $\alpha = 0.05$, which is 1,162 (refer to **Equations I-2 and I-3** in **Appendix I**). In **Table 8-14**, the sum of the ranks of the adjusted reference area weighted sums is 1,281. This exceeds the critical value, so the null hypothesis is rejected. For Scenario A, rejecting the null hypothesis

means the survey unit meets the release criteria. As a final check, the difference between the mean of the weighted sums in the survey unit and the reference area is calculated to ensure that the difference between the means is less than the DCGL. The calculated difference between the means of the weighted sums is $1.86 - 1.16 = 0.7$. Thus, the estimated dose or risk due to residual radioactive material in the survey unit is approximately equal to 70 percent of the release criterion. An EMC may still need to be performed before deciding that the survey unit has met the release criteria. The cognizant regulatory authority should be consulted on the need for elevated measurement criteria.

Table 8-14 Example 8-11 WRS Test for Two Radionuclides

Sample Number	Reference Area		Survey Unit		Weighted Sum			Ranks	
	¹³⁷ Cs	⁶⁰ Co	¹³⁷ Cs	⁶⁰ Co	Ref	Survey	Adj Ref	Survey	Adj Ref
1	2.00	0	1.12	0.06	1.43	0.83	2.43	1	56
2	1.23	0	1.66	1.99	0.88	2.18	1.88	43	21
3	0.99	0	3.02	0.56	0.71	2.44	1.71	57	14
4	1.98	0	2.47	0.26	1.41	1.89	2.41	23	55
5	1.78	0	2.08	0.21	1.27	1.59	2.27	9	50
6	1.93	0	2.96	0.00	1.38	2.11	2.38	37	54
7	1.73	0	2.05	0.20	1.23	1.56	2.23	7	46
8	1.83	0	2.41	0.00	1.30	1.72	2.30	16	52
9	1.27	0	1.74	0.00	0.91	1.24	1.91	2	24
10	0.74	0	2.65	0.16	0.53	1.97	1.53	27	6
11	1.17	0	1.92	0.63	0.83	1.68	1.83	13	18
12	1.51	0	1.91	0.69	1.08	1.71	2.08	15	32
13	2.25	0	3.06	0.13	1.61	2.25	2.61	47	63
14	1.36	0	2.18	0.98	0.97	2.05	1.97	30	28
15	2.05	0	2.08	1.26	1.46	2.12	2.46	39	58
16	1.61	0	2.30	1.16	1.15	2.22	2.15	45	41
17	1.29	0	2.20	0.00	0.92	1.57	1.92	8	25
18	1.55	0	3.11	0.50	1.11	2.47	2.11	59	35
19	1.82	0	2.31	0.00	1.30	1.65	2.30	11	51
20	1.17	0	2.82	0.41	0.84	2.22	1.84	44	19
21	1.76	0	1.81	1.18	1.26	1.88	2.26	22	48
22	2.21	0	2.71	0.17	1.58	2.02	2.58	29	62
23	2.35	0	1.89	0.00	1.68	1.35	2.68	3	64
24	1.51	0	2.12	0.34	1.08	1.68	2.08	12	33
25	0.66	0	2.59	0.14	0.47	1.92	1.47	26	5

Sample Number	Reference Area		Survey Unit		Weighted Sum			Ranks	
	¹³⁷ Cs	⁶⁰ Co	¹³⁷ Cs	⁶⁰ Co	Ref	Survey	Adj Ref	Survey	Adj Ref
26	1.56	0	1.75	0.71	1.12	1.60	2.12	10	38
27	1.93	0	2.35	0.85	1.38	2.10	2.38	34	53
28	2.15	0	2.28	0.87	1.54	2.06	2.54	31	61
29	2.07	0	2.56	0.56	1.48	2.11	2.48	36	60
30	1.77	0	2.50	0.00	1.27	1.78	2.27	17	49
31	1.19	0	1.79	0.30	0.85	1.43	1.85	4	20
32	1.57	0	2.55	0.70	1.12	2.17	2.12	42	40
Avg	1.62	0	2.28	0.47	1.16	1.86	2.16	sum =	sum =
Std Dev	0.43	0	0.46	0.48	0.31	0.36	0.31	799	1,281

Example 8-12: Use of ProUCL for the WRS Test for Multiple Radionuclides

As **Table 8-14** does for **Example 8-11**, **Table 8-15** provides sample results for a survey unit with residual radioactive material that includes ⁶⁰Co and ¹³⁷Cs. Because ¹³⁷Cs from fallout is found in the background, samples were also collected and analyzed from a reference area. The DCGL_{WS} for ¹³⁷Cs and ⁶⁰Co are 1.4 and 2.0 Bq/kg, respectively. The unity rule is used to determine whether the survey unit meets the release criteria. Scenario A was selected. To perform the WRS test, ProUCL, Version 5.0, was used. ProUCL is a freeware statistical software program provided by the EPA.

The data can be entered by hand or copied and pasted from another software program. Descriptions can be provided for the column headers by right-clicking the column header and selecting "Header Name." For this example, the columns were named "Reference" and "Survey Unit." **Figure 8-4** shows the initial program inputs of the weighted sums of the reference area and survey unit with their column headings.

To perform the WRS test, the two-sample Wilcoxon-Mann-Whitney test was selected. The Wilcoxon-Mann-Whitney test is a nonparametric test of the same hypothesis as the WRS test. The two tests use a different test statistic and critical value, but both tests will provide the same conclusion. The test can be selected by first choosing "Two Sample" from the "Hypothesis Testing" menu, and then selecting "Wilcoxon-Mann-Whitney."

Variables are selected by clicking on the variable name in the list of variables, and then clicking the corresponding ">>" button. The Reference Area results are selected as the "Background/Ambient" variable, and the Survey Unit results are selected as the "Area of Concern/Site" variable, as shown in **Figure 8-5**.

Clicking the "Options" in the dialog window shown in **Figure 8-5** generates another dialog window (**Figure 8-6**). This window allows the user to specify the "Confidence Coefficient." The confidence coefficient is equal to $(1 - \alpha)$. For this example, the "Confidence Coefficient" of 95 percent is selected, corresponding to $\alpha = 0.05$. The dialog window also allows the user to specify the form of the hypothesis. For this example, Form 2 is selected, and the value of 1

is entered for the “Substantial Difference.” When using Form 2, the unadjusted reference area results should be used instead of the adjusted reference area results.

Clicking the “OK” button shown in **Figure 8-6** saves the changes and closes the dialog window. Clicking the “OK” button shown in **Figure 8-5** closes that dialog window and generates the output sheet shown in **Figure 8-7**. As shown near the bottom of **Figure 8-7**, the null hypothesis is rejected, and the survey unit is demonstrated to pass the statistical test. The EMC would still need to be performed before deciding that the survey unit has met the release criteria.

Table 8-15 Example 8-12 WRS Test for Two Radionuclides

Sample Number	Reference Area Results (Bq/kg)		Survey Unit (Bq/kg)		Reference Area (x_i)	Survey Unit (y_i)	Adjusted Reference Area (z_i)
	¹³⁷ Cs	⁶⁰ Co	¹³⁷ Cs	⁶⁰ Co			
1	2.00	0.00	1.12	0.06	1.429	0.830	2.429
2	1.23	0.00	1.66	1.99	0.879	2.181	1.879
3	0.99	0.00	3.02	0.56	0.707	2.437	1.707
4	1.98	0.00	2.47	0.26	1.414	1.894	2.414
5	1.78	0.00	2.08	0.21	1.271	1.591	2.271
6	1.93	0.00	2.96	0.00	1.379	2.114	2.379
7	1.73	0.00	2.05	0.20	1.236	1.564	2.236
8	1.83	0.00	2.41	0.00	1.307	1.721	2.307
9	1.27	0.00	1.74	0.00	0.907	1.243	1.907
10	0.74	0.00	2.65	0.16	0.529	1.973	1.529
11	1.17	0.00	1.92	0.63	0.836	1.686	1.836
12	1.51	0.00	1.91	0.69	1.079	1.709	2.079
13	2.25	0.00	3.06	0.13	1.607	2.251	2.607
14	1.36	0.00	2.18	0.98	0.971	2.047	1.971
15	2.05	0.00	2.08	1.26	1.464	2.116	2.464
16	1.61	0.00	2.30	1.16	1.150	2.223	2.150
17	1.29	0.00	2.20	0.00	0.921	1.571	1.921
18	1.55	0.00	3.11	0.50	1.107	2.471	2.107
19	1.82	0.00	2.31	0.00	1.300	1.650	2.300
20	1.17	0.00	2.82	0.41	0.836	2.219	1.836
21	1.76	0.00	1.81	1.18	1.257	1.883	2.257
22	2.21	0.00	2.71	0.17	1.579	2.021	2.579
23	2.35	0.00	1.89	0.00	1.679	1.350	2.679
24	1.51	0.00	2.12	0.34	1.079	1.684	2.079
25	0.66	0.00	2.59	0.14	0.471	1.920	1.471

Sample Number	Reference Area Results (Bq/kg)		Survey Unit (Bq/kg)		Reference Area (x_i)	Survey Unit (y_i)	Adjusted Reference Area (z_i)
	^{137}Cs	^{60}Co	^{137}Cs	^{60}Co			
26	1.56	0.00	1.75	0.71	1.114	1.605	2.114
27	1.93	0.00	2.35	0.85	1.379	2.104	2.379
28	2.15	0.00	2.28	0.87	1.536	2.064	2.536
29	2.07	0.00	2.56	0.56	1.479	2.109	2.479
30	1.77	0.00	2.50	0.00	1.264	1.786	2.264
31	1.19	0.00	1.79	0.30	0.850	1.429	1.850
32	1.57	0.00	2.55	0.70	1.121	2.171	2.121

ProUCL 4.1 - [C:\Users\MARSSIM User\Documents\Example.wst]

File Edit Configure Number of Samples Summary Statistics ROS Est. NDs Graphs Outlier Tests Goodness-of-Fit Hypothesis Testing ANOVA Trend Tests

Background UCL Window Help

Navigation Panel

Name

Example.wst

	0	1	2	3	4	5	6	7	8	9	10	11
	Reference	Survey Unit										
1	1.429	0.83										
2	0.879	2.181										
3	0.707	2.437										
4	1.414	1.894										
5	1.271	1.591										
6	1.379	2.114										
7	1.236	1.564										
8	1.307	1.721										
9	0.907	1.243										
10	0.529	1.973										
11	0.836	1.686										
12	1.079	1.709										
13	1.607	2.251										
14	0.971	2.047										
15	1.464	2.116										
16	1.15	2.223										
17	0.921	1.571										
18	1.107	2.471										
19	1.3	1.65										
20	0.836	2.219										
21	1.257	1.883										

Log Panel

LOG: 5:17:54 PM >[Information] worksheet.wst created!

LOG: 5:22:26 PM >[Information] C:\Users\MARSSIM User\Documents\Example.wst successfully saved!

Loading internal files ...

Figure 8-4 ProUCL Worksheet for Example 8-12

Select Variables

Name	ID	Count
Reference	0	32
Survey Unit	1	32

☒ Without Group Variable

>> Background / Ambient

>> Area of Concern / Site

☐ With Group Variable

>> Variable

Group Var

Background / Ambient

Area of Concern / Site

Options

OK Cancel

Figure 8-5 ProUCL Select Variables Window for Hypothesis Testing for Example 8-12

Site vs Background Comparison

Substantial Difference, S
(Used with Test Form 2)

Confidence Coefficient

☐ 99.9% ☐ 97.5%

☐ 99.5% ☒ 95%

☐ 99% ☐ 90%

Select Null Hypothesis Form

☐ AOC <= Background (Form 1)

☐ AOC >= Background (Form 2)

☒ AOC >= Background + S (Form 2)

☐ AOC = Background (2 Sided)

OK Cancel

Figure 8-6 ProUCL Hypothesis Testing Options Window for Example 8-12

Wilcoxon-Mann-Whitney Site vs Background Comparison Test for Full Data Sets without NDs						
User Selected Options						
From File	C:\Users\MARSSIM User\Documents\Example.wst					
Full Precision	OFF					
Confidence Coefficient	95%					
Substantial Difference	1					
Selected Null Hypothesis	Site or AOC Mean/Median >= Background Mean/Median Plus Substantial Difference, S (Form 2)					
Alternative Hypothesis	Site or AOC Mean/Median Less Than Background Mean/Median Plus Substantial Difference, S					
Area of Concern Data: Survey Unit						
Background Data: Reference						
Raw Statistics						
	Site	Background				
Number of Valid Observations	32	32				
Number of Distinct Observations	32	29				
Minimum	0.83	0.471				
Maximum	2.471	1.679				
Mean	1.863	1.161				
Median	1.907	1.193				
SD	0.361	0.308				
SE of Mean	0.0638	0.0544				
Wilcoxon-Mann-Whitney (WMW) Test						
H0: Mean/Median of Site or AOC >= Mean/Median of Background + 1						
Site Rank Sum W-Stat	799.5					
WMW Test U-Stat	-3.223					
WMW Critical Value (0.050)	-1.645					
P-Value	0.0006354					
Conclusion with Alpha = 0.05						
Reject H0, Conclude Site < Background + 1.00						
P-Value < alpha (0.05)						

Figure 8-7 ProUCL Output for Example 8-12

8.5 Site-Specific Scanning Surveys

The use of the UCL can apply to both Scenario A and Scenario B for site-specific scanning surveys where individual results are recorded. When release decisions are made about the estimated mean of a sampled population, the assessment of the survey results is accomplished by comparing a UCL for the mean to the DCGL_W or DL for Scenarios A and B, respectively.

8.5.1 Site-Specific Scanning Survey Where Radionuclide Is Not Present in Background

Where individual scan-only survey results are recorded, such as for site-specific scanning surveys, a nonparametric confidence limit can be used to evaluate the results of the release survey. Similarly, a confidence limit can be used to evaluate a series of direct measurements with overlapping fields of view. A one-tailed version of Chebyshev's inequality, or a software tool such as EPA's ProUCL, can be used to evaluate the probability of exceeding the UBGR (i.e., using a UCL). The use of a UCL applies to both Scenario A (where the UBGR equals the DCGL_W) and Scenario B (where the UBGR equals the DL).

Chebyshev's inequality calculates the probability that the absolute value of the difference between the true but unknown mean of the population and a random number from the dataset is

at least a specified value. That is, given a specified positive number (n), a mean (μ), and a random number from the dataset (r), then the probability that $[\mu - r]$ is greater than or equal to n is equal to α . In addition, a one-tailed version of the inequality can be used to calculate a UCL for a dataset that is independent of the data distribution (i.e., there is no requirement to verify the data are from a normal, lognormal, or any other specified kind of distribution) by letting the inequality equal the UCL.

The UCL can be calculated using **Equation 8-4**:

$$\text{UCL} = \bar{x} + \sqrt{\frac{s^2}{n\alpha} - \frac{s^2}{n}} \quad \text{Equation 8-4}$$

where:

- $\bar{x}$ = arithmetic mean of the data for the survey unit
- s = sample standard deviation of the data for the survey unit
- n = number of measurements in the survey unit
- α = Type I error rate used to design the survey

The comparison to the UCL is performed in the following steps:

- (1) Calculate the mean ($\bar{x}$) and standard deviation (s) of the number of results (n) in the dataset.
- (2) For Scenario A, retrieve the Type I error rate (α) used to design the survey. For Scenario B, substitute the Type II error rate (β) used to design the survey for α in **Equation 8-4**.
- (3) Using Chebyshev's inequality, calculate the maximum UCL using **Equation 8-4**.

If the maximum UCL is less than the UBGR, the survey demonstrates compliance with the disposition criterion (i.e., reject the null hypothesis for Scenario A or fail to reject the null hypothesis for Scenario B).

Chebyshev's inequality must be used with caution when there are very few points in the dataset. This is because the population mean and standard deviation in the Chebyshev formula are being estimated by the sample mean and sample standard deviation. In a small dataset from a highly skewed distribution, the sample mean and sample standard deviation may be underestimated if the sample dataset does not capture the high concentration but low probability portion of the distribution. However, it is unlikely that there will be only a few data points in a site-specific scanning survey. With more than 30 points, it may be less conservative to use the Z-test, or Chen's skewed t -test as mentioned in **Section 8.2.3**.

Example 8-13: The survey unit was scanned as part of a site-specific scanning survey. There were 1,000 measurements in the survey unit.

The arithmetic sample mean of the data for the survey unit is 1.50. The sample standard deviation of the data for the survey unit is 0.30. For $\alpha = 0.05$, the UCL can be calculated as follows:

$$\begin{aligned} \text{UCL} &= \bar{x} + \sqrt{\frac{s^2}{n\alpha} - \frac{s^2}{n}} \\ &= 1.50 + \sqrt{\frac{(0.30)^2}{0.05 \times 1,000} + \frac{(0.30)^2}{1,000}} \\ &= 1.54 \end{aligned}$$

8.5.2 Site-Specific Scanning Survey Where Radionuclide Is Present in Background

For site-specific scanning surveys where the radionuclides are present in background, the upper bound of the confidence limit of the difference in means between the survey unit and the reference area is used as the UCL for comparison to the DCGL_W . Additional examples are provided in **Appendix O** to show how simulation can also be used to verify the analytical expressions below as well as to test other sampling problems (e.g., different number of samples, standard deviations, and confidence limits).

To calculate the UCL, first compute the arithmetic mean of the data for the survey unit and reference area:

$$\bar{x}_s = \frac{1}{n_s} \sum_{i=1}^{n_s} x_{s,i} \quad \text{Equation 8-5}$$

$$\bar{x}_r = \frac{1}{n_r} \sum_{i=1}^{n_r} x_{r,i} \quad \text{Equation 8-6}$$

where:

- $\bar{x}_s$ = arithmetic mean of the data for the survey unit
- $\bar{x}_r$ = arithmetic mean of the data for the reference area
- $x_{s,i}$ = result of the i th measurement in the survey unit
- $x_{r,i}$ = result of the i th measurement in the reference area
- n_s = number of measurements in the survey unit
- n_r = number of measurements in the reference area

Then, compute the sample standard deviation of the data for the survey unit and reference area:

$$s_s = \sqrt{\frac{1}{n_s - 1} \sum_{i=1}^{n_s} (x_{s,i} - \bar{x}_s)^2} \quad \text{Equation 8-7}$$

$$s_r = \sqrt{\frac{1}{n_r - 1} \sum_{i=1}^{n_r} (x_{r,i} - \bar{x}_r)^2} \quad \text{Equation 8-8}$$

where:

- s_s = sample standard deviation of the data for the survey unit
- s_r = sample standard deviation of the data for the reference area

The UCL can then be calculated by computing the one-sided $(1 - \alpha)$ UCL of the mean:

$$UCL_{1-\alpha} = (\bar{x}_s - \bar{x}_r) + t_{1-\alpha, \nu} \sqrt{\frac{s_s^2}{n_s} + \frac{s_r^2}{n_r}} \quad \text{Equation 8-9}$$

where:

- $t_{\alpha, \nu}$ = critical value from the t -distribution for a confidence limit of $(1 - \alpha)$ and ν degrees of freedom

Assuming the standard deviation of the data for the survey unit is equal to the standard deviation of the data for the reference area, the number of degrees of freedom is calculated as follows:

$$\nu = n_s + n_r - 2 \quad \text{Equation 8-10}$$

Alternatively, if the standard deviation of the data for the survey unit is not assumed to be equal to the standard deviation of the data for the reference area, the number of degrees of freedom can be approximated by the following:

$$\nu = \frac{\left(\frac{s_s^2}{n_s} + \frac{s_r^2}{n_r}\right)^2}{\frac{(s_s^2/n_s)^2}{n_s - 1} + \frac{(s_r^2/n_r)^2}{n_r - 1}} \quad \text{Equation 8-11}$$

Example 8-14: The survey unit and an appropriate reference area were scanned. There were 1,000 measurements in the survey unit and 900 measurements in the reference area. The number of degrees of freedom can be calculated as follows:

$$\begin{aligned} \nu &= n_s + n_r - 2 \\ &= 1,000 + 900 - 2 \\ &= 1,898 \end{aligned}$$

The arithmetic sample mean of the data for the survey unit is 1.50 and for the reference area is 1.01. The sample standard deviation of the data is 0.30 for both the survey unit and the reference area. For $\alpha = 0.05$ and $\nu = 1,898$, $t_{1-\alpha,\nu} = 1.647$.

The UCL can be calculated as follows:

$$\begin{aligned} UCL_{1-\alpha} &= (\bar{x}_s - \bar{x}_r) + t_{1-\alpha,\nu} \sqrt{\frac{s_s^2}{n_s} + \frac{s_r^2}{n_r}} \\ &= (1.50 - 1.01) + 1.647 \sqrt{\frac{(0.30)^2}{1,000} + \frac{(0.30)^2}{900}} \\ &= 0.51 \end{aligned}$$

8.6 Evaluate the Results: The Decision

When the data and the results of the tests have been obtained, the specific steps required to achieve survey unit release depend on the procedures instituted by the governing regulatory agencies. The considerations suggested in this section are for the interpretation of the test results with respect to the release limit established for the site or survey unit. Note that the tests need not be performed in any particular order.

8.6.1 Elevated Measurement Comparison

If applicable release criteria for elevated measurements exist, then the EMC consists of comparing each measurement from the survey unit with the investigation levels discussed in **Section 5.3.8**. The EMC is performed both for measurements obtained on the systematic sampling grid and for locations flagged by scanning measurements. Any measurement from the survey unit that is equal to or greater than an investigation level indicates an area of relatively high concentrations that should be investigated, regardless of the outcome of the nonparametric statistical tests.

Under Scenario A, the statistical tests may reject the null hypothesis when only a very few high measurements are obtained in the survey unit, regardless of how high the measurements are. In a similar manner, under Scenario B, the statistical tests might not reject the null hypothesis when only a few high measurements are obtained in the survey unit. The use of the Quantile test and the EMC against the investigation levels may be viewed as assurance that unusually large measurements will receive proper attention regardless of the outcome of those tests and that any area having the potential for significant dose or risk contributions will be identified. The EMC is intended to flag potential failures in the remediation process. This should not be considered the primary means to identify whether a survey unit meets the release criteria.

Note that the $DCGL_{EMC}$ is an a priori limit, based initially on the grid spacing or area between measurements. The true extent of an area of elevated activity can be determined only after performing the survey and taking additional measurements. Upon the completion of further investigation, the a posteriori limit can be established. The area of elevated activity is generally bordered by concentration measurements below the $DCGL_W$. An individual elevated measurement on a systematic grid, such as judgment measurements and samples, could conceivably represent an area four times as large as the systematic grid area for a square grid pattern and six times as large for a triangular pattern as used to define the $DCGL_{EMC}$. This is the area bounded by the nearest neighbors of the elevated measurement location. The results of the investigation should show that the appropriate $DCGL_{EMC}$ is not exceeded. If measurements above the stated scan MDC are found by sampling or by direct measurements at locations that were not flagged during the scanning survey, then this may indicate the scanning method does not meet the DQOs. **Table I-8 in Appendix I** shows the probability that an area of elevated concentration of residual radioactive material of a certain size and shape would be missed by a triangular grid.

The preceding discussion primarily concerns Class 1 survey units. Measurements exceeding the $DCGL_W$ in Class 2 or Class 3 areas may indicate survey unit misclassification. Scanning coverage for Class 2 and Class 3 survey units is less stringent than for Class 1. If the investigation levels of **Section 5.3.8** are exceeded, an investigation should (1) ensure that the area of elevated activity discovered meets the release criteria, and (2) provide reasonable assurance that other undiscovered areas of elevated activity do not exist. If further investigation determines that the survey unit was misclassified with regard to potential for residual radioactive material, then a resurvey using the method appropriate for the new survey unit classification is appropriate.

8.6.2 Interpretation of Statistical Test Results

The result of the statistical test is the decision to reject or not to reject the null hypothesis. Provided that the results of investigations triggered by the EMC were resolved, a rejection of the null hypothesis leads to the decision that the survey unit meets the release criteria in Scenario A. In Scenario B, failure to reject the null hypothesis in both the WRS and Quantile tests leads to the decision that the survey unit meets the release criteria, provided that EMC results are acceptable. However, estimating the mean concentration of residual radioactive material in the survey unit may also be necessary so that dose or risk calculations can be made. This estimate is designated by δ . The mean concentration is generally the best estimator for δ . However, only the unbiased measurements from the statistically designed survey should be used in the calculation of δ .

If residual radioactive material is found in an isolated area of elevated activity—in addition to residual radioactive material distributed relatively uniformly across the survey unit—the unity rule (**Section 4.4**) can be used to ensure that the total dose is within the release criteria, as shown in **Equation 8-12**:

$$\delta DCGL_W + \text{mean concentration in elevated area} - \delta DCGL_{EMC} \leq 1 \quad \text{Equation 8-12}$$

All samples in the systematic grid sampling should be included in calculating the mean concentration used in **Equation 8-12**. If there is more than one elevated area, a separate term could be included in **Equation 8-12** for each area. The use of the unity rule for more than one elevated area may imply that a person is centered on each area of elevated radioactive material and exposed simultaneously. This is an impossible situation, and calculations based on it could

lead to significant overestimates in the potential dose. If there are multiple elevated areas, then alternative approaches may be considered:

- The MARSSIM user could determine the elevated area (primary area) that contributes the most to the total dose or risk. As shown by Abelquist 2008, the doses from elevated areas other than the primary area can be very small and might be negligible. Reasonably conservative assumptions should be made regarding exposure assumptions for the primary elevated area.
- The dose or risk due to the actual spatial distribution of residual radioactive material could be calculated if an appropriate exposure pathway model is available.

Other approaches for handling elevated concentrations of radioactive material may be used and should be coordinated with the regulator.

The MARSSIM user should consult with the responsible regulatory agency for guidance on an acceptable approach to address the dose or risk from elevated areas of residual radioactive material. Note that these approaches generally apply only to Class 1 survey units, because areas of elevated activity above the DCGL_W should not exist in Class 2 or Class 3 survey units.

A retrospective power analysis for the test will often be useful, especially when the null hypothesis is not rejected (see **Appendix M**). When the null hypothesis is not rejected, it may be because the null hypothesis is true, or it may be because the test did not have sufficient power to detect that the null hypothesis is not true. The power of the test will be primarily affected by changes in the actual number of measurements obtained and their standard deviation. An effective survey design will slightly overestimate both the number of measurements and the standard deviation to ensure adequate power. This ensures that a survey unit is not subjected to additional remediation or dose modeling refinements simply because the FSS is not powerful enough to show with sufficient confidence that the mean residual radioactive concentration in the survey unit is below the DCGL_W. When the null hypothesis is rejected in Scenario A, the power of the test becomes a moot question. Nonetheless, even in this case, a retrospective power curve can be a useful diagnostic tool and an aid to designing future surveys and for other survey units at the site. When the null hypothesis is accepted in Scenario B, retrospective power calculations are required. If too few samples were collected, the null hypothesis that the survey unit meets the release criteria may not have been rejected simply because of the lack of sufficient power. If the retrospective power analysis in Scenario B reveals insufficient power, it would be important to revisit the DQO process with the updated estimate of σ .

8.6.3 If the Survey Unit Does Not Pass the Final Status Survey

The systematic planning process included in MARSSIM should include planning for possible survey unit failure. Early discussions with appropriate regulatory personnel about what actions can and should be taken if the survey unit does not pass the FSS may prevent long delays later in the project. However, if the survey unit fails to pass the FSS in a way that is not anticipated, agreed-upon actions may not be applicable, and discussions will need to take place to address the unanticipated results.

The information provided in MARSSIM is fairly explicit concerning the steps that should be taken to show that a survey unit meets the release criteria. Less has been said about the procedures that should be used if the survey unit does not pass the FSS at any point. This is

primarily because there are many different ways that a survey unit may not pass the FSS, such as in the following examples:

- The mean concentration of residual radioactive material may exceed the $DCGL_W$ if the radionuclide is not present in background.
- Further investigation following the EMC may show a large enough area with a concentration too high to meet the release criteria.
- Investigation levels may have caused locations to be flagged during scanning that indicate unexpected levels of residual radioactive material for the survey unit classification.

Site-specific information is needed to fully evaluate all the possible reasons for failures, their causes, and their remedies.

When a survey unit does not pass the FSS, the first step is to review and confirm the data that led to the decision. Once this is done, the DQO process (**Appendix D**) can be used to identify and evaluate potential solutions to the problem. The concentration of residual radioactive material in the survey unit should be determined to help define the problem. Once the problem has been stated, the decision concerning the survey unit should be developed into a decision rule. Next, the investigator should determine the additional data, if any, that are needed to document that the survey unit passes the FSS. Alternatives to resolving the decision statement should be developed for each survey unit that fails the tests. These alternatives are evaluated against the DQOs, and a survey design that meets the objectives of the project is selected. **Example 8-15** discusses a Class 2 survey unit with measurements exceeding the $DCGL_W$.

Example 8-15: Class 2 Survey Unit with Measurements Exceeding the $DCGL_W$

A Class 2 survey unit passes the nonparametric statistical tests but has several measurements on the sampling grid that exceed the $DCGL_W$. This is unexpected in a Class 2 area, so these measurements are flagged for further investigation. Additional sampling confirms several areas where the concentration exceeds the $DCGL_W$. This indicates that the survey unit was misclassified. However, the scanning technique that was used was sufficient to detect concentrations of residual radioactive material at the $DCGL_{EMC}$ calculated for the sample grid. No areas exceeding the $DCGL_{EMC}$ were found. Thus, the only difference between the performed FSS and the required FSS for a Class 1 area is that scanning may not have covered 100 percent of the survey unit area. In this case, one might simply increase the scan coverage to 100 percent. Reasons the survey unit was misclassified should be noted. If no areas exceeding the $DCGL_{EMC}$ are found, the survey unit essentially demonstrates compliance with the release criteria as a Class 1 survey unit.

If a survey unit has been misclassified as Class 2 when the data show it should have been designated as Class 1, the size of the survey unit should be considered to determine whether the survey unit should be divided into two or more smaller survey units, based on the recommended survey sizes in **Table 4-1** and the concentration of radioactive material in different areas of the survey unit. If the scanning technique was not sufficiently sensitive, it may be possible to reclassify as Class 1 only that portion of the survey unit containing the higher measurements. This portion would be resampled at the higher measurement density required for a Class 1 survey unit, with the rest of the survey unit remaining as Class 2.

Example 8-16 discusses a Class 1 survey unit with elevated areas.

Example 8-16: Class 1 Survey Unit with Elevated Areas

A Class 1 survey unit passes the nonparametric statistical tests but contains some areas that were flagged for investigation during scanning. Further investigation, sampling, and analysis indicate one area is truly elevated. This area has a concentration that exceeds the $DCGL_{EMC}$. This area is then remediated. Remediation control sampling shows that the residual radioactive material was removed, and no other areas were affected by residual radioactive material. In this case, one may simply document the original FSS, the fact that remediation was performed, the results of the remedial action support survey, and the additional remediation data. In some cases, additional FSS data may not be needed to meet the release criteria.

Example 8-17 discusses a Class 1 survey unit that fails the statistical test.

Example 8-17: Class 1 Survey Unit Fails the Statistical Test

A Class 1 area fails the nonparametric statistical tests. Confirmatory data indicate that the mean concentration in the survey unit exceeds the $DCGL_W$. This indicates remediation of the entire survey unit is necessary, followed by another FSS. Reasons for performing an FSS in a survey unit with significant amounts of residual radioactive material should be noted.

Example 8-15 through **Example 8-17** are meant to illustrate the actions that may be necessary to secure the release of a survey unit that has failed to meet the release criteria. The DQO process should be revisited to plan how to attain the original objective, which is to safely release the survey unit by showing that it meets the release criteria. Whatever data are necessary to meet this objective will be in addition to the FSS data already in hand.

8.6.4 Removable Radioactive Material

Some regulatory agencies may require taking smear samples at indoor grid locations as an indication of removable surface activity. In addition, the percentage of removable activity assumed in the dose modeling can have a large impact on estimated doses. As such, it might be necessary to confirm this assumption regarding the amount of removable contamination. However, measurements of smears are very difficult to interpret quantitatively. In general, the results of smear samples should be used for determining compliance with requirements that specifically call for a smear measurement. In addition, they may be used as a diagnostic tool to determine whether further investigation is necessary.

8.7 Documentation

Documentation of the FSS should provide a complete and unambiguous record of the radiological status of the survey unit relative to the established DCGLs. In addition, sufficient data and information should be provided to enable an independent evaluation of the results of the survey—including repeating, when possible, measurements at some future time. The documentation should comply with all applicable regulatory requirements. Additional information on documentation is provided in **Chapter 3**, **Chapter 5**, and **Appendix D**.

Much of the information in the final status report will be available from other decommissioning documents. However, to the extent practicable, this report should be a stand-alone document with minimum information incorporated by reference. This document should describe the instrumentation or analytical methods applied, how the data were converted to DCGL units, the process of comparing the results to the DCGLs, and the process of determining that the DQOs were met.

The results of actions taken as a consequence of individual measurements or sample concentrations in excess of the investigation levels should be reported, along with any additional data, remediation, or resurveys performed to demonstrate that issues concerning potential areas of elevated activity were resolved. The report should describe the results of the data evaluation using statistical methods to determine whether release criteria were satisfied. If the criteria were not met, or if results indicate a need for additional data, appropriate further actions should be determined by the site management in consultation with the responsible regulatory agency. **Example 8-18** provides an example of a data interpretation checklist.

Example 8-18: Example Data Interpretation Checklist

Convert Data to Standard Units

- _____ Structure activity should be in becquerels per square meter (Bq/m²) (decays per minute [dpm]/100 square centimeters [cm²]).
- _____ Solid media (soil, building surfaces, etc.) activity should be in Bq/kilogram (kg) (picocuries/gram [pCi/g]).

Evaluate Elevated Measurements

- _____ Identify elevated data.
- _____ Compare data with derived elevated area criteria.
- _____ Determine need to remediate or reinvestigate elevated condition, or both.
- _____ Compare data with survey unit classification criteria.
- _____ Determine need to investigate or reclassify, or both.

Assess Survey Data

- _____ Review data quality objectives (DQOs), measurement quality objectives (MQOs), and survey design.
- _____ Verify that data of adequate quantity and quality were obtained.
- _____ Perform preliminary assessments (graphical methods) for unusual or suspicious trends or results—investigate further as appropriate.

Perform Statistical Tests

- _____ Select appropriate tests for the radionuclide.
- _____ Conduct tests.
- _____ Compare test results against hypotheses.
- _____ Confirm power level of tests.

Compare Results to Guidelines

- _____ Determine mean or median concentrations.
- _____ Confirm that residual activity satisfies guidelines.

Compare Results with DQOs and MQOs

- _____ Determine whether all DQOs and MQOs are satisfied.
- _____ Explain/describe deviations from design-basis DQOs/MQOs.

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11. ABSTRACT (200 words or less)

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides information on planning, conducting, evaluating, and documenting building surface and surface soil radiological surveys for demonstrating compliance with requirements, often as part of a dose- or risk-based regulation or standard. MARSSIM is a multiagency consensus document that was developed collaboratively by four Federal agencies having authority and control over radioactive materials: U.S. Department of Defense (DoD), U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), and U.S. Nuclear Regulatory Commission (NRC). MARSSIM's objective is to describe a consistent approach for planning, performing, and assessing building surface and surface soil radiological surveys to meet established criteria, while concurrently encouraging an effective use of resources.

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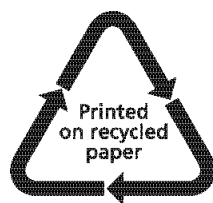
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