APPENDIX H

DESCRIPTION OF FIELD SURVEY AND LABORATORY ANALYSIS EQUIPMENT

H.1 INTRODUCTION

This appendix provides information on various field and laboratory equipment used to measure radiation levels and radioactive material concentrations. The descriptions provide general guidance, and those interested in purchasing or using the equipment are encouraged to contact vendors and users of the equipment for specific information and recommendations. Although most of this equipment is in common use, a few specialty items are included to demonstrate promising developments.

The equipment is divided into two broad groupings of field survey and laboratory instruments, and each group is subdivided into equipment that measures alpha, beta, gamma, x-rays, and radon. A single sheet provides information for each system and includes its type of use (field or lab), the primary and secondary radiation detected, applicability for site surveys, operation, specificity/sensitivity, and cost of the equipment and surveys performed.

The Applicability for Site Surveys section discusses how the equipment is most useful for performing site radiological surveys. The Operation section provides basic technical information on what the system includes, how it works, how to use it practically in the field, and its features. The Specificity/Sensitivity section addresses the system's strengths and weaknesses, and the levels of radioactivity it can measure. Information for the Cost section was obtained primarily from discussions with manufacturers, users, and reviews of product literature. The cost per measurement is an estimate of the cost of producing and documenting a single data point, generally as part of a multipoint survey. It assumes times for instrument calibration (primarily if conducted at the time of the survey), use, sample analysis, and report preparation and review. It should be recognized that these values will change over time due to factors like inflation and market expansion.

It is assumed that the user of this appendix has a basic familiarity with field and laboratory equipment. Some of the typical instrument features and terms are listed below and may not be described separately for the individual instruments:

- Field survey equipment consists of a detector, a survey meter, and interconnected cables, although these are sometimes packaged in a single container. **The detector** or probe is the portion which is sensitive to radiation. It is designed in such a manner, made of selected materials, and operated at a high voltage that makes it sensitive to one or more types of radiation. Some detectors feature a window or a shield whose construction material and thickness make the detector more or less sensitive to a particular radiation. The size of the detector can vary depending on the specific need, but is often limited by the characteristics of the construction materials and the physics of the detection process. **The survey meter** contains the electronics and provides high voltage to the detector, processes the detector's signal, and displays the readings in analog or digital fashion. An analog survey meter has a continuous swing needle and typically a manually operated scale switch, used to keep the needle on scale. The scaling switch may not be required on a digital survey meter. **The interconnecting cables** serve to transfer the high voltage and detector signals in the proper direction. These cables may be inside those units which combine the meter and detector into a single box, but they are often external with connectors that allow the user to interchange detectors.

- Scanning and measuring surveys. In a scanning survey, the field survey meter is operated while moving the detector over an area to search for a change in readings. Since the meter's audible signal responds faster than the meter display, listening to the built-in speaker or using headphones allows the user to more quickly discern changes in radiation level. When a scanning survey detects a change, the meter can be held in place for a more accurate static measurement.

- Integrated readings. Where additional sensitivity is desired, the reading can be integrated using internal electronics or an external scaler to give total values over time. The degree to which the sensitivity can be improved depends largely on the integration time selected.

- Units of measure. Survey meters with conventional meter faces measure radiation levels in units of counts, microRoentgen (μR), millirad (mrad), or millirem (mrem) in terms of unit time, *e.g.*, cpm or μR/hr. Those with SI meter faces use units of microSievert (μSv) or milliGray per unit time, *e.g.*, μSv/hr or mGy/hr.

H.2 FIELD SURVEY EQUIPMENT

H.2.1 Alpha Particle Detectors

System: ALPHA SCINTILLATION SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha **Secondary**: None (in relatively low gamma fields)

Applicability to Site Surveys: The alpha scintillation survey meter is useful for determining the presence or absence of alpha-emitting contamination on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.

Operation: This survey meter uses an alpha radiation detector with a sensitive area of approximately 50 to 100 cm^2 (8 to 16 $in.^2$). The detector has a thin, aluminized window of mylar that blocks ambient light but allows alpha radiation to pass through. The detecting medium is silver activated zinc sulfide, ZnS(Ag). When the discriminator is appropriately adjusted, the meter is sensitive only to alpha radiation. Light pulses are amplified by a photomultiplier tube and passed to the survey meter.

The probe is generally placed close to the surface due to the short range of alpha particles in air. A scanning survey is used to identify areas of elevated surface contamination and then a direct survey is performed to obtain actual measurements. Integrating the readings over time improves the sensitivity enough to make the instrument very useful for alpha surface contamination measurements for many isotopes. The readings are displayed in counts per minute, but factors can usually be obtained to convert readings from cpm to dpm. Conversion factors, however, can be adversely affected by the short range of alpha particles which allows them to be shielded to often uncertain degrees if they are embedded in the surface. Systems typically use 2 to 6 "C" or "D" cells and will operate for 100-300 hours.

Specificity/Sensitivity: When the alpha discriminator is correctly adjusted, the alpha scintillation survey meter measures only alpha radiation, even if there are other radiations present. A scanning survey gives a quick indication of the presence or absence of surface contamination, while integrating the readings provides a measure of the activity on a surface, swipe, or filter. Alpha radiation is easily adsorbed by irregular, porous, moist, or over painted surfaces, and this should be carefully considered when converting count rate data to surface contamination levels. This also requires wet swipes and filters to be dried before counting. The minimum sensitivity is around 10 cpm using the needle deflection or 1 to 2 cpm when using headphones or a scaler. Some headphones or scalers give one click for every two counts, so the manual should be consulted to preclude underestimating the radioactivity by a factor of two.

Cost of Equipment: $1000

Cost per Measurement: $5

System: ALPHA TRACK DETECTOR
Lab/Field: Field and Indoor Surfaces
Radiation Detected: **Primary:** Alpha **Secondary:** None

Applicability to Site Surveys: Alpha track detectors measure gross alpha surface contamination, soil activity levels, or the depth profile of contamination.

Operation: This is a passive integrating detector. It consists of a l mm-thick sheet of polycarbonate material which is deployed directly on the soil surface or in close proximity to the contaminated surface. When alpha particles strike the detector surface, they cause microscopic damage centers to form in the plastic matrix. After deployment, the detector is etched in a caustic solution which preferentially attacks the damage centers. The etch pits may then be counted in an optical scanner. The density of etch pits, divided by the deployment time, is proportional to the soil or surface alpha activity. The measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The area of a standard detector is 2 cm^2 (0.3 $in.^2$), but it may be cut into a variety of shapes and sizes to suit particular needs.

Specificity/Sensitivity: Alpha track detectors are relatively inexpensive, simple, passive, and have no measurable response to beta/gamma radiation. They provide a gross alpha measurement where the lower limit of detection is a function of deployment time. For surface contamination it is 330 Bq/m^2 (200 $dpm/100cm^2$) @ l hour, 50 Bq/m^2 (30 $dpm/100cm^2$) @ 8 hours, and 17 Bq/m^2 (10 $dpm/100cm^2$) @ 48 hours. For soil contamination it is 11,000 Bq/kg (300 pCi/g) @ 1 hour, 3,700 Bq/kg (100 pCi/g) @ 8 hours, and 740 Bq/kg (20 pCi/g) @ 96 hours. High surface contamination or soil activity levels may be measured with deployment times of a few minutes, while activity down to background levels may require deployment times of 48-96 hours. When placed on a surface, they provide an estimate of alpha surface contamination or soil concentration. When deployed against the side of a trench, they can provide an estimate of the depth profile of contamination. They may also be used in pipes and under/inside of equipment.

For most applications, the devices are purchased for a fixed price per measurement, which includes readout. This requires that the detectors be returned to the vendor and the data are not immediately available. For programs having continuing needs and a large number of measurements, automated optical scanners may be purchased. The cost per measurement is then a function of the number of measurements required.

Cost of Equipment: $65,000

Cost per Measurement: $5 to $10

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, beta, gamma, or radon **Secondary:** None
Applicability to Site Surveys: An electret is a passive integrating detector for measurements of alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration.

Operation: The system consists of a charged Teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation, the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incident on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity, with appropriate compensation for background gamma levels. A thin Mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a Mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector. Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (3.8 cm tall by 7.6 cm diameter or l.5 in. tall by 3 in. diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 µR/hr, a 1000 mL chamber may be deployed for two days or a 50 mL chamber deployed for 30 days. The smallest chamber is particularly useful for long-term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 83 Bq/m^2 (50 dpm/100 cm^2) @ 1 hour, 25 Bq/m^2 (l5 dpm/100 cm^2) @ 8 hours, and 13 Bq/m^2 (8 dpm/100 cm) @ 24 hours. For beta radiation from tritium it is 10,000 Bq/m^2 (6,000 dpm/cm^2) @ 1 hour and 500 Bq/m^2 (300 dpm/cm^2) @ 24 hours. For beta radiation from ^{99}Tc it is 830 Bq/m^2 (500 dpm/cm^2) @ 1 hour and 33 Bq/m^2 (20 dpm/cm^2) @ 24 hours.

Cost of Equipment: $4,000 to $25,000, for system if purchased.
Cost per Measurement: $8-$25, for use under service contract

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This equipment measures gross alpha or gross beta/gamma surface contamination levels on relatively flat surfaces like the floors and walls of facilities. It also serves as a screen to determine whether or not more nuclide-specific analyses may be needed.
Operation: This system consists of a gas-flow proportional detector, gas supply, supporting electronics, and a scaler or rate meter. Small detectors (~100 cm^2) are hand-held and large detectors (~400-600 cm^2) are mounted on a rolling cart. The detector entrance window can be <1 to almost 10 mg/cm^2 depending on whether alpha, alpha-beta, or gamma radiation is monitored. The gas used is normally P-10, a mixture of 10% methane and 90% argon. The detector is positioned as close as practical to the surface being monitored for good counting efficiency without risking damage from the detector touching the surface. Quick disconnect fittings allow the system to be disconnected from the gas bottle for hours with little loss of counting efficiency. The detector operating voltage can be set to make it sensitive only to alpha radiation, to both alpha and beta radiation, or to beta and low energy gamma radiation. These voltages are determined for each system by placing either an alpha source, such as ^{230}Th or ^{241}Am, or a beta source, such as ^{90}Sr, facing and near the detector window, then increasing the high voltage in incremental steps until the count rate becomes constant. The alpha plateau, the region of constant count rate, will be almost flat. The beta plateau will have a slope of 5 to 15 percent per 100 volts. Operation on the beta plateau allows detection of some gamma radiation, but the efficiency is very low. Some systems use a spectrometer to separate alpha, and beta/gamma events, allowing simultaneous determination of both the alpha and beta/gamma surface contamination levels.
Specificity/Sensitivity: These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides. Background for operation on the alpha plateau is very low, 2 to 3 counts per minute, which is higher than for laboratory detectors because of the larger detector size. Background for operation on the beta plateau is dependent on the ambient gamma and cosmic ray background, and typically ranges from several hundred to a thousand counts per minute. Typical efficiencies for unattenuated alpha sources are 15-20%. Beta efficiency depends on the window thickness and the beta energy. For $^{90}Sr/^{90}Y$ in equilibrium, efficiencies range from 5% for highly attenuated to about 35% for unattenuated sources. Typical gamma ray efficiency is <1%. The presence of natural radionuclides in the surfaces could interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radionuclides is well known, this system is better used for assessing gross surface contamination levels. The texture and porosity of the surface can hide or shield radioactive material from the detector, causing levels to be underestimated. Changes in temperature can affect the detectors's sensitivity. Incomplete flushing with gas can cause a nonuniform response over the detector's surface. Condensation in the gas lines or using the quick disconnect fittings can cause count rate instability.
Cost of Equipment: $2,000 to $4,000
Cost per Measurement: $2-$10 per m^2

System: LONG RANGE ALPHA DETECTOR (LRAD)
Lab/Field: Field
Radiation Detected: **Primary:** Alpha **Secondary:** None

Applicability to Site Surveys: The LRAD is a rugged field-type unit for measuring alpha surface soil concentration over a variety of dry, solid, flat terrains.

Operation: The LRAD system consists of a large (1 m x 1 m) aluminum box, open on the bottom side, containing copper plates that collect ions produced in the soil or surface under the box, and used to measure alpha surface contamination or soil concentration. It is attached to a lifting device on the front of a tractor and can be readily moved to new locations. Bias power is supplied by a 300-V dry cell battery, and the electrometer and computer are powered by an automobile battery and DC-to-AC inverter. A 50 cm grounding rod provides electrical grounding. A notebook computer is used for data logging and graphical interpretation of the data. Alpha particles emitted by radionuclides in soil travel only about 3 cm in air. However, these alpha particles interact with the air and produce ions that travel considerably farther. The LRAD detector box is lowered to the ground to form an enclosed ionization region. The copper detector plate is raised to +300V along with a guard detector mounted above the detector plate to control leakage current. The ions are then allowed to collect on the copper plate producing a current that is measured with a sensitive electrometer. The signal is then averaged and processed on a computer. The electric current produced is proportional to the ionization within the sensitive area of the detector and to the amount of alpha contamination present on the surface soil.

Due to its size and weight (300 lb), the unit can be mounted on a tractor for ease of movement. All metal surfaces are covered with plastic to reduce the contribution from ion sources outside the detector box. At each site, a ground rod is driven into the ground. Each location is monitored for at least 5 min. After each location is monitored, its data is fed into a notebook computer and an interpolative graph of alpha concentration produced. The unit is calibrated using standard alpha sources.

Sensitivity/Specificity: The terrain over which this system is used must be dry, to prevent the shielding of alpha particles by residual moisture, and flat, to prevent air infiltration from outside the detector, both of which can lead to large errors. The unit can detect a thin layer of alpha surface contamination at levels of 33-83 Bq/m^2 (20-50 dpm/100 cm^2), but does not measure alpha contamination of deeper layers. Alpha concentration errors are $\pm$74-740 Bq/kg ($\pm$2-20 pCi/g), with daily repeat accuracies of $\pm$370-3,700 Bq/kg ($\pm$10-100 pCi/g), depending on the contamination level. The dynamic measurement range appears to be 370-110,00 Bq/kg (10-3,000 pCi/g).

Cost of Equipment: $25,000 (est. for tractor, computer, software, electrometer, and detector)
Cost per Measurement: $80 (based on 30 min per point and a 2 person team)

H.2 FIELD SURVEY EQUIPMENT

H.2.2 Beta Particle Detectors

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Low energy beta (*e.g.* tritium, ^{99}Tc, ^{14}C, ^{90}Sr, ^{63}Ni), alpha, gamma, or radon **Secondary:** None

Applicability to Site Surveys: This system measures alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration, depending on how it is configured.

Operation: The system consists of a charged Teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation, the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incident on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity, with appropriate compensation for background gamma levels. A thin Mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a Mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector. Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (3.8 cm tall by 7.6 cm diameter or l.5 in. tall by 3 in. diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 µR/hr, a 1000 mL chamber may be deployed for two days or a 50 mL chamber deployed for 30 days. The smallest chamber is particularly useful for long-term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 83 Bq/m^2 (50 dpm/100 cm^2) @ 1 hour, 25 Bq/m^2 (15 dpm/100 cm^2) @ 8 hours, and 13 Bq/m^2 (8 dpm/100 cm^2) @ 24 hours. For beta radiation from tritium it is 10,000 Bq/m^2 (6,000 dpm/cm^2) @ 1 hour and 500 Bq/m^2 (300 dpm/cm^2) @ 24 hours. For beta radiation from ^{99}Tc it is 830 Bq/m^2(500 dpm/cm^2) @ 1 hour and 33 Bq/m^2 (20 dpm/cm^2) @ 24 hours.

Cost of Equipment: $4,000 to $25,000, for system if purchased.

Cost per Measurement: $8-$25, for use under service contract

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Field
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This equipment measures gross alpha or gross beta/gamma surface contamination levels on relatively flat surfaces like the floors and walls of facilities. It would serve as a screen to determine whether or not more nuclide-specific analyses were needed.
Operation: This system consists of a gas-flow proportional detector, gas supply, supporting electronics, and a scaler or rate meter. Small detectors (~100 cm^2) are hand-held and large detectors (~400-600 cm^2) are mounted on a rolling cart. The detector entrance window can be <1 to almost 10 mg/cm^2 depending on whether alpha, alpha-beta, or gamma radiation is monitored. The gas used is normally P-10, a mixture of 10% methane and 90% argon. The detector is positioned as close as practical to the surface being monitored for good counting efficiency without risking damage from the detector touching the surface. Quick disconnect fittings allow the system to be disconnected from the gas bottle for hours with little loss of counting efficiency. The detector operating voltage can be set to make it sensitive only to alpha radiation, to both alpha and beta radiation, or to beta and low energy gamma radiation. These voltages are determined for each system by placing either an alpha source, such as ^{230}Th or ^{241}Am, or a beta source, such as ^{90}Sr, facing and near the detector window, then increasing the high voltage in incremental steps until the count rate becomes constant. The alpha plateau, the region of constant count rate, will be almost flat. The beta plateau will have a slope of 5 to 15 percent per 100 volts. Operation on the beta plateau allows detection of some gamma radiation, but the efficiency is very low. Some systems use a spectrometer to separate alpha, and beta/gamma events, allowing simultaneous determination of both the alpha and beta/gamma surface contamination levels.
Specificity/Sensitivity: These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides. Background for operation on the alpha plateau is very low, 2 to 3 counts per minute, which is higher than for laboratory detectors because of the larger detector size. Background for operation on the beta plateau is dependent on the ambient gamma and cosmic ray background, and typically ranges from several hundred to a thousand counts per minute. Typical efficiencies for unattenuated alpha sources are 15-20%. Beta efficiency depends on the window thickness and the beta energy. For $^{90}Sr/^{90}Y$ in equilibrium, efficiencies range from 5% for highly attenuated to about 35% for unattenuated sources. Typical gamma ray efficiency is <1%. The presence of natural radionuclides in the surfaces could interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radionuclides is well known, this system is better used for assessing gross surface contamination levels. The texture and porosity of the surface can hide or shield radioactive material from the detector, causing levels to be underestimated. Changes in temperature can affect the detectors's sensitivity. Incomplete flushing with gas can cause a nonuniform response over the detector's surface. Condensation in the gas lines or using the quick disconnect fittings can cause count rate instability.
Cost of Equipment: $2,000 to $4,000
Cost per Measurement: $2-$10 per m^2

System: GM SURVEY METER WITH BETA PANCAKE PROBE
Lab/Field: Field
Radiation Detected: **Primary:** Beta **Secondary:** Gamma and alpha
Applicability to Site Surveys: This instrument is used to find and measure low levels of beta/gamma contamination on relatively flat surfaces.
Operation: This instrument consists of a flat "pancake" type Geiger-Mueller detector connected to a survey meter which measures radiation response in counts per minute. The detector housing is typically a rigid metal on all sides except the radiation entrance face or window, which is made of Mylar, mica, or a similar material. A steel, aluminum, lead, or tungsten housing surrounds the detector on all sides except the window, giving the detector a directional response. The detector requires approximately 900 volts for operation. It is held within a few cm of the surface to minimize the thickness of air shielding in between the radioactive material and the detector. It is moved slowly to scan the surface in search of elevated readings, then held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. The counts per minute meter reading is converted to a beta surface contamination level in the range of 1,700 Bq/m^2 (1,000 dpm/100 cm^2) using isotope specific factors.

Specificity/Sensitivity: Pancake type GM detectors primarily measure beta count rate in close contact with surfaces to indicate the presence of contamination. They are sensitive to any alpha, beta, or gamma radiation that enters the detector and causes ionization. As a result, they cannot determine the type or energy of that radiation, except by using a set of absorbers. To be detected, beta particles must have enough energy to penetrate through any surface material that the contamination is absorbed in, plus the detector window, and the layer of air and other shielding materials in between. Low energy beta particles from emitters like ^{3}H (17 keV) that cannot penetrate the window alone are not detectable, while higher energy betas like those from ^{60}Co (314 keV) can be readily detected. The beta detection efficiency at a field site is primarily a function of the beta energy, window thickness, and the surface condition. The detection sensitivity can be improved by using headphones or the audible response during scans. By integrating the count rate over a longer period or by counting the removable radioactive material collected on a swipe , the ability to detect surface contamination can be improved. The nominal 2 in. diameter detector can measure an increase of around 100 cpm above background, which equates to 4,200 Bq/m^2 (2,500 dpm/100 cm^2) of ^{60}Co on a surface under the detector or 20 Bq (500 pCi) on a swipe. Larger 100 cm^2 detectors improve sensitivity and eliminate the need to swipe. A swipe's collection efficiency may be below 100%, and depends on the wiping technique, the actual surface area covered, the texture and porosity of the surface, the affinity of the contamination for the swipe material, and the dryness of the swipe. This will proportionately change the values above. The sensitivity to gamma radiation is around 10% or less of the beta sensitivity, while the alpha detection efficiency is difficult to evaluate.

Cost of equipment: $400 to $1,500
Cost per Measurement: $5 to $10 per location

H.2 FIELD SURVEY EQUIPMENT

H.2.3 Gamma Ray Detectors

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Low energy beta (*e.g.* tritium, ^{99}Tc, ^{14}C, ^{90}Sr, ^{63}Ni), alpha, gamma, or radon **Secondary:** None

Applicability to Site Surveys: This system measures alpha- or beta-emitting contaminants on surfaces and in soils, gamma radiation dose, or radon air concentration, depending on how it is configured.

Operation: The system consists of a charged Teflon disk (electret), open-faced ionization chamber, and electret voltage reader/data logger. When the electret is screwed into the chamber, a static electric field is established and a passive ionization chamber is formed. For alpha or beta radiation, the chamber is opened and deployed directly on the surface or soil to be measured so the particles can enter the chamber. For gammas, however, the chamber is left closed and the gamma rays incident on the chamber penetrate the 2 mm-thick plastic detector wall. These particles or rays ionize the air molecules, the ions are attracted to the charged electret, and the electret's charge is reduced. The electret charge is measured before and after deployment with the voltmeter, and the rate of change of the charge is proportional to the alpha or beta surface or soil activity, with appropriate compensation for background gamma levels. A thin Mylar window may be used to protect the electret from dust. In low-level gamma measurements, the electret is sealed inside a Mylar bag during deployment to minimize radon interference. For alpha and beta measurements, corrections must be made for background gamma radiation and radon response. This correction is accomplished by deploying additional gamma or radon-sensitive detectors in parallel with the alpha or beta detector. Electrets are simple and can usually be reused several times before recharging by a vendor. Due to their small size (3.8 cm tall by 7.6 cm diameter or l.5 in. tall by 3 in. diameter), they may be deployed in hard-to-access locations.

Specificity/Sensitivity: This method gives a gross alpha, gross beta, gross gamma, or gross radon measurement. The lower limit of detection depends on the exposure time and the volume of the chamber used. High surface alpha or beta contamination levels or high gamma radiation levels may be measured with deployment times of a few minutes. Much lower levels can be measured by extending the deployment time to 24 hours or longer. For gamma radiation, the response of the detector is nearly independent of energy from 15 to 1200 keV, and fading corrections are not required. To quantify ambient gamma radiation fields of 10 µR/hr, a 1000 mL chamber may be deployed for two days or a 50 mL chamber deployed for 30 days. The smallest chamber is particularly useful for long-term monitoring and reporting of monthly or quarterly measurements. For alpha and beta particles, the measurement may be converted to isotopic concentration if the isotopes are known or measured separately. The lower limit of detection for alpha radiation is 83 Bq/m^2 (50 dpm/100 cm^2) @ 1 hour, 25 Bq/m^2 (15 dpm/100 cm^2) @ 8 hours, and 13 Bq/m^2 (8 dpm/100 cm^2) @ 24 hours. For beta radiation from tritium it is 10,000 Bq/m^2 (6,000 dpm/cm^2) @ 1 hour and 500 Bq/m^2 (300 dpm/cm^2) @ 24 hours. For beta radiation from ^{99}Tc it is 830 Bq/m^2(500 dpm/cm^2) @ 1 hour and 33 Bq/m^2 (20 dpm/cm^2) @ 24 hours.

Cost of Equipment: $4,000 to $25,000, for system if purchased.

Cost per Measurement: $8-$25, for use under service contract

System: GM SURVEY METER WITH GAMMA PROBE
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** Beta

Applicability to Site Surveys: This instrument is used to give a quick indication of gamma-radiation levels present at a site. Due to its high detection limit, the GM survey meter may be useful during characterization surveys but may not meet the needs of final status surveys.

Operation: This instrument consists of a cylindrical Geiger Mueller detector connected to a survey meter. It is calibrated to measure gamma exposure rate in mR/hr. The detector is surrounded on all sides by a protective rigid metal housing. Some units called end window or side window have a hinged door or rotating sleeve that opens to expose an entry window of Mylar, mica, or a similar material, allowing beta radiation to enter the sensitive volume. The detector requires approximately 900 volts for operation. It is normally held at waist height, but is sometimes placed in contact with an item be evaluated. It is moved slowly over the area to scan for elevated readings, observing the meter or, preferably, listening to the audible signal. Then it is held in place long enough to obtain a stable measurement. Radiation entering the detector ionizes the gas, causes a discharge throughout the entire tube, and results in a single count being sent to the meter. Conversion from count rate to exposure rate is accomplished at calibration by exposing the detector at discrete levels and adjusting the meter scale(s) to read accordingly. In the field, the exposure rate is read directly from the meter. If the detector housing has an entry window , an increase in “open-door” over “closed-door” reading indicates the presence of beta radiation in the radiation field, but the difference is not a direct measure of the beta radiation level.

Specificity/Sensitivity: GM meters measure gamma exposure rate, and those with an entry window can identify if the radiation field includes beta radiation. Since GM detectors are sensitive to any energy of alpha, beta, or gamma radiation that enters the detector, instruments that use these detectors cannot identify the type or energy of that radiation, or the specific radionuclide(s) present. The sensitivity can be improved by using headphones or the audible response during scans, or by integrating the exposure rate over time. The instrument has two primary limitations for environmental work. First, its minimum sensitivity is high, around 0.1 mR/hr in rate meter mode or 0.01 mR/hr in integrate mode. Some instruments use a large detector to improve low end sensitivity. However, in many instances the instrument is not sensitive enough for site survey work. Second, the detector’s energy response is nonlinear. Energy compensated survey meters are commercially available, but the instrument's sensitivity may be reduced.

Cost of Equipment: $400 to $1,500.

Cost per Measurement: $5 per measurement for survey and report.

System: HAND-HELD ION CHAMBER SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None

Applicability to Site Surveys: The hand-held ion chamber survey meter measures true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Due to their high detection limit, these instruments are not applicable for many final status surveys.

Operation: This device uses an ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to generate secondary ion pairs as a proportional counter does. The units of readout are mR/hr, or some multiple of mR/hr. If equipped with an integrating mode, the operator can measure the total exposure over a period of time. The instrument may operate on two “D” cells or a 9 volt battery that will last for 100 to 200 hours of operation.

Specificity/Sensitivity: Ion chamber instruments respond only to gamma or x-radiation. They have no means to provide the identity of contaminants. Typical ion chamber instruments have a lower limit of detection of 0.5 mR/hr. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them. In integrate mode, the instrument sensitivity can be as low as 0.05 mR/hr.

Cost of Equipment: $800 to $1,200

Cost per Measurement: $5, or higher for making integrated exposure measurements.

System: HAND-HELD PRESSURIZED ION CHAMBER (PIC) SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None

Applicability to Site Surveys: The hand-held pressurized ion chamber survey meter measures true gamma radiation exposure rate, in contrast to most other survey meter/probe combinations which are calibrated to measure exposure rate at one energy and approximate the exposure rate at all other energies. Due to their high detection limit, these instruments are not applicable for many final status surveys.

Operation: This device uses a pressurized air ion chamber operated at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to cause secondary ionization.. The instrument is identical to the ion chamber meter on the previous page, except in this case the ion chamber is sealed and pressurized to 2 to 3 atmospheres to increase the sensitivity of the instrument by the same factors. The units of readout are µR/hr or mR/hr. A digital meter will allow an operator to integrate the total exposure over a period of time. The unit may use two “D” cells or a 9-volt battery that will last for 100 to 200 hours of operation.

Specificity/Sensitivity: Since the ion chamber is sealed, pressurized ion chamber instruments respond only to gamma or X-radiation. They have no means to provide the identity of contaminants. Typical instruments have a lower limit of detection of 0.1 mR/hr, or as low as 0.01 mR in integrate mode. These instruments can display readings below this, but the readings may be erratic and have large errors associated with them.

Cost of Equipment: $1,000 to $1,500

Cost per Measurement: $5, or higher for making integrated exposure measurements.

System: PORTABLE GERMANIUM MULTICHANNEL ANALYZER (MCA) SYSTEM
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None

Applicability for Site Surveys: This system produces semi-quantitative estimates of concentration of uranium and plutonium in soil, water, air filters, and quantitative estimates of many other gamma-emitting isotopes. With an appropriate dewar, the detector may be used in a vertical orientation to determine, *in situ*, gamma isotopes concentrations in soil.

Operation: This system consists of a portable germanium detector connected to a dewar of liquid nitrogen, high voltage power supply, and multichannel analyzer. It is used to identify and quantify gamma-emitting isotopes in soil or other surfaces.

Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighboring atoms. The charge is collected rapidly and is proportional to the deposited energy.

The typical system consists of a portable multichannel analyzer (MCA) weighing about 7-10 lbs with batteries, a special portable low energy germanium detector with a built-in shield, and the acquisition control and spectrum analysis software. The detector is integrally mounted to a liquid nitrogen dewar. The liquid nitrogen is added 2-4 hours before use and replenished every 4-24 hours based on capacity.

The MCA includes all required front end electronics, such as a high voltage power supply, an amplifier, a digital stabilizer, and an analog-to-digital converter (ADC), which are fully controllable from a laptop computer and software.

One method uses the 94-104 keV peak region to analyze the plutonium isotopes from either “fresh” or aged materials. It requires virtually no user input or calibration. The source-to-detector distance for this method does not need to be calibrated as long as there are enough counts in the spectrum to perform the analysis.

For *in situ* applications, a collimated detector is positioned at a fixed distance from a surface to provide multichannel spectral data for a defined surface area. It is especially useful for qualitative and (based on careful field calibration or appropriate algorithms) quantitative analysis of freshly deposited contamination. Additionally, with prior knowledge of the depth distribution of the primary radionuclides of interest, which is usually not known, or using algorithms that match the site, the *in situ* system can be used to estimate the content of radionuclides distributed below the surface (dependent, of course, on adequate detection capability.)

Calibration based on Monte Carlo modeling of the assumed source-to-detector geometry or computation of fluence rates with analytical expressions is an important component to the accurate use of field spectrometry, when it is not feasible or desirable to use real radioactive sources. Such modeling used in conjunction with field spectrometry is becoming much more common recently, especially using the MCNP Monte Carlo computer software system.

Specificity/Sensitivity: With proper calibration or algorithms, field spectrometers can identify and quantify concentrations of gamma emitting radionuclides in the middle to upper energy range (*i.e.*, 50 keV with a P-type detector or 10 keV with an N-type detector).

For lower energy photons, as are important for plutonium and americium, an N-type detector or a planar crystal is preferred with a very thin beryllium (Be) window. This configuration allows measurement of photons in the energy range 5 to 80 keV. The Be window is quite fragile and a target of corrosion, and should be protected accordingly.

The detector high voltage should only be applied when the cryostat has contained sufficient liquid nitrogen for several hours. These systems can accurately identify plutonium, uranium, and many gamma-emitting isotopes in environmental media, even if a mixture of radionuclides is present. Germanium has an advantage over sodium iodide because it can produce a quantitative estimate of concentrations of multiple radionuclides in samples like soil, water, and air filters.

A specially designed low energy germanium detector that exhibits very little deterioration in the resolution as a function of count rate may be used to analyze uranium and plutonium, or other gamma-emitting radionuclides. When equipped with a built-in shield, it is unnecessary to build complicated shielding arrangements while making field measurements. Tin filters can be used to reduce the count rate from the ^{241}Am 59 keV line which allows the electronics to process more of the signal coming from Pu or U.

A plutonium content of 10 mg can be detected in a 55 gallon waste drum in about 30 minutes, although with high uncertainty. A uranium analysis can be performed for an enrichment range from depleted to 93% enrichment. The measurement time can be in the order of minutes depending on the enrichment and the attenuating materials.

Cost of Equipment: $40,000

Cost per Measurement: $100 to $200

System: PRESSURIZED IONIZATION CHAMBER (PIC)
Lab/Field: Field
Radiation Detected: **Primary:** Moderate (>80 keV) to high energy photons
Secondary: None

Applicability to Site Surveys: The PIC is a highly accurate ionization chamber for measuring gamma exposure rate in air, and for correcting for the energy dependence of other instruments due to their energy sensitivities. It is excellent for characterizing and evaluating the effectiveness of remediation of contaminated sites based on exposure rate. However, most sites also require nuclide-specific identification of the contributing radionuclides. Under these circumstances, PICs must be used in conjunction with other soil sampling or spectrometry techniques to evaluate the success of remediation efforts.

Operation: The PIC detector is a large sphere of compressed argon-nitrogen gas at 10 to 40 atmospheres pressure surrounded by a protective box. The detector is normally mounted on a tripod and positioned to sit about three feet off the ground. It is connected to an electronics box in which a strip chart recorder or digital integrator measures instantaneous and integrated exposure rate. It operates at a bias voltage sufficient to collect all ion pairs created by the passage of ionizing radiation, but not sufficiently high to amplify or increase the number of ion pairs . The high pressure inside the detector and the integrate feature make the PIC much more sensitive and precise than other ion chambers for measuring low exposures. The average exposure rate is calculated from the integrated exposure and the operating time. Arrays of PIC systems can be linked by telecommunications so their data can be observed from a central and remote location.

Specificity/Sensitivity: The PIC measures gamma or x-radiation and cosmic radiation. It is highly stable, relatively energy independent, and serves as an excellent tool to calibrate (in the field) other survey equipment to measure exposure rate. Since the PIC is normally uncollimated, it measures cosmic, terrestrial, and foreign source contributions without discrimination. Its rugged and stable behavior makes it an excellent choice for an unattended sensor where area monitors for gamma emitters are needed. PICs are highly sensitive, precise, and accurate to vast changes in exposure rate (1 µR/ hr up to 10 R/hr). PICs lack any ability to distinguish either energy spectral characteristics or source type. If sufficient background information is obtained , the data can be processed using algorithms that employ time and frequency domain analysis of the recorded systems to effectively separate terrestrial, cosmic, and "foreign" source contributions. One major advantage of PIC systems is that they can record exposure rate over ranges of 1 to 10,000,000 µR per hour (*i.e.*, µR/hr to 10 R/hr) with good precision and accuracy.

Cost of Equipment: $15,000 to $50,000 depending on the associated electronics, data processing, and telecommunications equipment.

Cost per Measurement: $50 to $500 based on the operating time at each site and the number of measurements performed.

System: SODIUM IODIDE SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site Surveys: Sodium iodide survey meters can be response checked against a pressurized ionization chamber(PIC) and then used in its place so readings can be taken more quickly. This check should be performed often, possibly several times each day. They are useful for determining ambient radiation levels and for estimating the concentration of radioactive materials at a site.
Operation: The sodium iodide survey meter measures gamma radiation levels in µR/hr (10^{-6} R/hr) or counts per minute (cpm). Its response is energy and count rate dependent, so comparison with a pressurized ion chamber necessitates a conversion factor for adjusting the meter readings to true µR/hr values. The conversion factor obtained from this comparison is valid only in locations where the radionuclide mix is identical to that where the comparison is performed, and over a moderate range of readings. The detector is held at waist level or suspended near the surface and walked through an area listening to the audio and watching the display for changes. It is held in place and the response allowed to stabilize before each measurement is taken, with longer times required for lower responses. Generally, the center of the needle swing or the integrated reading is recorded. The detector is a sodium iodide crystal inside an aluminum container with an optical glass window that is connected to a photomultiplier tube. A gamma ray that interacts with the crystal produces light that travels out of the crystal and into the photomultiplier tube. There, electrons are produced and multiplied to produce a readily measurable pulse whose magnitude is proportional to the energy the gamma ray incident on the crystal. Electronic filters accept the pulse as a count if certain discrimination height restrictions are met. This translates into a meter response. Instruments with pulse height discrimination circuitry can be calibrated to view the primary gamma decay energy of a particular isotope. If laboratory analysis has shown a particular isotope to be present, the discrimination circuitry can be adjusted to partially tune out other isotopes, but this also limits its ability to measure exposure rate.
Specificity/Sensitivity: Sodium iodide survey meters measure gamma radiation in µR/hr or cpm with a minimum sensitivity of around 1-5 µR per hour, or 200-1,000 cpm, or lower in digital integrate mode. The reading error of 50% can occur at low count rates because of a large needle swing, but this decreases with increased count rate. The instrument is quite energy sensitive, with the greatest response around 100-120 keV and decreasing in either direction. Measuring the radiation level at a location with both a PIC and the survey meter gives a factor for converting subsequent readings to actual exposure rates. This ratio can change with location. Some meters have circuitry that looks at a few selected ranges of gamma energies, or one at a time with the aide of a single channel analyzer. This feature is used to determine if a particular isotope is present. The detector should be protected against thermal or mechanical shock which can break the sodium iodide crystal or the photomultiplier tube. Covering at least the crystal end with padding is often sufficient. The detector is heavy, so adding a carrying strap to the meter and a means of easily attaching and detaching the detector from the meter case helps the user endure long surveys.
Cost of Equipment: $2,000
Cost per Measurement: $5

System: THERMOLUMINESCENCE DOSIMETER (TLD)
Lab/Field: Field and lab
Radiation Detected: **Primary:** Gamma **Secondary:** Neutron, beta, x-ray
Applicability to Site Surveys: TLDs can be used to measure such a low dose equivalent that they can identify gamma levels slightly above natural background. TLDs should be placed in areas outside the site but over similar media to determine the average natural background radiation level in the area. Other TLDs should be posted on site to determine the difference from background. Groups should be posted quarterly for days to quarters and compared to identify locations of increased onsite doses.
Operation: A TLD is a crystal that measures radiation dose. TLDs are semiconductor crystals that contain small amounts of added impurities. When radiation interacts with the crystal, electrons in the valence band are excited into the conduction band. Many lose their energy and return directly to the valence band, but some are trapped at an elevated energy state by the impurity atoms. This trapped energy can be stored for long periods, but the signal can fade with age, temperature, and light. Heating the TLD in a TLD reader releases the excess energy in the form of heat and light. The quantity or intensity of the light given off gives a measure of the radiation dose the TLD received. If the TLDs are processed at an off site location, the transit dose (from the location to the site and return) must be determined and subtracted from the net dose. The ability to determine this transit dose affects the net sensitivity of the measurements. The TLD is left in the field for a period of a day to a quarter and then removed from the field and read in the laboratory on a calibrated TLD reader. The reading is the total dose received by the TLD during the posting period. TLDs come in various shapes (thin-rectangles, rods, and powder), sizes (0.08 cm to 0.6 cm (1/32 in. to 1/4 in.) on a side), and materials (CaF_2:Mn, $CaSO_4$:Dy, ^{6}LiF:Mn, ^{7}LiF:Mn, $LiBO_4$, LiF:Mg,Cu,P and Al_2O_3:C). The TLD crystals can be held loosely inside a holder, sandwiched between layers of Teflon, affixed to a substrate, or attached to a heater strip and surrounded by a glass envelope. Most are surrounded by special thin shields to correct for an over response to low-energy radiation. Many have special radiation filters to allow the same type TLD to measure various types and energies of radiation.
Specificity/Sensitivity: TLDs are primarily sensitive to gamma radiation, but selected TLD/filter arrangements can be used to measure beta, x-ray, and neutron radiation. They are posted both on site and off site in comparable areas. These readings are compared to determine if the site can cause personnel to receive more radiation exposure than would be received from background radiation. The low-end sensitivity can be reduced by specially calibrating each TLD and selecting those with high accuracy and good precision. The new Al_2O_3 TLD may be capable of measuring doses as low as 0.1 µSv (0.01 mrem) while specially calibrated CaF_2 TLDs posted quarterly can measure dose differences as low as 0.05 mSv/y (5 mrem/y). This is in contrast to standard TLDs that are posted monthly and may not measure doses below 1 mSv/y (100 mrem/y). TLDs should be protected from damage as the manufacturer recommends. Some are sensitive to visible light, direct sunlight, fluorescent light, excessive heat, or high humidity.
Cost of Equipment: $5K-$ 100K (reader), $25-$40 (TLD). TLDs cost $5 to $40 per rental.
Cost per Measurement: $25 to $125

H.2 FIELD SURVEY EQUIPMENT

H.2.4 Radon Detectors

System: ACTIVATED CHARCOAL ADSORPTION
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas **Secondary:** None

Applicability to Site Surveys: Activated charcoal adsorption is a passive low cost screening method for measuring indoor air radon concentration. The charcoal adsorption method is not designed for outdoor measurements. For contaminated structures, charcoal is a good short-term indicator of radon contamination. Vendors provide measurement services which includes the detector and subsequent readout.

Operation: For this method, an airtight container with activated charcoal is opened in the area to be sampled and radon in the air adsorbs onto the charcoal. The detector, depending on its design, is deployed for 2 to 7 days. At the end of the sampling period, the container is sealed and sent to a laboratory for analysis. Proper deployment and analysis will yield accurate results.

Two analysis methods are commonly used in activated charcoal adsorption. The first method calculates the radon concentration based on the gamma decay from the radon progeny analyzed on a gamma scintillation or semiconductor detection system. The second method is liquid scintillation which employs a small vial containing activated charcoal for sampling. After exposure, scintillation fluid is added to the vial and the radon concentration is determined by the alpha and beta decay of the radon and progeny when counted in a liquid scintillation spectrometer.

Specificity/Sensitivity: Charcoal absorbers are designed to measure radon concentrations in indoor air. Some charcoal absorbers are sensitive to drafts, temperature and humidity. However, the use of a diffusion barrier over the charcoal reduces these effects. The minimum detectable concentration for this method ranges from 0.007-0.04 Bq/L (0.2-1.0 pCi/L).

Cost of Equipment: $10,000 for a liquid scintillation counter, $10,000 for a sodium iodide multichannel analyzer system, or $30,000+ for a germanium multichannel analyzer system. The cost of the activated charcoal itself is minimal.

Cost per Measurement: $5 to $30 including canister.

System: ALPHA TRACK DETECTOR
Lab/Field: Field
Radiation Detected: **Primary:** Radon Gas (Alpha Particles) **Secondary:** None
Applicability to Site Surveys: An alpha track detector is a passive, low cost, long term method used for measuring radon. Alpha track detectors can be used for site assessments both indoors and outdoors (with adequate protection from the elements).

Operation: Alpha track detectors employ a small piece of special plastic or film inside a small container. Air being tested diffuses through a filtering mechanism into the container. When alpha particles from the decay of radon and its progeny strike the detector, they cause damage tracks. At the end of exposure, the container is sealed and returned to the laboratory for analysis.

The plastic or film detector is chemically treated to amplify the damage tracks and then the number of tracks over a predetermined area are counted using a microscope, optical reader, or spark counter. The radon concentration is determined by the number of tracks per unit area. Detectors are usually exposed for 3 to 12 months, although shorter time frames may be used when measuring high radon concentrations.

Specificity/Sensitivity: Alpha track detectors are primarily used for indoor air measurements but specially designed detectors are available for outdoor measurements. Alpha track results are usually expressed as the radon concentration over the exposure period (Bq/L-days). The sensitivity is a function of detector design and exposure duration, and is on the order of 0.04 Bq/L-day (1 pCi/L-day).

Cost of Equipment: Not applicable when provided by a vendor

Cost per Measurement: $5 to $25

System: CONTINUOUS RADON MONITOR
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas **Secondary:** None

Applicability to Site Surveys: Continuous radon monitors are devices that measure and record real-time measurements of radon gas or variations in radon concentration on an hourly basis. Since continuous monitors display real-time hourly radon measurements, they are useful for short-term site investigation.

Operation: Continuous radon monitors are precision devices that track and record real-time measurements and variations in radon gas concentration on an hourly basis. Air either diffuses or is pumped into a counting chamber. The counting chamber is typically a scintillation cell or ionization chamber. Using a calibration factor, the counts are processed electronically, and radon concentrations for predetermined intervals are stored in memory or directly transmitted to a printer.

Most continuous monitors are used for a relatively short measurement period, usually 1 to 7 days. These devices do require some operator skills and often have a ramp-up period to equilibrate with the surrounding atmosphere. This ramp-up time can range from 1 to 4 hours depending on the size of the counting chamber and rate of air movement into the chamber.

Specificity/Sensitivity: Most continuous monitors are designed for both indoor and outdoor radon measurements. The limiting factor for outdoor usage is the need for electrical power. In locations where external power is unavailable, the available operating time depends on the battery lifetime of the monitor. The minimum detectable concentration for these detectors ranges from 0.004-0.04 Bq/L (0.1-1.0 pCi/L).

Cost of Equipment: $1,000 to $5,000.

Cost per Measurement: $80+ based on duration of survey.

System: ELECTRET ION CHAMBER
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas (alpha, beta) **Secondary:** Gamma

Applicability to Site Surveys: Electrets are used to measure radon concentration in indoor environments. For contaminated structures, the electret ion chamber is a good indicator of short-term and long-term radon concentrations.

Operation: For this method, an electrostatically charged disk (electret) is situated within a small container (ion chamber). During the measurement period, radon diffuses through a filter into the ion chamber, where the ionization produced by the decay of radon and its progeny reduces the charge on the electret. A calibration factor relates the voltage drop, due to the charge reduction, to the radon concentration. Variations in electret design enable the detector to make long-term or short-term measurements. Short-term detectors are deployed for 2 to 7 days, whereas long-term detectors may be deployed from 1 to 12 months.

Electrets are relatively inexpensive, passive, and can be used several times before discarding or recharging, except in areas of extreme radon concentrations. These detectors need to be corrected for the background gamma radiation during exposure since this ionization also discharges the electret.

Specificity/Sensitivity: Electrets are designed to make radon measurements primarily in indoor environments. Care must be taken to measure the background gamma radiation at the site during the exposure period. Extreme temperatures and humidity encountered outdoors may affect electret voltage. The minimum detectable concentration ranges from 0.007-0.02 Bq/L (0.2 to 0.5 pCi/L).

Cost of Equipment: Included in rental price

Cost per Measurement: $8 to $25 rental for an electret supplied by a vendor

System: LARGE AREA ACTIVATED CHARCOAL COLLECTOR
Lab/Field: Field
Radiation Detected: **Primary:** Radon gas **Secondary:** None

Applicability to Site Surveys: This method is used to make radon flux measurements (the surface emanation rate of radon gas) and involves the adsorption of radon on activated carbon in a large area collector.

Operation: The collector consists of a 10 inch diameter PVC end cap, spacer pads, charcoal distribution grid, retainer pad with screen, and a steel retainer spring. Between 170 and 200 grams of activated charcoal is spread in the distribution grid and held in place by the retainer pad and spring.

The collector is deployed by firmly twisting the end cap into the surface of 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. This data is used to calculate the radon flux in units of Bq m^{-2} s^{-1}.

Specificity/Sensitivity: These collectors give an accurate short-term assessment of the radon gas surface emanation rate from a material. The minimum detectable concentration of this method is 0.007 Bq m^{-2} s^{-1} (0.2 pCi m^{-2} s^{-1}).

Exposures greater than 24 hours are not recommended due to atmospheric and surface moisture and temperature extremes which may affect charcoal efficiency.

Cost of Equipment: Not applicable

Cost per Measurement: \$20 - \$50 including canister

H.2 FIELD SURVEY EQUIPMENT

H.2.5 X-Ray and Low Energy Gamma Detectors

System: FIDLER PROBE WITH SURVEY METER
Lab/Field: Field
Radiation Detected: **Primary:** X-ray **Secondary:** Low Energy Gamma
Applicability to Site Surveys: The FIDLER (Field Instrument for the Detection of Low Energy Radiation) probe is a specialized detector consisting of a thin layer of sodium or cesium iodide which is optimized to detect gamma and x-radiation below 100 keV. It is most widely used for determining the presence of Pu and ^{241}Am, and can be used for estimating radionuclide concentrations in the field.
Operation: The FIDLER consists of a thin beryllium or aluminum window, a thin crystal of sodium iodide, a quartz light pipe, and photomultiplier tube. The probe can have either a 3 in. or 5 in. crystal. The discussion below is applicable to 5 in. crystals. The survey meter requires electronics capable of setting a window about an x-ray or gamma ray energy. This window allows the probe and meter to detect specific energies and, in most cases, provide information about a single element or radionuclide. The window also lowers the background count. Two types of survey meters are generally used with FIDLER probes. One type resembles those used with GM and alpha scintillation probes. They have an analog meter and range switch. The second type is a digital survey meter, which can display the count rate or accumulate counts in a scaler mode for a preset length of time. Both types have adjustable high voltage and window settings. The advantage of the digital meter is that both background and sample counts can be acquired in scaler mode, yielding a net count above background. The activity of a radionuclide can then be estimated in the field.
Specificity/Sensitivity: The FIDLER probe is quite sensitive to x-ray and low energy gamma radiation. Since it has the ability to discriminate energies, an energy window can be set that makes it possible to determine the presence of specific radionuclides when the nature of the contamination is known. If the identity of a contaminant is known, the FIDLER can be used to quantitatively determine the concentration. However, interferences can cause erroneous results if other radionuclides are present. The FIDLER can also be used as a survey instrument to detect the presence of x-ray or low energy gamma contaminates, and to determine the extent of the contamination. FIDLER probes are most useful for determining the presence of Pu and ^{241}Am. These isotopes have a complex of x-rays and gamma rays from 13-21 keV that have energies centered around 17 keV, and ^{241}Am has a gamma at 59 keV. There is an interference at 13 keV from both americium and uranium x-rays. The FIDLER cannot distinguish which isotope of Pu is present. ^{241}Am can be identified based on the 59 keV gamma. Typical sensitivities for ^{238}Pu and ^{239}Pu at one foot above the surface of a contaminated area are 500 to 700 and 250 to 350 counts per minute per µCi per square meter (cpm/µCi/m^2), respectively. Assuming a soil density of 1.5, uniform contamination of the first 1 mm of soil, and a typical background of 400 counts per minute, the MDC for ^{238}Pu and ^{239}Pu would be 370 and 740 Bq/kg (10 and 20 pCi/g), or 1500 and 3000 Bq/m^2 (900 and 1,800 dpm/100 cm^2). This MDC is for fresh deposition; and will be significantly less as the plutonium migrates into the soil. Because the window is fragile, most operations with a FIDLER probe require a low mass protective cover to prevent damaging the window. Styrofoam, cardboard, and other cushioning materials are common choices for a protective cover.
Cost of Equipment: $4,000 to $7,000
Cost per Measurement: $10 to $20

System: FIELD X-RAY FLUORESCENCE SPECTROMETER
Lab/Field: Field
Radiation Detected: **Primary:** X-ray and low energy gamma radiation
Secondary: None

Applicability to Site Surveys: The system accurately measures relative concentrations of metal atoms in soil or water samples down to the ppm range.

Operation: This system is a rugged form of x-ray fluorescence system that measures the characteristic x-rays of metals as they are released from excited electron structures. The associated electronic and multi-channel analyzer systems are essentially identical to those used with germanium spectrometry systems. The spectra of characteristic x-rays gives information for both quantitative and qualitative analysis; however, most frequently, the systems are only calibrated for relative atomic abundance or percent composition.

Specificity/Sensitivity: This is ideal for cases of contamination by metals that have strong x-ray emissions within 5-100 keV. Application for quantification of the transition metals (in the periodic table) is most common because of the x-ray emissions. Operation of this equipment is possible with only a moderate amount of training. The sensitivity ranges from a few percent to ppm depending on the particular atoms and their characteristic x-rays. When converted to activity concentration, the minimum detectable concentration for ^{238}U is around 1,850 Bq/kg (50 pCi/g) for typical soil matrices.

Cost of Equipment: $15,000 - $75,000 depending on size, speed of operation and auxiliary features employed for automatic analysis of the results.

Cost per Measurement: $200

H.2 FIELD SURVEY EQUIPMENT

H.2.6 Other Field Survey Equipment

System: CHEMICAL SPECIES LASER ABLATION MASS SPECTROMETER
Lab/Field: Field
Radiation Detected: None

Applicability to Site Surveys: Chemical Species Laser Ablation Mass Spectrometry has been successfully applied to the analysis of organic and inorganic molecular species in condensed material with high sensitivity and specificity.

Operation: Solids can be converted into aerosol particles which contain much of the molecular species information present in the original material. (One way this is done is by laser excitation of one component of a solid mixture which, when volatilized, carries along the other molecular species without fragmentation.) Aerosol particles can be carried hundreds of feet without significant loss in a confined or directed air stream before analysis by mass spectrometry. Some analytes of interest already exist in the form of aerosol particles. Laser ablation is also preferred over traditional means for the conversion of the aerosol particles into molecular ions for mass spectral analysis. Instrument manufacturers are working with scientists at national laboratories and universities in the development of compact portable laser ablation mass spectrometry instrumentation for field based analyses.

Specificity/Sensitivity: This system can analyze soils and surfaces for organic and inorganic molecular species, with extremely good sensitivity. Environmental concentrations in the range of 10^{-9} - 10^{-14} g/g can be determined, depending on environmental conditions. It is highly effective when used by a skilled operator, but of limited use due to high costs. It may be possible to quantify an individual radionuclide if no other nuclides of that isotope are present in the sample matrix. Potential MDC's are $4x10^{-8}$ Bq/kg ($1x10^{-9}$ pCi/g) for ^{238}U, 0.04 Bq/kg (10^{-3} pCi/g) for ^{239}Pu, 4 Bq/kg (1 pCi/g) for ^{137}Cs, and 37 Bq/kg (10 pCi/g) for ^{60}Co.

Cost of Equipment: Very expensive (prototype)

Cost per Measurement: May be comparable to laser ablation inductively coupled plasma atomic emission spectrometry (LA-ICP-AES) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). When using the Atomic Emission Spectrometer, the reported cost is $4,000 per sample, or 80% of conventional sampling and analysis costs. This high cost for conventional samples is partly due to the 2-3 day time to analyze a sample for thorium by conventional methods. When using the mass spectrometer, the time required is about 30 minutes per sample.

System: LA-ICP-AES AND LA-ICP-MS
Lab/Field: Field
Radiation Detected: None

Applicability to Site Surveys: LA-ICP-AES and LA-ICP-MS are acronyms for Laser Ablation-Inductively Coupled Plasma-Atomic Emission Spectrometry or Mass Spectrometry. LA-ICP-AES/MS techniques are used to screen/characterize very small samples of soils and concrete (non-destructively) *in situ* to determine the level of contamination. It is particularly suited to measuring the surface concentration of uranium and thorium. The unit can assess the concentrations at various depths when lower levels are exposed by some means. It has the advantages of not consuming surface material, providing real time response, reducing sampling and analysis time, and keeping personnel clear of the materials being sampled. The information developed can assist in identifying locations for excavation. It is currently being tested.

Operation: Components of the system include a sampling system, fiber optics cables, spectrometer, potable water supply, cryogenic and high-pressure gas supply, a robotics arm, control computers, inductively coupled plasma torch, and video monitor.

Sampling probes have been developed and prototyped that will screen/characterize surface soils, concrete floors or pads, and subsurface soils. The sampling probes, both surface and subsurface, contain the laser (a 50-Hz Nd/YAG laser), associated optics, and control circuitry to raster the laser (ablation) energy across one square inch of sample surface. Either sampling probe is connected by an umbilical, currently 20 m long, to the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST), a completely self-contained mobile laboratory containing the instrumentation to immediately analyze the samples generated by the laser ablation.

A fiber optic cable delivers laser light to the surface of interest. This ablates a small quantity of material that is carried away in a stream of argon gas. The material enters the plasma torch where it is vaporized, atomized, ionized, and electrically excited at about 8,000 K. This produces an ionic emission spectrum that is analyzed on the atomic emission spectrometer.

The analysis instrumentation (ICP-AES/MS) in the MDLEST does not depend on radioactive decay for detection but looks directly at the atomic make up of the elements(s) of interest. A large number of metals including the longer half-life radioactive elements can be detected and quantified. The spectrometer is set up using either hardware, software, or both to simultaneously detect all elements of interest in each sample.

The MDLEST can be set up on site to monitor soil treatment processes. This function enables the remediation manager to monitor, in real time, the treatment processes removing the contaminants and ensure that satisfactory agreement with both regulatory agency and QC/QA requirements is attained.

Specificity/Sensitivity: This system measures the surface or depth concentration of atomic species, and is particularly suited to uranium and thorium analysis. It is highly effective with skilled operators. Some advantages are no contact with the soil, real time results, and no samples to dispose of. The sample results are quickly available for field remediation decisions, with the LA-ICP-AES taking about 10 minutes and LA-ICP-MS taking about 30 minutes. The detection limits for the two spectrometers that have been used are as follows:

1) The AES (atomic emission spectrometer) can see ppm levels for some 70 elements and reportedly detects uranium and thorium concentrations at 1 ppm, or 10 Bq/kg (0.3 pCi/g) for ^{238}U and 0.4 Bq/kg (0.1 pCi/g) for ^{232}Th. However, the technique is only sensitive to elements; it cannot discriminate between the different isotopes of uranium and thorium. This prevents it from being used for assessing lower Z elements that have stable isotopes, or from determining relative abundances of isotopes of any element. This may significantly limit its use at some sites.
2) The MS (mass spectrometer) can see sub-ppb levels and is capable of quantifying the uranium and thorium isotopes. This system has been used to search for ^{230}Th and ^{226}Ra and is reportedly useful in reaching 0.8 ppm or 0.6 Bq/g (15 pCi/g) for ^{230}Th content for remediated soil. It appears to measure uranium and thorium concentration of soil more sensitively than the LA-ICP-AES system.

Cost of Equipment: Very expensive, >$1M.

Cost per Measurement: When using the Atomic Emission Spectrometer, the reported cost is $4,000 per sample. When using the mass spectrometer, a dollar price was not provided.

H.3 LABORATORY INSTRUMENTS

H.3.1 Alpha Particle Analysis

System: ALPHA SPECTROSCOPY WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected: **Primary:** Alpha **Secondary:** None
Applicability to Site: This is a very powerful tool for accurately identifying and quantifying the activity of multiple alpha-emitting radionuclides in a sample of soil, water, air filters, etc. Methods exist for the analyses of most alpha emitting radionuclides including uranium, thorium, plutonium, polonium, and americium. Samples must first be prepared in a chemistry lab to isolate the radionuclides of interest from the environmental matrix.
Operation: This system consists of an alpha detector housed in a light-tight vacuum chamber, a bias supply, amplifier, analog-to-digital converter, multichannel analyzer, and computer. The bias is typically 25 to 100 volts. The vacuum is typically less than 10 microns (0.1 millitorr). The detector is a silicon diode that is reverse biased. Alpha particles which strike the diode create electron-hole pairs; the number of pairs is directly related to the energy of each alpha. These pairs cause a breakdown of the diode and a current pulse to flow. The charge is collected by a preamplifier and converted to a voltage pulse which is proportional to the alpha energy. It is amplified and shaped by an amplifier. The MCA stores the resultant pulses and displays a histogram of the number of counts vs. alpha energy. Since most alphas will loose all of their energy to the diode, peaks are seen on the MCA display that can be identified by specific alpha energies. Two system calibrations are necessary. A source with at least two known alpha energies is counted to correlate the voltage pulses with alpha energy. A standard source of known activity is analyzed to determine the system efficiency for detecting alphas. Since the sample and detector are in a vacuum, most commonly encountered alpha energies will be detected with approximately the same efficiency, provided there is no self-absorption in the sample. Samples are prepared in a chemistry lab. The sample is placed in solution and the element of interest (uranium, plutonium, *etc.*) separated. A tracer of known activity is added before separation to determine the overall recovery of the sample from the chemical procedures. The sample is converted to a particulate having very little mass and collected on a special filter, or it is collected from solution by electroplating onto a metal disk. It is then placed in the vacuum chamber at a fixed distance from the diode and analyzed. For environmental levels, samples are typically analyzed for 1000 minutes or more.
Specificity/Sensitivity: The system can accurately identify and quantify the various alpha emitting radioactive isotopes of each elemental species provided each has a different alpha energy that can be resolved by the system. For soils, a radionuclide can be measured below 0.004 Bq/g (0.1 pCi/g) . The system is appropriate for all alphas except those from gaseous radionuclides.
Cost of Equipment: $10,000 - $100,000 based on the number of detectors and sophistication of the computer and data reduction software. This does not include the cost of equipment for the chemistry lab.
Cost per Measurement: $250-$400 for the first element, $100-200 for each additional element per sample. The additional element cost depends on the separation chemistry involved and may not always be less. $200-$300 additional for a rush analysis.

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Lab
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate if nuclide-specific analysis is needed.
Operation: The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector. Systems with guard detectors operate sample and guard detectors in anticoincidence mode to reduce the background and MDC. The detector high voltage and discriminator are set to count alpha radiation, beta radiation, or both simultaneously. The alpha and beta operating voltages are determined for each system by placing an alpha source, like ^{230}Th or ^{241}Am, in the detector and increasing the high voltage incrementally until the count rate becomes constant, then repeating with a beta source, like ^{90}Sr. The alpha plateau, or region of constant count rate, should have a slope <2%/100V and be >800V long. The beta plateau should have a slope of <2.5%/100V and be >200V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (x-rays), but the efficiency is very low. Crosstalk between the α-to-β channels is typically around 10% while β-to-α channels should be <1%. The activity in soil samples is chemically extracted, separated if necessary, deposited in a thin layer in a planchet to minimize self absorption, and heated to dryness. Liquids are deposited and dried, while air filters and swipes are placed directly in the planchet. After each sample is placed under the detector, P-10 counting gas constantly flows through the detector. Systems with automatic sample changers can analyze tens to hundreds of planchet samples in a single run.
Specificity/Sensitivity: Natural radionuclides present in soil samples can interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radionuclides is well known, this system is better used for screening samples. Although it is possible to use a proportional counter to roughly determine the energies of alpha and beta radiation, the normal mode of operation is to detect all alpha events or all alpha and beta events. Some systems use a discriminator to separate alpha and beta events, allowing simultaneous determination of both the alpha and beta activity in a sample. These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides. The alpha channel background is very low, <0.2 cpm (<0.04 cpm guarded), depending on detector size. Typical, 4-pi, efficiencies for very thin alpha sources are 35-45% (window) and 40-50% (windowless). Efficiency depends on window thickness, particle energy, source-detector geometry, backscatter from the sample and holder, and detector size. The beta channel background ranges from 2 to 15 cpm (<0.5 cpm guarded). The 4-pi efficiency for a thin ^{90}Sr/^{90}Y source is >50% (window) to >60% (windowless), but can reduce to <5% for a thick source. MDA's for guarded gas-flow proportional counters are somewhat lower for beta emitters than for internal proportional counters because of the lower backgrounds. Analyzing a high radioactivity sample or flushing the detector with P10 gas at too high a flow rate can suspend fine particles and contaminate the detector.
Cost of Equipment: $4K-$5K (manual), $25K-$30K (automatic)
Cost per Measurement: $30 to $50 plus radiochemistry

System: LIQUID SCINTILLATION SPECTROMETER
Lab/Field: Lab (primarily), field (secondarily)
Radiation Detected: **Primary:** Alpha, beta **Secondary:** Gamma
Applicability to Site Surveys: Liquid Scintillation can be a very effective tool for measuring the concentration of radionuclides in soil, water, air filters, and swipes. Liquid scintillation has historically been applied more to beta emitters, particularly the low energy beta emitters ^{3}H and ^{14}C, but it can also apply to other radionuclides. More recently it has been used for measuring radon in air and water. Initial scoping surveys may be done (particularly for loose surface contamination) with surface swipes or air particulate filters. They may be counted directly in liquid scintillation cocktails with no paper dissolution or other sample preparation.
Operation: The liquid scintillation process involves detection of light pulses (usually in the near visible range) by photo-multiplier tubes (or conceptually similar devices). The detected light pulses originate from the re-structuring of previously excited molecular electron structures. The molecular species that first absorb and then re-admit the visible light are called "liquid scintillators" and the solutions in which they reside are called "liquid scintillation cocktails." For gross counting, samples may be placed directly into a LSC vial of cocktail, and counted with no preparation. Inaccuracies result when the sample itself absorbs the radiation before it can reach the LSC cocktail, or when the sample absorbs the light produced by the cocktail. For accurate results, these interferences are minimized. Interferences in liquid scintillation counting due to the inability of the solution to deliver the full energy pulse to the photo-multiplier detector, for a variety of reasons, are called "pulse quenching." Raw samples that cloud or color the LSC cocktail so the resulting scintillations are absorbed will "quench" the sample and result in underestimates of the activity. Such samples are first processed by ashing, radiochemical or solvent extraction, or pulverizing to place the sample in intimate contact with the LSC cocktail. Actions like bleaching the sample may also be necessary to make the cocktail solution transparent to the wavelength of light it emits. The analyst has several reliable computational or experimental procedures to account for "quenching." One is by exposing the sample and pure cocktail to an external radioactive standard and measuring the difference in response.
Specificity/Sensitivity: The method is extremely flexible and accurate when used with proper calibration and compensation for quenching effects. Energy spectra are 10 to 100 times broader than gamma spectrum photopeaks so that quantitative determination of complex multi-energy beta spectra is impossible. Sample preparation can range from none to complex chemical reactions. In some cases, liquid scintillation offers many unique advantages; no sample preparation before counting in contrast to conventional sample preparation for gas proportional counting. Recent advances in electronic stability and energy pulse shape discrimination has greatly expanded uses. Liquid scintillation counters are ideal instruments for moderate to high energy beta as well as alpha emitters, where the use of pulse shape discrimination has allowed dramatic increases in sensitivity by electronic discrimination against beta and gamma emitters. Additionally, very high energy beta emitters (above 1.5 MeV) may be counted using liquid scintillation equipment without "liquid scintillation cocktails" by use of the Cerenkov light pulse emitted as high energy charged particles move through water or similar substances.
Cost of Equipment: $20,000 to $70,000 based on the specific features and degree of automation
Cost per Measurement: $50 -200 plus cost of chemical separation, if required

System: LOW-RESOLUTION ALPHA SPECTROSCOPY
Lab/Field: Lab (Soil Samples)
Radiation Detected: **Primary:** Alpha **Secondary:**

Applicability to Site Surveys: Low-resolution alpha spectroscopy is a method for measuring alpha activity in soils with a minimum of sample preparation. Some isotopic information can be obtained.

Operation: The system consists of a 2 in. diameter silicon detector, small vacuum chamber, roughing pump, multichannel analyzer, laptop or benchtop computer, and analysis software. Soil samples are dried, milled to improve homogeneity, distributed into 2 in. planchets, loaded into the vacuum chamber, and counted. The accumulated alpha spectrum is displayed in real time. When sufficient counts have been accumulated, the spectrum is transferred to a data file and the operator inputs the known or suspected contaminant isotopes. The analysis software then fits the alpha spectrum with a set of trapezoidal peaks, one for each isotope, and outputs an estimate of the specific activity of each isotope.

Specificity/Sensitivity: This method fills the gap between gross alpha analysis and radiochemical separation/high-resolution alpha spectroscopy. Unlike gross alpha analysis, it does provide some isotopic information. Because this is a low-resolution technique, isotopes with energies closer than ~0.2 MeV cannot be separated. For example, ^{238}U (4.20 MeV) can be readily distinguished from ^{234}U (4.78 MeV), but ^{230}Th (4.69 MeV) cannot be distinguished from ^{234}U.

Because no chemical separation of isotopes is involved, only modest MDC's can be achieved. Detection limits are determined by the background alpha activity in the region of interest of the contaminant of concern, and also by the counting time. Typical MDC's are 1,500 Bq/kg (40 pCi/g) @ l5 min counting time, 260 Bq/kg (7 pCi/g) @ 8 hours, and 185 Bq/kg (5 pCi/g) @ 24 hours. The method does not generate any new waste streams and does not require a sophisticated laboratory or highly-trained personnel.

Cost of Equipment: $11,000

Cost per Measurement: $25-$100

H.3 LABORATORY INSTRUMENTS

H.3.2 Beta Particle Analysis

System: GAS-FLOW PROPORTIONAL COUNTER
Lab/Field: Lab
Radiation Detected: **Primary:** Alpha, Beta **Secondary:** Gamma
Applicability to Site Surveys: This system can determine the gross alpha or gross beta activity of water, soil, air filters, or swipes. Results can indicate if nuclide-specific analysis is needed.
Operation: The system consists of a gas-flow detector, supporting electronics, and an optional guard detector for reducing background count rate. A thin window can be placed between the gas-flow detector and sample to protect the detector from contamination, or the sample can be placed directly into the detector. Systems with guard detectors operate sample and guard detectors in anticoincidence mode to reduce the background and MDC. The detector high voltage and discriminator are set to count alpha radiation, beta radiation, or both simultaneously. The alpha and beta operating voltages are determined for each system by placing an alpha source, like ^{230}Th or ^{241}Am, in the detector and increasing the high voltage incrementally until the count rate becomes constant, then repeating with a beta source, like ^{90}Sr. The alpha plateau, or region of constant count rate, should have a slope <2%/100V and be >800V long. The beta plateau should have a slope of <2.5%/100V and be >200V long. Operation on the beta plateau will also allow detection of some gamma radiation and bremsstrahlung (x-rays), but the efficiency is very low. Crosstalk between the α-to-β channels is typically around 10% while β-to-α channels should be <1%. The activity in soil samples is chemically extracted, separated if necessary, deposited in a thin layer in a planchet to minimize self absorption, and heated to dryness. Liquids are deposited and dried, while air filters and swipes are placed directly in the planchet. After each sample is placed under the detector, P-10 counting gas constantly flows through the detector. Systems with automatic sample changers can analyze tens to hundreds of planchet samples in a single run.
Specificity/Sensitivity: Natural radionuclides present in soil samples can interfere with the detection of other contaminants. Unless the nature of the contaminant and any naturally-occurring radionuclides is well known, this system is better used for screening samples. Although it is possible to use a proportional counter to roughly determine the energies of alpha and beta radiation, the normal mode of operation is to detect all alpha events or all alpha and beta events. Some systems use a discriminator to separate alpha and beta events, allowing simultaneous determination of both the alpha and beta activity in a sample. These systems do not identify the alpha or beta energies detected and cannot be used to identify specific radionuclides. The alpha channel background is very low, <0.2 cpm (<0.04 cpm guarded), depending on detector size. Typical, 4-pi, efficiencies for very thin alpha sources are 35-45% (window) and 40-50% (windowless). Efficiency depends on window thickness, particle energy, source-detector geometry, backscatter from the sample and holder, and detector size. The beta channel background ranges from 2 to 15 cpm (<0.5 cpm guarded). The 4-pi efficiency for a thin ^{90}Sr/^{90}Y source is >50% (window) to >60% (windowless), but can reduce to <5% for a thick source. MDA's for guarded gas-flow proportional counters are somewhat lower for beta emitters than for internal proportional counters because of the lower backgrounds. Analyzing a high radioactivity sample or flushing the detector with P10 gas at too high a flow rate can suspend fine particles and contaminate the detector.
Cost of Equipment: $4K-$5K (manual), $25K-$30K (automatic)
Cost per Measurement: $30 to $50 plus radiochemistry

System: LIQUID SCINTILLATION SPECTROMETER
Lab/Field: Lab (primarily), field (secondarily)
Radiation Detected: **Primary:** Alpha, beta **Secondary:** Gamma
Applicability to Site Surveys: Liquid Scintillation can be a very effective tool for measuring the concentration of radionuclides in soil, water, air filters, and swipes. Liquid scintillation has historically been applied more to beta emitters, particularly the low energy beta emitters ^{3}H and ^{14}C, but it can also apply to other radionuclides. More recently it has been used for measuring radon in air and water. Initial scoping surveys may be done (particularly for loose surface contamination) with surface swipes or air particulate filters. They may be counted directly in liquid scintillation cocktails with no paper dissolution or other sample preparation.
Operation: The liquid scintillation process involves detection of light pulses (usually in the near visible range) by photo-multiplier tubes (or conceptually similar devices). The detected light pulses originate from the re-structuring of previously excited molecular electron structures. The molecular species that first absorb and then re-admit the visible light are called "liquid scintillators" and the solutions in which they reside are called "liquid scintillation cocktails." For gross counting, samples may be placed directly into a LSC vial of cocktail, and counted with no preparation. Inaccuracies result when the sample itself absorbs the radiation before it can reach the LSC cocktail, or when the sample absorbs the light produced by the cocktail. For accurate results, these interferences are minimized. Interferences in liquid scintillation counting due to the inability of the solution to deliver the full energy pulse to the photo-multiplier detector, for a variety of reasons, are called "pulse quenching." Raw samples that cloud or color the LSC cocktail so the resulting scintillations are absorbed will "quench" the sample and result in underestimates of the activity. Such samples are first processed by ashing, radiochemical or solvent extraction, or pulverizing to place the sample in intimate contact with the LSC cocktail. Actions like bleaching the sample may also be necessary to make the cocktail solution transparent to the wavelength of light it emits. The analyst has several reliable computational or experimental procedures to account for "quenching." One is by exposing the sample and pure cocktail to an external radioactive standard and measuring the difference in response.
Specificity/Sensitivity: The method is extremely flexible and accurate when used with proper calibration and compensation for quenching effects. Energy spectra are 10 to 100 times broader than gamma spectrum photopeaks so that quantitative determination of complex multi-energy beta spectra is impossible. Sample preparation can range from none to complex chemical reactions. In some cases, liquid scintillation offers many unique advantages such as no sample preparation before counting in contrast to conventional sample preparation for gas proportional counting. Recent advances in electronic stability and energy pulse shape discrimination has greatly expanded uses. Liquid scintillation counters are ideal instruments for moderate to high energy beta as well as alpha emitters, where the use of pulse shape discrimination has allowed dramatic increases in sensitivity by electronic discrimination against beta and gamma emitters. Additionally, very high energy beta emitters (above 1.5 MeV) may be counted using liquid scintillation equipment without "liquid scintillation cocktails" by use of the Cerenkov light pulse emitted as high energy charged particles move through water or similar substances.
Cost of Equipment: $20,000 to $70,000 based on the specific features and degree of automation
Cost per Measurement: $50 -200 plus cost of chemical separation, if required

H.3 LABORATORY INSTRUMENTS

H.3.3 Gamma Ray Analysis

System: GERMANIUM DETECTOR WITH MULTICHANNEL ANALYZER (MCA)
Lab/Field: Lab
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site: This system accurately measures the activity of gamma-emitting radionuclides in a variety of materials like soil, water, air filters, etc. with little preparation. Germanium is especially powerful in dealing with multiple radionuclides and complicated spectra.
Operation: This system consists of a germanium detector connected to a dewar of liquid nitrogen, high voltage power supply, spectroscopy grade amplifier, analog to digital converter, and a multichannel analyzer. P-type germanium detectors typically operate from +2000 to +5000 volts. N-type germanium detectors operate from -2000 to -5000 volts. Germanium is a semiconductor material. When a gamma ray interacts with a germanium crystal, it produces electron-hole pairs. An electric field is applied which causes the electrons to move in the conduction band and the holes to pass the charge from atom to neighboring atom. The charge is collected rapidly and is proportional to the deposited energy. The count rate/energy spectrum is displayed on the MCA screen with the full energy photopeaks providing more useful information than the general smear of Compton scattering events shown in between. The system is energy calibrated using isotopes that emit at least two known gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's display then becomes a display of intensity versus energy. Efficiency calibration is performed using known concentrations of mixed isotopes. A curve of gamma ray energy versus counting efficiency is generated, and it shows that P-type germanium is most sensitive at 120 keV and trails off to either side. Since the counting efficiency depends on the distance from the sample to the detector, each geometry must be given a separate efficiency calibration curve. From that point the center of each gaussian-shaped peak tells the gamma ray energy that produced it, the combination of peaks identifies each isotope, and the area under selected peaks is a measure of the amount of that isotope in the sample. Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. Counting times of 1000 seconds to 1000 minutes are typical. Each peak is identified manually or by gamma spectrometry analysis software. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope's decay scheme are factored together to give the sample concentration.
Specificity/Sensitivity: The system accurately identifies and quantifies the concentrations of multiple gamma-emitting radionuclides in samples like soil, water, and air filters with minimum preparation. A P-type detector is good for energies over 50 keV. An N-type or P-type planar (thin crystal) detector with beryllium-end window is good for 5-80 keV energies using a thinner sample placed over the window.
Cost of Equipment: $35,000 to $150,000 based on detector efficiency and sophistication of MCA/computer/software system
Cost per Measurement: $ 100 to $200 (rush requests can double or triple costs)

System: SODIUM IODIDE DETECTOR WITH MULTICHANNEL ANALYZER
Lab/Field: Lab
Radiation Detected: **Primary:** Gamma **Secondary:** None
Applicability to Site Surveys: This system accurately measures the activity of gamma-emitting radionuclides in a variety of materials like soil, water, air filters, etc. with little preparation. Sodium iodide is inherently more efficient for detecting gamma rays but has lower resolution than germanium, particularly if multiple radionuclides and complicated spectra are involved.
Operation: This system consists of a sodium iodide detector, a high voltage power supply, an amplifier, an analog to digital converter, and a multichannel analyzer. The detector is a sodium iodide crystal connected to a photomultiplier tube (PMT). Crystal shapes can vary extensively and typical detector high voltage are 900-1,000 V. Sodium iodide is a scintillation material. A gamma ray interacting with a sodium iodide crystal produces light which is passed to the PMT. This light ejects electrons which the PMT multiplies into a pulse that is proportional to the energy the gamma ray imparted to the crystal. The MCA assesses the pulse size and places a count in the corresponding channel. The count rate and energy spectrum is displayed on the MCA screen with the full energy photopeaks providing more useful information than the general smear of Compton scattering events shown in between. The system is energy calibrated using isotopes that emit at least two gamma ray energies, so the MCA data channels are given an energy equivalence. The MCA's CRT then becomes a display of intensity versus energy. A non-linear energy response and lower resolution make isotopic identification less precise than with a germanium detector. Efficiency calibration is performed using known concentrations of single or mixed isotopes. The single isotope method develops a count rate to activity factor. The mixed isotope method produces a gamma ray energy versus counting efficiency curve that shows that sodium iodide is most sensitive around 100-120 keV and trails off to either side. Counting efficiency is a function of sample to detector distance, so each geometry must have a separate efficiency calibration curve. The center of each peak tells the gamma ray energy that produced it and the combination of peaks identifies each isotope. Although the area under a peak relates to that isotope's activity in the sample, integrating a band of channels often provides better sensitivity. Samples are placed in containers and tare weighed. Plastic petri dishes sit atop the detector and are useful for small volumes or low energies, while Marinelli beakers fit around the detector and provide exceptional counting efficiency for volume samples. Counting times of 60 seconds to 1,000 minutes are typical. The CRT display is scanned and each peak is identified by isotope. The counts in each peak or energy band, the sample weight, the efficiency calibration curve, and the isotope's decay scheme are factored together to give the sample concentration.
Specificity/Sensitivity: This system analyzes gamma-emitting isotopes with minimum preparation, better efficiency, but lower resolution compared to most germanium detectors. Germanium detectors do reach efficiencies of 150% compared with a 3 in. by 3 in. sodium iodide detector, but the cost is around $100,000 each compared with $3,000. Sodium iodide measures energies over 80 keV. The instrument response is energy dependent, the resolution is not superb, and the energy calibration is not totally linear, so care should be taken when identifying or quantifying multiple isotopes. Computer software can help interpret complicated spectra. Sodium iodide is fragile and should be protected from shock and sudden temperature changes.
Cost of Equipment: $6K-$20K
Cost per Measurement: $100-$200 per sample.

EQUIPMENT SUMMARY TABLES

Table H.1 Radiation Detectors with Applications to Alpha Surveys

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Alpha spectroscopy	A system using silicon diode surface barrier detectors for alpha energy identification and quantification	Accurately identifies and measures the activity of multiple alpha radionuclides in a thin extracted sample of soil, water, or air filters.	Sample requires radiochemical separation or other preparation before counting	$10K-$100K	$250-$400
Alpha scintillation survey meter	<1 mg/cm^2 window, probe face area 50 to 100 cm^2.	Field measurement of presence or absence of alpha contamination on nonporous surfaces, swipes, and air filters, or on irregular surfaces if the degree of surface shielding is known.	Minimum sensitivity is 10 cpm, or 1 cpm with headphones	$1000	$5
Alpha Track Detector	Polycarbonate plastic sheet is placed in contact with a contaminated surface and kept in place	Measures gross alpha surface contamination, soil activity level, or the depth profile of contamination	Alpha radiation produces holes that are enlarged chemically. Density of holes gives a measure of the radioactivity level.		$5-$25
Electret ion chamber	A charged Teflon disk in an open-faced ion chamber	Measures alpha or beta contamination on surfaces and in soils, plus gamma radiation dose or radon concentration	The type of radiation is determined by how the electret is employed, *e.g.*, the unit is kept closed and bagged in plastic to measure gammas	$4,000-$5,000	$8-$25
Long range alpha detector (LRAD)	1m x 1m detector measures ionization inside the box. Attached to tractor for movement. Has location finder and plots graph of contamination.	Measures surface contamination or soil concentration at grid points and plots curves of constant contamination. Intended for large areas.	Alpha detection limit is 20-50 dpm/100 cm^2 or 0.4 Bq/g (10 pCi/g).	$25,000	$80

Table H.1 Radiation Detectors with Applications to Alpha Surveys

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation. < 1-10 mg/cm^2 window, probe face area 50 to 100 cm^2 for hand held detectors; up to 600 cm^2 if cart mounted	Surface scanning, surface activity measurement, or field evaluation of swipes. Serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other contaminants. Requires P10 gas	$2K-$4K	$2-$10/m^2
Gas-flow proportional counter (lab)	Windowless (internal proportional) or window <0.1 mg/cm^2, probe face area 10 to 20 cm^2. May have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air, and swipe samples	Requires P10 gas. Windowless detectors can be contaminated.	$4K-$30K	$50
Liquid scintillation counter (LSC)	Samples are mixed with LSC cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha or beta emitters, including spectrometry capabilities.	Highly selective for alpha or beta radiation by pulse shape discrimination. Requires LSC cocktail.	$20K-$70K	$50-$200

Table H.2 Radiation Detectors with Applications to Beta Surveys

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
GM survey meter with beta pancake probe	Thin 1.4 mg/cm^2 window detector, probe area 10 to 100 cm^2	Surface scanning of personnel, working areas, equipment, and swipes for beta contamination. Laboratory measurement of swipes when connected to a scaler.	Relatively high detection limit making it of limited value in final status surveys.	\$400-\$1,500	\$5-\$10
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation. < 1-10 mg/cm^2 window, probe face area 50 to 100 cm^2	Surface scanning, surface activity measurement, or field evaluation of swipes. Serves as a screen to determine if more nuclide-specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other contaminants. Requires P10 gas, but can be disconnected for hours.	\$2K-\$4K	\$2-\$10/m^2
Gas-flow proportional counter (lab)	Windowless (internal proportional) or window <0.1 mg/cm^2, probe face area 10 to 20 cm^2. May have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air, and swipe samples	Requires P10 gas. Windowless detectors can be contaminated.	\$4K-\$30K	\$50
Liquid scintillation counter (LSC)	Samples are mixed with LSC cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha and beta emitters, including spectrometry capabilities.	Highly selective for alpha and beta radiation by pulse shape discrimination. Requires LSC cocktail.	\$20K-\$70K	\$100-\$200

Table H.3 Radiation Detectors with Applications to Gamma and X-Ray Surveys

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
GM survey meter with gamma probe	Thick-walled 30 mg/cm^2 detector	Measure radiation levels above 0.1 mR/hr.	Its non-linear energy response can be corrected by using an energy compensated probe.	\$400-\$1,000	\$5
Pressurized ion chamber (PIC)	A highly accurate ionization chamber that is rugged and stable.	Excellent for measuring gamma exposure rate during site remediation.	Is used in conjunction with radionuclide identification equipment.	\$15K - \$50K	\$50 - \$500
Electret ion chamber	Electrostatically charged disk inside an ion chamber	Gamma exposure rate	N/A, rented	included in rental price	\$8 - \$25
Hand-held ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate.	Not very useful for site surveys because of high detection limit above background levels.	\$800-\$1,200	\$5
Hand-held pressurized ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate with more sensitivity than the unpressurized ion chamber.	Not very useful for site surveys because of high detection limit above background levels.	\$1,000-\$1,500	\$5
Sodium Iodide survey meter	Detectors sizes up to 8"x8". Used in micro R-meter in smaller sizes.	Measures low levels of environmental radiation.	Its energy response is not linear, so it should be calibrated for the energy field it will measure or have calibration factors developed by comparison with a PIC for a specific site.	\$2K	\$5
FIDLER (Field Instrument for Detection of Low Energy Radiation)	Thin crystals of NaI or CsI.	Scanning of gamma/X radiation from plutonium and americium.		\$6K-\$7K	\$10-\$20

Table H.3 Radiation Detectors with Applications to Gamma and X-Ray Surveys

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
Sodium iodide detector with multichannel analyzer (MCA)	Sodium iodide crystal with a large range of sizes and shapes, connected to a photomultiplier tube and MCA.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radionuclides in a sample.	Sensitive for surface soil or groundwater contamination. Analysis programs have difficulty if sample contains more than a few isotopes.	$6K-$20K	$100 to $200
Germanium detector with multichannel analyzer (MCA)	Intrinsic germanium semiconductor in p- or n-type configuration and without a beryllium window.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radionuclides in a sample.	Very sensitive for surface soil or groundwater contamination. Is especially powerful when more than one radionuclide is present in a sample.	$35K-$150K	$100 to $200
Portable Germanium Multichannel Analyzer (MCA) System	A portable version of a laboratory based germanium detector and multichannel analyzer.	Excellent during characterization through final status survey to identify and quantify the concentration of gamma ray emitting radionuclides and in situ concentrations of soil and other media	Requires a supply of liquid nitrogen or a mechanical cooling system, as well as highly trained operators.	$40K	$100
Field x-ray fluorescence spectrometer	Uses silicon or germanium semiconductor	Determining fractional abundance of low percentage metal atoms.		$15K-$75K	$200
Thermoluminescence dosimeters (TLDs)	Crystals that are sensitive to gamma radiation	Measure cumulative radiation dose over a period of days to months.	Requires special calibration to achieve high accuracy and reproducibility of results.	$5K-$50K for reader + $25-$40 per TLD	$25-$125

Table H.4 Radiation Detectors with Applications to Radon Surveys

System	Description	Application	Remarks	Equipment Cost	Measurement Cost
Large area activated charcoal collector	A canister containing activated charcoal is twisted into the surface and left for 24 hours.	Short term radon flux measurements	The LLD is 0.007 Bq $m^{-2}s^{-1}$ (0.2 pCi $m^{-2}s^{-1}$).	N/A, rented	\$20-\$50 including canister
Continuous radon monitor	Air pump and scintillation cell or ionization chamber	Track the real time concentration of radon	Takes 1 to 4 hours for system to equilibrate before starting. The LLD is 0.004-0.04 Bq/L (0.1-1.0 pCi/L).	\$1K-\$5K	\$80
Activated charcoal adsorption	Activated charcoal is opened to the ambient air, then gamma counted on a gamma scintillator or in a liquid scintillation counter.	Measure radon concentration in indoor air	Detector is deployed for 2 to 7 days. The LLD is 0.007-0.04 Bq/L (0.2 to 1.0 pCi/L).	\$10K-\$30K	\$5-\$30 including canister if outsourced.
Electret ion chamber	This is a charged plastic vessel that can be opened for air to pass into.	Measure short-term or long-term radon concentration in indoor air.	Must correct reading for gamma background concentration. Electret is sensitive to extremes of temperature and humidity. LLD is 0.007-0.02 Bq/L (0.2-0.5 pCi/L).	N/A, rented	\$8-\$25 for rental
Alpha track detection	A small piece of special plastic or film inside a small container. Damage tracks from alpha particles are chemically etched and tracks counted.	Measure indoor or outdoor radon concentration in air.	LLD is 0.04 Bq $L^{-1}d^{-1}$ (1 pCi $L^{-1}d^{-1}$).		\$5-\$25

Table H.5 Systems that Measure Atomic Mass or Emissions

System	Description	Application	Remarks	Cost of Equipment	Cost per Measurement
LA-ICP-AES (Laser Ablation Inductively Coupled Plasma Atomic Emissions Spectrometer)	Vaporizes and ionizes the surface material, and measures emissions from the resulting atoms.	Live time analysis of radioactive U and Th contamination in the field.	Requires expensive equipment and skilled operators. LLD is 0.004 Bq/g (0.1 pCi/g) for ^{232}Th and 0.01 Bq/g (0.3 pCi/g) for ^{238}U.	>$1,000,000	$4,000
LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometer)	Vaporizes and ionizes the surface material, then measures the mass of the resulting atoms.	Live time analysis of radioactive U and Th contamination in the field.	Requires expensive equipment and skilled operators. More sensitive than LA-ICP-AES. LLD is 0.6 Bq/g (15 pCi/g) for ^{230}Th.	>$1,000,000	>$4,000
Chemical speciation laser ablation/mass spectrometer	A laser changes the sample into an aerosol that it analyzed with a mass spectrometer.	Analyze organic and inorganic species with high sensitivity and specificity.	Volatilized samples can be carried hundreds of feet to the analysis area.	>$1,000,000	>$4,000