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ENVIRONMENTAL CHARACTERISTICS OF EPA, NRC, AND DOE SITES CONTAMINATED WITH RADIOACTIVE SUBSTANCES

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A Cooperative Effort By

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PREFACE

This report is the product of the Interagency Environmental Pathway Modeling Workgroup. The Workgroup is composed of representatives of the Environmental Protection Agency Office of Radiation and Indoor Air and Office of Solid Waste and Emergency Response, the Department of Energy Office of Environmental Restoration, and the Nuclear Regulatory Commission Office of Nuclear Material Safety and Safeguards. This report is one of several consensus documents being developed cooperatively by the Workgroup. These documents will help bring a uniform approach to solving environmental modeling problems common to these three participating agencies in their site remediation and restoration efforts. The conclusions and recommendations contained in this report represent a consensus among the Workgroup members.

ABSTRACT

The U.S. Environmental Protection Agency (EPA) Offices of Radiation and Indoor Air Programs and Solid Waste and Emergency Response, the U.S. Department of Energy (DOE) Office of Environmental Restoration and Waste Management, and the Nuclear Regulatory Commission (NRC) Office of Nuclear Material Safety and Safeguards have initiated preliminary efforts to promote the more appropriate and consistent use of computer models in the remediation of sites contaminated by radioactive substances and managed by the participating Federal agencies. As a baseline for these overall efforts, the nature and types of problems present at these sites must be understood. This report responds to this need. It presents in textual, tabular, and graphical formats: a list of the 45 EPA National Priorities List Superfund sites and the 38 NRC Site Decommissioning Management Plan sites containing radioactive waste materials, the types of wastes found at each site, a description of the physical form of the waste, physical characteristics of the site itself, and demographic characteristics of the region surrounding the site. The summary information presented in this report will support other programmatic efforts to identify benchmark type sites and problems for computer model selection and evaluation purposes. Similarly, the report provides a broad overview of the general and unique problems prevalent at radioactively contaminated sites.

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1 Introduction

The U.S. Environmental Protection Agency (EPA) Offices of Radiation Programs (ORP) and Solid Waste and Emergency Response (OSWER), the U.S. Department of Energy (DOE) Office of Environmental Restoration and Waste Management (EM), and the Nuclear Regulatory Commission (NRC) Office of Nuclear Material Safety and Safeguards (ONMSS) have initiated preliminary efforts to promote the more appropriate and consistent use of computer models by the participating federal agencies to remediate sites contaminated with radioactive substances. To coordinate modeling activities within and among the three participating agencies, a project has been initiated to describe the roles of modeling at each stage in the remedial process; to identify models in actual use at EPA Superfund National Priorities List (NPL)/Resource Conservation and Recovery Act (RCRA) sites, DOE Environmental Restoration and Waste Management (EM) sites and NRC Decontamination and Decommissioning (D&D) sites; to produce detailed critical reviews of selected models in widespread use; and to produce draft guidance for Remedial Project Managers (RPMs), On-Scene Coordinators (OSCs) and their equivalents to select and review models used in remediation and restoration submittals. As the program matures and a portfolio of reviews is completed, efforts will be initiated to produce an inventory of models for specific remediation and restoration problems, and a guidance document for model selection and evaluation purposes.

As a baseline for these overall efforts, the nature and types of problems present at the several types of remediation sites contaminated with radioactive materials must be understood. Characterizations are available for every site on the NPL in the form of Hazard Ranking System (HRS) screening packages, as well as for NRC Site Decommissioning Management Plan (SDMP) and DOE/EM sites. However, a broad overview is needed. This report responds to this need.

Following administrative guidance, the emphasis in this report is on the 45 NPL sites containing radioactive materials. Among these are included 10 DOE/EM sites (which account for 14 of the 45 NPL sites). For completeness, 38 NRC/SDMP sites are also reviewed (one of which is also on the NPL), but in less detail. Because effort was concentrated on the NPL sites, data for the SDMP sites may in some cases be sparse.

Figure 1 illustrates the framework which was used to select site characteristics most important in controlling the transport of contaminants from a site to the environment. Specifically, this report presents in textual, graphical and tabular formats:

- a brief overview of the statutory and regulatory processes administered by EPA and NRC to remediate abandoned hazardous waste sites,
- a list of the 45 Superfund sites and 38 SDMP sites containing radioactive materials,
- a list of the radioactive isotopes found, and the media contaminated at each site,
- a description of the physical form of the waste (*e.g.*, packaged in a drum or buried in a trench),
- environmental and geohydrologic characteristics of the site, (*e.g.*, depth to groundwater and mean annual precipitation), and
- characteristics of the region surrounding the site (*e.g.*, population density and type of land use).

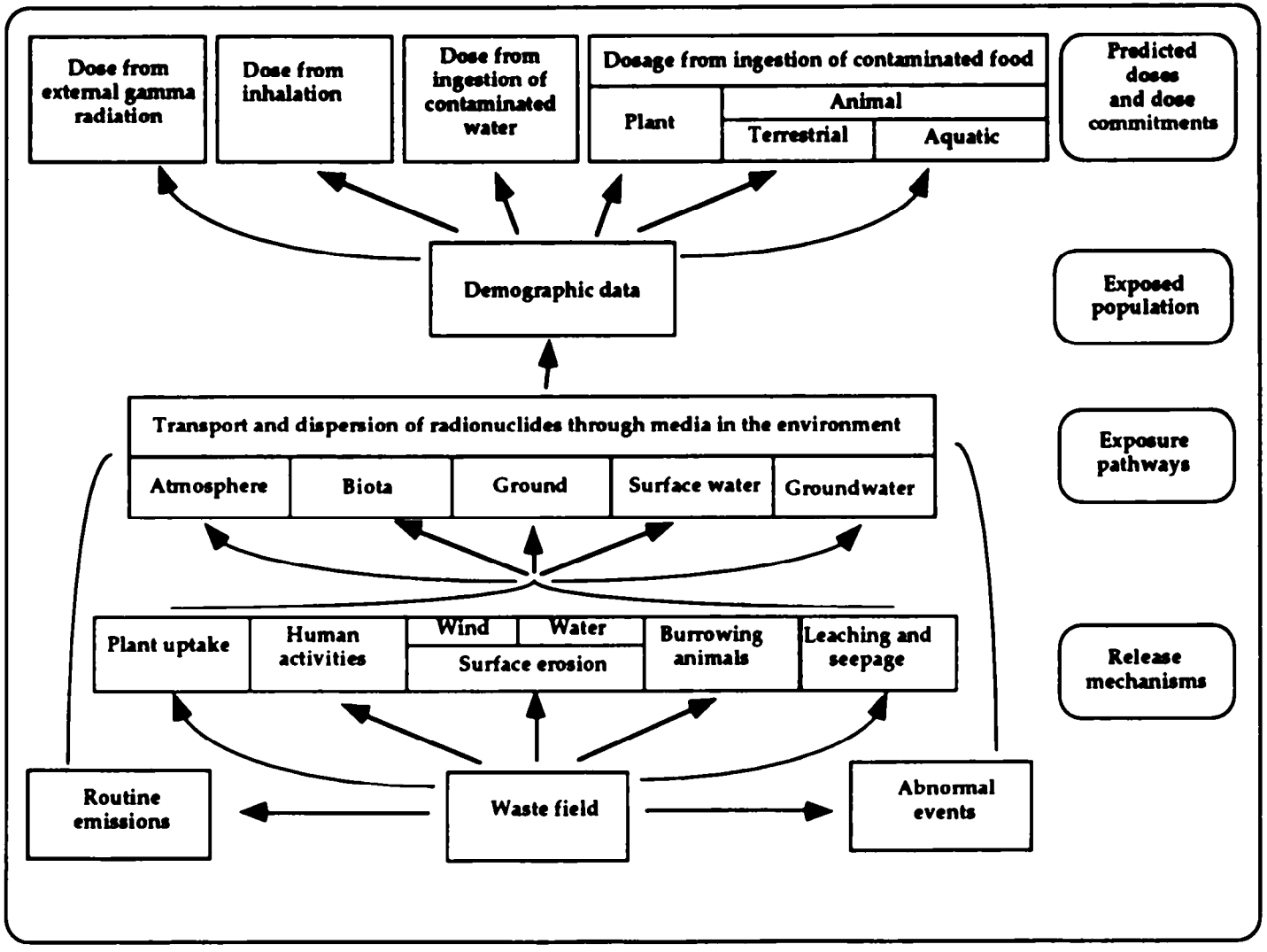

Figure 1. Exposure pathways

This report does not intend to provide a complete description of every site, neither are the data presented necessarily input to any particular pathway model. Likewise data may have been omitted which are essential to processes of computer simulation of contaminant transport. The characteristics data found in these tables will drive the selection of particular pathway models. In addition, every model will require a given set of data which are defined by the pathway be modelled. It should be noted here that data quality could at some sites be considered a site characteristic. As noted throughout this document, data quality varies significantly; at many sites certain data may be unreliable, sparse or absent.

In spite of these limitations the summary information presented in this report will support other programmatic efforts to identify bench-mark type sites and problems for model selection and evaluation purposes. Similarly, the report provides a broad overview of the general and unique problems prevalent at Superfund NPL, DOE/EM and NRC SDMP radioactively-contaminated sites.

2 Statutory and Regulatory Considerations

2.1 CERCLA/SARA

Under the authority of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1984 (42 USC 9601) as amended by the Superfund Amendments Reauthorization Act of 1986 (SARA) (Public Law 99-499), EPA is charged to determine priorities for the clean-up of abandoned hazardous waste sites and to take remedial actions. To help meet this mandate and to help set priorities, EPA has adopted and used the Hazard Ranking System (HRS) (47 FR 31180, July 16, 1982; 55 FR 51532, December 14, 1990). The HRS is a scoring system used to assess the relative threat associated with the actual or potential releases of hazardous substances at a site. Each environmental pathway at a site is scored according to potential transport pathways and waste and receptor characteristics. The composite score is used by EPA to determine whether a site is to be included on the NPL, the Agency's list of sites that are priorities for long-term evaluation and remedial response.

In the original HRS (47 FR 31180, July 16, 1982) and its subsequent revision (55 FR 51532, December 14, 1990), sites at which radionuclides are found are treated differently. In the original HRS, all radionuclides were assigned a maximum toxicity value by default because they are categorized by EPA as known human carcinogens (See Section 4). In the revised HRS, radionuclides are evaluated within the same basic structure as other hazardous substances, and the evaluation of many individual HRS factors is the same whether radionuclides are present or not. For sites containing only radionuclides, the revised HRS scoring process is very similar to the process for other hazardous wastes, except that different scoring rules are applied to a number of radiation-specific factors and a few other factors. For sites containing both radionuclides and other hazardous substances, both types of substances are scored for all HRS factors.

All but two of the sites on the NPL which have been classified by EPA as "radioactive" were scored using the original HRS. As noted above, under the orginal HRS there was limited instruction for assessing the radioactive portion of the hazard at a site. Consequently, sites listed on the NPL were most likely scored due to the nonradiologic component. With the advent of the revised HRS, radioactive materials are treated in a manner consistent with other hazardous wastes. Irrespective of the scoring process used, EPA classifies all sites containing significant amounts of radioactive substances as "radioactive" for the purposes of remediation.

2.2 Site Decommissioning Management Plan (SDMP)

Under the Atomic Energy Act, as amended, the NRC has regulatory authority for source, special nuclear, and by-product material. Though not regulated under CERCLA and RCRA, the technical issues associated with the cleanup of NRC licensed sites are in many respects similar to those associated with the remediation of sites under CERCLA/SARA.

In SECY-88-308 and SECY-89-369 the NRC staff identified over 30 material facilities sites that have a sufficient level of contamination to require special attention from the Staff. The Office of Material Safety and Safeguards (ONMSS) has regulatory responsibility for these sites and cannot terminate the licenses nor release these sites for unrestricted use until the sites are decontaminated. The objective of the SDMP is the timely cleanup of these sites. The NRC has directed that the sites be prioritized according to a combination of health and safety factors, including:

- timeliness of action needed,
- status of regulatory efforts,
- knowledge of responsible parties, and
- Congressional commitments.

In contrast to the quantitative approach of HRS ranking, these factors are assigned weighted priority scores based on subjective analysis of site status. Overall toxicity of the radioactive species, migration potential of the radioactive material, and proximity to a potentially exposed population are considered in assigning the Timeliness score, for example. The SDMP sites are assigned priority level A, B, or C, with level A having the highest priority for use of NRC resources. This process is discussed in greater detail in NRC (1991).

It should be noted that the NRC's approach to prioritization and remediation is pragmatic, and level A sites do not necessarily present the greatest risk to health and safety. For example, if prompt regulatory action and cleanup at a relatively low risk site will result in the most efficient use of resources, by deleting the site from the SDMP list, for example, that site may receive a higher priority.

3 Radioactively Contaminated Sites

Table 1 lists and Figure 2 displays the 45 sites on the NPL and the 38 SDMP sites which are contaminated with radioactive substances (FR 54(134):29820-29825, July 14, 1989; NRC, 1991). While each of the sites has specific physical and environmental characteristics which will be discussed later in this report, and while some sites could be placed in more than one group, it is possible to broadly characterize these sites based on their historical usage. Nine general site types exist:

- defense plants
- mill tailings, processing and disposal sites
- radium and thorium sites
- commercial landfills

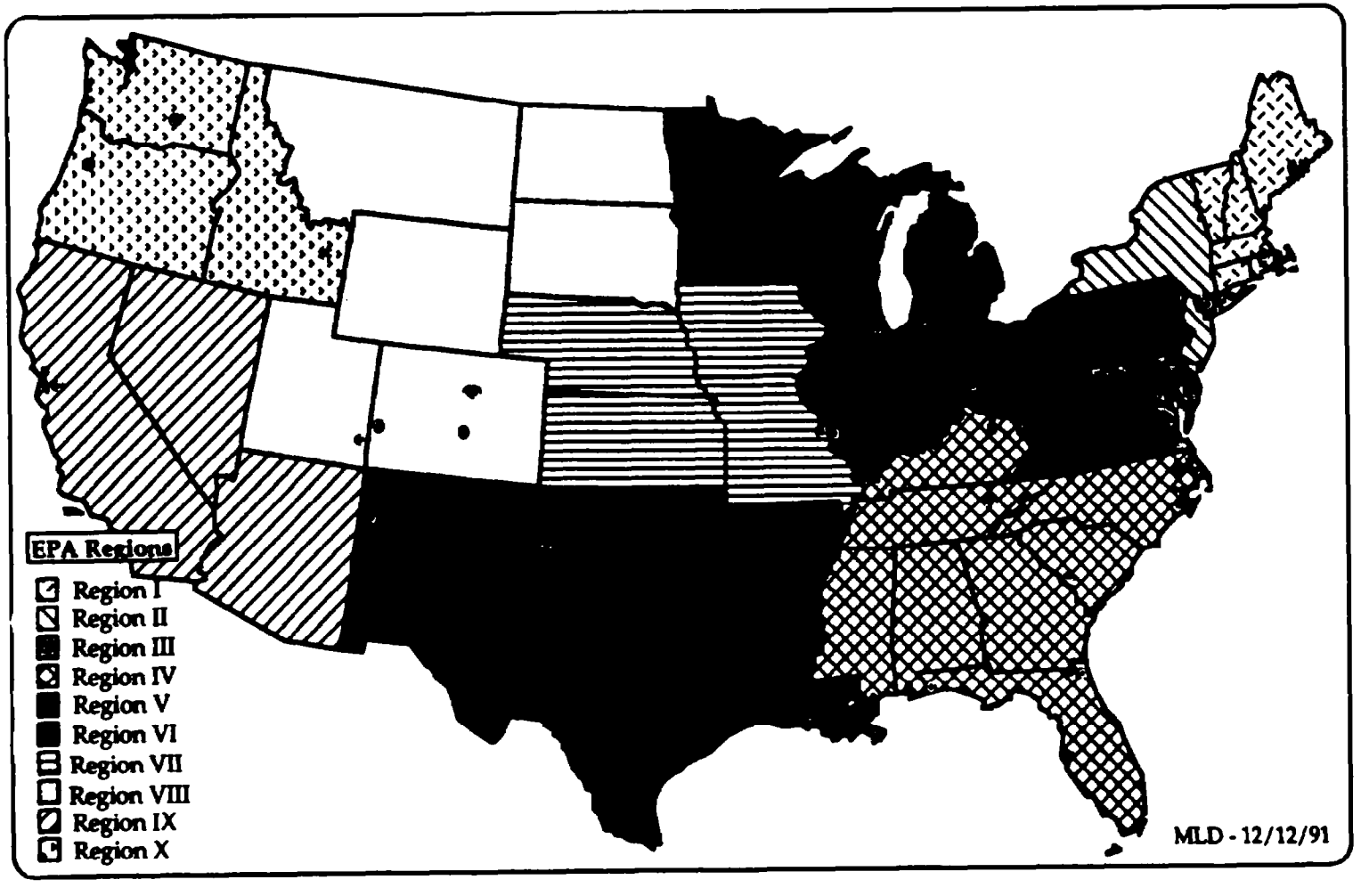

Figure 2a. Locations of EPA NPL radioactively contaminated sites

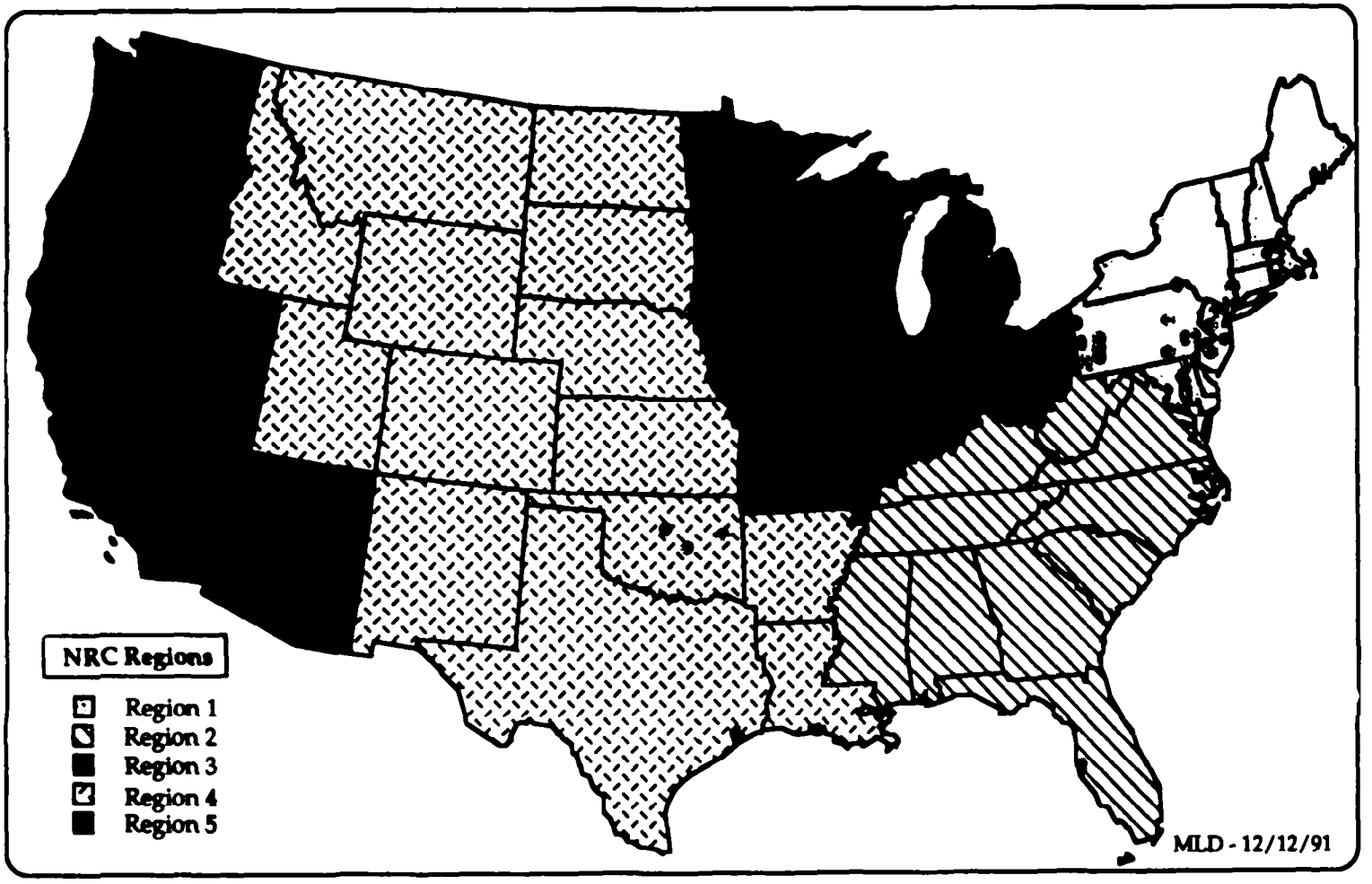

Figure 2b. Locations of NRC SDMP sites

- low-level waste disposal sites
- research facilities
- commercial manufacturing
- fuel fabrication and processing
- scrap metal recovery.

Background data for these groupings are presented below:

3.1 NPL Sites

3.1.1 Defense plants

Fourteen of the 45 radioactively contaminated sites were involved in operations in some way related to weapons manufacture. Included in this group (all of which are under DOE supervision) are:

Fernald Environmental Remediation Project (FEMP)

Hanford 100-, 200-, 300-, and 1100-Areas (4 sites)

Idaho National Engineering Laboratory

Lawrence Livermore National Laboratory (2 sites)

Mound Plant

Oak Ridge Reservation (includes Oak Ridge National Laboratory)

Pantex Plant

Rocky Flats Plant

Savannah River Site

Weldon Spring Former Army Ordnance Works and Quarry/Plant/Pits (2 sites)

Many of these sites have been in operation since World War II. They were involved in the handling of very high levels of actinide elements, uranium, thorium, and plutonium, along with various daughter and fission products. Each site's involvement with these radioactive materials spans a time over which there was an evolution of concern for the environmental consequences of such disposal (see, for example, Eisenbud 1963 and 1990). The potential risks to human health and environment from these sites are primarily attributed to the elevated activity levels and large volumes of materials at each site. In addition the distribution of contamination tends to be complex. For security reasons many of these sites were located in sparsely-populated regions and, as a consequence it is not surprising that half of these sites are in arid or semi-arid areas not particularly suitable for agricultural or residential use.

3.1.2 Mill tailings, processing, and disposal

Twelve sites were or still are involved in the processing and disposal of uranium ore, thorium, and/or rare earth for military and commercial operations. These operations easily rank first in terms of the sheer volume of contaminated materials involved. Included in this list are:

Homestake Mining Co.

Kerr-McGee (Kress Creek, Reed-Keppler Park, Residential Areas, Sewage Treatment Plant) (4 sites)

Lincoln Park

United Nuclear

Monticello Mill Tailings and Radioactively Contaminated Vicinity Properties (2 sites)

St. Louis Airport/Hazelwood Interim Storage/Futura Coatings

Uravan Uranium (Union Carbide)

W.R. Grace/Wayne Interim Storage (DOE)

Common to these sites is a large volume of actinide wastes (primarily U and Th and their daughters). Activity levels, however, are generally low. In some cases contaminated materials have been widely distributed for use as fill or in construction materials long after their initial disposal.

3.1.3 Radium and thorium sites

Radium was the first radioisotope to enter into commercial use in the early part of the twentieth century. Radium was and still is used in a wide range of applications, from luminous dials on watches and instrument dials to medical applications in cancer therapy. Similarly, many small urban industrial sites were involved in the processing of thorium for such uses as lamp mantles. Eleven of the 45 radioactively contaminated sites fall in this radium/thorium processing category:

Denver Radium Site

Glen Ridge Radium Site

Jacksonville Naval Air Station

Lansdowne Radiation Site (note: deleted from NPL September 10, 1991)

Lodi Municipal Well

Maywood Chemical Co.

Montclair/West Orange Radium Site

Ottawa Radiation Sites

Pensacola Naval Air Station

Radium Chemical Co.

U.S. Radium Corp.

Many of these sites were in operation long before any harmful effects of radiation were recognized and before any regulatory mechanisms were in place to control the use of radioactive materials. The operations were, in general, relatively small, primarily limited to radium and thorium and their daughters (especially radon), and often located in urban areas. Because of the relatively long history of these sites, contaminated materials often received wide distribution including incorporation into building materials.

3.1.4 Commercial landfills

Four of the 45 sites were operated as general-purpose waste landfills which were at sometime during their operation contaminated by radioactive wastes:

Forest Glen Mobile Home

Himco Inc., Dump

Shpack Landfill (DOE)

Westlake Landfill

There is no indication that the operators of these sites were aware or concerned with the presence of radioactive materials in the wastes or that any special plans were made to isolate or contain radioactive materials other than the routine practices at landfills. The isotopes that are present at these sites vary widely, having originated from various medical, research and defense operations. For these sites, it is commonly not known in what precise form or what original concentration the radioactive materials are present.

3.1.5 Low-level waste disposal sites

One site, the Maxey Flats Nuclear Disposal Site (MFDS), in Morehead, Kentucky, operated as a licensed low-level radioactive waste disposal site from 1963 to 1977, when operations ceased due to the determination that waste was migrating through the subsurface media. As a low-level waste disposal site, the MFDS received a variety of radioactive waste types. However, the risk assessments performed in support of the RI/FS report for the site reveal that tritium in the leachate is of primary concern due to its relatively large inventory and mobility.

3.1.6 Research facilities

One of the 45 sites, Brookhaven National Laboratory, is a research facility operated for the DOE. Radioactive materials are employed or produced in various research activities not directly related to defense. A wide range of isotopes was disposed of at low activity levels in landfills, trenches, and other disposal facilities which has resulted in groundwater contamination.

3.1.7 Commercial manufacturing

One site, Teledyne Wah Chang, is involved in the commercial manufacture of products related to the nuclear industry. In that capacity sludge materials were contaminated with actinide elements. The nature and distribution of contaminated materials is fairly well defined at this site.

None of the NPL sites falls into the categories of Fuel fabrication and processing or Scrap metal recovery.

3.2 SDMP Sites

The majority of the NRC SDMP sites are located in the northeastern U.S., with the remainder in the middle west. This distribution reflects the fact that most of these sites are or were commercial enterprises, engaged in manufacturing, uranium processing, or other industrial activity. The NRC sites have been grouped according to the same classification that was used for the NPL sites (sec. 3.1), with the addition of two categories, Commercial Fuel Fabrication and Processing, and Scrap Metal Recovery. One site, Amax, could not be classified. There are no low-level waste disposal sites and no radium sites in the NRC SDMP program.

3.2.1 Defense plants

Three NRC sites were involved in weapons manufacture. Responsibility for the Watertown Arsenal site has been transferred from DOE to the General Services Administration (GSA); the other two are under the control of the Department of Defense (DOD).

Aberdeen Proving Ground

GSA Watertown Arsenal Site (2 sites)

Remington Arms Co., Inc.

Whereas the NPL Defense sites are generally located in the western U.S., the NRC Defense sites are located in the east or midwest. The NPL (DOE) sites are large, having been developed primarily for the manufacture and testing of nuclear bombs under the Manhattan Engineering District during World War II. The NRC sites, on the other hand, were involved in development and testing of ammunition for the U.S. Army and are comparatively smaller. The principal contaminant at all three sites is depleted uranium (DU); natural uranium is found in the soil at Watertown. Because DU is relatively insoluble, the potential for groundwater contamination at these sites is low.

3.2.2 Mill tailings, processing, and disposal

Ten NRC sites fall into this category. Unlike the NPL sites in this group, however, not all of these sites deal with uranium ore. Some sites process other ores (tantallum, columbium, zircon, leucoxene) which contain U or Th as a byproduct.

Cabot Corporation (3 sites)

Fansteel, Inc.

Heritage Minerals

Magnesium Elektron, Inc.

Molycorp., Inc. (2 sites)

Shieldalloy Metallurgical Corporation (2 sites)

3.2.3 Commercial landfills

The two commercial landfills in the NRC Site Decommissioning Management Plan are:

Kawkawlin Landfill

West Lake Landfill

These two sites present different problems: some groundwater contamination (Ra-226) is evident at the West Lake site, but the groundwater at the Kawkawlin site, where the principal contaminant is insoluble Th/Mg, has not been affected. The West Lake Landfill is also on the NPL list.

3.2.4 Research facilities

The NRC research facilities are all private (commercial) operations.

Gulf United Nuclear Fuels Corporation

Permagrain Products

Westinghouse Electric (Waltz Mill)

The Gulf site carries out nuclear fuels research and development and includes both laboratories and reactors. The Permagrain site is now owned by the Pennsylvania Forest Service. In addition to engineering design, research, and development, the Westinghouse facility provides decontamination services to nuclear power plants. Sr-90 contamination has been detected at both the Permagrain and Westinghouse sites, but groundwater contamination has appeared only at Westinghouse. Contaminated media at the other two sites include facilities and surrounding soils. Pu and Cs-137 are the principal contaminants at the Gulf site.

3.2.5 Commercial manufacturing

Ten NRC/SDMP sites are or were involved in manufacturing processes using licensable radioactive materials:

Allied Signal

BP Chemicals

The Budd Company

Dow Chemical Company (3 sites)

Nuclear Metals, Inc.

Process Technology of New Jersey, Inc.

Safety Light Corporation

Schott Glass Technologies

Whittaker Corporation

Wyman-Gordon Company

Two of the Dow sites, at Midland and Bay City, Michigan, are manufacturing operations; the third, at Salzburg, Michigan, is a landfill owned and operated by Dow which is to be used for disposal of low-level radioactive materials from the other two sites. Most of the commercial sites involve contaminated facilities (buildings and equipment) or soils; three sites show evidence of groundwater contamination due to migration of the radionuclides through the soil . However, only at Safety Light is groundwater contamination a significant problem.

3.2.6 Fuel fabrication and processing

Seven NRC sites are or have been involved in uranium fuel fabrication and processing. One, Babcock & Wilcox (Parks Township), was also used for plutonium fuel fabrication.

Babcock & Wilcox (Apollo)

Babcock & Wilcox (Parks Township)

Chemetron (Best Ave.)

Chemetron (Harvard Ave.)

Kerr-McGee (Cimmaron)

Kerr-McGee (Cushing)

Texas Instruments

Contamination at these sites is usually in the form of U in the soils in the vicinity of burial trenches, occasionally in surface soil around buildings in former processing areas. Th, Pu and Ra are also found. The Kerr-McGee plant at Cushing, OK, was formerly on the NPL but was deleted in 1991.

3.2.7 Scrap metal mecovery

Two sites are industrial, but cannot properly be classified as manufacturing operations. Both were involved in scrap metal recovery from contaminated materials; both have been closed for about a decade:

Pesses Company (METCOA)

UNC Recovery Systems

These sites have little in common. The UNC site is no longer functioning and has been remediated, though some traces of U exist in the groundwater. Sources of Th contamination at the Pesses site include leaking containers and several slag piles.

4 Contaminant Properties

Table 2 identifies the isotopes present at each of the 45 NPL and 38 SDMP radioactively contaminated sites. These are also graphically presented in Figure 3. These data were obtained from several primary and secondary sources, including the original HRS documentation, documents in support of site RI/FS, lists and analyses of radioactive contamination at NPL sites, published surveys of

Superfund sites, DOE Environmental Surveys and Five-Year Plans, and the annual summary of the NRC Site Decommissioning Management Plan.

In addition Table 2 lists the media contaminated at each site by the particular isotope. In the case of the NPL sites these are not necessarily the media which received high HRS scores. Ra-226 and Rn-222, for example, are present at detectable levels in surface water and groundwater at the Glen Ridge site, yet neither medium received a significant HRS score. Conversely, a particular medium may have scored at a site but may not be contaminated by radioactive materials. For example, even though surface water was the driving medium for listing the Hanford 1100-Area on the NPL, radioactivity in surface water, though present at the sites, does not drive the selection of the site for placement on the NPL.

Figures 4a-c present data compiled from Table 2 on exposure pathways and environmental media impacted at NPL and NRC sites. A comparison of these two figures indicates that there is no significant difference between the frequency of pathways noted as contaminated and those scored under the HRS system (those with contaminants at levels that according to the HRS process pose a significant health risk). In both cases, each medium is about equally represented. This is contrary to the original assumptions at the time of project initiation, when it was believed that groundwater contamination would dominate.

By their nature, radioactive materials spontaneously transform with time. While the isotope may have certain chemical characteristics which will control its concentration in solution, the manner and rate of decay of a radioisotope may be more significant than its concentration. The risk to health posed by any particular isotope will be the product of the amount that is delivered to some segment of the environment, the rate at which a given radioisotope decays and the type of transformation it undergoes. In addition radioisotopes may have effects on living organisms which are directly or indirectly related to the emission of ionizing radiation. Thus, it is important to understand the chemical, radioactive and biological characteristics of these elements. In Table 3, properties of the radioisotopes identified at the 83 radioactively-contaminated sites are given.

Because many of these radioactive contaminants will be transported from their source through the environment in solution in surface or groundwater, the emphasis in the following discussion is on the aqueous geochemical properties of these isotopes.

4.1 Chemical Properties

A review of Table 2 reveals that the more than 30 isotopes present at the radioactively contaminated sites span the entire gamut of chemical behavior. These can be divided into four behavioral groups:

- non-metals and organics (C, H, I, Rn, Se)
- transition, platinum-group metals, and lanthanides (Mn, Ni, Co, Ru, Tc, Eu, Pm)

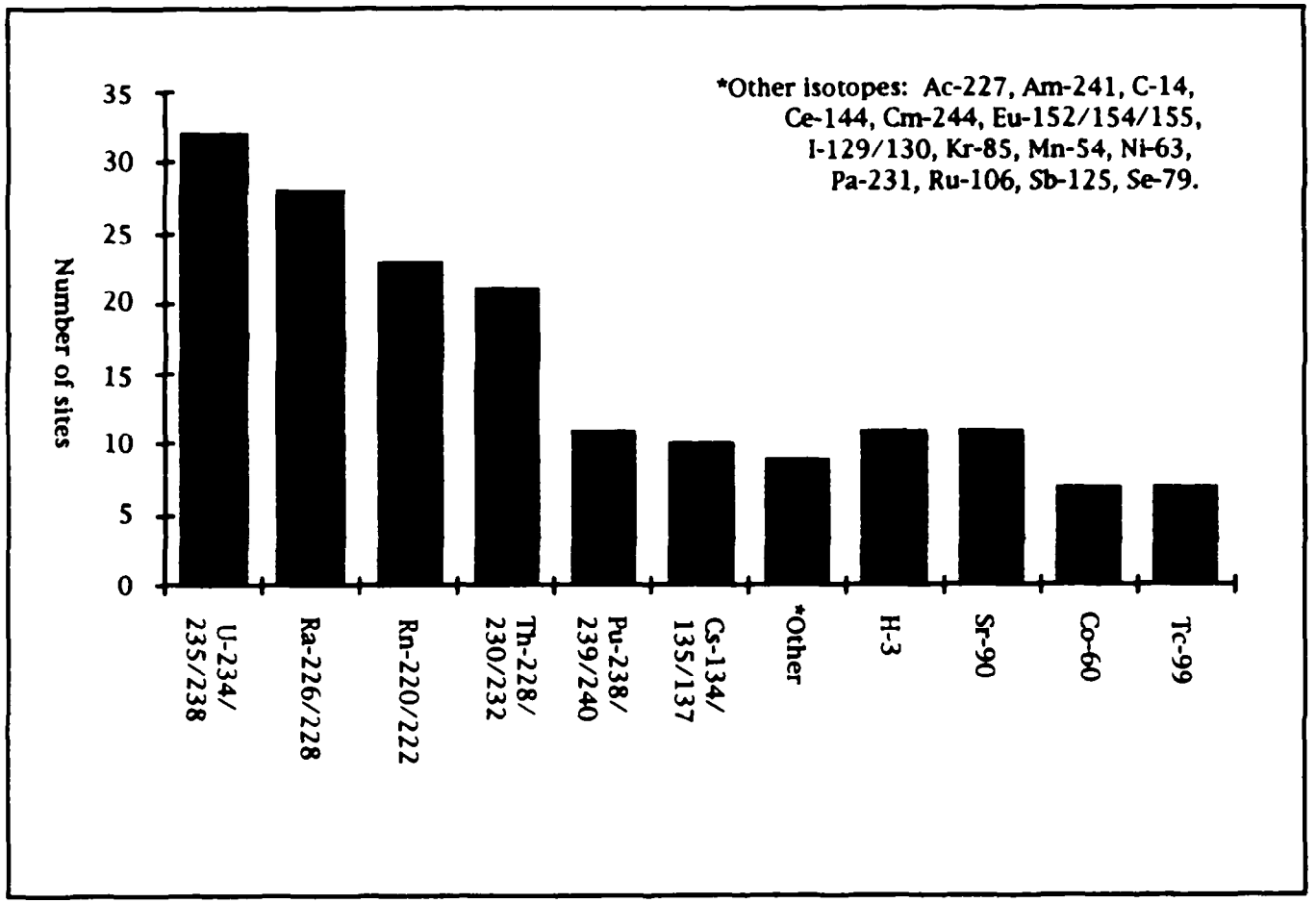

Figure 3a. Isotope distribution at NPL radioactively contaminated sites.

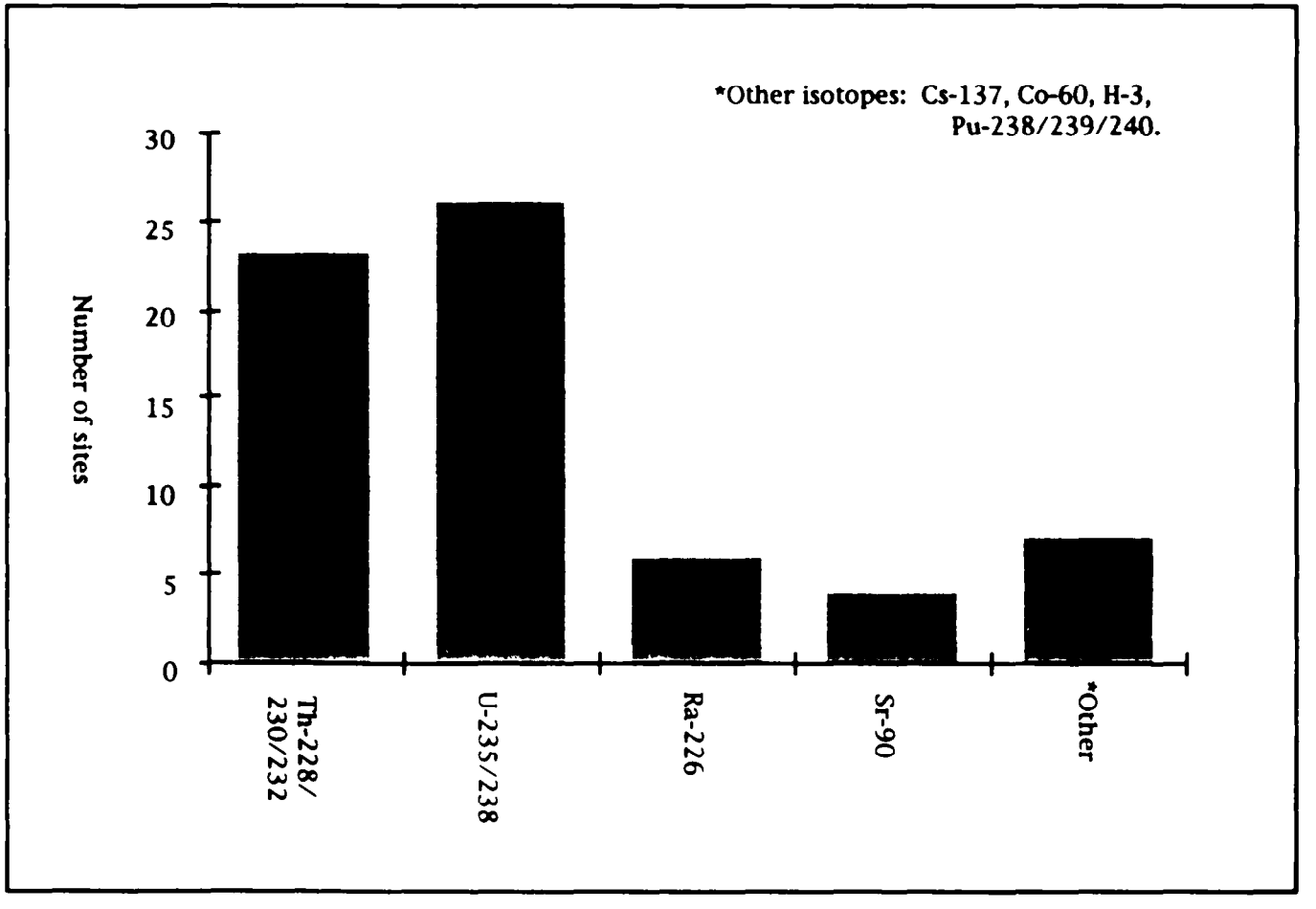

Figure 3b. Isotope distribution at NRC SDMP sites.

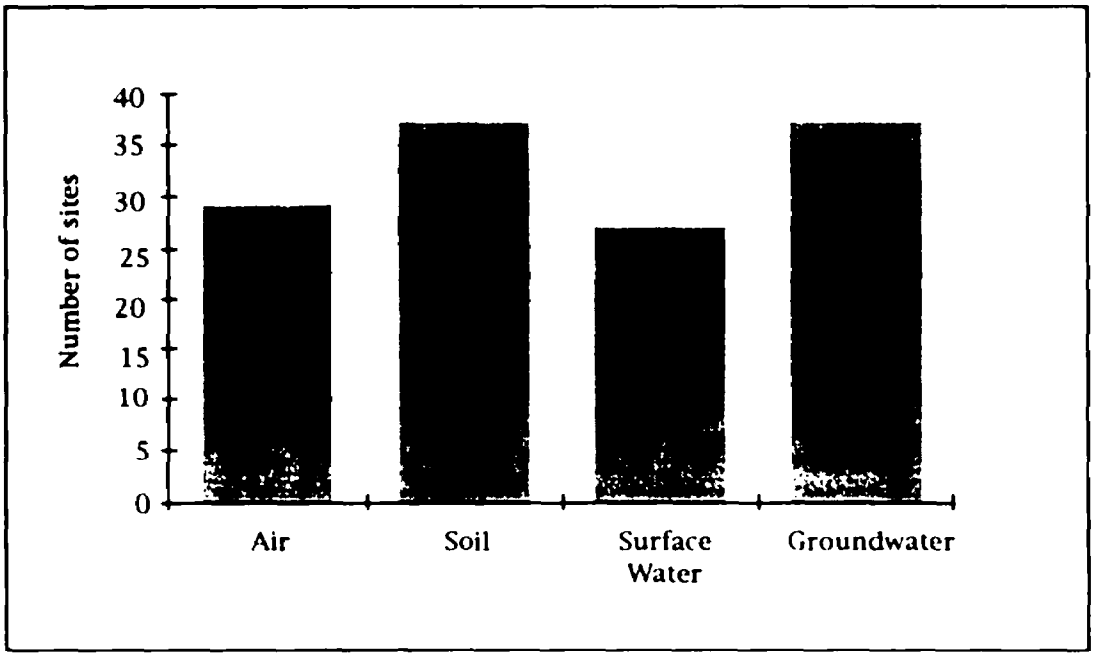

Figure 4a. Exposure pathway distribution at NPL radioactively contaminated sites (as reported).

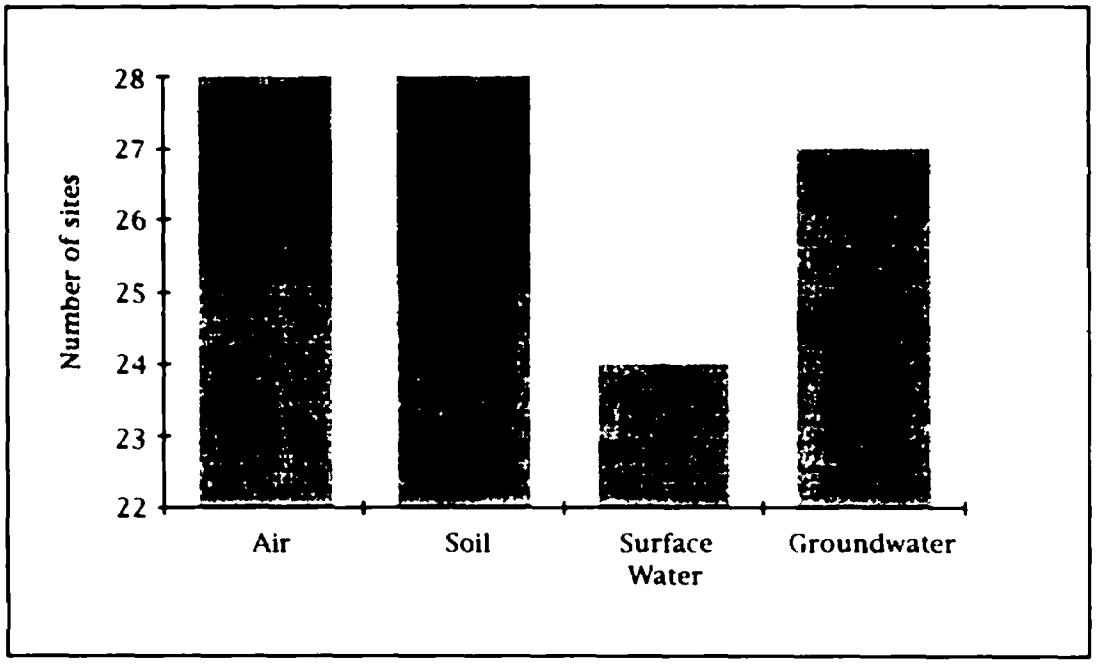

Figure 4b. Exposure pathway distribution at NPL radioactively contaminated sites (HRS scored).

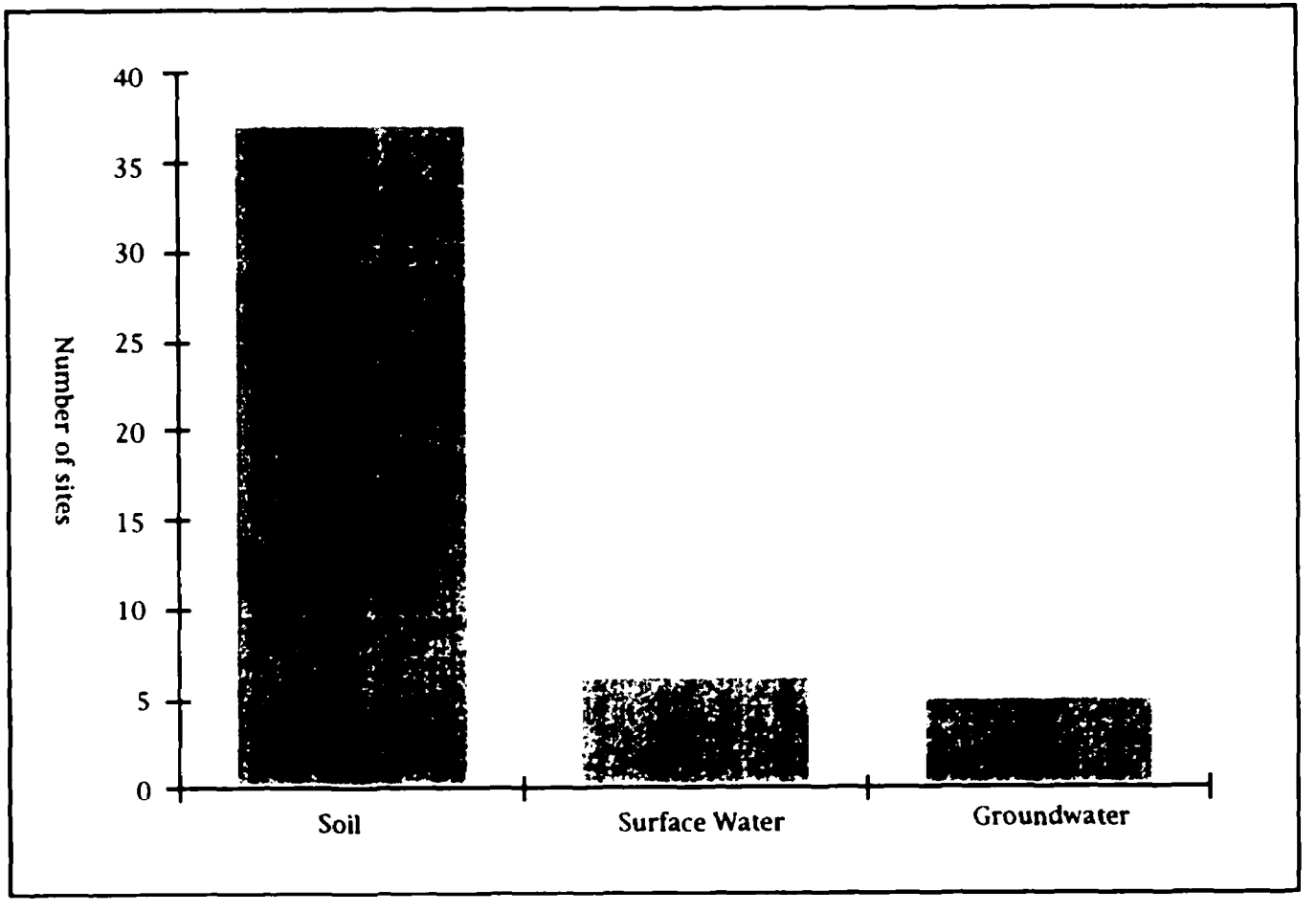

Figure 4c. Exposure pathway distribution at NRC SDMP sites.

- alkaline metals and earths (Cs, Ra, Sr)
- actinides and transuranics (U, Th, Pu, Am, Ac, Pa).

4.1.1 Non-metals

The non-metallic elements (C, H, I, Rn, and Se) will, under normal geochemical conditions exist as either gases or as anions dissolved in water. As gases these elements pose a completely different set of problems from the other radioisotopes. As anions, such as carbonate or selenate, these radioisotopes will be much less affected by adsorption and ion exchange than will the other, primarily cationic, radioisotopes.

4.1.2 Transition, noble metals, and lanthanides

These elements (Mn, Ni, Co, Ru, Tc, Eu, and Pm) exist as atoms with 1, 2, 3 or more valence electrons (except for the lanthanides, Eu and Ru which exhibit only the +3 valence state and behave similarly). In solution they exist as simple cations in most common geochemical environments. Reactions which lead to the precipitation of oxides, sulfides, carbonates and sulfates, etc. and ion-exchange will dominate the behavior of these elements.

4.1.3 Alkaline metals and earths

Cs, Ra, and Sr occur in nature at only one valence state (+1 for Cs, and +2 for Ra and Sr). They tend to form very soluble cations in water. Ra and Sr will behave similar to Ca while Cs will tend to follow K and Na in solution.

4.1.4 Actinides and transuranics

Unlike the lanthanide series whose members have essentially identical chemistry, the actinide series elements exhibit a more varied and complex array of chemical behaviors. This complexity is the consequence of their potential for existing at more than one oxidation state and their related tendency to form complexes with anions and/or organic substances dissolved in water.

The geochemical behavior of many of the actinides (and some of the transition metals) will, therefore, be controlled not only by their concentration, but also by the redox conditions which prevail in the media through which the isotopes are transported. Uranium, for example, can be found in any of five valence states (+2,+3,+4,+5,+6) with two (+4 and +6) of geochemical significance. In most geologic environments, the reduced uranous ion (U^{4+}) is insoluble, while the oxidized uranyl ion (UO_2^{++}) is considerably more soluble. At virtually every Superfund site of concern to this report the possibility exists for transitions within media from reducing to oxidizing conditions on both a macro and micro scale.

While multiple oxidation states will generally suggest that redox conditions will be a controlling factor in the behavior of actinides, other properties may mask the charge effect. For example, although Pu can exist in any of five oxidation states (+3,+4,+5,+6,+7) few of these are, in fact, of geochemical importance. In practice, the property that controls the behavior of Pu, for example, is the insolubility of Pu(IV) hydrolysis products, which are, in turn, strongly adsorbed to particle surfaces (Watters, *et al.*, 1983). Similarly, Th can be considered to be insoluble in the vast majority of freshwater and marine environments due to the formation of insoluble $Th(OH)_4$.

4.2 Radioactive Properties

The decay of radioisotopes can produce daughter products which may differ both physically and chemically from their parents. These daughter products may, as well, be more or less hazardous than their parents. In addition, radioisotopes decay by several different paths, emitting several different types of radiation in simple steps or in complex decay chains.

Those isotopes which decay with very long half-lives relative to their travel time along some environmental pathway may be considered stable in a study of their transport. Similarly, most isotopes with very short half-lives can be ignored at a site because the travel time of most groundwater will allow for their complete decay before reaching a receptor. However, for the purpose of assessing the importance of a short-lived daughter in association with a long-lived parent, the activity of the daughter will rapidly equilibrate with the parent.

Simple linear decay involves the first-order transformation of one substance into another. Radioactive decay of a chemically inert parent into a stable, inert daughter at low concentrations is, in concept, simpler even than the decay of organic compounds, for example, since it occurs independent of environmental conditions or the concentration of any other species. Decidedly non-linear behavior can be encountered with multiple-step decay series, on the other hand, and/or decays which involve reactive parents that decay to reactive daughters. An example of such a decay series is the U-238 -> Pb-206 series in which intermediate daughter products have both different chemistries and different phases.

Multi-step decay schemes not only impose additional complexity on the characterization of contamination at a site but also place certain limits on the occurrence of daughter products at sites where chemical processing leads to disequilibrium within a series. For example, if uranium at a site was processed in the form of raw uranium ore, the concentration of uranium daughters in processing materials may be expected to have been in secular equilibrium with the parent. However, if purified ore was used at a processing plant, like, for example, uranium ore ("yellowcake") then the activity of daughters will be considerably less than unity for very long periods of time. For U-238, for example, the activity of daughters will be minimal for periods of time comparable to the half-life of Th-230, which is 75,000 years. On the other hand the activity of daughters in mill tailings may far exceed the activity of the parent isotope. This explains the frequency that Ra and its daughter Rn are identified as contaminants at many of the mill-tailing sites.

Table 3a presents radiochemical data for the isotopes listed in Table 2. Data have been compiled from several sources (U. S. Department of Health, Education, and Welfare, 1970; Diem and Lentner, 1970; and Weast, 1990) for the more fundamental radiochemical parameters including half-life, specific activity, decay product, and the energy levels of the emitted radiation. As shown, there are isotopes which decay to stable daughters (*e.g.*, C-14 to N-14) and others that decay to unstable daughters (*e.g.*, I-131 to Xe-131); different radioactive decay chains (*e.g.*, Th and U); and a mix of alpha (*e.g.*, U-238), beta (*e.g.*, Ra-228), and gamma (*e.g.*, Mn-54) emitters. Isotopes which decay to stable daughters through long chains of radioactive daughters are the most common materials at the 45 NPL sites (see Figure 4). Simple, single-step radioactive isotopes are found at less than 25% of the sites in this survey.

4.3 Environmental Mobility

For transport from source to receptor to occur the radionuclide must be carried by a fluid, either air or water. In both cases the radionuclide may exist either in solution or associated with solid particles. In water the partitioning of an element between dissolved and adsorbed forms is a function of both the characteristics of the solution and those of the adsorbing surfaces. Because both the geochemical characteristics of natural and artificial solutions and the adsorption characteristics of soils are so complex and dynamic, thermodynamic models based on steady-state conditions may not adequately describe the proportion of any given isotope in solution relative to that adsorbed on soil

particles. It is necessary, therefore, to rely on empirical estimates of the distribution coefficient, or K_d, to express the ratio of the concentration of adsorbed isotope relative to dissolved isotope:

$$K_d\ (ml/g) = \frac{\text{concen adsorbed on particle (Ci/g)}}{\text{concen dissolved in solution (Ci/ml)}}$$

The higher the K_d, the more of an isotope that can be expected to be found associated with solid particle and less in solution. Unfortunately, the adsorption properties of particles vary so greatly that K_d must often be determined for each site or even for each subsurface unit at each site. Thus, for summary purposes the mean, standard deviation, and range of the adsorption properties of elements of concern in this report are presented in Table 3b.

4.4 Biological and Health Effects Properties

EPA estimates of the biological potency of the identified isotopes (*i.e.*, estimates of lifetime cancer risks for exposures from air, drinking water, external radiation, and soil ingestion) are listed in Table 3. With respect to the biological potency of these materials, EPA classifies all radionuclides as Group A carcinogens (*i.e.*, sufficient evidence of carcinogenicity in humans). This classification is based on their property of emitting ionizing radiation and on the extensive weight of evidence provided by epidemiological studies of radiation induced cancers in humans. As noted in the EPA Health Effects Assessment Summary Tables (EPA, 1991):

> "Data derived from both human studies and animal experiments are used by EPA to construct mathematical models of exposure, dose, and risk to estimate radionuclide slope factor values. These models consider pathways of exposure, the distinct metabolic behavior of each element by compound and the radiological characteristics of each nuclide of concern, the time and duration of exposure, the radiosensitivity of each target organ in the body, the latency period for cancer expression in these organs, and the age and sex of individuals in the exposed population....
>
> Unit risk estimates for air, drinking water and soil ingestion pathways...were calculated by multiplying the appropriate inhalation rate (20 m^3/day), the water consumption rate (2 L/day), or the soil ingestion rate, respectively, and by multiplying all values by the total number of days in 70 years..."

The data presented under "Pathway-Specific Unit Risk" in Table 3 may be used to identify isotopes of special interest from a health perspective. Since the risk to health is a function of the human exposure levels combined with the unit risk estimates, the actual importance of any single isotope can only be determined by developing site-specific human exposure estimates. These can be secured through field measurements or through computer pathway modeling exercises.

Some radionuclides are also of potential concern because of their non-cancer health effects. Uranium, for example, is unusual in that the primary health effect of concern is renal toxicity, rather than cancer risk. This is also the health effect upon which the EPA is basing its proposed drinking water standard for uranium (Federal Register, 1991). Based on an EPA analysis (Federal Register, 1991) a uranium concentration of 170 pCi/l (113 ug/l) is associated with a lifetime mortality risk of 1 x 10^{-4}. Kidney toxicity may occur at levels below the 10^{-4} risk level for uranium, and the proposed MCL for uranium is 20 ug/l (30 pCi/l).

5 Waste Characterization

Sources of hazardous waste may be classified as either point sources or area sources. Point sources release contaminants to the environment from a single location which potentially can be precisely identified (*e.g.*, a leak in a drum). Area releases, on the other hand, occur over a measurable (two-dimensional) area whose boundaries may be difficult to identify.

Hazardous wastes are often sequestered in a form that limits their release to the environment. Although the nature of the containment is not strictly a characteristic which governs environmental transport at a site, it may affect the type of release (point vs. area) as well as the rate of delivery to the environment. Even if containment was not deliberate, as is the case for many of the urban, radium-contaminated sites, soils and man-made materials themselves provide a minimum amount of containment. The form of containment varies very widely, but some broad classes are appropriate. Below is a brief description of the characteristics of these containments which are listed in Table 4 for each site:

- Water-based
  - *ponds:* unlined or lined excavated into the land surface into which hazardous wastes were originally deposited in fluids, usually water.
  - *surface water:* deliberate or accidental discharge to streams or lakes.
  - *wells:* deliberate or accidental subsurface injection of waste.
- Containers
  - *containerized:* 55 gallon steel drums and concrete slurry.
  - *tanks:* large surface or buried structures designed to contain waste for long periods.
- Ground-based
  - *landfills:* engineered above-ground facilities designed to limit the escape of materials more or less indefinitely; usually excavated into the landscape somewhat and surrounded by some form of dike or embankment.
  - *piles:* aboveground heaps of material with or without controls on leaching or erosion.
  - *burial:* accidental or intentional burial of wastes below ground level.
  - *asphalt and aggregate:* the use of radioactively contaminated materials for construction purposes, generally by those unaware that the materials were contaminated.

Since most of the burials and piles and a portion of the landfills and ponds at the 83 sites can be described as uncontrolled (Figure 5), the difficulties that must be faced in characterizing the source term at these sites are considerable. Only about 25% of the containment of radioactive materials at these sites is in a form that might be described as localized.

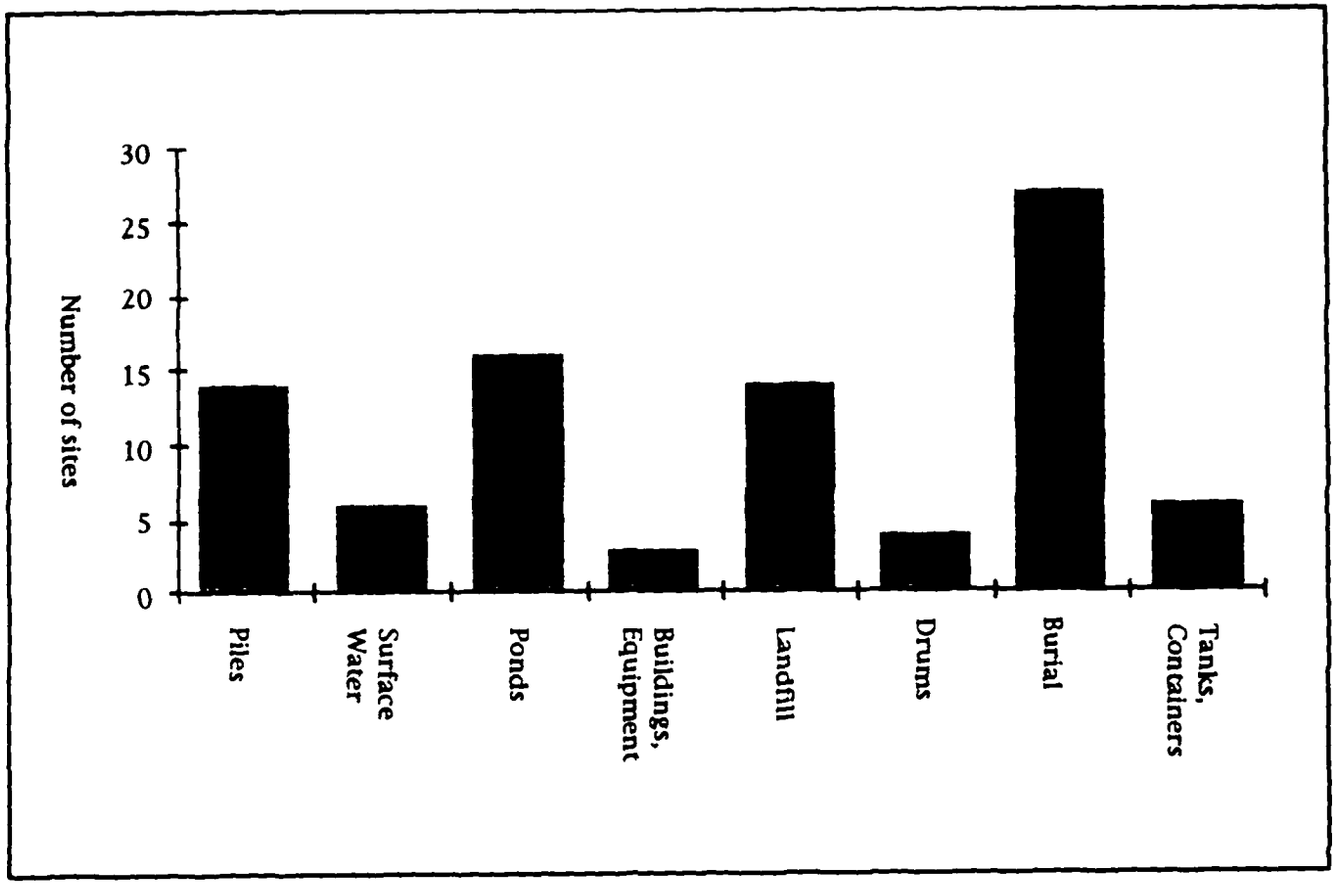

Figure 5a. Source characteristics at NPL radioactively contaminated sites.

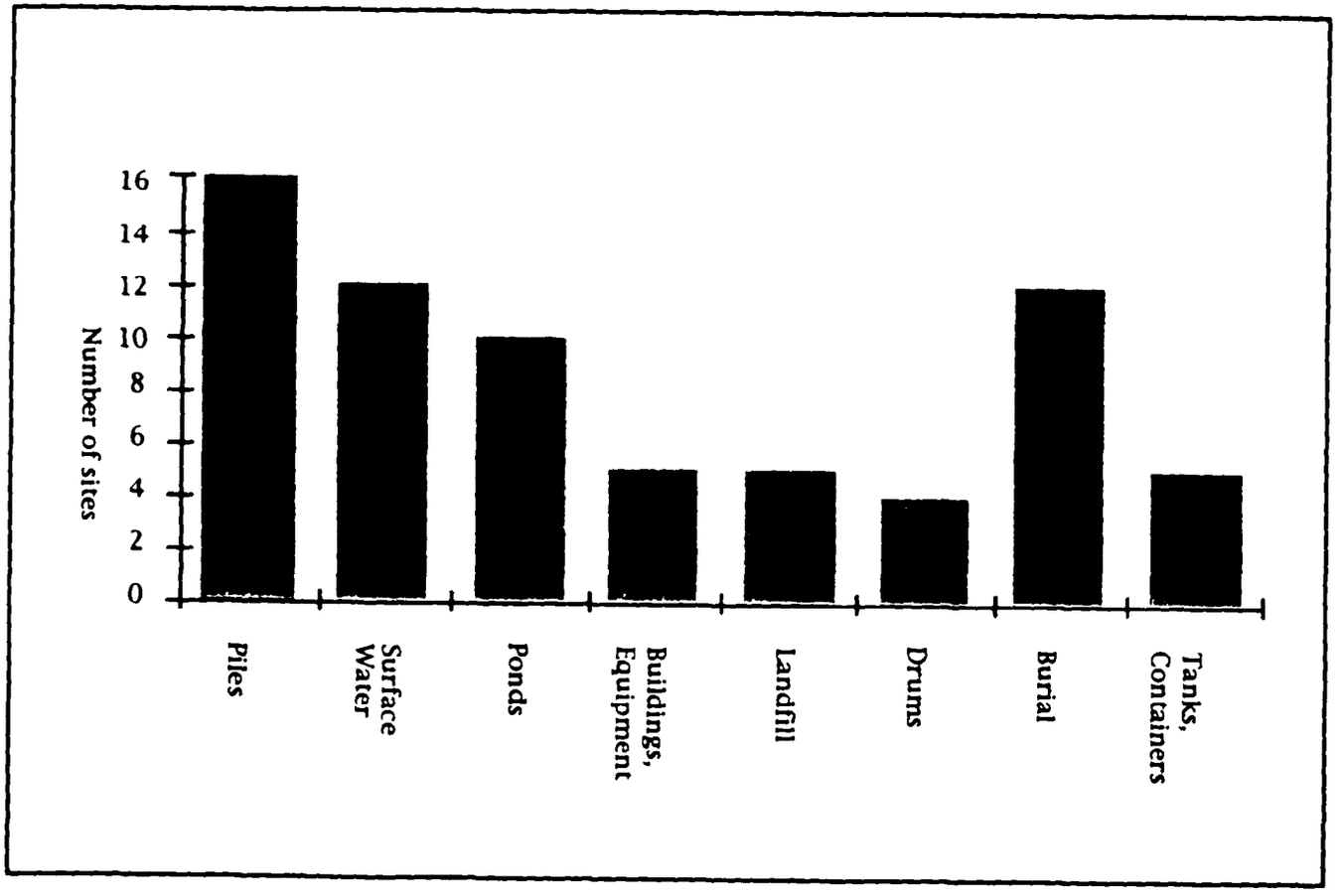

Figure 5b. Source characteristics at NRC SDMP sites.

The physical form of hazardous waste can be characterized by the volume of waste and the concentration of contaminants in the waste. These data, while critical to an adequate understanding of the environmental threat of a contaminant release, are frequently difficult to obtain and have a high degree of uncertainty. The quantity and concentration figures shown in Table 4 are approximate and are given for comparison purposes only. It can be seen that the quantity and variety of isotopes present at NPL defense facilities is frequently orders of magnitude greater than at other types of sites. This pattern is not apparent at the NRC defense sites, which, as previously noted, are different in nature from the NPL (DOE) defense sites.

6 Site Environmental Characteristics

The NPL sites are distributed across the 48 contiguous United States (see Figure 2a). They span most of the large-scale physiographic and climatic regions of the North American continent. The terrain in which these sites are located is underlain by a wide range of soils and geologic formations. Therefore, no single assumption can be made about the climatic or hydrogeologic characteristics of these sites. Sites must be evaluated for the specific conditions under which contaminants may be mobilized and the atmospheric and subsurface properties that will control the direction and velocity of contaminant transport. The NRC sites, on the other hand, are concentrated in the northeastern U.S., with a few in the midwest and Oklahoma (Figure 2b). Over one third are in Pennsylvania.

In this report a set of characteristics have been selected which will aid in classifying each of the sites into a limited number of environmental types. These site characteristics can then be considered in light of the general type of site operation and nature of the source as discussed above and in terms of the receptor characteristics (human population and ecosystem) as discussed below. All of these data are then summarized in one table (Table 4).

Environmental characteristics have been divided into two groups in the following discussion: surface and subsurface characteristics. This classification follows the traditional distinctions made between above-ground and below-ground processes and in general reflects a distinction both in kind and degree. Below are listed each of the characteristics likely to effect the transport of radioactive materials, the reasons for inclusion in the table, and a summary of the data for each characteristic from all the sites.

6.1 Surface

At approximately half of the 45 NPL sites (Figures 4a,b) either surface water or groundwater is the principal transport mechanism. Rainfall will therefore be of principal importance, since surface runoff and percolation of water through surface impoundments and containments will ultimately deliver contaminants to receptors. Atmospheric dispersion of gaseous or particulate contaminants is also an important site surface characteristic.

6.1.1 Precipitation

Gross precipitation, the average total rainfall for a site, is only a rough measure of the relative importance of runoff and infiltration to the overall transport processes. As noted earlier, these sites span a considerable geographic area. Thus, the same amount of rain falling in Richland, Washington as in Pensacola, Florida will not have the same consequences for contaminant transport. Similarly, a simple measure of net precipitation (average precipitation cumulative losses) does not give proper weight to that fraction of precipitation which ultimately enters into surface and groundwater systems even in arid regions. On the other hand, an exhaustive analysis of the actual rate of runoff, soil percolation and groundwater recharge, such as defined by Dunne and Leopold (1978), is beyond the scope of this report. For the present purpose, therefore, average annual precipitation at each of the sites is

given; this information is usually available in HRS documents, site Environmental Reports, or standard climate reference works.

The data for the NPL sites are summarized in Figure 6a. Sixteen of the 45 sites occur in regions which are arid or semiarid. This reflects the fact, discussed below in Sec. 7, that many of these sites were located in remote (and, therefore, generally not prime agricultural) regions for both safety and security reasons. A similar figure for the SDMP sites is not shown because all of the NRC sites are in relatively humid areas; the driest receives 73 cm/yr.

6.1.2 Air transport

Rather than attempt to arrive at some set of parameters that would describe the general atmospheric characteristics of each site, the actual transport vector for air-borne contaminants was chosen as the differentiating characteristic. For sites where air transport poses an environmental hazard, Table 4 indicates whether contamination is either in the form of a particle (dust), gas (most often Rn-222 or Rn-220), or both. These data are summarized in Figure 6b.

Sites with unique atmospheric conditions which may impose special conditions on transport mechanism are noted in the "Other" column of Table 4. For example, Oak Ridge National Laboratory has a high frequency of atmospheric inversions which would certainly have to be considered when evaluating air transport at the site.

Figure 6b summarizes the frequency of occurrence of each of these possible transport mechanisms. For about 30% of the NPL sites air transport is a significant vector. The overwhelming importance of gas over particulate reflects the importance of gaseous daughter products of U, Th, and Pu at these sites. While various actinide elements may exist at relatively low levels in soils or containers as solid particles which are demonstrably immobile, gaseous decay products are very difficult to control.

6.1.3 Surface water

Surface transport is a consequence of the complex interaction of climate and geology. Streams may or may not be present; existing streams may be perennial or intermittent. Natural standing bodies of water can serve as sinks to which contaminants are transported or as sources for transporting media. Both standing bodies of water and streams can interact with groundwater, affecting both the delivery of contaminants and the hydrologic characteristics of groundwater flow. Contact between surface and groundwater can be especially significant if frequent fluctuations in surface water level impose similar fluctuations in groundwater levels.

Most of the sites contain perennial streams which may act as vectors for contaminant transport (see Table 4). In addition, seven sites contain or are contained within freshwater wetlands. The presence of continuous standing bodies of water surrounding contaminated materials or of bodies of water which may act as transient sinks for contaminants is an important site characteristic. Only two of the sites (Pensacola and Jacksonville in Florida) are sufficiently close to estuaries to suggest that tidal transport mechanisms may be important.

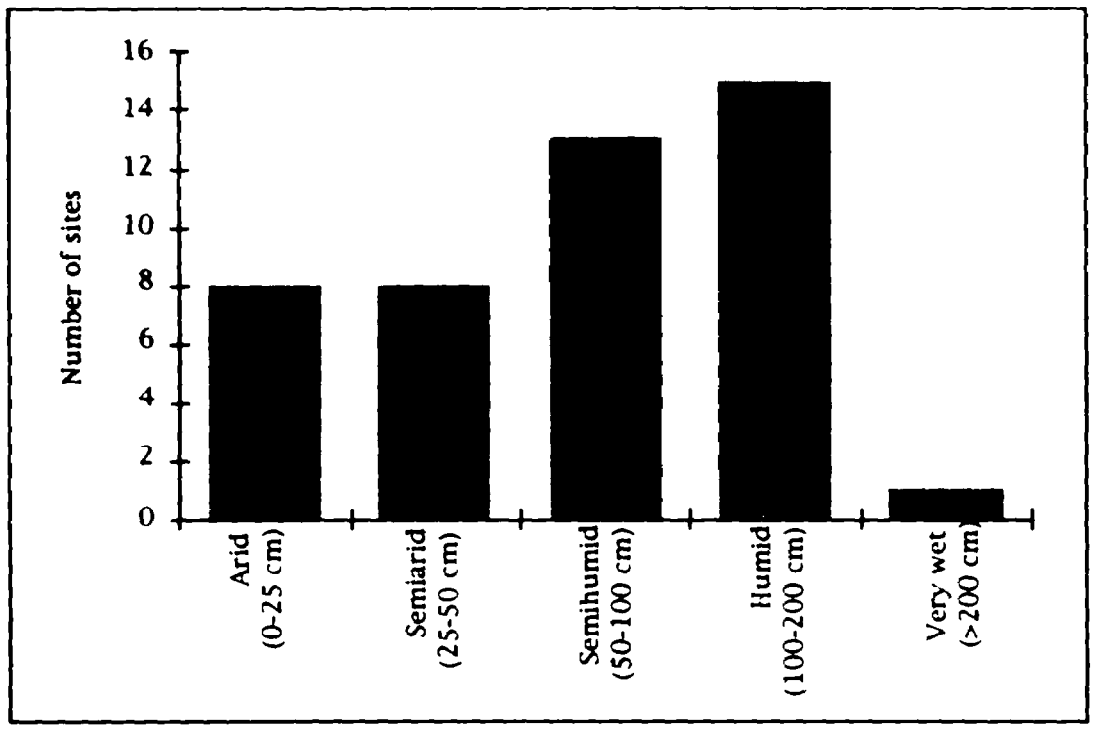

Figure 6a. Mean annual precipitation by category for NPL radioactively contaminated sites.

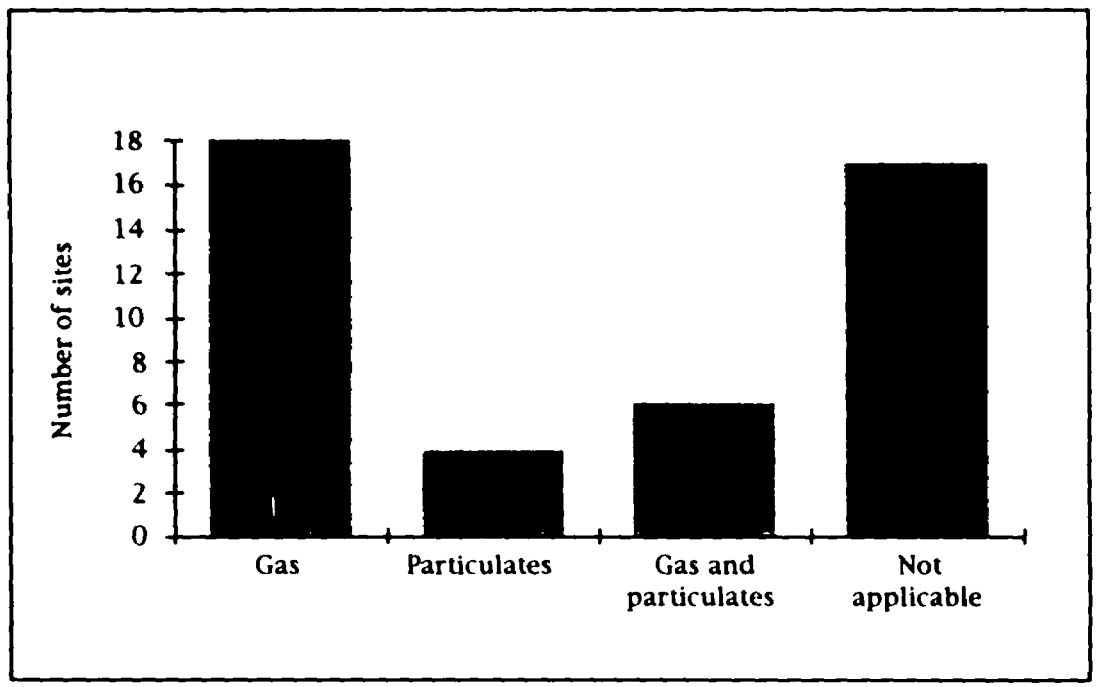

Figure 6b. Air transport vectors at NPL radioactively contaminated sites.

6.2 Subsurface

6.2.1 Solid transport

Subsurface movement of contaminants may occur by either solid or fluid (liquid or vapor) transport. In the case of solid transport, soils and unconsolidated rocks may have physical or chemical properties that make them resistant to transport while others may have properties that actively promote vertical and/or horizontal movement. Stream transport of particulate materials is to be expected at every site. In addition, one site, Idaho National Engineering Laboratory, is flooded with sufficient frequency to suggest that fluvial transport mechanisms should be given particular attention. With the possible exception of the mill tailings sites, the direct transport of solid materials by mass wasting of subsurface materials (landslides, for example) is not a significant vector at most of the sites. Possible subsurface transport of bulk materials may occur via mechanisms unique to given sites. For example, the activity of burrowing animals can lead to the excavation of substantial quantities of contaminated unconsolidated materials (O'Farrell and Gilbert, 1975; Winsor and Whicker, 1980; Hakonson and Martinez, 1981; Arthur and Markham, 1983). Others (Smith, 1977) have noted that grazing animals may ingest soil. Humans may excavate contaminated materials and subsequently incorporate them into structures or use them as landfill.

The importance of solid transport mechanisms at these sites must be evaluated on a site by site basis even though certain mechanisms are fairly common. For example, at most of the radium/thorium and mill tailings and processing sites, excavation and incorporation into remote (off-site) structures has been an important mechanism of transport and has been primarily responsible for the wide dispersion of radium contamination.

6.2.2 Fluid transport

Generally speaking, the major mechanism of transport below the upper soil layers will be vapor transport and the movement of materials dissolved in water. Groundwater movement is often controlled by a complex interaction of forces which impart or resist fluid motion. Gravity, fluid pressure and other physical forces provide the energy required to move groundwater. The resistance to flow is provided by the geologic medium through which the water moves. That resistance can vary substantially both geographically from region to region, vertically down through a stratigraphic column, and horizontally within a hydrostratigraphic unit. Various attempts have been made to categorize hydrogeologic regions throughout the U.S. (for a review see Aller *et al.*, 1985). Figure 7 reflects Heath's system (1984) dividing the continental U.S. into 11 hydrogeologic regions. There is at least one site from among the radioactively-contaminated sites considered in this report in each of these 11 regions (see Table 4).

Groundwater flow will occur by similar processes in any of the hydrogeologic regions. For example, on a local basis, given a similar geologic setting across a site, water transport below the ground surface can be divided into two relatively distinct phases, transport through the unsaturated or vadose zone (subsurface materials not saturated with water) and transport through the saturated or phreatic zone.

Unsaturated zone transport. Transport through the unsaturated or vadose zone is an extremely complex process (Campbell, 1985; Hanks and Ashcroft, 1980; Hillel, 1980a,b; Koorevaar, Menelik, and Dirksen, 1983) for the following reasons:

First, unsaturated zone transport may occur in more than one phase. Contaminant materials may enter the soil in rainwater solution, be precipitated within the upper portions of the soil as solids, move from one section of the soil to another along with solid particles due, for example, to animal burrowing, and even, for materials with significant vapor pressures, move across pore spaces by gaseous diffusion.

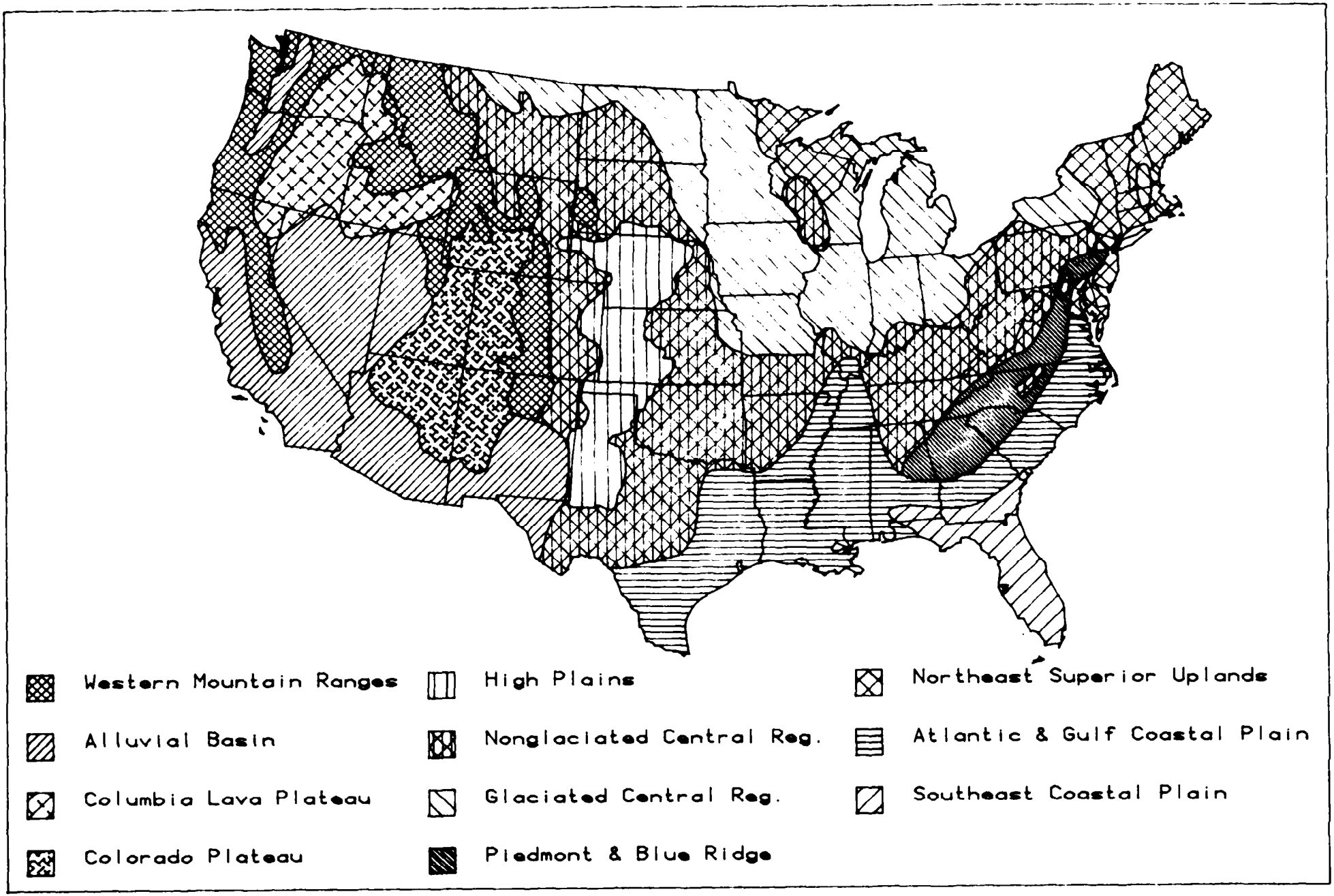

Figure 7. Hydrogeologic regions of the Continental United States (after Heath, 1984)

Also, liquid transport through the unsaturated zone may not occur by physical means which are appropriately described by Darcy's Law, the single most common approach to conceptualizing transport in porous media. Liquid transport may occur in part due to vapor transfer and in part due to turbulent flow.

As a first approximation to the importance of unsaturated zone transport, depth to groundwater represents a characteristic variable. Depth to groundwater will be closely related to annual precipitation given the caveats discussed above, but will also be controlled by the soil, overburden and bedrock characteristics at a given site.

Depth to groundwater has not been compiled in a central location for every site. For sites where these data are available, average figures are given in Figure 8.

Saturated zone transport. Within the saturated zone groundwater transport is usually less complex than transport through the unsaturated zone. When water completely fills available interconnected pores in the subsurface material, transport will be a function of two principal factors.

The first of these factors is whether the aquifer is confined or unconfined. If, for example, the aquifer is confined by aquitards above and below, then transport may be adequately described by relatively simple laws as long as flow falls within limits appropriate for Darcy's Law. Such solutions to groundwater flow are termed "analytical" or exact solutions (Bear, 1972; Freeze and Cherry, 1979; Fetter, 1988). Unconfined flow cannot be completely described by analytical equations, because the upper surface of unconfined flow (the water table) can move. Only in cases where the water table is nearly constant with time is unconfined flow susceptible to appropriate mathematical formulation and description.

The second factor is the nature of flow within the aquifer. The only flow through porous materials which can be completely described is diffuse flow through pores driven by differences in hydrostatic head, known as Darcian flow (Bear, 1972; Freeze and Cherry, 1979; Fetter, 1988). Such flow occurs through porous media. If flow occurs through some other mechanism, for example through channels or fractures in the soil, regolith, or rock, then the medium cannot be considered to be continuous. Various methods have been suggested to arrive at an approximate description of such flow, but, while such methods may indeed provide adequate solutions under certain conditions, they are rarely applied. The potential for transport through channels and fractures is important enough to warrant listing in the matrix.

Table 4 includes a listing of the hydrogeologic regions defined by Heath (1984) and sub-regions as defined by Aller, *et al.* (1985) in the DRASTIC system of classification. The sites cover all the major geologic features of the U.S. Twenty percent of the NPL sites, including many with the largest quantities and highest concentrations of radioactively contaminated materials, occur in areas where either karst or volcanic terrains exist. In these settings open fracture flow may important. In contrast, only one of the SDMP sites lies in a karst area.

7 Receptor Characteristics

Potential receptors of contamination at a site include both the human population and its natural environment (threatened species, fragile ecosystems). Inclusion on the NPL is weighted most heavily by potential human risk. Total risk is a function of both population itself and the ways that the population uses the environment.

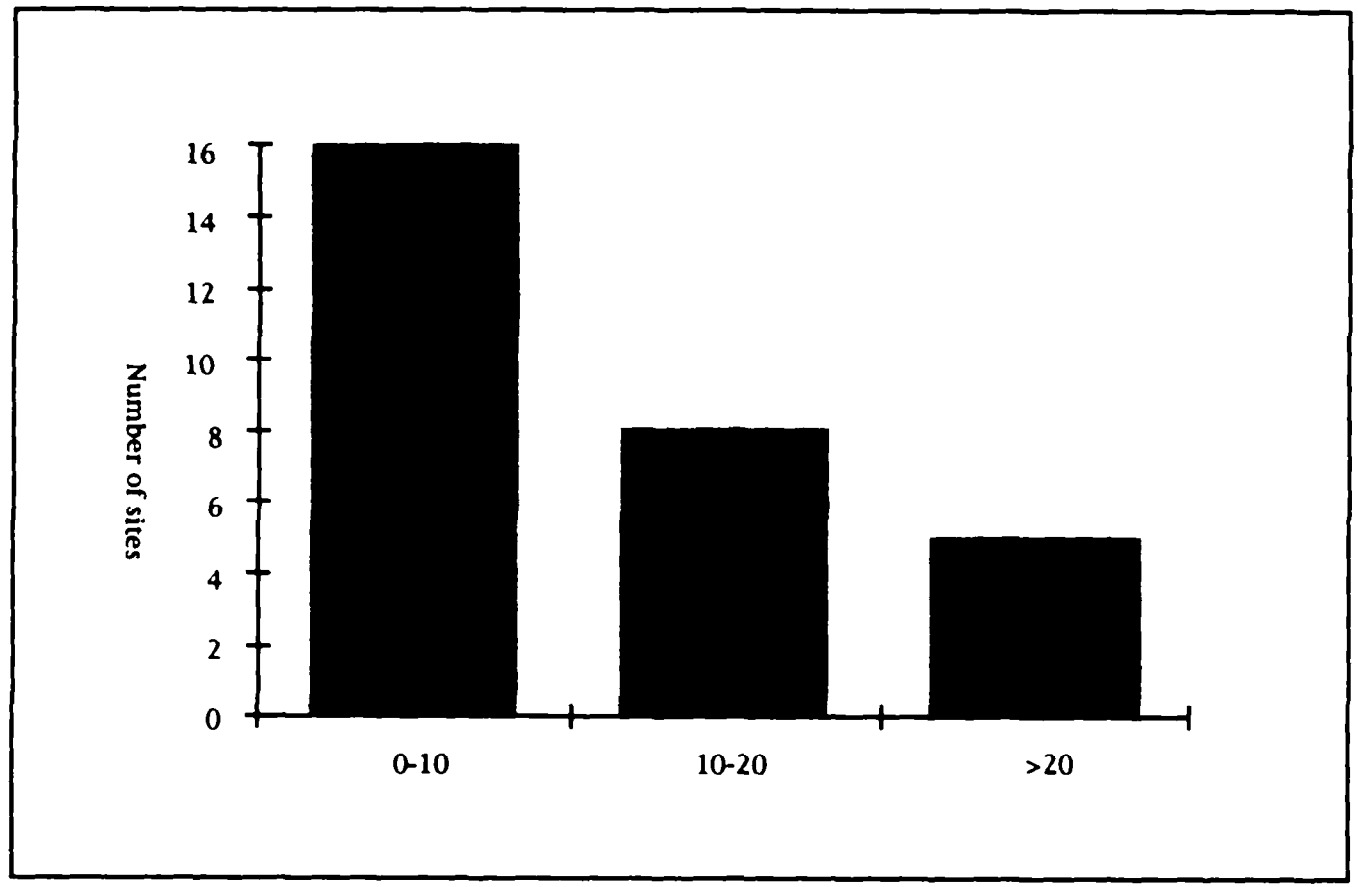

Figure 8. Frequency distribution of depth to water table at NPL radioactively contaminated sites (number of sites for which data were available).

7.1 Population

County population or population density is frequently chosen as a gross measure of the population potentially at risk because it is an easily available statistic and provides a rough "region" around the site. However, county population is not necessarily characteristic of the area immediately surrounding the site. For this reason, population in the immediate area must also be known. Table 4a shows both the county population density and the density within a 5 km radius for the 45 NPL radioactively contaminated sites. Table 4b shows county population density only for the 38 SDMP sites.

Population densities at both the county and local levels vary considerably among the 45 NPL radioactively contaminated sites As shown in Figure 9a, the county population densities tend to fall into four logarithmic groups. Where the population is less than $10/km^2$, an area may be considered unpopulated. Rural regions are those with a population density of $10\text{-}100/km^2$. From $100\text{-}1000/km^2$ an area is classed as suburban, and population densities of $1000/km^2$ or greater are labelled urban. Defense plants are generally located in sparsely populated areas, frequently in the western U.S., largely for security reasons. Even sites in densely populated counties (*e.g.*, FEMP) are located in less-populated rural areas. Similarly, mining and processing of ore is a spatially extensive industrial activity necessarily found in areas of low population density, though disposal of wastes from the final processing stages may occur in more populated settings (*e.g.*, Kerr-McGee/W. Chicago, Wayne Interim Storage). In contrast, the radium sites are more characteristically located in higher-density urban areas. Other types of sites are less easily categorized.

As indicated in Figure 2b, most of the SDMP sites are located in the eastern half of the country. This is reflected in the population densities of the counties where these sites are located; none fall in the "unpopulated" group (Figure 9b).

It is necessary to examine population at several impact distances, since neither small-scale nor large-scale regional densities can necessarily be extrapolated to each other and since contaminant concentrations may vary considerably over distance. For example, the Monticello site is located in a remote rural county in southeastern Utah with a very low population density. However, the commercial center of the town of Monticello, as well as several residences, lie adjacent to the mill site; the population density of the immediate area is nearly 200 times that of the county as a whole. Conversely, the Maywood site is located in a heavily urbanized county in New Jersey with a high population density. The area immediately surrounding the site is mainly industrial, with a residential population density less than a third that of the surrounding county. The appropriate target distance for population estimates/measurements depends on the contaminant(s) in question and the various factors affecting contaminant transport to the potential receptors (see 40 CFR Part 300).

7.2 Water Use

The principal transport media for radioactive contaminants are water and air. Unlike air, water use may vary from site to site. Groundwater or surface water in the immediate site area may be used for drinking, irrigation, watering of livestock, or for recreational purposes. Table 4 indicates how local water is used in the vicinity of the radioactively contaminated sites. Water for drinking is obtained from local supplies at 30 of the 45 NPL sites. Four sites, Brookhaven National Laboratory, Himco, Inc., Dump, Feed Materials Production Center, and Idaho National Engineering Laboratory, are located above Safe Drinking Water Act Sole-Source Aquifers. Local surface waters are used for recreation at seven sites and for agricultural purposes at five sites. Information on local groundwater and surface water use was not generally available for the SDMP sites.

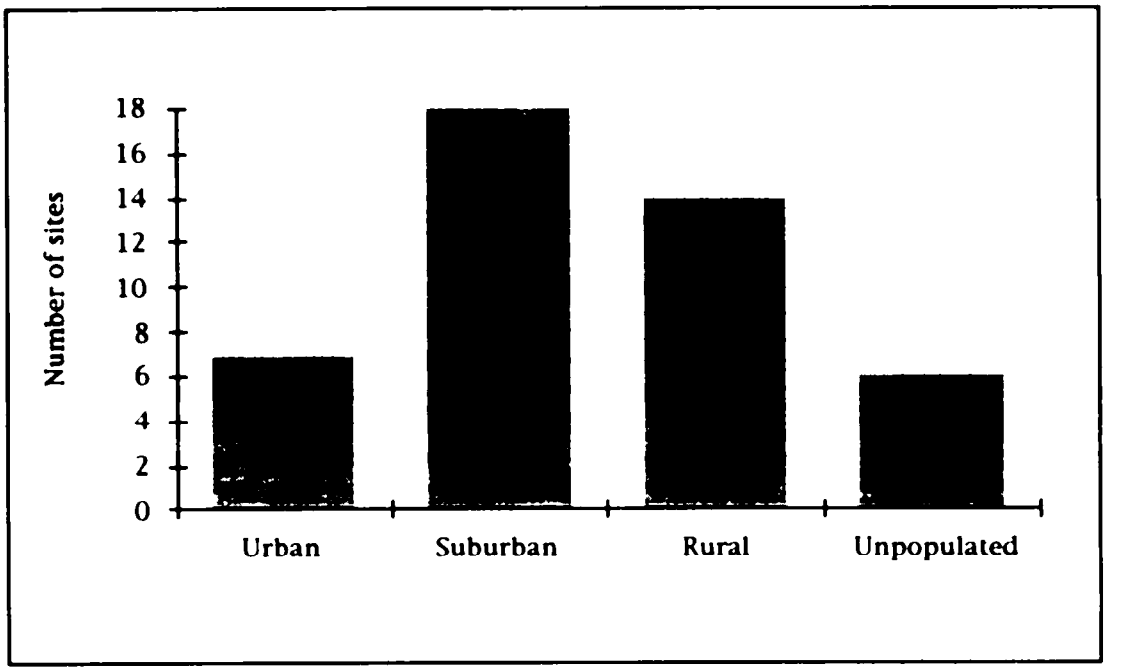

Figure 9a. County population density at NPL radioactively contaminated sites.

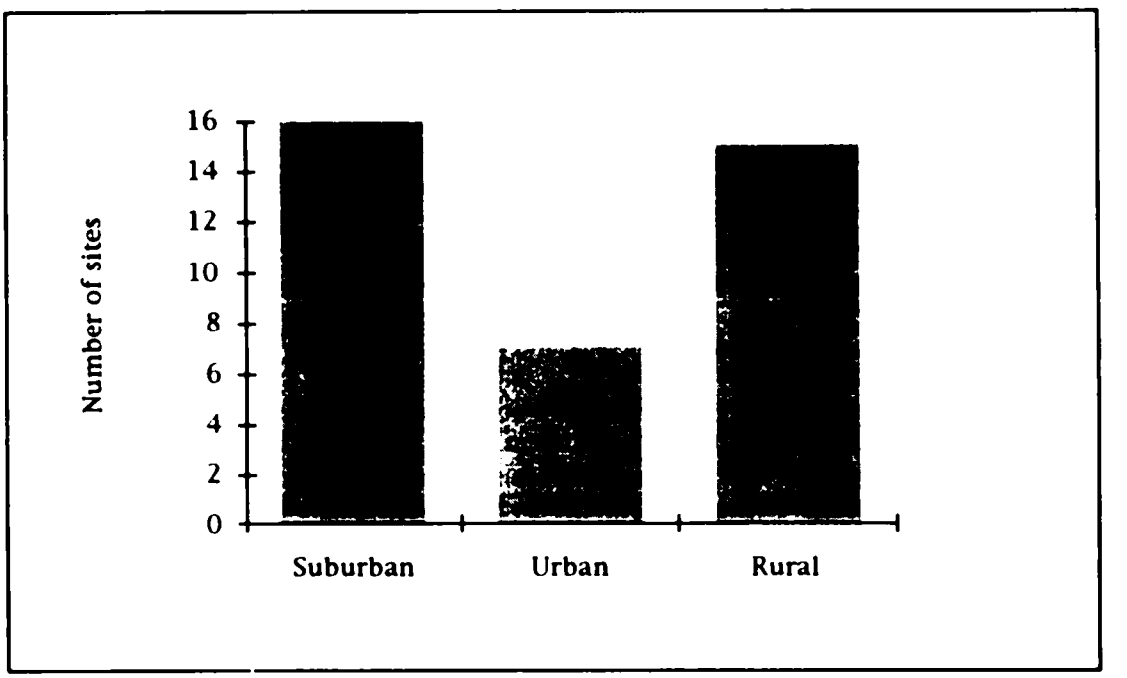

Figure 9b. County population density at NRC SDMP sites.

7.3 Land Use

Another aspect of receptor characterization is the land use associated with the area surrounding a site. Broadly speaking, land use and population density are related: urban areas have higher population densities than do rural regions. Within these groups, particular land uses can be distinguished which affect receptor status. Awareness of land use permits consideration of potentially exposed non-resident populations. The four population density groupings previously mentioned can also be translated into categories of land use.

- *Urban* land use includes commercial, industrial, and medium- to high-density residential uses. Commercial zones have a large but transient (non-resident) population. Population density is far higher during the day than in residential areas, but may drop to nearly empty at night. Industrial areas have the lowest potential population at risk of the primary urban land use groups (Murphy, 1966).

- *Suburban* land use is usually thought of as medium- to low-density residential, but it also includes large areas of commercial land (shopping malls) and industrial parks. The transient populations of suburban commercial and industrial areas tends to be lower than those of their urban counterparts.

- *Rural* areas include both agricultural and non-agricultural land. Agricultural land uses can expose non-resident populations to risks from contamination in several ways. Cattle or other animals may graze on contaminated ground or drink contaminated water. Contaminated water may also be used to irrigate crops. The primary non-agricultural rural land use which may result in population exposures is recreation. Potential risks arise from swimming in contaminated surface waters, soil ingestion by children at picnic sites, or eating contaminated fish or game.

- *Unpopulated* regions have effectively no regular use by human populations. Large areas of desert which were used for nuclear weapons testing are an example of this land "use."

Approximately 70% of both the NPL sites and the SDMP sites are located in rural or suburban areas. Only seven NPL sites are located in urban areas, all of which are radium sites. Six of the seven are in the greater New York City area; the other (Lansdowne) is near Philadelphia. Seven SDMP sites are located in urban counties, four in the vicinity of Philadelphia. Four different types of sites are represented. There are also seven NPL sites in counties classed as unpopulated. These sites are all located in the western U.S.; all are mill tailings/processing/disposal sites.

8 Discussion

This summary review of the characteristics of the 83 NPL and NRC radioactively contaminated sites is a first step in establishing the conceptual boundaries within which environmental pathway models will necessarily be applied. While it was not the intent at the outset of this review to create a general-purpose list of all possible environmental characteristics which should be treated in environmental pathway models, in the final analysis the sites themselves present so broad a range of characteristics that few, if any, can be ignored. In this section the implications of these characteristics for modeling contaminant mobility at these sites are discussed.

The sites described in this report differ on the most fundamental level in the quality and quantity of information available for characterization. Some have been monitored for long periods of time and are subjected to repeated and detailed surveys. Others can be described in little more detail

than the minimum needed to initially identify contamination. Thus some of the data summarized in the tables in this report are presented with a great deal of confidence, while for other variables information must simply be left blank or listed as "unknown."

In the absence of reliable data and long-term records, compromises must be made in order to implement a conceptual model that assumes that site characteristics are well known. While data quantity and quality are not in themselves site characteristics, the absence of high quality data may influence the choice and operation of environmental pathway models.

One of the most common areas where data are scant or ambiguous is in the characterization of the source of radiochemical contamination. Where the source is well defined, the problem can be approached from a deterministic perspective employing well-understood and well-documented methodologies. For example, at the K-65 silos at Fernald, the quantities of radioactive materials within the silos are well known, the physical characteristics of the containment are well known, and the emissions of radioactive materials from the silos have been monitored in detail for an extended period of time.

On the other hand, if the source is ill-defined, it may be necessary to use techniques such as stochastic methods to estimate the quantity of material present. At many of the landfill sites (Himco, Inc., Dump, Shpack Landfill, and Kawlawlin Landfill, for example), it is only known that radioactive materials are present at the site and are contaminating one or more pathways. Neither the exact form of the contaminants nor the characteristics of the containment are known.

The physical settings of these sites range from urban, industrial centers to near wilderness. Local environments vary from deserts to temperate rainforests and from simple to highly complex and varied hydrogeology. The quantities and concentrations of radionuclides are in some cases minor components of primarily non-radiochemical contamination problems; in other cases the level of radiochemical contamination alone would pose a serious threat to human health and environmental integrity if those radiochemicals were not located within the boundaries of controlled and closely-managed facilities.

There are few sites in which it would be appropriate to examine a single environmental pathway, for example, air or water. This situation is due primarily to the fact that the most common radioactive contaminants themselves have diverse physical characteristics, occurring as gases, as solutes in water, as solids, or adsorbed onto the surfaces of particles. Thus, simultaneous contamination of multiple media (air, soil, surface- and groundwater) is the rule at these sites rather than the exception.

Similarly, at those sites where the contamination of one environmental pathway may pose a more significant problem than any other, it is frequently found that the contaminated medium is neither homogeneous or isotropic. This is primarily a consequence of both the size and the geographic location of these sites. Some sites, the Savannah River Site and Idaho National Engineering Laboratory, for example, are so large that subsurface characteristics alone span a range of geologic and hydrogeologic types. Yet even the smaller sites tend to entail a remarkable degree of environmental complexity. This situation prevails because more than half of the sites examined in this study are located within the formerly glaciated regions of North America. Glacial terrain is commonly complex. While in a few cases glacial materials were laid down over bedrock which, in itself, posses no particular problem with respect to complexity, in many cases ice deposits both modify previously complex terrain and have been modified since deposition into even more complex features. The influence of continental glaciation and the superimposition of that influence on a pre-existing complex terrain is particularly evident in the U.S. midwest and northeast. It is not uncommon in these regions to find a number of different bedrock lithologies in close proximity. Glacial deposits of very limited areal extent can easily vary from impervious tills to sand and gravel deposits with significant aquifer potential. In addition, the geomorphic complexity which often follows glacial modification of these areas leads to a varied and intricate drainage pattern which can have further implications for present-

day surface- and groundwater flow. Glaciation also complicates the geochemical conditions which may prevail at any particular site by having carried and deposited exotic materials at a site and by having imposed climatic conditions in the recent past far different than those existing today.

Finally, receptor characteristics generally have no direct impact on the pathways by which radionuclides are transported through the environment, except in cases such as drinking wells, where human activity will actually modify contaminant transport. Yet receptor characteristics may, like data quality, exert an influence on the approach taken in modeling a given pathway at a site. It may be assumed that even under circumstances where two sites have the same or very similar environmental characteristics, there may be a need to employ different models if, for example, local population is distributed randomly or in clusters about the site.

9 Summary and Conclusions

The information presented in the previous sections characterizes the types of isotopes and package forms, site characteristics, and receptor characteristics at Federal (EPA, DOE, and NRC) radioactive waste sites. Since the purpose of this effort was to bound the nature of the problems at these sites, these characterizations by necessity are limited. Nevertheless, important issues have been identified:

- The sites listed on the NPL as radioactive are so classified because radioactive materials have been found there. The hazard to health from these materials, however, is not necessarily related to or dominated by the radiation component. In fact, radioactive contamination scored for toxicity persistence in the original HRS process at only 25 of the 45 NPL sites. The 38 SDMP sites are by administrative definition low-level radioactive waste sites. Prioritization of these sites within the SDMP does not necessarily reflect level of contamination or potential risk.

- Although it was originally believed that groundwater would be the dominant medium of concern (and for this reason data collection efforts were focused in this area), the data show that all exposure pathways are present in roughly equal amounts. For this reason, a broader characterization of the sites may be needed if other media are to be considered.

- Most of the 45 NPL sites (38 out of 45) can be classified as either defense related facilities, mill tailing sites, or radium or thorium contaminated sites. Nineteen of these sites are owned or operated by the DOE. The SDMP sites, on the other hand, are dominated by manufacturing, mill tailings, and fuel processing sites (27 out of 38).

- Although a total of 30 radionuclides were identified at the sites, U (U-234, -235, -238), Th (Th-228, -230, -232) Ra (Ra-226, -228), and Pu (Pu-238, -239, -240) were found most frequently.

- For the same set of dominant isotopes, radioactive daughters may be created which may have different chemical, physical, and biological properties from their parents.

- While the actual physical and chemical processes which control the concentration of a given substance may be rather complex, it is possible to describe the behavior of these substances with relatively simple paradigms (*e.g.*, K_d). However, this simple approach may not be valid for many radioisotopes (*e.g.*, U) whose aqueous geochemical behavior is complex and can strongly affect contaminant mobility.

- The source terms, *i.e.*, contaminant types, quantities, and activity levels, are not well defined. Nevertheless, all of the sites have sources or contamination which can be treated as point sources.

- Most of the sites have more than one aquifer of concern. Almost all sites are underlain by both confined and unconfined aquifers.

- Depth to groundwater at these sites is shallow (less than 10 m) at about 33% of the NPL sites and nearly all the SDMP sites. As a consequence transport of contaminants to groundwater may be relatively rapid in humid regions as there may be little opportunity for adsorption in soils. The site with the greatest depth to groundwater is Pantex, where groundwater is at more than 140 m.

- The sites cover all the major geologic features of the U.S. However, many of the NPL sites, including many with the largest quantities and highest concentrations of radioactively contaminated materials, occur in areas where either karst or volcanic terrains exist. In these settings open fracture flow may be important.

- At present, there are no good estimates of the population potentially impacted now or in the future from the contamination at these sites. Groundwater drawn from wells proximate to at least 33 of these sites, however, is used for drinking water purposes. Four sites (BNL, Himco, FEMP, and INEL) are located above designated "Sole Source Aquifers."

- Many (~40%) of the sites are located in suburban regions (areas of population between 100 and 1000 persons per km^2).

The 83 NPL and NRC sites reviewed here pose a wide range of challenges to the efficacious use of models in environmental and health risk assessment. Since the stated goal of this project is to foster the consistent use of appropriate environmental pathway models, the findings imply that a mix of models capable of addressing the widest possible range of environmental characteristics may be needed. Model defaults and assumptions, strengths and weaknesses, must be carefully examined within the context of the prevailing characteristics at any given site. This document provides a framework in which those challenges can be addressed and decisions based on models can be optimized.

Table 1a. Geographic and administrative data for NPL sites

Site	FINDS	EPA Region	Type	State	City	Zip Code	County	FIPS	NPL History Proposed	NPL History Final
Brookhaven Nat'l Lab	NY7890008975	II	DOE	NY	Upton	11973	Suffolk	36013	14-Jul-89	21-Nov-89
Denver Radium Site	COD980716955	VIII	SF	CO	Denver	80204	Adams	08031	23-Oct-81	8-Sep-83
Fernald Environ. Remed. Proj.	OH6890008976	V	DOE	OH	Fernald	45218	Hamilton	39061	14-Jul-89	21-Nov-89
Forest Glen Mobile Home	NYD981560923	II	SF	NY	Niagara	14094	Niagara	36063	29-Aug-89	21-Nov-89
Glen Ridge Radium Site	NJD980785646	II	SF	NJ	Glen Ridge	07028	Essex	34013	1-Oct-84	14-Feb-85
Hanford (100 Area)	WA3890090076	X	DOE	WA	Richland	99352	Benton	53005	24-Jun-88	4-Oct-89
Hanford (1100 Area)	WA4890090075	X	DOE	WA	Richland	99352	Benton	53005	24-Jun-88	4-Oct-89
Hanford (200 Area)	WA1890090078	X	DOE	WA	Richland	99352	Benton	53005	24-Jun-88	4-Oct-89
Hanford (300 Area)	WA2890090077	X	DOE	WA	Richland	99352	Benton	53005	24-Jun-88	4-Oct-89
Himco Inc., Dump	IND980500292	V	SF	IN	Elkhart	46514	Elkhart	18039	24-Jun-88	21-Feb-90
Homestake Mining Co.	NMD007860935	VI	SF	NM	Grants/Milan	87021	Valencia	35000	23-Oct-81	8-Sep-83
INEL	ID4890008952	X	DOE	ID	Idaho Falls	83401	Bonneville	16019	14-Jul-89	21-Nov-89
Jacksonville NAS	FL6170024412	IV	DOD	FL	Jacksonville	32218	Duval	12031	14-Jul-89	21-Nov-89
Kerr-McGee (Kress Creek)	ILD980823991	V	SF	IL	Chicago	60185	DuPage	17043	15-Oct-84	11-Feb-91
Kerr-McGee (Reed-Keppler)	ILD980824007	V	SF	IL	Chicago	60185	DuPage	17043	15-Oct-84	30-Aug-90
Kerr-McGee (Res. Area)	ILD980824015	V	SF	IL	Chicago	60185	DuPage	17043	15-Oct-84	30-Aug-90
Kerr-McGee (Sewage TP)	ILD980824031	V	SF	IL	Chicago	60185	DuPage	17043	15-Oct-84	30-Aug-90
Lansdowne Rad. Site	PAD980830921	III	SF	PA	Lansdowne	19050	Delaware	42045	1-Apr-85	16-Sep-85
Lincoln Park	COD042167858	VIII	SF	CO	Canon City	81212	Fremont	08043	8-Sep-83	21-Sep-84
LLNL	CA2890012584	IX	DOE	CA	Livermore	94500	Alameda	06001	15-Oct-84	22-Jul-87
LLNL (Site 300)	CA2890090002	IX	DOE	CA	Tracy	95376	San Joaquin	06077	14-Jul-89	30-Aug-90
Lodi Municpal Well	NJD980769301	II	SF	NJ	Lodi	07644	Bergen	34003	15-Oct-84	30-Aug-90
Maxey Flats Nuclear Disp.	KYD980729107	IV	SF	KY	Hillsboro	41049	Fleming	21069	15-Oct-84	10-Jun-86
Maywood Chemical Co.	NJD980529762	II	SF	NJ	Maywood	07602	Bergen	34003	1-Dec-82	8-Sep-83
Montclair Radium Site	NJD980785653	II	SF	NJ	Montclair	07052	Essex	34013	1-Oct-84	14-Feb-85
Monticello Mill Tailings	UTD980717979	VIII	DOE	UT	Monticello	84535	San Juan	49037	1-Jul-89	21-Nov-89
Monticello RCP	UTD980667208	VIII	SF	UT	Monticello	84535	San Juan	49037	15-Oct-84	10-Jun-86
Mound Plant	OH6890008984	V	DOE	OH	Miamisburg	45342	Montgomery	39113	14-Jul-89	21-Nov-89
Oak Ridge Res.	TN1890090003	IV	DOE	TN	Oak Ridge	37830	Anderson	47145	14-Jul-89	21-Nov-89

Table 1a. Geographic and administrative data for NPL sites

Ottawa Radioactive Areas		V	SF	IL	Ottawa	61350	LaSalle	56926	1-Jul-91	
Pantex Plant		VI	DOE	TX	Pantex Village	79068	Carson	54960	1-Jul-91	
Pensacola NAS	FL9170024567	IV	DOD	FL	Pensacola	32508	Escambia	12033	14-Jul-89	21-Nov-89
Radium Chemical	NYD001667872	II	SF	NY	Woodside	11377	Queens	36081	29-Aug-89	21-Nov-89
Rocky Flats Plant	CO7890010526	VIII	DOE	CO	Golden	80401	Jefferson	08059	15-Oct-84	4-Oct-89
Savannah River Site	SC1890008989	IV	SF	SC	Aiken	29812	Barnwell	45003	14-Jul-89	21-Nov-89
Shpack Landfill	MAD980503973	I	DOE	MA	Norton/Attleboro	02766	Bristol	25005	15-Oct-84	10-Jun-86
St. Louis Airport	MOD980633176	VII	SF	MO	Lambert	63134	St. Louis	29510	5-May-89	4-Oct-89
Teledyne Wah Chang	ORD050955848	X	SF	OR	Millersburg	97321	Linn	41043	30-Dec-82	8-Sep-83
U.S. Radium Corp.	NJD980654172	II	SF	NJ	Orange	07050	Essex	34013	1-Dec-82	8-Sep-83
United Nuclear Corp.	NMD030443303	VI	SF	NM	Church Rock	87311	McKinley	35031	23-Oct-81	8-Sep-83
Uravan Uranium	COD007063274	VIII	SF	CO	Uravan	81436	Montrose	08085	15-Oct-84	10-Jun-86
Wayne Interim Storage	NJ1891837980	II	DOE	NJ	Wayne	07470	Passaic	34031	1-Sep-83	21-Sep-84
Weldon Springs Army OW	MO5210021288	VII	DOE	MO	Weldon Spring	63386	St. Charles	29183	14-Jul-89	21-Feb-90
Weldon Springs Quarry	MO3210090004	VII	DOE	MO	Weldon Spring	63386	St. Charles	29183	15-Oct-84	22-Jul-87
Westlake Landfill	MOD079900932	VII	SF	MO	Bridgeton	63044	St. Louis	29189	26-Oct-89	30-Aug-90

Table 1b. Geographic and administrative data for SDMP sites

Site	Docket No.	NRC Region	State	City	Zip Code	County	FIPS	Priority
Aberdeen Proving Gnd.	040-06354	I	MD	Aberdeen Proving Ground	21005	Harford	24025	C
Allied Signal (2 sites)	040-00772	I	NJ	Teterboro	07608	Bergen	34003	A
Amax	040-8820	II	WV	Washington Bottoms	28181	Wood	54107	B
Babcock & W ilcox (1)	70-135	I	PA	Apollo	15613	Armstrong	42005	B
Babcock & W ilcox (2)	70-364	I	PA	Parks Township		Armstrong	42005	B
BP Chemicals	040-07604	III	OH	Lima	45805	Allen	39003	B
Budd	030-19963	I	PA	Philadelphia		Philadelphia	42101	C
Cabot (1)	040-06940	I	PA	Boyertown	19512	Berks	42001	C
Cabot (2)	040-06940	I	PA	Reading		Berks	42001	B
Cabot (3)	040-06940	I	PA	Revere	18953	Bucks	42017	B
Chemetron (1)	040-08724	III	OH	Newburgh Hts	44105	Cuyohoga	39035	A
Chemetron (2)	040-08724	III	OH	Newburgh Hts	44105	Cuyohoga	39035	A
Dow Chemical(3 sites)	040-00017	III	MI	Midland		Midland	26111	B
Fansteel	040-7580	IV	OK	Muskogee		Muskogee	40101	C
GSA Arsenal(2 sites)	n/a	I	MA	Watertown	02172	Middlesex	25017	B
Gulf United Nuclear	[1]	I	NY	Pawling	12564	Dutchess	36027	A
Heritage	040-08980	I	NJ	Lakehurst	08733	Ocean	34029	B
Kawkawlin Landfill	n/a	III	MI	Bay City		Bay	26017	B
Kerr-McGee - Cimmaron	[2]	IV	OK	Crescent	73028	Logan	40083	A
Kerr-McGee - Cushing	[3]	IV	OK	Cushing	74023	Payne	40119	A
Magnesium Elektron	040-08984	I	NJ	Flemington	08822	Hunterdon	34019	B
Molycorp (1)	40-8778	I	PA	Washington	15301	Washington	42125	B
Molycorp (2)	40-8794	I	PA	York		York	42133	B
Nuclear Metals	040-00672	I	MA	Concord	01740	Bristol	25005	C
Permagrain	030-29288	I	PA	Media		Delaware	42045	C
Pesses (METCOA)	040-08405	I	PA	Pulaski	16143	Beaver	42007	B
Process Technology	030-07022	I	NJ	Rockaway	07866	Morris	34027	B
Remington	[4]	III	MO	Independence		Jackson	29095	C
Safety Light	030-05980	I	PA	Bloomsburg	17815	Columbia	42037	A

Table 1b. Geographic and administrative data for SDMP sites

Schott Glass	040-07924	I	PA	Duryea		Luzerne	42079	B
Shieldalloy (1)	40-8948	I	NJ	Newfield	08344	Gloucester	34015	C
Shieldalloy (2)	40-7102	III	OH	Cambridge	43725	Guernsey	39059	B
Texas Instruments	70-33	I	MA	Attleboro	02703	Bristol	25005	A
UNC Recovery	70-820	I	RI	Wood River Jct	02894	Washington	44009	A
West Lake Landfill	[5]	III	MO	Bridgeton	63044	St Louis	29189	A
Westinghouse	070-00698	I	PA	Madison	15663	Westmoreland	42129	B
Whittaker	040-07455	I	PA	Greenville	16125	Mercer	42085	C
Wyman-Gordon	n/a	I	MA	North Grafton	01536	Worcester	25027	C

(1) 50-23, 50-101, 50-290, 70-903
(2) 070-00925, 070-01193
(3) 040-01478, 070-00712 (term.)
(4) 040-8303, 40-8767
(5)040-08035, 040-08801

Footnotes:

FINDS - Facility Index System Identification Number (EPA).
FIPS - Federal Information Processing Standards place code (National Bureau of Standards).
NPL History - data that the site was proposed/assigned to the National Priorities List.

Table 2a. Isotopes identified at NPL radioactively contaminated sites

			Brookhaven Nat'l Lab	Denver Radium Site	Fernald Envir. Remed. Project	Forest Glenn Mobile Home
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	NUS-ROA&DAR, EMR, NPL	SAFFIRE, 1989GSS, HRS, NPL, MITRE, UNC-Geotech	NUS-ROA&DAR, DOE-ES, NPL, HRS	NPL, HRS
		HRS scored:	GW	A,S	A,S,SW,GW	A,S
Element	**Symb.**	**Mass**				
Actinium	Ac	227				
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60				
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137	S,SW			
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3	GW			
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238			SW	
Plutonium	Pu	239			A,SW	
Plutonium	Pu	240			A,SW	
Radium	Ra	226		A,S,SW,GW		
Radium	Ra	228				
Radon	Rn	220				
Radon	Rn	222		A,S	A	
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90	GW		SW	
Technitium	Tc	99			S,SW	
Thorium	Th	228				
Thorium	Th	230		S	SW	
Thorium	Th	232		S	A,S	
Uranium	U	234		S	A,S,SW,GW	
Uranium	U	235			A,S,SW,GW	
Uranium	U	238		S	A,S,SW,GW	

Table 2a. (NPL sites), cont.

			Glen Ridge Radium Site	Hanford 100 Area	Hanford 200 Area	Hanford 300 Area
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	SAFFIRE, MITRE, 1989GSS, HRS, NPL	SAFFIRE, DOE-ES, NPL, MITRE, EMR, 1989GSS, NUS-DAR	SAFFIRE, DOE-ES, EMR, HRS, MITRE, NUS-DAR, 1989GSS	SAFFIRE, DOE-ES, EMR, HRS, MITRE, NUS-DAR, 1989GSS
		HRS scored:	A,S	SW,GW	SW,GW	S,SW,GW
Element	**Symb.**	**Mass**				
Actinium	Ac	227				
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60		S,SW,GW	GW	SW,GW
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137		S,SW,GW	GW	SW
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3		SW,GW	SW,GW	GW
Iodine	I	129		GW	A	
Iodine	I	131		SW		
Krypton	Kr	85				A
Manganese	Mn	54		S		
Nickel	Ni	63		GW		
Protactinium	Pa	231				
Plutonium	Pu	238		SW		
Plutonium	Pu	239		S,SW	SW,GW	
Plutonium	Pu	240		SW	SW,GW	
Radium	Ra	226	S,SW,GW		GW	
Radium	Ra	228			GW	
Radon	Rn	220				
Radon	Rn	222	A,S,SW,GW			
Ruthenium	Ru	106		GW		
Selenium	Se	79				
Strontium	Sr	90		S,SW,GW	A,GW	SW,GW
Technitium	Tc	99		GW	GW	GW
Thorium	Th	228				
Thorium	Th	230				
Thorium	Th	232				
Uranium	U	234	S	SW	S,SW,GW	A,GW
Uranium	U	235			S,GW	A,GW
Uranium	U	238		SW,GW	S,SW,GW	A,GW

Table 2a. (NPL sites), cont.

			Hanford 1100 Area	Himco, Inc. Dump	Homestake Mining Corp.	Idaho Nat'l Engineering Lab
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	NPL, NUS-DAR	HRS, NPL	SAFFIRE, MITRE, NPL	NPL, NUS-ROA&DAR
		HRS scored:	SW	GW	GW	A,S,SW,GW
Element	**Symb.**	**Mass**				
Actinium	Ac	227				
Americium	Am	241				SW,GW
Antimony	Sb	125				GW
Carbon	C	14				
Cobalt	Co	60				S,GW,SW
Cerium	Ce	144				GW
Cesium	Cs	134				GW
Cesium	Cs	135				S
Cesium	Cs	137				S,GW,SW
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3				GW,SW
Iodine	I	129				A,S
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238				S,SW
Plutonium	Pu	239				S
Plutonium	Pu	240				
Radium	Ra	226			A,S,SW	
Radium	Ra	228				
Radon	Rn	220				
Radon	Rn	222			A,S	
Ruthenium	Ru	106				
Selenium	Se	79				S
Strontium	Sr	90				S,SW,GW
Technitium	Tc	99	GW			S
Thorium	Th	228				
Thorium	Th	230				
Thorium	Th	232				
Uranium	U	234			A,S,GW	SW
Uranium	U	235				
Uranium	U	238			A,S,GW	SW

Table 2a. (NPL sites), cont.

			Jacksonville Naval Air Station	Kerr-McGee Kress Creek	Kerr-McGee Reed-Keppler Park	Kerr-McGee Residential Area
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	NPL, HRS	SAFFIRE, HRS, 1989GSS, NPL	SAFFIRE, MITRE, 1989GSS, NPL, Logan	SAFFIRE, MITRE, 1989GSS, HRS, NPL, Bluck,Logan
		HRS scored:	S,SW,GW	SW,GW	A,S	A,S
Element	Symb.	Mass				
Actinium	Ac	227				
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60				
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137				
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3				
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238				
Plutonium	Pu	239				
Plutonium	Pu	240				
Radium	Ra	226	S	S	S,GW	S,GW
Radium	Ra	228	S		S	S
Radon	Rn	220			A	A
Radon	Rn	222			A	A
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90				
Technitium	Tc	99				
Thorium	Th	228		S		
Thorium	Th	230				
Thorium	Th	232		S,SW,GW	S,GW	S,GW
Uranium	U	234		S	A,S,GW	S,GW
Uranium	U	235				
Uranium	U	238		S	A,S,GW	S,GW

Table 2a. (NPL sites), cont.

			Kerr-McGee Sewage Treatmt Plant	Lansdowne Radiation Site	Lawrence Livermore Nat'l Lab	Lawrence Livermore (Site 300)
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	SAFFIRE, MITRE, 1989GSS, HRS, NPL, Bluck,Logan	SAFFIRE, MITRE, 1989GSS, NPL	EMR, NUS-ROA&DAR	NPL, EMR, NUS-ROA&DAR
		HRS scored:	A,S	A,S,GW	GW	SW,GW
Element	**Symb.**	**Mass**				
Actinium	Ac	227		A,S		
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60				
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137				
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3			S,GW	S,GW
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231		A,S		
Plutonium	Pu	238				
Plutonium	Pu	239				
Plutonium	Pu	240				
Radium	Ra	226	S,GW	A,S,SW,GW		
Radium	Ra	228	S			
Radon	Rn	220	A	A		
Radon	Rn	222	A	A,S		
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90				
Technitium	Tc	99				
Thorium	Th	228				
Thorium	Th	230	GW	S		
Thorium	Th	232	S,GW			
Uranium	U	234	S,GW			
Uranium	U	235				
Uranium	U	238	S,GW			A,S

Table 2a. (NPL sites), cont.

			Lincoln Park	Lodi Municipal Well	Maxey Flats	Maywood Chemical Co.
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	SAFFIRE, MITRE, NPL, 1989GSS	1989GSS, NPL, HRS, SAFFIRE, NUS-ROA&DAR	SAFFIRE, MITRE, HRS, 1989GSS	1989GSS, SAFFIRE, NPL
		HRS scored:	S,SW,GW	GW	A,S,GW	A,S
Element	**Symb.**	**Mass**				
Actinium	Ac	227				
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60			S	
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137			S,SW	
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3			A,S,SW,GW	
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238			SW,GW	
Plutonium	Pu	239			SW,GW	
Plutonium	Pu	240				
Radium	Ra	226	GW	GW	SW,GW	S,SW
Radium	Ra	228				
Radon	Rn	220				
Radon	Rn	222				A
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90			SW,GW	
Technitium	Tc	99				
Thorium	Th	228				
Thorium	Th	230				
Thorium	Th	232				S,SW
Uranium	U	234	S,SW,GW	GW		S,SW
Uranium	U	235				
Uranium	U	238	S,SW,GW	GW		S,SW

Table 2a. (NPL sites), cont.

			Montclair West Orange Radium Site	Monticello Mill Taillings	Monticello Radioactively Contam. Prop.	Mound Plant
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	SAFFIRE, MITRE, 1989GSS, RI/FS, NPL	NPL, MITRE, SAFFIRE, HRS	NPL, MITRE, SAFFIRE, HRS	NUS, HRS
		HRS scored:	A,S,GW	A,SW	A	A,S,SW
Element	**Symb.**	**Mass**				
Actinium	Ac	227				A,SW,GW
Americium	Am	241				S
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60				A,S,SW,GW
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137				S,SW,GW
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3				SW,GW
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238				A,S,SW
Plutonium	Pu	239				
Plutonium	Pu	240				
Radium	Ra	226	S,GW		S,SW,GW	S
Radium	Ra	228				
Radon	Rn	220				
Radon	Rn	222	A,GW	A	A	
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90				
Technitium	Tc	99				
Thorium	Th	228				S
Thorium	Th	230			S	S
Thorium	Th	232				A,S,SW,GW
Uranium	U	234	S	GW	S	
Uranium	U	235				
Uranium	U	238		GW	S	

Table 2a. (NPL sites), cont.

			Oak Ridge National Lab	Ottawa Radiation Areas	Pantex Plant	Pensacola Naval Air Station
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	NUS-ROA&DAR NPL, DOE-ES	NPL	NUS-DAR, DOE-ES, NPL	NPL
		HRS scored:	A,S,SW		A,S,SW,GW	A,S
Element	**Symb.**	**Mass**				
Actinium	Ac	227				
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60				
Cerium	Ce	144				
Cesium	Cs	134	S			
Cesium	Cs	135				
Cesium	Cs	137	S,SW,GW			
Curium	Cm	244				
Europium	Eu	152	S			
Europium	Eu	154	S			
Europium	Eu	155	S			
Hydrogen	H	3	S,SW,GW			
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238	S			
Plutonium	Pu	239	S			
Plutonium	Pu	240	S			
Radium	Ra	226		S		S
Radium	Ra	228				
Radon	Rn	220				
Radon	Rn	222		S		
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90	S,SW,GW		A,S	
Technitium	Tc	99	GW			
Thorium	Th	228				
Thorium	Th	230				
Thorium	Th	232				
Uranium	U	234	S,SW,GW		A,S,SW,GW	
Uranium	U	235	S,SW,GW			
Uranium	U	238	S,SW,GW		A,S,SW,GW	

Table 2a. (NPL sites), cont.

			Radium Chemical Corporation	Rocky Flats Plant	Savannah River Site	Shpack Landfill
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	NPL, HRS	SAFFIRE, MITRE, NPL, DOE-ES, 1989-GSS, NUS-ROA&DAR	NUS, HRS, DOE-ES	SAFFIRE, MITRE, NPL
		HRS scored:	NONE	A,S,SW,GW	A,S,SW,GW	S,SW,GW
Element	Symb.	Mass				
Actinium	Ac	227				
Americium	Am	241		A,S,SW,GW	GW	
Antimony	Sb	125				
Carbon	C	14			A,S,GW	
Cobalt	Co	60			SW,GW	
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137			S,SW,GW	
Curium	Cm	244			S,GW	
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3		S,SW	A,SW,GW	
Iodine	I	129			SW,GW	
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63			S,GW	
Protactinium	Pa	231				
Plutonium	Pu	238		A,S,SW	S,GW	
Plutonium	Pu	239		A,S,SW,GW	S,GW	
Plutonium	Pu	240		GW		
Radium	Ra	226	S			S,GW
Radium	Ra	228				
Radon	Rn	220				
Radon	Rn	222	A			GW
Ruthenium	Ru	106			S,SW,GW	
Selenium	Se	79				
Strontium	Sr	90		GW	SW,GW	
Technitium	Tc	99			SW,GW	
Thorium	Th	228				S
Thorium	Th	230			SW,GW	S
Thorium	Th	232		SW		
Uranium	U	234		A,S,SW,GW	S,SW,GW	S,GW
Uranium	U	235		GW	SW	S
Uranium	U	238		A,S,SW,GW	S,SW,GW	S,SW,GW

Table 2a. (NPL sites), cont.

			St. Louis Airpt. Hazelwood Int. Stg/Futura Ctgs	Teledyne Wah Chang	U.S. Radium Corporation	United Nuclear Corporation
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	SAFFIRE, NPL	SAFFIRE, MITRE, NPL	SAFFIRE, HRS, 1989GSS, NPL, MITRE	SAFFIRE, NPL, 1989GSS
		HRS scored:	A,SW	A,SW,GW	A,S	A,S,SW,GW
Element	**Symb.**	**Mass**				
Actinium	Ac	227				
Americium	Am	241				
Antimony	Sb	125				
Carbon	C	14				
Cobalt	Co	60				
Cerium	Ce	144				
Cesium	Cs	134				
Cesium	Cs	135				
Cesium	Cs	137				
Curium	Cm	244				
Europium	Eu	152				
Europium	Eu	154				
Europium	Eu	155				
Hydrogen	H	3				
Iodine	I	129				
Iodine	I	131				
Krypton	Kr	85				
Manganese	Mn	54				
Nickel	Ni	63				
Protactinium	Pa	231				
Plutonium	Pu	238				
Plutonium	Pu	239				
Plutonium	Pu	240				
Radium	Ra	226	S	S,SW,GW	S	S,SW,GW
Radium	Ra	228		GW		SW,GW
Radon	Rn	220				
Radon	Rn	222	A	A	A	S,SW
Ruthenium	Ru	106				
Selenium	Se	79				
Strontium	Sr	90				
Technitium	Tc	99				
Thorium	Th	228				
Thorium	Th	230	S	S		S,SW,GW
Thorium	Th	232	S	S		
Uranium	U	234	S	S,SW		A,S,SW
Uranium	U	235				
Uranium	U	238	S	S,SW		A,S,SW

Table 2a. (NPL sites), cont.

			Uravan Uranium (Union Carbide)	Weldon Spring Quarry Plant / Pits	Weldon Spring Former Army Ordnance Works	Westlake Landfill	Wayne Interim Storage
A=air S=soil, sediment SW=surface water GW=groundwater		REF:	SAFFIRE, MITRE, 1989GSS, NPL	HRS, DOE-ES, 1989GSS, MITRE, SAFFIRE	NPL, SAFFIRE, 1989GSS, HRS, MITRE	NPL	SAFFIRE, 1989GSS, MITRE, HRS, NPL
		HRS scored:	A,S,SW,GW	A,SW,GW	A,SW,GW	S,GW	A,S,SW,GW
Element	**Symb.**	**Mass**					
Actinium	Ac	227					
Americium	Am	241					
Antimony	Sb	125					
Carbon	C	14					
Cobalt	Co	60					
Cerium	Ce	144					
Cesium	Cs	134					
Cesium	Cs	135					
Cesium	Cs	137					
Curium	Cm	244					
Europium	Eu	152					
Europium	Eu	154					
Europium	Eu	155					
Hydrogen	H	3					
Iodine	I	129					
Iodine	I	131					
Krypton	Kr	85					
Manganese	Mn	54					
Nickel	Ni	63					
Protactinium	Pa	231					
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226	A,SW,GW	S,SW,GW	S,SW,GW		S,SW,GW
Radium	Ra	228		SW	SW		S,SW,GW
Radon	Rn	220					A
Radon	Rn	222	A	A			A
Ruthenium	Ru	106					
Selenium	Se	79					
Strontium	Sr	90					
Technitium	Tc	99					
Thorium	Th	228					
Thorium	Th	230	SW,GW	S,SW,GW	S		
Thorium	Th	232		S,SW,GW	S,SW		S,SW,GW
Uranium	U	234	SW,GW	S,SW,GW	S,SW	S,GW	S,SW,GW
Uranium	U	235		S	SW		
Uranium	U	238	SW,GW	S,SW,GW	S,SW	S,GW	S,SW,GW

Table 2b. Isotopes identified at NRC SDMP sites

A=air S=soil, sediment SW=surface water GW=groundwater			Aberdeen Proving Ground	Allied Signal	Amax	Babcock & Wilcox (Apollo)	Babcock & Wilcox (Parks)
		Priority:	C	A	B	B	B
Element	Symb.	Mass					
Cobalt	Co	60					
Cesium	Cs	137					
Hydrogen	H	3					
Plutonium	Pu						S
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226		S			
Strontium	Sr	90					
Thorium	Th			S	S		S
Thorium	Th	228					
Thorium	Th	230					
Thorium	Th	232					
Uranium	U		S		S	S	S
Uranium	U	235					
Uranium	U	238					

			BP Chemicals	The Budd Co.	Cabot Corp. Boyertown	Cabot Corp. Reading	Cabot Corp. Revere
		Priority:	B	C	C	B	B
Element	Symb.	Mass					
Cobalt	Co	60		S			
Cesium	Cs	137					
Hydrogen	H	3					
Plutonium	Pu						
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226					
Strontium	Sr	90					
Thorium	Th				S	S	S
Thorium	Th	228					
Thorium	Th	230					
Thorium	Th	232					
Uranium	U		S		S	S	S
Uranium	U	235					
Uranium	U	238					

Table 2b. (NRC sites), cont.

A=air S=soil, sediment SW=surface water GW=groundwater			Chemetron (Best Ave.)	Chemetron (Harvard Ave.)	Dow Chemical	Fansteel	GSA Watertown Arsenal
		Priority:	A	A	B	C	B
Element	Symb.	Mass					
Cobalt	Co	60					
Cesium	Cs	137					
Hydrogen	H	3					
Plutonium	Pu						
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226					
Strontium	Sr	90					
Thorium	Th		S		S, SW, GW	S, SW	
Thorium	Th	228					
Thorium	Th	230					
Thorium	Th	232					
Uranium	U		S	S		S, SW	S
Uranium	U	235					
Uranium	U	238					

			Gulf United Nuclear Fuels	Heritage Minerals	Kawkawlin Landfill	Kerr-McGee (Cimmaron)	Kerr-McGee (Cushing)
		Priority:	A	B	B	A	A
Element	Symb.	Mass					
Cobalt	Co	60					
Cesium	Cs	137	S				
Hydrogen	H	3					
Plutonium	Pu						
Plutonium	Pu	238	S				
Plutonium	Pu	239	S				
Plutonium	Pu	240	S				
Radium	Ra	226					S
Strontium	Sr	90					
Thorium	Th			S		S	
Thorium	Th	228			S		
Thorium	Th	230					
Thorium	Th	232			S		S
Uranium	U			S		S	
Uranium	U	235					
Uranium	U	238	S, SW				S

Table 2b. (NRC sites), cont.

A=air S=soil, sediment SW=surface water GW=groundwater			Magnesium Elektron	Molycorp Washington	Molycorp York	Nuclear Metals	Permagrain
		Priority:	B	B	B	C	C
Element	Symb.	Mass					
Cobalt	Co	60					
Cesium	Cs	137					
Hydrogen	H	3					
Plutonium	Pu						
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226					
Strontium	Sr	90					S
Thorium	Th		S, SW	S	S		
Thorium	Th	228					
Thorium	Th	230					
Thorium	Th	232					
Uranium	U		S, SW			SW	
Uranium	U	235					
Uranium	U	238					

			Pesses (METCOA)	Process Technology of NJ, Inc.	Remington Arms Co.	Safety Light	Schott Glass
		Priority:	B	B	C	A	B
Element	Symb.	Mass					
Cobalt	Co	60		S			
Cesium	Cs	137				S, SW, GW	
Hydrogen	H	3				S, SW, GW	
Plutonium	Pu						
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226				S, SW, GW	
Strontium	Sr	90				S, SW, GW	
Thorium	Th						S
Thorium	Th	228	S				
Thorium	Th	230					
Thorium	Th	232	S				
Uranium	U				S		S
Uranium	U	235					
Uranium	U	238					

Table 2b. (NRC sites), cont.

A=air S=soil, sediment SW=surface water GW=groundwater			Shieldalloy Metallurgical Corp., NJ	Shieldalloy Metallurgical Corp., OH	Texas Instruments Inc.	UNC Recovery Systems	West Lake Landfill
		Priority:	C	B	A	A	A
Element	Symb.	Mass					
Cobalt	Co	60					
Cesium	Cs	137					
Hydrogen	H	3					
Plutonium	Pu						
Plutonium	Pu	238					
Plutonium	Pu	239					
Plutonium	Pu	240					
Radium	Ra	226	S	S			S, GW
Strontium	Sr	90				GW	
Thorium	Th						
Thorium	Th	228					
Thorium	Th	230					S
Thorium	Th	232	S	S			
Uranium	U				S	S, GW	S
Uranium	U	235			S		
Uranium	U	238	S	S			

			Westinghouse Electric (Waltz Mill)	Whittaker Corp.	Wyman-Gordon
		Priority:	B	C	C
Element	Symb.	Mass			
Cobalt	Co	60			
Cesium	Cs	137			
Hydrogen	H	3			
Plutonium	Pu				
Plutonium	Pu	238			
Plutonium	Pu	239			
Plutonium	Pu	240			
Radium	Ra	226			
Strontium	Sr	90	GW		
Thorium	Th			S	S
Thorium	Th	228			
Thorium	Th	230			
Thorium	Th	232			
Uranium	U			S	
Uranium	U	235			
Uranium	U	238			

Table 2a,b. (cont.)

Footnotes:

HRS Scored - pathways which received a significant score (> 26.5) according to the EPA Hazard Ranking system (applies to NPL sites only).

References:

SAFFIRE	Daum *et al.* (1991)
1989GSS	Glass and Mura (1989)
HRS	(several publications; see References)
UNC-Geotech	(several publications; see References)
EMR	Annual Environmental Monitoring Report for the site (see References)
NUS-ROA	NUS (1989/90)
NUS-DAR	NUS (1990)
DOE-ES	DOE (1988)
Logan	Logan (1988)
Bluck	Bluck (1986)

Table 3a. Radiochemical and biological properties of isotopes identified at NPL Superfund and NRC SDMP radioactively-contaminated sites

Element	Symbol	Mass	Decay Constant	Unit (-1)	Half-Life Physical	Unit	Specific Activity (Ci/gr)	Decay Product
Actinium	Ac	227	3.270E-02	yr	2.1E+01	yr	7.4E+01	Th-227
Americium	Am	241	1.513E-03	yr	4.6E+02	yr	3.2E+00	Np-237
Carbon	C	14	1.210E-04	yr	5.7E+03	yr	4.5E+00	stable
Cobalt	Co	60	1.318E-01	yr	5.3E+00	yr	1.1E+03	stable
Cerium	Ce	144	2.436E-03	day	2.8E+02	day	8.7E+00	Pr-144
Cesium	Cs	134	3.357E-01	yr	2.1E+00	yr	1.3E+03	stable
Cesium	Cs	135	2.310E-07	yr	3.0E+06	yr	8.8E-04	stable
Cesium	Cs	137	2.310E-02	yr	3.0E+01	yr	8.7E+01	Ba-137
Curium	Cm	244	3.830E-02	yr	1.8E+01	yr	8.1E+01	Am-244
Europium	Eu	152	5.776E-02	yr	1.2E+01	yr	2.0E+02	Gd-152
Europium	Eu	154	4.332E-02	yr	1.6E+01	yr	1.5E+02	stable
Europium	Eu	155	3.827E-01	yr	1.8E+00	yr	1.3E+03	stable
Hydrogen	H	3	5.635E-02	yr	1.2E+01	yr	9.7E+03	stable
Iodine	I	129	5.924E-08	yr	1.2E+07	yr	2.4E-04	stable
Iodine	I	131	8.611E-02	day	8.1E+00	day	1.2E+05	Xe-131
Krypton	Kr	85	6.460E-02	yr	1.1E+01	yr	1.4E+05	stable
Manganese	Mn	54	2.288E-03	day	3.0E+02	day	8.0E+03	stable
Nickel	Ni	63	7.534E-03	day	9.2E+01	yr	6.2E+01	stable
Protactinium	Pa	231	2.139E-05	yr	3.2E+04	yr	4.8E-02	Ac-227
Plutonium	Pu	238	8.023E-03	yr	8.6E+01	yr	1.7E+01	U-234
Plutonium	Pu	239	2.841E-05	yr	2.4E+04	yr	6.1E-02	U-235
Plutonium	Pu	240	1.053E-04	yr	6.6E+03	yr	2.3E-01	U-236
Radium	Ra	226	4.327E-04	yr	1.6E+03	yr	9.9E-01	Rn-222
Radium	Ra	228	1.205E-01	yr	5.8E+00	yr	2.7E+02	Ac-228
Radon	Rn	220	1.247E-02	sec	5.6E+01	sec	9.2E+08	Po-216
Radon	Rn	222	1.813E-01	day	3.8E+00	day	1.5E+05	Po-218
Ruthenium	Ru	106	1.889E-03	day	3.7E+02	day	3.4E+03	Tc-106
Selenium	Se	79	1.066E-05	yr	6.5E+04	yr	7.0E-02	stable
Strontium	Sr	90	2.467E-02	yr	2.8E+01	yr	1.4E+02	Rb-90
Technitium	Tc	99	3.270E-06	yr	2.1E+05	yr	1.7E-02	Mo-99
Thorium	Th	228	3.623E-01	yr	1.9E+00	yr	8.2E+02	Ra-224
Thorium	Th	230	8.887E-06	yr	7.8E+04	yr	2.0E-02	Ra-226
Thorium	Th	232	4.916E-11	yr	1.4E+10	yr	1.1E-07	Ra-228
Uranium	U	234	2.806E-06	yr	2.5E+05	yr	6.2E-03	Th-230
Uranium	U	235	9.7626E-10	yr	7.1E+08	yr	2.1E-06	Th-231
Uranium	U	238	1.5369E-10	yr	4.5E+09	yr	3.3E-07	Th-234

(cont.)

Table 3a. (cont.)

Element	Symbol	Mass	Radiation Type (MeV)			Pathway-Specific Unit Risk			
			Alpha	Beta (avg)	Gamma	Air (pCi/ m^3)$^{-1}$	Drinking Water (pCi/L)$^{-1}$	External Exposure (pCi/g)$^{-1}$	Soil Ingestion (pCi/g)$^{-1}$
Actinium	Ac	227		0.0100		4.2E-02	1.8E-05	1.3E-07	9.5E-07
Americium	Am	241	5.4857		0.0595	2.1E-02	1.6E-05	1.6E-05	8.4E-07
Carbon	C	14		0.0490		3.2E-09	4.7E-08	0.0E+00	2.5E-09
Cobalt	Co	60		0.0940	1.3325	8.1E-05	7.8E-07	1.3E-03	4.1E-08
Cerium	Ce	144		0.081	0.1335	1.7E-04	3.0E-07	1.2E-05	1.6E-08
Cesium	Cs	134		0.152	0.6047	1.4E-05	2.1E-06	8.9E-04	1.1E-07
Cesium	Cs	135		0.0570	0.7869	1.4E-06	2.1E-07	0.0E+00	1.1E-08
Cesium	Cs	137		0.1950	0.6617	9.6E-06	1.4E-06	0.0E+00	7.6E-08
Curium	Cm	244	5.8048			n/a	n/a	n/a	n/a
Europium	Eu	152		0.288	0.1218	6.1E-03	1.1E-07	6.3E-04	5.7E-09
Europium	Eu	154		0.228	0.1231	7.2E-05	1.5E-07	6.8E-04	8.1E-09
Europium	Eu	155		0.044	0.0865	n/a	n/a	n/a	n/a
Hydrogen	H	3		0.0050		4.0E-08	2.8E-09	0.0E+00	1.5E-10
Iodine	I	129		0.0400	0.0396	6.1E-05	9.6E-06	1.5E-05	5.1E-07
Iodine	I	131		0.1800	0.3645	1.2E-05	1.8E-06	2.9E-04	9.7E-08
Krypton	Kr	85		0.249		n/a	n/a	n/a	n/a
Manganese	Mn	54			0.8348	2.6E-06	5.7E-08	4.8E-04	3.0E-09
Nickel	Ni	63		0.0170		8.7E-07	1.2E-08	0.0E+00	6.2E-10
Protactinium	Pa	231	5.0130		0.0274	2.0E-02	9.7E-06	2.0E-05	5.1E-07
Plutonium	Pu	238	5.4992			2.1E-02	1.4E-05	5.9E-07	7.6E-07
Plutonium	Pu	239	5.1560		0.0516	2.6E-02	1.6E-06	2.6E-07	8.4E-08
Plutonium	Pu	240	5.1683			2.1E-02	1.6E-05	5.9E-07	8.4E-08
Radium	Ra	226	4.7844		0.1861	1.5E-03	6.1E-05	4.1E-06	3.2E-07
Radium	Ra	228		0.0140		3.4E-04	5.1E-06	5.6E-13	2.7E-07
Radon	Rn	220	6.2882		0.5497	6.1E-08	n/a	3.0E-07	n/a
Radon	Rn	222	5.4895		0.5100	3.7E-07	n/a	2.2E-07	n/a
Ruthenium	Ru	106		0.0090		2.3E-04	4.9E-07	0.0E+00	2.6E-08
Selenium	Se	79		0.0580		n/a	n/a	n/a	n/a
Strontium	Sr	90		0.2000		2.8E-05	1.7E-06	0.0E+00	8.9E-08
Technitium	Tc	99		0.0850		4.2E-06	6.6E-08	3.4E-10	3.5E-09
Thorium	Th	228	5.4230			3.9E-02	7.7E-07	1.6E-06	4.1E-08
Thorium	Th	230	4.6880		0.0677	1.6E-02	1.2E-06	5.9E-07	6.5E-08
Thorium	Th	232	4.0130			1.6E-02	1.1E-06	4.5E-07	5.9E-08
Uranium	U	234	4.7760		0.0532	1.4E-02	7.2E-06	5.6E-07	3.8E-07
Uranium	U	235	4.4000		0.1857	1.3E-02	6.6E-06	9.7E-05	3.5E-07
Uranium	U	238	4.1970			1.2E-02	6.6E-06	4.5E-07	3.5E-07

Refs.: GE (1989); CRC (1990); Diem and Lentner (1975); HEW (1970); EPA (1991).

Table 3b. Ranges for K_ds for elements found at radioactively contaminated sites.

Element	Symbol	K_d		
		Observed Range (ml/g)	Mean[1]	Std. Dev.[2]
Actinium	Ac			
Americium	Am	1.0 - 47,230	6.7	3.0
Carbon	C			
Cobalt	Co	0.2 - 3800	4.0	2.3
Cerium	Ce	58 - 6000	7.0	1.3
Cesium	Cs	10 - 52,000	7.0	1.9
Curium	Cm	93 - 51,900	8.1	1.9
Europium	Eu			
Hydrogen	H			
Iodine	I			
Krypton	Kr			
Manganese	Mn	0.2 - 10,000	5.0	2.7
Nickel	Ni			
Protactinium	Pa			
Plutonium	Pu			
Radium	Ra			
Ruthenium	Ru	48 - 1000	6.4	1.0
Selenium (IV)	Se	1.2 - 8.6	1.0	0.7
Strontium	Sr	0.2 - 3300	3.3	2.0
Technitium	Tc	0.003 - 0.28	3.4	1.1
Thorium	Th	2000 - 510,000	11.0	1.5
Uranium	U	11 - 4400	3.8	1.3

1. Mean of the logarithms of the observed values
2. Standard deviation of the logarithms of the observed values

Ref.: Baes and Sharp (1983).

Table 4a. Summary of source, environmental, and receptor characteristics of NPL sites

Site Name	Site Type	Waste Form
Brookhaven Nat'l Lab	research	landfill
Denver Radium Site	radium	pile, unlined landfill, burial, asphalt
Fernald Envir. Remediation Proj.	defense	tanks, piles, drums, cans, burial
Forest Glen Mobile Home	landfill	burial, drums
Glen Ridge Radium Site	radium	burial
Hanford (100 Area)	defense	unlined ponds, burial, cribs
Hanford (1100 Area)	defense	unlined ponds, unlined tank
Hanford (200 Area)	defense	unlined ponds, burial, cribs
Hanford (300 Area)	defense	unlined ponds, burial, tanks
Himco, Inc., Dump	landfill	unlined landfill
Homestake Mining Co.	mill	piles
INEL	defense	unlined ponds, injection well, burial, drums
Jacksonville NAS	radium	landfills, unlined ponds, surf. water, injection well
Kerr-McGee (Kress Creek)	mill	surface water
Kerr-McGee (Reed-Keppler)	mill	landfill, burial
Kerr-McGee (Res. Area)	mill	landfill, burial
Kerr-McGee (Sewage TP)	mill	landfill, burial, tank (?), piles
Lansdowne Rad. Site	radium	burial
Lincoln Park	mill	surface water, burial
LLNL	defense	unlined ponds
LLNL (Site 300)	defense	lined ponds, landfills
Lodi Municpal Well	radium	burial
Maxey Flats Nuclear Disp.	LLW disposal	landfills
Maywood Chemical Co.	radium	burial, pond
Montclair Radium Site	radium	burial
Monticello Mill Tailings	mill	piles, unlined ponds
Monticello RCP	mill	aggregate, burial, piles
Mound Plant	defense	unlined(?) landfill, burial
Oak Ridge Res.	defense	surface water, landfill, unlined ponds
Ottawa Radiation Area	radium	burial
Pantex Plant	defense	burial, landfill, surface water
Pensacola NAS	radium	unlined ponds, landfill, surface water, burial, piles
Radium Chemical	radium	burial, asphalt
Rocky Flats Plant	defense	underground tanks, burial, landfill, lined ponds
Savannah River Site	defense	piles, unlined(?) ponds, surface water, tanks
Shpack Landfill	landfill	landfill, piles
St. Louis Airport	mill	burial, drums, piles
Teledyne Wah Chang	manufacture	unlined ponds
U.S. Radium Corp.	radium	burial
United Nuclear Corp.	mill	piles
Uravan Uranium	mill	piles, unlined ponds
Wayne Interim Storage	mill	lined pile, soil
Weldon Springs Former Army OW	defense	unlined ponds, burial
Weldon Springs Quarry/Plant/Pits	defense	burial
Westlake Landfill	landfill	unlined landfill

Table 4a. (NPL sites), cont.

Site Name	Quantity of Contam. Mat'l.	Representative Concentration	Avg. Precip. (cm)
Brookhaven			110
Denver Radium	29,000 m^3 soil		41
FEMP	600,000 m^3 soil		99
Forest Glen			82.8
Glen Ridge	230,000 m^3 soil		117
Hanford 100 Area	~5 E+06 m^3 soil		16
Hanford 1100 Area			16
Hanford 200 Area	~700 E+06 m^3 soil		16
Hanford 300 Area	~21 E+06 m^3 soil		16
Himco Dump	unknown	unknown	87.4
Homestake Mining	20 E+06 MT soil		30
INEL	15.7 MT soil		22
Jacksonville NAS	18,000 MT soil		138.4
K-M (Kress Creek)	~30,000 to 40,000 m^3 soil	unknown	84.9
K-M (Reed-Keppler)	15,000 m^3 soil	3300 pCi/g U, Th	84.9
K-M (Res. Area)	~6,600 m^3 soil	unknown	84.9
K-M (Sewage TP)	5,000 m^3 soil	3300 pCi/g U, Th	84.9
Lansdowne	none		112
Lincoln Park	unknown	unknown	33
LLNL			26.8
LLNL Site 300			26.8
Lodi Municpal Well	unknown	unknown	117
Maxey Flats	140,000 to 230,000 m^3 soil		112
Maywood	340,000 yd^3 soil	unknown	117
Montclair	230,000 m^3 soil		117
Monticello/Tailings	800,000 MT soil		16
Monticello RCP			16
Mound			95
Oak Ridge Res.	5850 kg U		135
Ottawa			76
Pantex			44.5
Pensacola NAS			156.5
Radium Chemical	110 Ci		112
Rocky Flats Plant	unknown	unknown	38
Savannah River			119
Shpack	unknown	unknown	114.6
St. Louis Airport			85.9
Teledyne Wah Chang			224.2
U.S. Radium	1450 MT soil		117
United Nuclear	3.2 E+06 MT soil		30
Uravan	unknown	unknown	10
Wayne Int. Storage	92,000 m^3 soil		122
Weldon (Army)	39,000 m^3 soil		85
Weldon Quarry	480,000 m^3 soil		85
Westlake Landfill	39,000 MT soil		85.9

Table 4a. (NPL sites), cont.

Site Name	Air	Water	Depth (m) to Water Table	DRASTIC Index
Brookhaven	not applic.	ps, l	5 to 15	127, 53
Denver Radium	gas	not applic.	3	83
FEMP	partic./gas	is, ps	15 to 18	127
Forest Glen	not applic.	ps	1	156
Glen Ridge	gas	ps	15	93
Hanford 100 Area	not applic.	ps	0 to 30	105
Hanford 1100 Area	not applic.	ps	20 to 40	105
Hanford 200 Area	not applic.	ps	40 to 100	105
Hanford 300 Area	not applic.	ps	0 to 30	105
Himco Dump	not applic.	ps,f w wetland	2	93
Homestake Mining	not applic.	is, ps		88
INEL	partic./gas	ps,is, floodplain		156
Jacksonville NAS	gas	ps, estuary	2	218
K-M (Kress Creek)	not applic.	ps		93
K-M (Reed-Keppler)	gas	ps		93
K-M (Res. Area)	gas	ps		93
K-M (Sewage TP)	gas	ps		93
Lansdowne	gas	not applic.		106
Lincoln Park	partic.	ps	11	83
LLNL	not applic.	ps	8 to 43	74
LLNL Site 300	not applic.	ps	30 to 130	74
Lodi Municpal Well	not applic.	ps		93
Maxey Flats	not applic.	ps, fw wetland	0	196
Maywood	gas	ps	2 to 4	93
Montclair	gas	ps	15	93
Monticello/Tailings	partic./gas	ps	21	162
Monticello RCP	gas	not applic.	30	162
Mound	partic.	ps	12	127
Oak Ridge Res.	partic./gas	ps,fw wetland	5	105
Ottawa	gas	ps		93
Pantex	partic.	is,fw wetland	142	109
Pensacola NAS	gas	ps,estuary	1	218
Radium Chemical	gas	not applic.	4	127
Rocky Flats Plant	partic.	is,l	8	83
Savannah River	partic./gas	ps	19	53, 106
Shpack	not applic.	ps,fw wetland	0	103
St. Louis Airport	gas	ps		105, 156
Teledyne Wah Chang	not applic.	ps	4	106
U.S. Radium	gas	ps		93
United Nuclear	partic./gas	is,ps		88
Uravan	gas	is,ps	unknown	162
Wayne Interim Stor.	gas	ps,l	21	93
Weldon (Army)	not applic.	ps,l		105, 156
Weldon Quarry	gas	ps,l	0	105, 156
Westlake Landfill	not applic.	ps		105, 156

Table 4a. (NPL sites), cont.

Site Name	Subsurface Hydrogeologic Setting Regional	Local
Brookhaven	Glaciated Central Region - Till over Outwash	unconsolidated sand and gravel
Denver Radium	Westerm Mountain Ranges - Mountain Flanks - East	alluvial valley fill/Miocene to Mississippian sandstones
FEMP	Glaciated Central Region - Till over Outwash	alluvial valley fill - Miami River
Forest Glen	Glaciated Central Region - Outwash over Sedimentary Rocks	Silurian and Devonian consolidated aquifer
Glen Ridge	Glaciated Central Region - Till over Sedimentary Rocks	Newark Basin - consolidated/confined
Hanford 100 Area	Columbia River Plateau - Not Connected	river and lake sediments over basalt
Hanford 1100 Area	Columbia River Plateau - Not Connected	river and lake sediments over basalt
Hanford 200 Area	Columbia River Plateau - Not Connected	river and lake sediments over basalt
Hanford 300 Area	Columbia River Plateau - Not Connected	river and lake sediments over basalt
Himco Dump	Glaciated Central Region - Till over Sedimentary Rocks	unconsolidated - high yield
Homestake Mining	Colorado Plateau and Wyoming Basin - Resistant Ridges	no local groundwater
INEL	Columbia River Plateau - Connected	Snake River Plain aquifer
Jacksonville NAS	Southeast Coastal Plain - Solution Limestone	unconfined/consolidated
K-M (Kress Creek)	Glaciated Central Region - Till over Sedimentary Rocks	unconsolidated/consolidated - high yield
K-M (Reed-Keppler)	Glaciated Central Region - Till over Sedimentary Rocks	unconsolidated/consolidated - high yield
K-M (Res. Area)	Glaciated Central Region - Till over Sedimentary Rocks	unconsolidated/consolidated - high yield
K-M (Sewage Treat-ment Plant)	Glaciated Central Region - Till over Sedimentary Rocks	unconsolidated/consolidated - high yield
Lansdowne	N.E. and Superior Uplands - Mountain Flanks	no local groundwater
Lincoln Park	Western Mountain Ranges - Mountain Flanks - East	alluvial valley fill - Arkansas River
LLNL	Alluvial Basins - Mountain Slopes	valley fill over Tertiary non-marine sandstone
LLNL Site 300	Alluvial Basins - Mountain Slopes	valley fill over Tertiary non-marine sandstone
Lodi Municpal Well	Glaciated Central Region - Till over Sedimentary Rocks	Newark Basin - consolidated/confined
Maxey Flats	Nonglaciated Central Region - Solution Limestone	>100 m subhorizontal shales and sandstone
Maywood	Glaciated Central Region - Till over Sedimentary Rocks	Newark Basin - consolidated/confined
Montclair	Glaciated Central Region - Till over Sedimentary Rocks	Newark Basin - consolidated/confined
Monticello/Tailings	Colorado Plateau and Wyoming Basin - River Alluvium	Cambrian to Tertiary sedimentary rocks - low yield
Monticello RCP	Colorado Plateau and Wyoming Basin - River Alluvium	Cambrian to Tertiary sedimentary rocks - low yield

Table 4a. (NPL sites), cont.

Site Name	Subsurface Hydrogeologic Setting (cont.) Regional	Local
Mound	Glaciated Central Region - Till over Outwash	alluvial valley fill - Miami River
Oak Ridge Res.	Nonglaciated Central Region - Mountain Flanks	consolidated/confined
Ottawa	Glaciated Central Region - Outwash over Sedimentary Rocks	alluvial valley fill/consolidated aquifer - high yield
Pantex	High Plains - Ogallala	Ogallala aquifer
Pensacola NAS	Southeast Coastal Plain - Solution Limestone	unconfined/consolidated
Radium Chemical	Glaciated Central Region - Till over Outwash	no local groundwater
Rocky Flats Plant	Western Mountain Ranges - Mountain Flanks - East	river alluvium over claystone and sandstone units - low yield
Savannah River	Atlantic and Gulf Coast Plain - Conf. Region Aquif.	alluvial valley fill, confined un-/consolidated
Shpack	N.E. and Superior Uplands - Mountain Flanks	unconsolidated sand and gravel
St. Louis Airport	Glaciated Central Region - Outwash over Sedimentary Rocks	alluvial valley fill - Mississippi River
Teledyne Wah Chang	Western Mountain Ranges - Mountain Flanks - West	alluvial valley fill - Willamette River
U.S. Radium	Glaciated Central Region - Till over Sedimentary Rocks	Newark Basin - consolidated/confined
United Nuclear	Colorado Plateau and Wyoming Basin - Resistant Ridges	no local groundwater
Uravan	Colorado Plateau and Wyoming Basin - River Alluvium	no local groundwater
Wayne Interim Stor.	Glaciated Central Region - Till over Sedimentary Rocks	Newark Basin - consolidated/confined
Weldon (Army)	Glaciated Central Region - Outwash over Sedimentary Rocks	alluvial valley fill - Missouri River
Weldon Quarry	Glaciated Central Region - Outwash over Sedimentary Rocks	alluvial valley fill - Missouri River
Westlake Landfill	Glaciated Central Region - Outwash over Sedimentary Rocks	alluvial valley fill - Mississippi River

Table 4a. (NPL sites), cont.

Site Name	Other, including sensitive environments	Popul'n. Density (/km^2) County	5 km	Land Use Type
Brookhaven	fw wetland	521	200	suburban,res/agric.
Denver Radium		67		urban,res/ind
FEMP		840		suburban,agric.
Forest Glen		172	172	suburban,res
Glen Ridge		2621	3700	urban,res
Hanford 100 Area	fw wetland; volc. terr.; sens. hab.	17		rural,agric/res/rec
Hanford 1100 Area	volcanic terrain; sens. hab.	17		rural,agric/res/rec
Hanford 200 Area	volcanic terrain; sens. hab.	17		rural,agric/res/rec
Hanford 300 Area	fw wetland; volc. terr.; sens. hab.	17		rural,agric/res/rec
Himco Dump	fw wetland	108	250	suburban
Homestake Mining		3.1	20 (1.7 km)	unpopulated,open
INEL	floodplain	12		rural
Jacksonville NAS	karst terrain, fw wetland	283		suburban,ind
K-M (Kress Creek)		646	250	suburban,res
K-M (Reed-Keppler)		646	250	suburban,res/rec
K-M (Res. Area)		646	250	suburban,res
K-M (Sewage T P)		646	250	suburban,res/open
Lansdowne	crystalline bedrock	1242	1250 (1.7 km)	urban,res
Lincoln Park		6.6		unpopulated,open
LLNL		575		suburban,res/ind/agr
LLNL Site 300		.36		rural, agric.
Lodi Municpal Well		1451		urban,res/ind/comm
Maxey Flats	karst terrain, fractured bedrock	20	17	rural,agric.
Maywood		1451	380	urban,res/ind/comm
Montclair		2621	3700 (1.7 km)	urban,res
Monticello/Tailings		0.8	170	unpopulated,ind
Monticello RCP		0.8	170	unpopulated,res/ind
Mound		494	215	suburban,res
Oak Ridge Res.	karst, atmos. inv.,fw wetland	71		rural,res/agric.
Ottawa		37		rural,res/rec
Pantex	playa	40		rural,agric.
Pensacola NAS	karst terrain	130	380	suburban,ind
Radium Chemical		7020	3100	urban,res/ind/comm
Rocky Flats Plant		155	45 (8.3 km)	suburb,res/ag/rec/com'l
Savannah River	perched aquifer	14	40	rural
Shpack	swamp,crystalline bedrock	323	510	suburban,open/res
St. Louis Airport		743	450	suburban,ind/res
Teledyne Wah Chang		14	250	rural,res
U.S. Radium		2621	3900	urban,res/ind
United Nuclear		3.5	1	unpopulated,open
Uravan		3.5	0	unpopulated,open
Wayne Interim Stor.		910		suburban,res/agr/comm
Weldon (Army)	karst terrain	81	65	rural
Weldon Quarry	karst terrain	81	65	rural
Westlake Landfill		743		rural,agric.

Table 4a. (NPL sites), cont.

Site Name	Water Use Type	Population Served by Groundwater
Brookhaven	drinking (sole source)/ agriculture	15400
Denver Radium	not applicable	not applicable
FEMP	drinking/ agric/ recreation (sole source)	1100
Forest Glen	not applicable	not applicable
Glen Ridge	not applicable	not applicable
Hanford 100 Area	drinking/ agric/ recreation	70000
Hanford 1100 Area	drinking/ agric/ recreation	70000
Hanford 200 Area	drinking/ agric/ recreation	70000
Hanford 300 Area	drinking/ agric/ recreation	70000
Himco Dump	drinking (sole source)	20000
Homestake Mining	not applicable	not applicable
INEL	drinking/ agriculture (sole source)	3000
Jacksonville NAS	drinking/ recreation	300
K-M (Kress Creek)	drinking	20000
K-M (Reed-Keppler)	drinking	20000
K-M (Res. Area)	drinking	20000
K-M (Sewage TP)	drinking	20000
Lansdowne	not applicable	not applicable
Lincoln Park	drinking	?
LLNL	drinking/ agriculture	10,000
LLNL Site 300	drinking/ agriculture	300
Lodi Municpal Well	drinking	24000
Maxey Flats	drinking	100
Maywood	not applicable (see Lodi)	not applicable
Montclair	not applicable	not applicable
Monticello/Tailings	drinking	1900
Monticello RCP	not applicable	not applicable
Mound	drinking/ recreation	17000
Oak Ridge Res.	drinking	43200
Ottawa	not applicable	not applicable
Pantex	drinking/ agriculture	160000
Pensacola NAS	drinking/ recreation	45000
Radium Chemical	not applicable	not applicable
Rocky Flats Plant	not applicable	not applicable
Savannah River	drinking/ agriculture	3200
Shpack	drinking	130
St. Louis Airport	not applicable	not applicable
Teledyne Wah Chang	agriculture/ recreation	not applicable
U.S. Radium	not applicable	not applicable
United Nuclear	not applicable	not applicable
Uravan	not applicable	not applicable
Wayne Interim Stor.	drinking/ agriculture/ recreation	51000
Weldon (Army)	drinking	46000
Weldon Quarry	drinking	58000
Westlake Landfill	drinking/ agriculture/ recreation	60

Table 4b. Summary of source, environmental, and receptor characteristics of NRC SDMP sites

Site Name	Site Type	Waste Form
Aberdeen Proving Ground	defense	soil
Allied Signal (2 sites)	manufacture	drums, soil
Amax, Inc.		soil, rubble (engineered cell)
Babcock and Wilcox (Apollo)	fuel processing	buildings, soil
Babcock and Wilcox (Parks)	fuel processing	buildings, burial
BP Chemicals	manufacture	drums, ponds, buildings, soil
The Budd Co.	manufacture	contained (hot cell)
Cabot Corp. (Boyertown)	mill	vaults, ponds
Cabot Corp. (Reading)	mill	pile
Cabot Corp. (Revere)	mill	piles
Chemetron (Best Ave.)	fuel processing	piles
Chemetron (Harvard Ave.)	fuel processing	soil
Dow Chemical Co. (3 sites)	manufacture	pile, landfill, pond
Fansteel, Inc.	mill	ponds, buildings
GSA Watertown Arsenal Site (2 sites)	defense	piles, soil, concrete
Gulf United Nuclear Fuels Corp.	research	buildings, soil
Heritage Minerals	mill	piles
Kawkawlin Landfill	landfill	landfill
Kerr-McGee Cimmaron Plants	fuel processing	buildings, soil
Kerr-McGee Cushing Plant	fuel processing	soil, tanks, burial, buildings
Magnesium Elektron, Inc.	mill	ponds
Molycorp, Inc. (Washington)	mill	ponds, pile, soil
Molycorp, Inc. (York)	mill	soil, drums
Nuclear Metals, Inc.	manufacture	unlined pond
Permagrain Products	research	buildings, tanks
Pesses Co. (METCOA)	scrap	drums, piles
Process Technology of NJ, Inc.	manufacture	pond, soil, burial
Remington Arms Co., Inc.	defense	soil
Safety Light Corp.	manufacture	buildings, soil, pond, pile
Schott Glass Technologies	manufacture	landfill
Shieldalloy Metallurgical Corp. (NJ)	mill	piles
Shieldalloy Metallurgical Corp. (OH)	mill	piles
Texas Instruments, Inc.	fuel processing	landfill, burial
UNC Recovery Systems	scrap	buildings, soil
West Lake Landfill	landfill	landfill, soil
Westinghouse Electric (Waltz Mill)	research	buildings, soil, pond
Whittaker Corp.	manufacture	piles
Wyman-Gordon Co.	manufacture	burial

Table 4b. (NRC sites), cont.

Site Name	Quantity of Contam. Mat'l.	Representative Concentration	Avg. Precip. (cm)
Aberdeen	7.0 E+04 kg fired rounds	unknown	118.60
Allied Signal (2 sites)	15-20 drums	0.7-25.4 pCi/gm (Th)	120.80
Amax	4.54 E+04 kg soil	(low, Th and U)	103.30
B and W (1)	5664 m^3 soil	100 pCi/g (U)	116.00
B and W (2)	>2832 m^3	<30 pCi/g (U, Th)	116.00
BP Chemicals	2.75 E+04 m^3 solid, liquid	>35 pCi/g (U in drums)	89.90
Budd	0.3 Ci Co-60		105.20
Cabot (1)	unknown	<1% by weight (U, Th)	108.40
Cabot (2)	545 MT slag	0.16% Th, 0.04% (U)	108.40
Cabot (3)	trace source material		108.40
Chemetron (1)	3115 m^3 solid waste	>100 pCi/g (U, Th)	89.90
Chemetron (2)	2 acres		89.90
Dow (3 sites)	3.98 E+05 m^3 solid waste	1000 pCi/g (Th-232)	73.00
Fansteel	8.2 E+04 kg sediment		101.60
GSA	unknown	240 pCi/gm (U)	115.40
Gulf	unknown	91 pCi/g (Pu)	102.00
Heritage	113 MT solid waste	0.074-0.585% (U, Th)	121.10
Kawkawlin	unknown	64-96 pCi/g (Th-232/228)	73.00
KM - Cimmaron	>5664 m^3 soil	30-100 pCi/g (Th)	78.80
KM - Cushing	unknown	10-90 pCi/g (Th, Ra, U)	86.20
Magnesium E	2451 MT/yr sludge	0.37% (U, Th)	118.50
Molycorp (1)	unknown	>10 pCi/g (Th)	92.30
Molycorp (2)	unknown	250 pCi/g (Th)	96.30
Nuclear Metals	1.13 E+05 kg source material		115.20
Permagrain	<15 mCi Sr-90		116.10
Pesses (METCOA)	382 m^3 soil	<2400 pCi/g (Th)	92.20
PTI	unknown		129.40
Remington	9.63 E+04 m^3 soil		74.30
Safety Light	unknown	3.5 pCi/g (Sr-90 in soil)	101.70
Schott Glass	7646 m^3 soil	2 pCi/g (Th)	107.00
Shieldalloy (1)	3.54 E+05 MT slag	2-4 pCi/g (Th)	113.90
Shieldalloy (2)	unknown	366-516 pCi/g (Th)	98.80
T I	unknown	1.35 pCi/g - 0.225 uCi/g (U)	122.00
UNC	none		123.20
West Lake	9.91 E+04 m^3 soil	90 pCi/g (Ra-226)	85.90
Westinghouse	unknown	<300 pCi/l (Sr-90)	116.00
Whittaker	2.97 E+04 m^3 slag	detect.-6779 pCi/g (Th)	97.10
Wyman-Gordon	2.27 E+04 kg solid waste		120.6

Table 4b. (NRC sites), cont.

Site Name	Subsurface Hydrogeologic Setting Regional	Local
Aberdeen	N.E. and Superior Uplands	coastal plain sand and gravel K to T unconsolidated
Allied Signal (2 sites)	N.E. and Superior Uplands	Newark basin consolidated/confined no local unconsolidated
Amax	Nonglaciated Central Region	alluvial valley fill - Ohio River
B and W (1)	Nonglaciated Central Region	consolidated rock aquifer
B and W (2)	Nonglaciated Central Region	consolidated rock aquifer
BP Chemicals	Glaciated Central Region	high yield valley fill
Budd	N.E. and Superior Uplands	sand and gravel - coastal plain
Cabot (1)	Piedmont and Blue Ridge	consolidated rock aquifers - limestone and sandstone
Cabot (2)	Piedmont and Blue Ridge	consolidated rock aquifers - limestone and sandstone
Cabot (3)	Piedmont and Blue Ridge	consolidated rock aquifers - limestone and sandstone
Chemetron (1)	Glaciated Central Region	Lake Erie
Chemetron (2)	Glaciated Central Region	Lake Erie
Dow (3 sites)	Glaciated Central Region	Lake Huron
Fansteel	Nonglaciated Central Region	buried alluvial valley
GSA	N.E. and Superior Uplands	no local groundwater
Gulf	N.E. and Superior Uplands	alluvial valley fill - consolidated carbonate aquifers
Heritage	N.E. and Superior Uplands	coastal plain sand and gravel - K to T unconsolidated
Kawkawlin	Glaciated Central Region	Lake Huron
KM - Cimmaron	Nonglaciated Central Region	buried alluvial valley
KM - Cushing	Nonglaciated Central Region	buried alluvial valley
Magnesium E	Piedmont and Blue Ridge	Newark Basin sandstone - consolidated/confined
Molycorp (1)	Nonglaciated Central Region	no local groundwater
Molycorp (2)	Nonglaciated Central Region	consolidated rock aquifers - limestone and dolomite
Nuclear Metals	N.E. and Superior Uplands	no detail
Permagrain	N.E. and Superior Uplands	sand and gravel - coastal plain
Pesses (METCOA)	Nonglaciated Central Region	consolidated/unconfined aquifer - Ohio River
PTI	Nonglaciated Central Region	no local groundwater
Remington	Glaciated Central Region	alluvial valley fill over P to IP confined
Safety Light	Nonglaciated Central Region	alluvial valley fill - Susquehanna River
Schott Glass	Glaciated Central Region	alluvial valley fill - Susquehanna River
Shieldalloy (1)	N.E. and Superior Uplands	coastal plain sand and gravel - K to T unconsolidated
Shieldalloy (2)	Nonglaciated Central Region	no local groundwater
T I	N.E. and Superior Uplands	no detail
UNC	N.E. and Superior Uplands	no detail
West Lake	Nonglaciated Central Region	Mississippi River, outwash and alluvial valley fill
Westinghouse	Nonglaciated Central Region	P to IP consolidated aquifer
Whittaker	Nonglaciated Central Region	consolidated/unconsolidated
Wyman-Gordon	Glaciated Central Region	no detail

Table 4b. (NRC sites), cont.

Site Name	Water	Other, including Sensitive Environ.	Pop. Density Cnty (/km^2)	Land Use Type	Water Use Type
Aberdeen	ps		136.51	suburban	
Allied Signal (2 sites)			1363.41	urban	
Amax			96.79	rural	
B and W (1)	ps		46.92	rural, res/comm	
B and W (2)	ps		46.92	rural	
BP Chemicals			105.34	suburban, ind	
Budd			4664.15	urban	
Cabot (1)			52.76	rural	
Cabot (2)			52.76	rural, ind	
Cabot (3)			2216.79	urban	
Chemetron (1)			1215.84	urban, ind	
Chemetron (2)			1215.84	urban, ind	
Dow (3 sites)	ps		53.25	rural	drinking
Fansteel			33.30	rural	
GSA	ps		642.09	suburban	not applic.
Gulf	ps, l		123.37	suburban	recreation
Heritage			236.48	suburban	
Kawkawlin	fw	marsh/game area	99.16	rural, res	drinking
KM - Cimmaron		gw for irrigation	20.69	rural	irrigation
KM - Cushing			36.26	rural	
Magnesium E			87.19	rural	
Molycorp (1)			95.63	rural	not applic.
Molycorp (2)			139.18	suburban	
Nuclear Metals			336.12	suburban, res/ind	
Permagrain		game preserve	1176.35	urban, non-res	
Pesses (METCOA)	ps		171.09	suburban, res/agr	drinking
PTI		reservoirs	344.29	suburban	not applic.
Remington	l		402.15	suburban, res/agr	recreation
Safety Light	ps	floodplain	48.70	rural, res	none
Schott Glass			143.48	suburban, ind	none
Shieldalloy (1)		open wetlands	249.73	suburban	not applic.
Shieldalloy (2)		no local groundwater	29.73	rural	
T I			336.12	suburban	
UNC	ps		117.45	suburban	
West Lake	ps		757.86	suburban	
Westinghouse	ps		142.44	suburban	
Whittaker	ps	signif. municipal gw use	71.01	rural	
Wyman-Gordon			1131.69	urban	drinking

Table 4b. (NRC sites), cont.

Footnotes:

Air: where applicable, form of air contamination of concern.

Water: significant surface water bodies.

ps - perennial stream	is - intermittant stream
fw wetland - freshwater wetland	l - lake

Sens. Hab.: sensitive wildlife habitat

DRASTIC Index: numerical value arrived at by the application of the DRASTIC system of evaluating groundwater pollution potential (Aller *et al.*, 1985).

Other: special characteristics of the site which may impact on transport processes.

Population density, 5km: local popluation density based on NPL site descriptions. Some other distance standards were used as noted in parentheses.

See report text for descriptions of other columns.

References:

Hydrogeologic regions: Heath (1984); Aller *et al.* (1985).
County population density: CCDB (1977).

References

10 CFR 61. 1981. Title 10. Code of Federal Regulations. Chapter 61. Licensing requirements for land disposal facilities for radioactive wastes.

40 CFR Part 300. Federal Register 55(241):51532-51667, December 14, 1990.

Aller, L., T. Bennet, J.H. Laher, and R.J. Betty. 1985. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrologic settings. National Water Well Association for the U.S. Environmental Protection Agency, Office of Research and Development, Ada, OK, EPA 600-285-018.

Archibald, J.K. 1989. Supplemental data collected along the railroad tracks at Operable Unit IV/V (Denver Radium Site). Memo to J. Brink, U.S. Environmental Protection Agency Region 8, March 20, 1989.

Arthur, W.J. and O.D. Markham. 1983. Small mammal soil burrowing as a radionuclide transport vector at a radioactive waste disposal area in southeastern Idaho. *Journal of Environmental Quality* 12(1):117-122.

Arya, A., T.A. Hewett, R.G. Larson, and L.W. Lake. 1988. Dispersion and reservoir hetrogeneity. *SPE Reservoir Engineering* 3(1):139-148.

Baas Becking, L.G.M., I.R. Kaplan, and D. Moore. 1960. Limits of the natural environment in terms of pH and oxidation-reduction potential. *Journal of Geology* 68:243-256.

Back, W. and R.A. Freeze. 1983. Chemical Hydrology: Benchmark Papers in Geology, Vol. 73. Stroudsburg, PA: Hutchinson Ross Publishing Co.

Bear, J. 1972. Dynamics of Fluids in Porous Media. New York: American Elsevier, 764 pp. Reprinted by Dover Publications, Inc., New York, 1988.

Bear, J. 1979. Hydraulics of Groundwater. New York: McGraw-Hill, 569 pp.

Bluck, W.V. 1986. Remedial investigation report, Kerr-McGee Radiation Sites, West Chicago, IL. WA No. 82-5L94.0, September 29, 1986.

Bogli, A. 1980. Karst Hydrology and Physical Speleology. New York: Springer-Verlag, 284 pp.

Bouwer, H. 1978. Groundwater Hydrology. New York: McGraw-Hill, 480 pp.

Bredehoeft, J.D. 1978. Geologic disposal of high-level radioactive waste: earth-science perspectives. United States Geological Survey Circular 779, pp. 13-15.

Brookins, D.G. 1978. Eh-pH diagrams for elements from Z=40 to Z=52: Application to the Oklo natural reactor. *Chemical Geology* 23:324-342.

Brookins, D.G. 1979. Thermodynamic considerations underlying the migration of radionuclides in geomedia: Oklo and other examples. In: G.J. McCarthy, ed., Basis for nuclear managment, v. 1, pp. 355-366. New York: The Scientific Plenum Press.

Brookins, D.G. 1984. Geochemical aspects of radioactive waste disposal. New York: Springer-Verlag, 347 pp.

Buddemeir, R.W., and J.R. Hunt. 1988. Transport of colloidal contaminants in groundwater: radionuclide migration at the Nevada Test Site. *Applied Geochemistry* 3:535-548.

Card, T.R., and G. Jansen, 1975. Solubility of elements in U.S. western desert groundwater and comparison with chemical and radiological concentration limits for drinking water. U. S. E. R. D. A., BNWL-B-378.

Carfagno, D.G. and B.M. Farmer. 1990. Environmental monitoring at Mound: 1989 report. EG&G Mound Applied Technologies, Miamisburg, Ohio.

Costain, D.B., ed. 1989. Rocky Flats Plant site environmental report for 1989. EG&G Rocky Flats, Inc., Golden Colorado.

CRC. 1990. Handbook of chemistry and physics, Robert C. Weast, ed. Chemical Rubber Company, CRC Press: Cleveland, Ohio.

Cummins, C.L., D.K.Martin, and J.L. Todd. 1990. Savannah River Site environmental report for 1989. Westinghouse Savannah River Company, Savannah River Site, Aiken, South Carolina.

Daum, M.L., G.A. Goldstein, and P.D. Moskowitz. 1991. SAFFIRE: Superfund and Federal Facilities Information System for Risk Evaluation. BNL 46247, Brookhaven National Laboratory, Upton, New York.

Davis, S.N., and R.J.M. DeWiest. 1966. Hydrogeology. New York: John Wiley and Sons, Inc., 463 pp.

De Laguna, W. 1963. Studies of sites for nuclear energy facilities -- Brookhaven National Laboratory. United States Geological Survey Bulletin, 1156 A-E., v. 1-5.

de Marsily, G. 1985. Flow and transport in fractured rocks: connectivity and scale effect. IAH International Symposium on the Hydrogeology of Rocks of Low Permeability, January 7-12, Tucson, Arizona.

deMarsily, G. 1986. Quantitative Hydrogeology. Orlando, Florida: Academic Press, 440 pp.

Dennison, D.I., D.R. Sherwood, and J.S. Young. Status report on remedial investigation of the 300 Area process ponds. PNL-6442, prepared by Pacific Northwest Laboratory for the U.S. Department of Energy, September 1989.

DeWiest, R.J.M. 1965. Geohydrology. New York: John Wiley and Sons, Inc., 366 pp.

Diem, K., and C. Lentner, eds.. 1975. Documenta GEIGY: Scientific tables, 7th ed. Ardsley, New York: Geigy Pharmaceuticals, 810 pp.

DOE. 1987a. Annual environmental monitoring report, Weldon Spring, MO - Calendar Year 1987. U. S. Department of Energy, Weldon Spring Remedial Action Project.

DOE. 1987b. Draft environmental impact statement, remedial action at the Weldon Spring Site. U. S. Department of Energy/EIS-0117D, U. S. Department of Energy, Office of Remedial Action and Waste Technology, February 1987.

DOE. 1987c. Draft environmental impact statement: remedial action at the Weldon Spring Site. U.S. Department of Energy, DOE/EIS-0117D.

DOE. 1987d. Environmental survey preliminary report, Feed Materials Production Center, Fernald, OH. U. S. Department of Energy/EH/-, U. S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, March 1987.

DOE. 1987e. Environmental survey preliminary report, Hanford Site, Richland, WA. U.S. Department of Energy/EH/OEV-05-P, U.S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, Washington, DC, August 1987.

DOE. 1987f. Environmental survey preliminary report, Rocky Flats Plant, Golden, Colorado. U.S. Department of Energy/EH/OEV-03-P, U. S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, Washington, DC, June, 1987.

DOE. 1987g. Environmental survey preliminary report, Y-12 Plant, Oak Ridge, TN. U.S. Department of Energy/EH/OEV-07-P, U.S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, November, 1987.

DOE. 1987h. Weldon Springs Site (WSS) environmental monitoring report. Prepared by MK-Ferguson Company and Jacobs Engineering Group, Inc., for the U. S. Department of Energy.

DOE. 1988a. Environmental survey preliminary report, Idaho National Engineering Laboratory, Idaho Falls, ID and Component Development and Integration Facility, Butte, MT. U.S. Department of Energy/EH/OEV-22-P, U.S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, September 1988.

DOE. 1988b. Environmental survey preliminary report, Oak Ridge National Laboratory (X-10), Oak Ridge, TN. U. S. Department of Energy/EH/OEV-31-P, U.S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, Washington, DC, July, 1988.

DOE. 1988c. Environmental survey preliminary summary report of the Defense Production Facilities. U. S. Department of Energy/EH-0072, U. S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, September 1988.

DOE. 1988d. Environmental survey preliminary summary report of the Defense Production Facilities. U.S. Department of Energy, Environment, Safety and Health Office of Environmental Audit, DOE/EH-0072.

DOE. 1988e. Integrated Data Base for 1988: Spent fuel and radioactive waste inventories, projections, and characteristics. U. S. Department of Energy/RW-0006, Rev. 4, Washington, DC, September, 1988.

DOE. 1989a. Environmental restoration and waste management five-y ear plan, U.S. Department of Energy/S-0070, Washington, DC, August 1989.

DOE. 1989b. Environmental restoration and waste management five-year plan for the Hanford Site (predecisional draft). U.S. Department of Energy/RL 89-10, U. S. Department of Energy, Environmental Division, Richland, WA, April 1989.

DOE. 1990a. Draft appendix report - Idaho National Engineering Laboratory. NUS Corporation for the U.S. Department of Energy, Washington, D.C.

DOE. 1990b. Draft appendix reports for environmental survey summary report. U. S. Department of Energy, Office of Environment, Safety and Health, Office of Environmental Audit, Washington, DC. (Draft, not for distribution).

DOE. 1990c. Environmental monitoring report on the U.S. Department of Energy's Inactive Millsite Facility, Monticello, Utah, for Calendar Year 1989. U.S. Department of Energy, Grand Junction Projects Office, Grand Junction, Colorado.

DOE. 1990d. Environmental restoration and waste management five-year plan, Fiscal Years 1992-1996. U. S. Department of Energy/S-0708P, Washington, DC, June 1990.

DOI. 1977. Ground Water Manual. U.S. Department of the Interior, U.S. Bureau of Reclamation.

Dosch, R.G. 1979. Assessment of potential radionuclide transport in site-specific geologic formations. Sandia National Laboratories Report SAND-79-2468.

Drever, J.I. 1982. The Geochemistry of Natural Waters. Englewood Cliffs, New Jersey: Prentice-Hall, 388 pp.

Driscoll, F.G. 1986. Groundwater and Wells. St. Paul, Minnesota: Johnson Division, 1089 pp.

Dugan, T.A., G.L. Gels, J.S. Oberjohn, and L.K. Rogers, eds. 1990. Feed Matreials Production Center snnual rnvironmental teport for Calendar Year 1989. Westinghouse Materials Co. of Ohio, Cincinnati, Ohio.

Duguid, J.O., and P.C.Y. Lee. 1977. Flow in ractured porous media. *Water Resources Research* 13:558-566.

Dykyslen, R.C. 1987. Transport of solutes through unsaturated fractured media. *Water Research* 12:1531-1539.

Eisenbud, M. 1963. Environmental radioactivity. New York: McGraw Hill.

Eisenbud, M. 1990. An overview of sites contaminated by radioactivity. In: Health and ecological implications of radioactively contaminated environments: Proceedings of the 26th Annual Meeting of the National Council on Radiation Protection and Measurements, No. 12, Washington, D.C., pp. 5-19.

Endo, H.K., J.C.S. Long, C.R. Wilson, and P.A. Withespoon,. 1984. A model for investigating transport in fracture networks. *Water Resources Research* 20:1390-1400.

EPA. 1982a. NPL HRS ranking work sheets for Denver Radium Site, Denver, CO, U.S. Environmental Protection Agency, August 12, 1982.

EPA. 1982b. NPL HRS ranking work sheets for United Nuclear Corporation, Churchrock, NM, U. S. Environmental Protection Agency, August 12, 1982.

EPA. 1982c. NPL HRS ranking work sheets for U.S. Radium Corporation, Orange, NJ, U. S. Environmental Protection Agency, August 23, 1982.

EPA. 1983a. NPL HRS ranking work sheets for Kerr-McGee (Residential Areas), West Chicago/DuPage County, IL. U. S. Environmental Protection Agency, NPL-U2-2-92, November 3, 1983.

EPA. 1983b. NPL HRS ranking work sheets for Kerr-McGee (Sewage Treatment Plant), West Chicago, IL. Kerr-McGee (Sewage Treatment Plant), NPL-U2-2-93, November 14, 1983.

EPA. 1984a. NPL HRS ranking work sheets for Kerr-McGee (Kress Creek/West Branch of DuPage River), DuPage County, IL. U. S. Environmental Protection Agency, NPL-U2-2-90, June 15, 1984.

EPA. 1984b. NPL HRS ranking work sheets for Monticello Radioactively Contaminated Properties, Monticello, UT. U.S. Environmental Protection Agency, NPL-U2-2-183, May 17, 1984.

EPA. 1984c. NPL HRS ranking work sheets for Weldon Spring Quarry, St. Charles County, MO, U. S. Environmental Protection Agency, NPL-02-2-168, May 22, 1984.

EPA. 1984d. NPL HRS ranking work sheets for Glen Ridge Radium Site, Glen Ridge, NJ. U. S. Environmental Protection Agency, NPL-U2-2-12, June 15, 1984.

EPA. 1986a. Denver Radium Site, Record of Decision; Remedial Alternative Selection, Operable Units IV & V (Robinson Brick Company and Denver & Rio Grande Western Railroad "ROBCO"), U. S. Environmental Protection Agency, September 30, 1986.

EPA. 1986b. Draft Interim Report of Existing Information, U.S. Radium Corporation Site, Orange, NJ. Chapter 4.0, Radiation Hazard Assessment. Attachment to memo from S. Meyers, U. S. Environmental Protection Agency Office of Radiation Programs, to P. Giardina, U. S. Environmental Protection Agency Region II, July 2, 1986.

EPA. 1987a. Denver Radium Site, Declaration for the Record of Decision, Operable Unit III (1000 West Louisiana Properties), U.S. Environmental Protection Agency, September 29, 1987.

EPA. 1987b. Ground water handbook. U.S. Environmental Protection Agency, Office of Research and Development, Report No. EPA/625/6-87/016, 230 pp.

EPA. 1988a. NPL HRS ranking work sheets for Feed Materials Production Center, Fernald, OH. U.S. Environmental Protection Agency, NPL-U9-2-22, May 31, 1988.

EPA. 1988b. NPL HRS ranking work sheets for Hanford 300-Area, Benton County, WA. U.S. Environmental Protection Agency, NPL-U7-2-232, June 9, 1988.

EPA. 1988c. NPL HRS ranking work sheets for Jacksonville Naval Air Station, Jacksonville, FL, U.S. Environmental Protection Agency, NPL-U9-2-16, January 12, 1988.

EPA. 1988d. NPL HRS ranking work sheets for Monticello Mill Tailings Site, Monticello UT. U.S. Environmental Protection Agency, NPL-U9-1-29, August 8, 1988; Adjusted Final Narrative NPL-U9-2-29.

EPA. 1988e. Superfund fact sheet: radium investigation in Ottawa, IL. U.S. Environmental Protection Agency, January 1988.

EPA. 1989a. NPL HRS ranking work sheets for Forest Glen Mobile Home Subdivision, Niagara Falls, NY. NPL-UHW-2-1, U. S. Environmental Protection Agency, November, 1989.

EPA. 1989b. NPL HRS ranking work sheets for Radium Chemical Co., Inc., New York City, NY. NPL-UHW-2-2, U. S. Environmental Protection Agency, November 1989.

EPA. 1989c. Seminar on site characterization for subsurface remediations, Robert S. Kerr Environmental Reserach Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma and the Center for Environmental Research Information, Cincinnati, Ohio, CERI-89-224.

EPA. 1989d. NPL HRS ranking work sheets for W.R. Grace & Co., Inc./Wayne Interim Storage Site (U. S. Department of Energy), Wayne Township, NJ. U.S. Environmental Protection Agency, March, 1989.

EPA. 1990a. Assessment of technologies for the remediation of radiologically contaminated Superfund sites. U. S. Environmental Protection Agency/540/2-90/001, U. S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Radiation Programs, Washington, DC, January, 1990.

EPA. 1990b. National Priority List Technical Data Files. U.S. Environmental Protection Agency (dBASE III© format data base computer file).

EPA. 1990c. NPL HRS ranking work sheets for Himco Dump, Elkhart, IN. U.S. Environmental Protection Agency, NPL-U7-2-128(?), February 1990.

EPA. 1990d. NPL HRS ranking work sheets for Weldon Spring Former Army Ordnance Works, St. Charles County, MO. U.S. Environmental Protection Agency, NPL-U9-2-27, February, 1990.

EPA. 1990e. Site characterization for subsurface remediations, Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma and the Center for Environmental Research Information, Cincinnati, Ohio.

EPA. 1991. Health effects assessment summary tables: FY-1991 Annual. OERR 9200.6-303(91-1), U. S. Environmental Protection Agency, Office of Research and Development and Office of Emergency and Remedial Response, Washington, D.C.

EPA. n.d. Special study waste summary, Monticello Mill Site, Monticello, UT, U.S. Environmental Protection Agency, NPL-U9-2-29A.

EPA/DOE. 1990. Feed Materials Production Center Federal Facilities Compliance Agreement, U. S. Environmental Protection Agency/U. S. Department of Energy, Administrative Docket Number V-W-90-C-057, April, 1990.

EPA/DOE/CO. n.d. Rocky Flats Plant Federal Facility Agreement. U.S. Environmental Protection Agency/U.S. Department of Energy/State of Colorado.

EPA/UT/DOE. 1988. Monticello Site (Monticello Vicinity Properties NPL site and Monticello Millsite) Federal Facilities Agreement, U.S. Environmental Protection Agency/State of Utah Department of Health/U.S. Department of Energy, December, 1988.

Evans, D., and T. Nicholson, eds. 1987. Flow and transport through unsaturated fractured rock. Geophysical Monograph 42, American Geophysical Union, Washington, D.C.

Evans, J.C., R.W. Bryce and D.R. Sherwood. 1989. Hanford Site ground-water monitoring for January through June 1988. PNL-6886 (UC-11,41), prepared for the U.S. Department of Energy by Pacific Northwest Laboratory, Richland, WA, May 1989.

Faure, G. 1977. Principles of isotope geology. New York: Wiley-Interscience.

Faure, G. 1991. Principles and Applications of Inorganic Geochemistry. New York: MacMillan Publishing Company, 626 pp.

Federal Register. 1991. National primary drinking water regulations, radionuclides. proposed rulemaking 56 (138), Thursday, July 18, pp. 33050-33127.

Fetter, C.W. 1988. Applied Hydrogeology, 2nd ed. New York: Macmillan Publishing Company, 592 pp.

Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Englewood Cliffs, New Jersey: Prentice-Hall Inc., 604 pp.

Freeze, R.A., and W. Back. 1983. Physical Hydrogeology - Benchmark Papers in Geology, Vol. 72. Stroudsburg, Pennsylvania: Hutchinson Ross Publishing Co.

Fried, J.J. 1975. Ground Water Pollution: Theory, Methodolgy, Modeling, and Practical Rules. Amsterdam: Elsevier, 330 pp.

Garrels, R.M. and C.G. Christ, C.G. 1965. Solutions, Minerals and Equilibria. New York: Harper and Row.

GE, 1989. Chart of the nuclides, 14th ed. San Jose, California: General Electric Company.

Geological Survey Open File Rep. 86-488.

Geological Survey, Bulletin, 1156-C, pp. 123-124.

Gera, F. 1975. Geochemical behavior of long-lived radioactive wastes. Oak Ridge National Laboratory Report ORNL-TM-4481, Oak Ridge, Tennessee.

Glass, J. and P. Musa, eds. 1989. 1989 Guide to Superfund sites. Pasha Publications, 829 pp.

Green, W.H. and C.A. Ampt. 1911. Studies on soil physics, I: Flow of air and water through soils. *Journal of Agricultural Science* 4:1-24.

Greenkorn, R.A. 1983. Flow Phenomena in Porous Media: Fundamentals and Applications in Petroleum, Water and Food Production. New York: Marcel Dekker, 550 pp.

Grisak, G.E. and J.F. Pickens. 1980. Solute transport through fractured media. *Water Resources Research* 16:719-730.

Hakonson, T.E. and J.L. Martinez. 1981. Disturbance of a low-level waste site cover by pocket gophers. *Health Physics* 42(6):868-872.

Hantush, M.S. 1964. Hydraulics of wells. *Advances in Hydroscience* 1:. 281-432.

Heath, R.C. 1984. Ground water regions of the United States. U. S. Geological Survey Water Supply Paper 2242, 78 pp.

Heath, R.C. and F.W. Trainer. 1968. Introduction to Groundwater Hydrology. New York: John Wiley and Sons, Inc., 284 pp.

Hem, J.D. 1985. Study and interpretation of the chemical characteristics of natural water, 3rd edition. U.S. Geological Survey Water-Supply Paper 2254, 263 pp.

HEW. 1970. Radiological health handbook. U. S. Department of Health, Education, and Welfare, Public Health Service, Food and Drug Administration, Bureau of Radiological

Hillel, D. 1971. Soil and Water: Physical Principles and Processes. New York: Academic Press.

IT Corporation. 1989. Assessment of radiation fose and cancer risk for emissions from 1951 through 1984, Feed Materials Production Center, Fernald, OH. Report on Project No. 303063, submitted to the U.S. Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN, August 1989.

Jaquish, R.E., and R.W. Bryce, eds. 1990. Hanford Site environmental report for Calendar Year 1989. Pacific Norethwest Laboratory, Richland, Washington.

Johnson, R.L., C.D. Palmer, and W. Fish. 1989. Subsurface chemical processes. In: Transport and Fate of Contaminants in the Subsurface. U.S. Environmental Protection Agency.

Keely, J.F., M.D. Piwoni, and J.T. Wilson. 1986. Evolving concepts of subsurface contaminant transport. *Journal of the Water Pollution Control Federation*, May, 1986, pp. 349-357.

Keller, C. 1971. The chemistry of the transuranium elements. Kernchemie in Einzeldarstellungen, Verlag Chemie Gmbh., v. 3.

Kerr-McGee (Sewage Treatment Plant)

Kleeschuite, M.J., L.F. Emmett, and J.H. Barks, J.H. 1986. Hydrologic data for the Weldon Spring radioactive waste-disposal sites, St. Charles County, Missouri. U.S.

Krauskopf, K.B. 1979. Introduction to Geochemistry, 2nd ed. New York: McGraw-Hill.

Layne. 1986. Groundwater hydrology investigation, Weldon Spring, Missouri. Layne Western Company, Inc., Hydrology Division, Kansas City, Kansas, v. 1.

Leichtweis, C.P., J.A. Liberatore, and T.M. Dravecky. 1987. Characterization report for the Sears Property, Maywood, New Jersey. U. S. Department of Energy/OR/20722-140, Bechtel National, Inc., Oak Ridge, TN, May 1987.

Lindberg, R.D. and D.D. Runnells. 1984. Ground water redox reactions: an analysis of equilibrium state applied to Eh measurements and geochemical modeling. *Science* 225:926.

Lloyd, J.W. and J.A. Heathcote. 1985. Natural Inorganic Hydrochemistry in Relation to Groundwater. Oxford: Clarendon Press, 296 pp.

Logan, M.P. 1988. Status assessment for Superfund sites with radiological contamination. U. S. Environmental Protection Agency, RPM, Waste Management Division, Region V, letter of October 18, 1988 to Jennifer Haley, U.S. Environmental Protection Agency, Washington D.C.

Lohman, S.W. 1972. Ground-water hydraulics. U.S. Geological Survey Professional Paper 708, U.S. Government Printing Office, Washington, D.C..

Mason & Hanger. 1991. Pantex Plant site environmental report for Calendar Year 1990. Mason & Hanger - Silas Mason Co., Inc., Amarillo, Texas.

Matthess, G. 1982. The Properties of Groundwater. New York: John Wiley and Sons.

McLennan, S.M. and S.R. Taylor. 1979. Rare earth elements mobility associated with uranium mineralization. *Nature* 282:247-249.

Millington, R.J. 1959. Gas diffusion in porous media. *Science*130:100-102.

Miltenberger, R.P., B.A. Royce, S.S.Chalasani, D. Morganelli, and J.R.Naidu. 1990. Brookhaven National Laboratory site environmental report for Calendar Year 1989. Brookhaven National Laboratory, Associated Universities, Inc., Upton, New York.

Mitre Corporation. 1988. Memo to the U. S. Environmental Protection Agency from The MITRE Corporation, Civil Systems Division, McLean, VA, 21 July 1988.

Moody, J.B. 1982. Radionuclide migration/retardation: research and development technology status report. Battelle Mem. Inst. Report ONWI-321, Columbus, Ohio.

Murphy, R.E. 1966. The American city: an urban geography. New York: McGraw-Hill Book Company.

n/a. 1988. Maxey Flats remedial investigation draft report, August 22, 1988.

Nielsen, D.R., R.D. Jackson, J.W. Cary, and D.E. Evans. 1972. Soil Water. Madison, Wisconsin: American Society of Agronomy.

Nielson, K.K., V.C. Rogers, and G.W. Gee. 1984. Diffusion of radon through soils. *Soil Science Society of America Journal* 48:482-487.

NRC. 1981. Radiological survey of Kress Creek. U.S. Nuclear Regulatory Commission.

NUS. 1989-1990. Record of Assumptions, U.S. Department of Energy Environmental Survey, Revision 3, NUS Corporation.

NUS. 1990a. Draft appendix report - Brookhaven National Laboratory. NUS Corporation for the U. S. Department of Energy.

NUS. 1990b. Draft appendix report - Feed Materials Center. NUS Corporation for the U.S. Department of Energy, Washington, D.C.

NUS. 1990c. Draft appendix report - Hanford Reservation. NUS Corporation for the U.S. Department of Energy, Washington, D.C.

NUS. 1990d. Draft appendix report - Lawrence Livermore Laboratory. NUS Corporation for the U.S. Department of Energy, Washington, D.C.

NUS. 1990e. Draft appendix report - Savannah River Site. NUS Corporation for the U.S. Department of Energy.

NUS. 1990f. Draft appendix report - Oak Ridge National Laboratory. NUS Corporation for the U.S. Department of Energy, January 1990.

O'Farrell, T.P. and R.O. Gilbert, 1975. Transport of radioactive materials by jackrabbits on the Hanford Reservation. *Helath Physics* 29:9-15.

ORNL. 1980. Radiological surveys at inactive uranium-mill sites. Oak Ridge National Laboratories Reports ORNL/TM-5251 and ORNL-5447-ORNL-5465.

Polzer, W.L. 1971. Solubility of Pu in soil/water environments: A theoretical study. In: Proc. Rocky Flats Sym. Safety in Pu Handling, p. 412-429. ORNL, AEC Report Conf. 710401.

Rice, R.E. 1988. Chemistry of Groundwater. Lewis Publishers.

Schulz, W.W. 1976. The chemistry of Americium. ORNL, ERDA Report TID 26971, pp. 47-121.

Schumm, R.H., D.D. Wagman, S. Bailey, W.H. Evans, and V.B. Parker. 1973. Selected values of chemical thermodynamic properties: tables for the lanthanide (rare earth) elements. National Bureau of Standards Technical Notes 270-7.

Sims, J.M., K.A. Surano, K.C. Lamson, and M.G. Brown, eds. 1989. Environmental report for 1989: Lawrence Livermore National Laboratory. Lawrence Livermore National Laboratory, Livermore, California.

Smedes, H.W. 1980. Rationale for geologic isolation of high-level radioactive waste, and assessment of the suitability of crystalline rocks. United States Geological Survey Open File Report 80-1065, pp. 51-57.

Smith, D.D. 1977. Review of grazing studies on plutonium-contaminated rangelands. In: M.G. White and P.B. Dunaway, eds., Transuranics in natural environments, NVO-178, Energy Research and Development Administration, NTIS.

Stenner, R.D., K.H. Cramer, K.A. Higley, S.J. Jette, D.A. Lamar, T.J. McLaughlin, D.R. Sherwood, and N.C. Van Houten. 1988. Hazard Ranking System evaluation of CERCLA inactive waste sites at Hanford. Vol. 2 - Engineered-facility sites (HISS data base). PNL-6456 Vol. 2, prepared for the U.S. Department of Energy by Pacific Northwest Laboratory, October 1988.

Stought, R.L., D.A. Edling, and D.G. Draper. The Mound Site survey project for the characterization of radioactive materials in site soils. MLM-3517, prepared by Monsanto Research Corporation, Miamisburg, OH, for the U.S. Department of Energy, May 16, 1988.

Stumm, W. and J.J. Morgan. 1981. Aquatic Chemistry, second edition. New York: Wiley.

Szalay, A. 1967. The role of humic acids in the geochemistry of uranium and their possible role in the geochemistry of other cations. In: Vinogradov, ed. Chemistry of the Earth's crust, Israel Prog. of Sci. Transl., Jerusalem, pp. 456-471.

Tkachyk, J.W., K.C Wright, and R.N. Wilhelmsen, eds. 1990. Annual report - 1989 environmental monitoring for EG&G Idaho facilities at the Idaho National Engineering Laboratory. EG&G Idaho, Inc., Idaho Falls, Idaho.

Todd, D.K. 1980. Groundwater Hydrology. New York: John Wiley & Sons, 535 pp.

Topp, S.V., ed. 1982. The scientific basis for nuclear waste management, v. IV. New York: Elsevier.

UNC Geotech. 1987a. Addendum to Denver Radium Site supplemental radiological data for Operable Unit IV/V. UNC Geotech, Grand Junction, CO, December 4, 1987.

UNC Geotech. 1987b. Denver Radium Site supplemental radiological data for Operable Unit IV/V. Prepared for U. S. Environmental Protection Agency and U. S. Department of Energy by UNC Geotech, Grand Junction, CO, November 6, 1987.

UNC Geotech. 1988a. Denver Radium Site supplemental data release for Operable Unit I. Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, December 1988.

UNC Geotech. 1988b. Denver Radium Site supplemental data release for Operable Unit II. Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, December 1988.

UNC Geotech. 1988c. Denver Radium Site supplemental data release for Operable Unit III. Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, December 1988.

UNC Geotech. 1988d. Denver Radium Site supplemental data release for Operable Unit X. Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, February 1988.

UNC Geotech. 1988e. Denver Radium Site supplemental data release for PSCO Property Operable Unit VI/IX/XI. Prepared for U.S. Environmental Protection Agency and U.S. Department of Energy by UNC Geotech, Grand Junction, CO, December, 1988.

UNC Geotech. 1989a. Denver Radium Site supplemental data release for a Part of Operable Unit VI (Allied Chemical and Dye Corporation). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, February 1989.

UNC Geotech. 1989b. Denver Radium Site supplemental data release for Operable Unit IX (for International House of Pancakes, Larry's Trading Post, and East Side Amusement Center). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, February 1989.

UNC Geotech. 1989c. Denver Radium Site supplemental data release for Operable Unit VI (Denver Water U. S. Department). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, January 1989.

UNC Geotech. 1989d. Denver Radium Site supplemental data release for Operable Unit VI (for CSSR and 2301 15th Street). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, May 1989.

UNC Geotech. 1989e. Denver Radium Site supplemental data release for Operable Unit XI (Thomas Real Estate Corporation). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, February 1989.

UNC Geotech. 1989f. Denver Radium Site supplemental data release for Part of Operable Unit VI (Brannan Sand and Gravel). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, January

UNC Geotech. 1989g. Denver Radium Site supplemental data release for the Alley Under the 6th Avenue Overpass (Part of Operable Unit VI). Prepared for the U.S. Environmental Protection Agency and the U.S. Department of Energy by UNC Geotech, Grand Junction, CO, February 1989.

USGS. 1976. Geology and hydrology of radioactive solid waste burial grounds at the Hanford Reservation, Washington. U.S. Geological Survey Open-File Report 075-625.

Verruijt, A. 1970. Theory of Groundwater Flow. New York: Gordon and Breach Sciences Publishers, 190 pp.

WA/EPA/DOE. 1989. Hanford Federal Facility Agreement and Consent Order. Washington State Department of Ecology, the U.S. Environmental Protection Agency, and the U.S. Department of Energy, May 1989.

Warren, M.A., De Laguna, W., and Luscznski, N.J., 1968. Hydrology of Brookhaven National Laboratory and vicinity, Suffolk County, New York. United States

Watters, R.L., T.E. Hakonson, and L.J. Lane. 1983. The behavior of actinides in the environment. *Radiochimica Acta* 32:89-103.

Westinghouse Hanford. 1989. Preliminary Operable Units sesignation project. WHC-EP-0216, prepared for the U.S. Department of Energy by Westinghouse Hanford Company, Richland, WA, February 1989.

Weston-Sper. 1988. Site assessment for Ottawa Radiation Sites, Ottawa, IL. TAT-52-G2-28, TDD# 5-8711-10, prepared for the U.S. Environmental Protection Agency Region V, Chicago, IL, July 1988.

Wilson, J.T., and J.F. McNabb. 1983. Biological transformation of organic pollutants in groundwater. *EOS Transactions*, American Geophysical Union 64(33):505.

Winsor, T.F. and F.W. Whicker, 1980. Effects of pocket gopher activity on soil plutonium distribution at Rocky Flats, Colorado. *Health Physics* 39:257-262.

Wood, W.W. and Signor. 1975. Geochemical factors affecting artificial recharge in the unsaturated zone. *Water Resources Research* 9(2):486-488.

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