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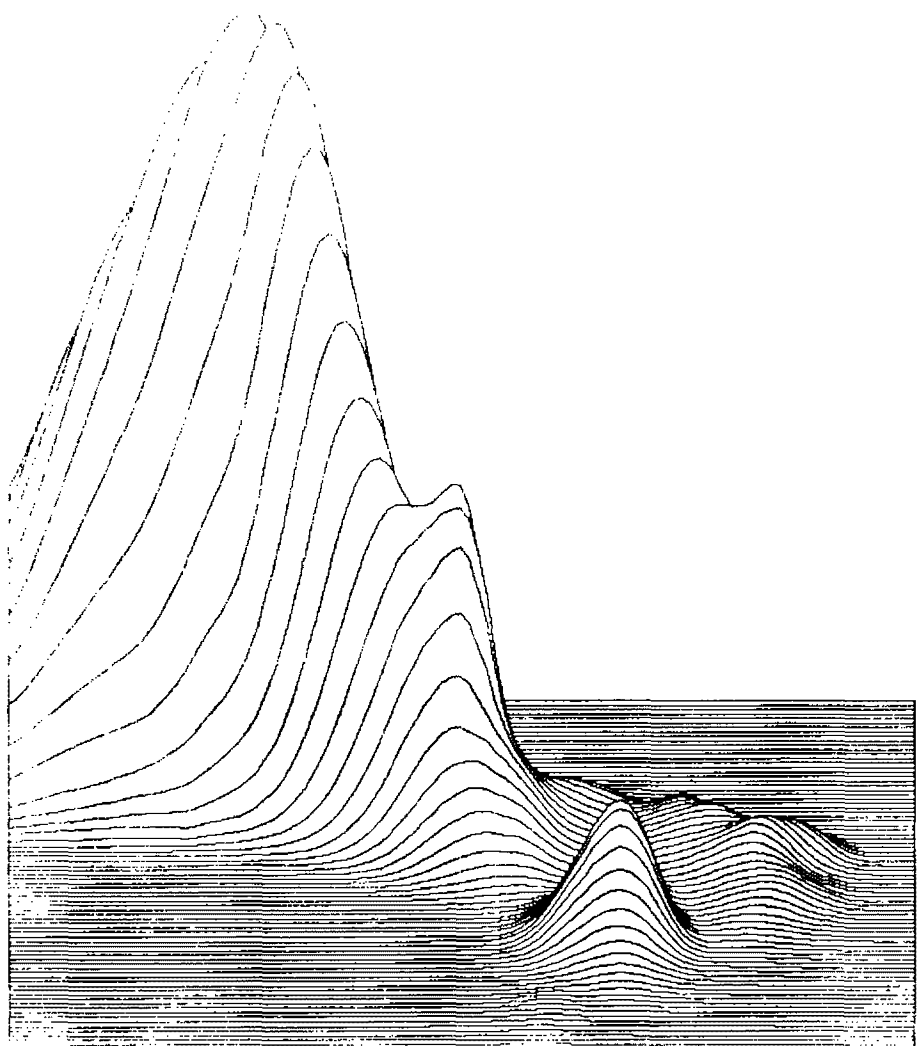
Environmental Pathway Models–Ground-Water Modeling In Support Of Remedial Decision-Making At Sites Contaminated With Radioactive Material



ENVIRONMENTAL PATHWAY MODELS - GROUND-WATER MODELING IN SUPPORT OF REMEDIAL DECISION-MAKING AT SITES CONTAMINATED WITH RADIOACTIVE MATERIAL

March 1993

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.

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EPA Office of Radiation and Indoor Air (ORIA)
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DOE Office of Environmental Restoration and Waste Management (EM)
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ACRONYMS

A/E	Architect/Engineer
AEA	Atomic Energy Act
ARARs	Applicable or Relevant and Appropriate Regulations
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CMA	Corrective Measures Assessment
CMI	Corrective Measures Investigation
D&D	Decontamination and Decommissioning
DOD	Department of Defense
DOE	Department of Energy
EDE	Effective Dose Equivalent
EM	Office of Environmental Restoration and Waste Management
EPA	Environmental Protection Agency
FFA	Federal Facility Agreement
FERP	Fernald Environmental Remediation Project
FMPC	Feed Materials Production Center
FS	Feasibility Study
GSA	General Services Administration
HHEM	Human Health Evaluation Manual
IAG	Interagency Agreement
INEL	Idaho National Engineering Laboratory
MFDS	Maxey Flats Disposal Site
NCP	National Contingency Plan
NORM	Naturally Occurring Radioactive Materials
NPL	National Priorities List
NRC	Nuclear Regulatory Commission
ONMSS	Office of Nuclear Material Safety and Safeguards
ORP	Office of Radiation Programs
OSC	On-Scene Coordinator
OSWER	Office of Solid Waste and Emergency Response
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RI	Remedial Investigation
RPMs	Remedial Project Managers
ROD	Record of Decision
SARA	Superfund Amendments and Reauthorization Act of 1986
SDMP	Site Decommissioning Management Program
TEDE	Total Effective Dose Equivalent

1. Introduction

1.1 PURPOSE AND SCOPE OF THE JOINT EPA/DOE/NRC PROGRAM ON MODELING

A joint program is underway between the EPA Offices of Radiation and Indoor Air (ORIA) and Solid Waste and Emergency Response (OSWER), the DOE Office of Environmental Restoration and Waste Management (EM), and the NRC Office of Nuclear Material Safety and Safeguards (ONMSS). The purpose of this program is to promote the appropriate and consistent use of mathematical models in the remediation and restoration process at sites containing, or contaminated with, radioactive materials. This report is one of a series of reports designed to accomplish this objective. The report specifically addresses the role of, and need for, modeling in support of remedial decision-making at sites contaminated with radioactive material. Other reports in this series will address the selection and application of models.

This report is intended to be used by the Remedial Project Manager (RPM) at National Priorities List (NPL) sites or the equivalent at non-NPL sites containing radioactive materials. It is also intended to be used by geologists and geoscientists responsible for identifying and implementing ground-water flow and transport models at such sites.

The overall joint program is concerned with the selection and use of mathematical models that simulate the environmental behavior and impacts of radionuclides via all potential pathways of exposure, including the air, surface water, ground water, and terrestrial pathways. Figure 1-1 presents an overview of the various exposure pathways.

Though the overall program is concerned with all pathways, it has been determined that, due to the magnitude of the undertaking, it would be appropriate to divide the program into smaller, more manageable phases, corresponding to each of the principal pathways of exposure. It was also determined that, in this, the first phase of the project, greatest attention would be given to the ground-water pathways.

Ground-water pathways were selected for consideration first for several reasons. At many sites currently regulated by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC) or owned by the Department of Energy (DOE), the principal concern is the existence of, or potential for, contamination of the underlying aquifers.

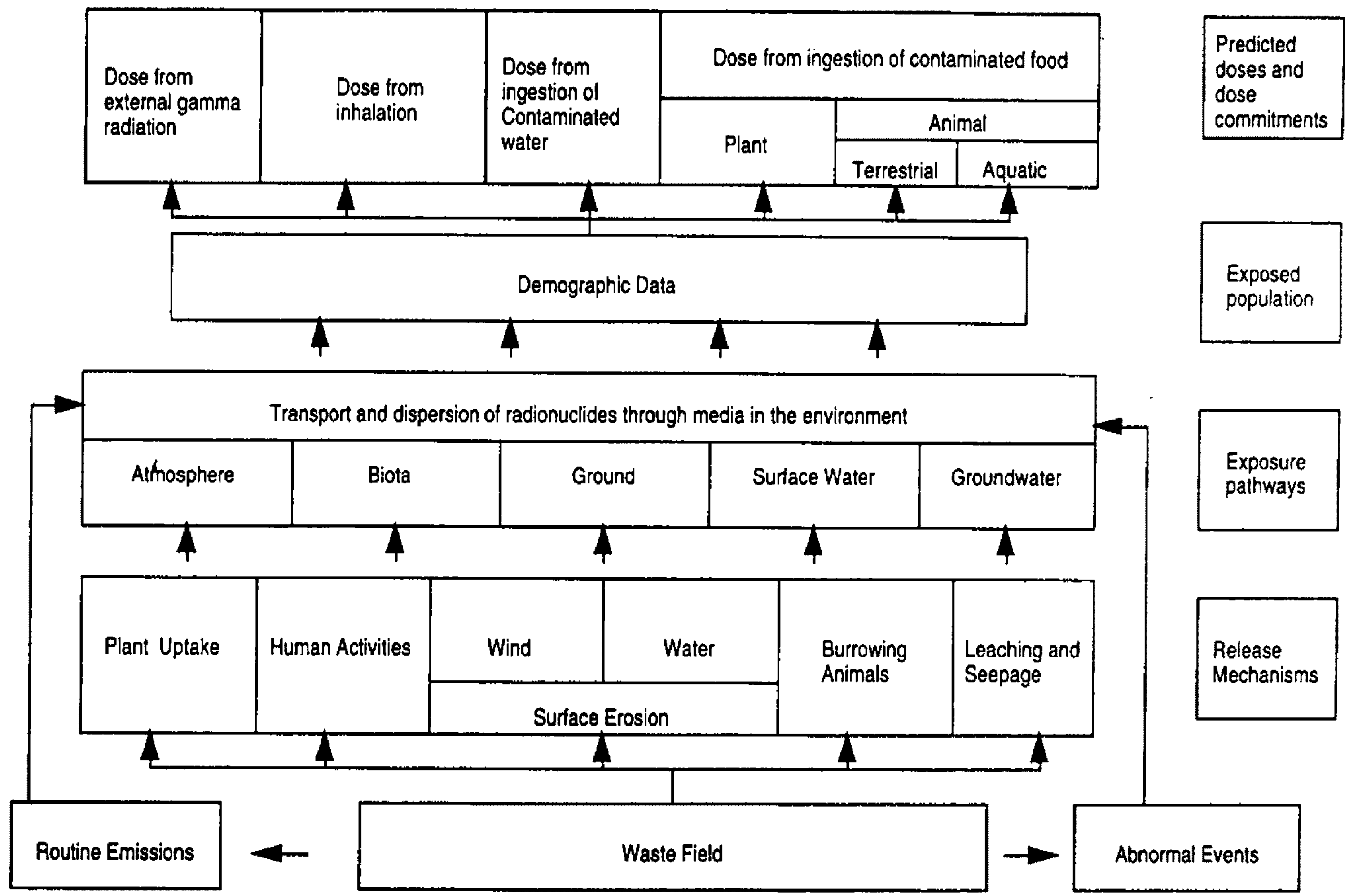

Figure 1-1. Exposure Pathways

In addition, compared to the air, surface water, and terrestrial pathways, ground-water contamination is more difficult to sample and monitor, thereby necessitating greater dependence on models to predict the locations and levels of contamination in the environment. The types of models used to simulate the behavior of radionuclides in ground water must be more complex than surface water and atmospheric pathway transport models in order to address the more complex settings and the highly diverse types of settings associated with different sites. As a result, the methods used to model ground water are not as standardized as those used in surface water and air dispersion modeling, and, therefore, there is considerably less regulatory guidance regarding appropriate methods for performing ground-water modeling.

In planning this project, it was also necessary to make judgments regarding the categories of sites that should be addressed. The categories of sites are relevant to the selection and use of models because they define the range of environmental settings of concern, the types and forms of the radioactive material requiring modeling, and, most importantly, the regulatory structure within which models are used to support remedial decisions. Investigations performed by the Agency have identified thousands of sites that contain, or are potentially contaminated with, radioactive materials and that may require some remediation. These sites include:

- Federal facilities under the authority of 18 federal agencies, predominantly consisting of DOE and Department of Defense (DOD) sites and facilities, and sites listed on the National Priorities List (NPL),
- Facilities licensed by the NRC and NRC Agreement States,
- State-licensed facilities,
- Facilities and sites under the authority of the states but not governed by specific regulations. These include sites containing elevated levels of naturally occurring radioactive materials (NORM).

All of these sites are of interest to this program. However, some categories of facilities and sites are not considered because they are being designed and licensed specifically to receive radioactive material for storage and disposal; i.e., licensed low-level and high-level waste storage and disposal sites. These sites are being managed within a highly structured regulatory context, and, though models are used to support the siting and design of such facilities, they are not remedial sites.

It was also necessary to limit the range of the categories of sites of interest to this program in order to keep their number at a manageable size. Specifically, it was determined that this phase of the program will be limited to (1) sites currently listed on the National Priorities List (NPL) that contain radioactive materials, and (2) sites currently or formerly licensed by the NRC that are part of the Site Decommissioning Management Program (SDMP). The NRC established the SDMP to decontaminate 46 facilities that require special attention by the NRC staff (NRC 91). As will be discussed, ground-water modeling needed to support remedial decision-making at NPL sites containing radioactive materials is in many ways similar to the ground-water modeling needs of the SDMP.

These categories of sites were selected because decisions are currently being made regarding their decontamination and remediation. In many cases, models are being used to support decision-making and demonstrate compliance with remediation goals. Though the program is designed to address the modeling needs of these categories of sites, the information contained in this report and the other reports prepared under this program should apply, to varying degrees, to the full range of categories of sites concerned with the disposition of radioactive contamination. In addition, much of the material may also apply to sites contaminated with chemically hazardous substances.

In order to meet its mission of promoting the appropriate and consistent use of mathematical models in the remediation and restoration process at sites containing, or contaminated with, radioactive materials, the overall program is designed to achieve the following four objectives:

1. Describe the roles of modeling and the modeling needs at each phase in the remedial process;

2. Identify models in actual use at NPL sites and facilities permitted under RCRA, at DOE sites, and at NRC sites undergoing decontamination and decommissioning (D&D);

3. Produce detailed critical reviews of selected models in widespread use; and

4. Produce informal guidance for Remedial Project Managers (RPMs), On-Scene Coordinators (OSCs), or their equivalents to use in selecting and reviewing models used in the remediation and restoration process.

1.2 PURPOSE AND SCOPE OF THIS REPORT

This report, which is the third in a series of reports planned for this program, identifies the role of modeling and modeling needs in support of remedial decision-making at sites contaminated with radioactive materials. For the reasons previously cited, the discussion of modeling needs focuses primarily on ground-water modeling at NPL and SDMP sites.

The two previous reports in this series include a survey of model users and a summary of the characteristics of selected sites contaminated with radioactive materials. The model survey report is entitled, "Computer Models Used to Support Cleanup Decision-Making at Hazardous and Radioactive Waste Sites." The site characterization report is entitled, "Environmental Characteristics of EPA, NRC, and DOE Sites Contaminated with Radioactive Substances."

The primary objective of this report is to describe when modeling is needed and the various processes that need to be modeled. In order to accomplish this objective, modeling needs are defined in terms of the various factors that determine the need. These include:

- The existing regulatory requirements that apply to the remediation of different categories of sites.

  The regulatory structure for sites on the NPL is different than that for sites in the SDMP. As a result, the role of and need for modeling may be expected to differ depending on specific regulatory requirements.

- The phase in the remedial process.

  The role of modeling may be quite different during the early scoping and planning phases of a remedial project, as compared to the later phases, when remedial decisions are made.

- Site characteristics.

  The need for modeling and the types of models that are needed depend, in part, on the characteristics of the site. For example, for ground-water modeling, waste form, the chemical and physical characteristics of the radionuclides, and the hydrogeological and demographic setting will, in part, determine modeling needs.

In this report, modeling needs are described in terms of the applicable regulatory requirements, the phase in the remedial process, and the site characteristics that apply to sites on the NPL contaminated with radionuclides and sites in the SDMP.

This report is intended for use by Remedial Project Managers at NPL sites or their equivalent at SDMP sites. It is assumed that the RPM or equivalent is not a modeler but is responsible for deciding when modeling is needed, authorizing the selection and implementation of the models, and determining how the results of the models will be used in support of the remedial process.

1.3 KEY TERMS

The following are definitions of some key terms used throughout the report.

Conceptual Model. The conceptual model of a site is a flow diagram or sketch of a site and its setting that depicts the types of waste and where they are located, how the waste is being transported offsite by runoff, percolation into the ground and transport in ground water, or suspension or volatization into the air and transport by the prevailing meteorological conditions. The conceptual model also attempts to help visualize the direction and path followed by the contaminants, the actual or potential locations of the receptors, and the ways in which receptors may be exposed, such as direct contact with the source, ingestion of contaminated food or water, or inhalation of airborne contaminants. As information regarding a site accumulates, the conceptual model is continually revised and refined.

Mathematical Model. A mathematical model translates the conceptual model into a series of equations which simulate the fate and effects of the contaminants as depicted in the conceptual model at a level of accuracy that can support remedial decision-making.

Computer Code. A computer code is simply a tool that is used to solve the equations which constitute the mathematical model of the site and display the results in a manner convenient to support remedial decision-making.

1.4 ORGANIZATION OF THE REPORT

Following this introduction, Section 2 presents a generic discussion of the role and purpose of modeling in support of remedial decision-making. The section discusses why modeling is needed and when it is needed. Beginning with Section 3, the report focusses on ground-water modeling. Section 3 describes the various ground-water flow and transport processes that may need to be modeled. A matrix is provided that describes ground-water modeling needs as a function of site characteristics and phase in the remedial process. Other reports being prepared under the joint program describe methods for selecting and applying models that meet these needs.

The report also include two appendices. Appendix A is an extension of Section 2 in that it addresses the role of modeling; however, it does so within the context of specific regulations and programs. An overview is provided of the current and developing CERCLA/RCRA requirements and guidelines that establish the role of, and need for, modeling in support of remedial decision-making. In addition, the principal DOE Orders for meeting these requirements are summarized. Appendix A also draws parallels between modeling required to support CERCLA/RCRA decision-making and the NRC modeling requirements needed to support remedial decision-making on the SDMP. The purpose of Appendix A is to provide background information on modeling needs within the context of specific EPA, DOE, and NRC requirements and programs pertaining to the remediation of sites contaminated with radioactive material.

Appendix B summarizes the characteristics of the current NPL sites contaminated with radioactive material and the sites currently being addressed by the NRC on the SDMP. The purpose of Appendix B is to define the range of site conditions where modeling may be used to support remedial decision-making. This information is used in Section 3, which addresses the need to use simple versus complex models to simulate flow and transport processes.

2. The Need For and Role of Fate and Effects Modeling on a Remedial Project

Modeling needs on a remedial project can be discussed from a number of perspectives, including: why do we need to use models, what determines modeling needs, what needs to be modeled, when is modeling needed, and when is it not needed? These questions are different but interrelated. This section provides generic responses to these questions.

2.1 WHY DO WE NEED TO MODEL?

Modeling is one of the techniques used to fulfill the regulatory requirements that apply to a specific site or category of sites. Ultimately, decisions regarding the selection and implementation of models on a remedial project are driven by the applicable regulations and regulatory guidelines. As discussed in Appendix A, currently no regulations pertaining to the early scoping, characterization, or remediation of NPL or SDMP sites explicitly require modeling. However, in order to make informed decisions about remedial actions at a site and in order to demonstrate compliance with remedial criteria, modeling is often required.

In general, models are used to evaluate existing data or assumptions and to make testable predictions about relationships among parameters and/or the behavior and actual or potential impacts of contaminants in the environment. Models are primarily hypothesis generators, which must be tested and supported by empirical field data. When used in the proper context of hypothesis generators, models can greatly assist in focusing expensive and time-consuming field sampling and monitoring activities. Table 2-1 presents the principal reasons why modeling may be needed on a project. These reasons for modeling can surface during any phase of the remedial process. However, as will be discussed in Section 3, some of these reasons for modeling are more likely to occur during specific phases of a remedial project.

In general, a combination of field measurements and fate and effects models is used at sites contaminated with radioactive material to determine the average and time-varying radionuclide concentrations in various media, the rate of transport of the radionuclides in the media, radiation fields, and the radiation doses and risks to individuals and populations exposed to the radioactive material. Models are used to screen sites to determine the need for remedial activities and remedial priorities. They are also used to support the design of

Table 2-1. Why is Modeling Needed?

1.	When it is not feasible to perform field measurements; i.e., • Cannot get access to sampling locations • Budget is limited • Time is limited
2.	When there is concern that downgradient locations may become contaminated at some time in the future; i.e., • When transport times from the source of the contamination to potential receptor locations are long relative to the period of time the source of the contaminant has been present. • When planning to store or dispose of waste at a specific location and impacts can be assessed only through the use of models.
3.	When field data alone are not sufficient to characterize fully the nature and extent of the contamination; i.e., • When field sampling is limited in space and time, and • When field sampling results are ambiguous or suspect.
4.	When there is concern that conditions at a site may change, thereby changing the fate and transport of the contaminants; i.e., • seasonal changes in environmental condition • severe weather (e.g., floods, tornadoes) • accidents (e.g., fires)
5.	When there is concern that institutional control at the site may be lost at some time in the future resulting in new or unusual exposure scenarios, or a change in the fate and transport of the contaminants; i.e., • trespassers • inadvertent intruder (construction/agriculture) • human intervention (drilling, excavations, mining)
6.	When remedial actions are planned and there is a need to predict the effectiveness of alternative remedies.
7.	When there is a need to predict the time when the concentration of specific contaminants at specific locations will decline to acceptable levels.
8.	When there is concern that at some time in the past individuals were exposed to elevated levels of contamination and it is desirable to reconstruct the doses.
9.	When there is concern that contaminants may be present but below the lower limits of detection.
10.	When field measurements reveal the presence of some contaminants, and it is desirable to determine if and when other contaminants associated with the source may arrive, and at what levels.
11.	When field measurements reveal the presence of contaminants and it is desirable to identify the source or sources of the contamination.
12.	When there is a need to determine the timing of the remedy; i.e., if the remedy is delayed, is there a potential for environmental or public health impacts in the future?
13.	When there is a need to determine remedial action priorities.

Table 2-1 (Continued)

14.	When estimating the benefit in a cost-benefit analysis of alternative remedies.
15.	When demonstrating compliance with regulatory requirements.
16.	When performing a quantitative dose or risk assessment pertaining to the protection of remediation workers, the public, and the environment prior to, during, and following remedial activities.
17.	When designing the site characterization program (e.g., placement of monitor wells, determining data needs).
18.	When there is a need to compute or predict the concentration distribution in space and time of daughter products from the original source of radionuclides.
19.	When there is a need to quantify the degree of uncertainty in the anticipated behavior of the radionuclides in the environment and the associated doses and risks.
20.	To facilitate communication with the public.

environmental measurement programs, identify the types and locations of samples, the types of analyses, and the required sensitivities of analytical techniques. In addition, modeling is used as a tool to help understand the processes that affect the behavior of the radionuclides at a site and the effectiveness of alternative strategies and techniques for mitigating the impacts of the contaminants.

Though models can be useful, remedial decision-making at a site can proceed effectively without the use of models. For example, if the levels of contamination in the environment are above predesignated criteria, and it is apparent that removal and proper permanent disposal of the contaminants is the appropriate remedy, modeling may be unnecessary. However, if a remedial decision is delayed and/or the remedy is other than removal, it is difficult to judge the prudence of such decisions without the aid of fate and effects models.

2.2 WHAT DETERMINES MODELING NEEDS?

Once it is determined that modeling may be needed to fulfill, at least in part, the letter or intent of the applicable regulatory requirements or guidelines, the need for modeling is further defined by:

- the reasons for modeling (as described in Table 2-1),
- the phase of the remedial process,
- the environmental setting and conditions,
- the characteristics of the waste, and
- the land use and demography in the vicinity of the site.

Throughout this report, the remedial process is divided into three phases. Phase 1 is referred to as the scoping and planning phase, wherein regional, sub-regional, and site-specific data are reviewed and analyzed in order to define the additional data and analyses needed to support remedial decision-making. Phase 2 is referred to as the site characterization phase, wherein the plans developed in Phase 1 are implemented. These data are used in Phase 2 to characterize more fully the nature and extent of the contamination at the site, to define the environmental and demographic characteristics of the site, and to support assessments of the actual or potential impacts of the site. In Phase 2, the data are analyzed to determine compliance with applicable regulations and to begin to define strategies for the remediation of the site. Phase 3 is referred to as the site remediation phase, wherein alternative remedies are identified, evaluated, selected, and implemented.

Conceptually, any remedial process can be described in terms of these three phases. However, depending on the regulatory framework, each phase may be highly structured, with clear boundaries between phases, as is the case for sites on the NPL. Conversely, each phase may be relatively unstructured, as is the case for sites in the SDMP. In either case, modeling needs will vary as a function of the phase of the remedial process.

During Phase 1, modeling can be used to identify the potentially significant radionuclides and pathways of exposure, which, in turn, can be used to support the design of comprehensive and cost-effective waste characterization, environmental measurements, and site characterization programs. During Phase 2, modeling is used primarily in support of dose and risk assessment of the site and to evaluate the adequacy of the site characterization program. During Phase 3, modeling is used primarily to support the selection and implementation of alternative remedies and, along with environmental measurements programs, is used to determine the degree to which the remedy has achieved the remedial goals.

The environmental setting and conditions at the site will also define modeling needs. The critical pathways of exposure and the complexity of the site will define the types of models needed to support decision-making at each phase in the remedial process.

The types of radionuclides, their chemical and physical form, and the degree to which they are contained in an engineered barrier will also define modeling needs. Finally, the land use and demography in the vicinity of the site will partly determine the potentially important exposure pathways, which, in turn, will define modeling needs.

2.3 WHAT NEEDS TO BE MODELED?

For a site contaminated with radioactive materials, the "end product" of the modeling process is typically one or more of the following results for a broad range of exposure scenarios, exposure pathways, and modeling assumptions:

- The time-varying and time-averaged radionuclide concentrations in air, surface water, ground water, soil, and food items. These are usually expressed in units of pCi/L of water or pCi/kg of soil or food item.
- The radiation field in the vicinity of radioactive material, expressed in units of μR/hr.
- The radionuclide flux in units of pCi/m^2-sec.
- The transit time or time of arrival of a radionuclide at a receptor location.
- The volume of water contained within or moving through a hydrogeological setting.
- Radiation doses to individual members of the public under expected and transient conditions and following accidents. The doses are evaluated for the site in its current condition (i.e., the no action alternative) and during and following a broad range of feasible alternative remedies. These doses are usually expressed in units of mrem/yr effective dose equivalent (EDE) for continuous exposures and mrem per event (EDE) for transients and postulated accidents.

- Radiation risks to individual members of the public under expected and transient conditions and following accidents. The risks are evaluated for the no action alternative and during and following a broad range of feasible remedies. These are usually expressed in units of individual lifetime risk of total and fatal cancers.

- Cumulative radiation doses to the population in the vicinity of the site under expected and transient conditions and following accidents. The cumulative doses are evaluated for the no action alternative and during and following a broad range of feasible remedies. These are usually expressed in units of person rem/yr (EDE) for continuous exposures and person rem per event (EDE) for transients and accidents.

- Cumulative radiation risks to the population in the vicinity of the site under expected and transient conditions and following accidents. The cumulative population risks are evaluated for the no action alternative and during and following a broad range of feasible remedies. These are usually expressed in units of total and fatal cancers per year in the exposed population.

- Radiation doses and risks to remedial workers for a broad range of alternative remedies. The units of dose and risk for individual and cumulative exposures are the same as those for members of the public.

- Uncertainties in the above impacts, expressed as a range of values or a cumulative probability distribution of dose and risk.

The specific regulatory requirements that apply to the remedial program determine which of these "end products" is needed. In general, these modeling results are used to assess impacts or compliance with applicable regulations; however, information regarding flux, transport times, and plume arrival times is also used to support a broad range of remedial decisions.

2.4 WHAT SCENARIOS NEED TO BE MODELED?

In order to model radionuclide concentrations, radiation fields, doses, and risks, as delineated in Section 2.3, it is necessary to postulate a set of hypothetical exposure scenarios. Depending on the regulatory requirements and the phase in the remedial process, the exposure scenarios that will need to be modeled can include any one or combination of the following:

- The no action alternative
- Trespassers
- Inadvertent intruder (construction, agricultural, and well water)
- Routine and transient emissions
- Accidents
- Alternative remedies

The "no action" alternative is a term used primarily with sites on the NPL and has a very specific meaning delineated in EPA 88. However, in its broadest interpretation, it simply refers to the impacts of the site if no action is taken to clean up the site or protect the public from the radioactive material at the site. As applied to NPL sites, the no action alternative refers to site conditions and exposure scenarios prior to any remedial action, including institutional control (EPA 88). In addition, the exposure scenarios must consider future use of the site for either residential, commercial, or recreational use (EPA 91). For sites not on the NPL, or portions of sites that are on the NPL but are in active use, such as several of the federal facilities on the NPL, it may be more appropriate to assume that institutional controls are in place to control access to the site, maintain the site, and ensure that emissions from the site are monitored and kept within acceptable levels.

In between these two extremes are scenarios where credit for institutional controls is taken for some reasonable period of time, such as 100 years, after which unrestricted access to the site is postulated.

Within the context of the no action alternatives, a number of scenarios may be postulated. For example, it may be assumed that a trespasser gains access to the site periodically. It may also be postulated that an individual gains access to the site and establishes residence. This scenario could include the construction, agriculture, and well water scenarios. The construction scenario postulates that an individual builds a home on the site. The agriculture scenario assumes that the resident maintains a farm or backyard garden at the site. The well water scenario assumes that the individual establishes a well on site. These scenarios are often referred to as the intruder scenarios because they postulate that an individual gains access to, or intrudes onto the site, either deliberately or inadvertently. These scenarios are addressed at NPL sites in accordance with guidance provided in EPA 91, 91a, and 91b. However, at sites in the SDMP, the concept of an intruder may not be appropriate since the site is under the direct control of an NRC licensee and will not be released for unrestricted use prior to decontamination to levels that will permit unrestricted access to the site.

In addition to the intruder scenarios, which are concerned with the potential impacts associated with a person gaining access to a site, it is usually necessary to model the impacts on the people and the environment in the vicinity of the site, outside the area where credit is taken for institutional control. The scenarios that could be postulated are routine or chronic releases to the atmosphere, surface water, or ground water, transient emissions, and postulated accidents. Routine emissions of radioactive materials are associated with normal erosion and transport processes. Transient releases typically include periodic releases associated with severe weather or other such phenomena that are anticipated to occur during the hazardous life of the contaminants at the site. Postulated accidents include unlikely events, such as fires, severe flooding, or earthquakes, which have a low probability of occurring but relatively large impacts as compared to routine or transient conditions.

Finally, it may also be necessary to model the effectiveness of a broad range of alternative remedies. Each remedy can be considered a separate scenario. In addition, for each remedy, it may be necessary to model the performance of the remedy under anticipated and offnormal conditions. For example, if stabilization of the site using an engineered cap is a feasible alternative, it will be necessary to model the impacts (i.e., doses and risks) of the site with the cap performing as designed and also following its postulated failure.

Clearly, the number of scenarios that can be postulated is virtually unlimited. Accordingly, it is necessary to determine which scenarios reasonably bound what may in fact occur at the site. The types of scenarios selected for consideration influence modeling needs because they define the receptor locations and exposure pathways that need to be modeled.

2.5 WHAT PATHWAYS NEED TO BE MODELED?

For each scenario, an individual or group of individuals may be exposed by a wide variety of pathways. The principal pathways include:

- External exposure to deposited radionuclides
- External exposures to airborne, suspended, and resuspended radionuclides
- Inhalation exposures to airborne, suspended, and resuspended radionuclides
- Ingestion of radionuclides in food items and drinking water
- Ingestion of contaminated soil and sediment
- External exposures from immersion in contaminated water

Each of these pathways, within the context of each postulated scenario, creates unique modeling needs. Which of these pathways will need to be explicitly modeled is initially determined during the planning phases and is based on judgments regarding the likelihood that a given pathway may be an important contributor to risk. For example, if available data indicate that the contamination is buried or covered with water, the suspension pathway need not be addressed unless it is postulated that the buried material is exhumed or the water covering the material is drained or evaporates. The relative importance of each pathway may also be evaluated by the use of scoping calculations, such as those described in Til 83, SCA 90, and EPA 88a.

2.6 WHEN IS MODELING NOT NEEDED OR INAPPROPRIATE?

The previous sections have identified the possible uses of models and the factors that determine modeling needs. However, it is equally important to be able to recognize the circumstances under which modeling would be ineffective and should probably not be performed. There are three general scenarios in which modeling would be of limited value. These are:

1. Presumptive remedies can be readily identified,
2. Decision-making is based on highly conservative assumptions, and/or
3. The site is too complex to model realistically.

The first case arises in situations where a presumptive remedy is apparent; that is, where the remedy is obvious based on regulatory requirements or previous experience, and there is a high level of assurance that the site is well understood and the presumptive remedy will be effective. An example would be conditions that obviously require excavation or removal of the contaminant source.

The second case is based on the assumption that decision-making can proceed based on conservative estimates of the behavior and impacts of contaminants at the site rather than detailed modeling. This strategy could be used in the initial scoping, site characterization, or remedial phase of the investigation. For example, a conservative approach to the risk assessment would be to assume that the contaminant concentrations at the receptor(s) are identical to the higher concentrations detected at the contaminant source, and that the concentrations diminish in time only through radioactive decay. Thus, the need for modeling to determine the effects of dilution and attenuation on contaminant concentrations is subsequently removed.

Although the need for modeling may be eliminated through the adoption of a conservative approach, a conservative approach should not be taken just to avoid ground-water modeling. There are far more important aspects of the remedial program which will dictate an acceptable remedial approach and which usually focus on the optimization between the remedial activities and the accompanying reduction in risk, whereas, an overly conservative approach may be contradictory to these objectives.

The third case involves sites where modeling would be helpful in supporting remedial decision-making, but the complexity of the site precludes reliable modeling. These complexities could be associated with the contaminant source, flow and transport processes, or characteristics of the wastes. For example, the contaminant source may be so poorly defined in terms of areal extent, release history, and composition that it cannot be reliably defined and little would be gained from flow and transport modeling. Complex flow and transport processes present another difficulty in that computer codes currently do not exist that accommodate a number of these processes, which include: turbulent ground-water flow, facilitated transport, and flow and transport through a fractured unsaturated zone.

The availability of computer codes is also an issue when characteristics of the wastes are typified by complex geochemical reactions; such as phase transformations and non-linear sorption processes. Currently, ground-water flow and contaminant transport codes have not been developed which provide credible mathematical descriptions of the more complex geochemical processes. If modeling is not possible because of the overall complexity of the site characteristics, it is common for a greater emphasis to be placed on empirical rather than predicted data. This may involve establishing long-term monitoring programs, which in effect, have similar objectives of the ground-water modeling.

In summary, models are data analysis tools which can be useful in supporting decisions, but are not substitutes for data acquisition and expert judgement. No model is "correct," but some are useful when used in the proper context. Models should not be used until the specific objectives of the modeling exercise are defined and the limitations of the models fully appreciated.

If a site is poorly characterized or poorly understood, any simulation of the transport and impacts of contaminants using mathematical models is speculative at best and could be highly misleading. Accordingly, the use of models under such circumstances is limited with regard to the types of decisions they can help to support. For example, when site specific data are limited or a site is poorly understood, models may be used to make conservative (i.e., upper bound) estimates of the potential public health and environmental impacts of a site or to identify those pathways and environmental parameters that must be better characterized in order to make more realistic estimates of the potential impacts of a site. As such, models may be helpful in planning and prioritizing activities. However, modeling alone generally cannot be used to support reliable risk assessments or remedial decisions.

Inappropriate use of models can lead to costly mistakes. Not only are models often expensive to implement, but, if used incorrectly, can lead to poorly designed site characterization programs, the selection and implementation of ineffective remedies, and erroneous conclusions regarding the actual or potential public health and environmental impacts of a site.

Notwithstanding the limitations of models, it is difficult to support remedial decisions or the assessment of risks at a site without the use of models. There are no easy answers or simple instructions that can be used to ensure the intelligent and effective use of models in support of remedial decision-making. However, as a general rule of thumb, it is prudent to ask continually, under what circumstances could the results of a given modeling exercise be wrong or misleading, what are the potential consequences of our decisions if the modeling exercise is wrong, and what can we do to verify independently the reliability of our modeling results?

3. Processes that Need to be Modeled: The Need for Complex Versus Simple Ground-water Flow and Transport Models

The previous sections of this report describe the need for, and role of, modeling on both a generic basis (Section 2) and also within the context of the regulations and guidelines governing site remedial activities (see Appendix A). This section describes the site conditions and fate and effects processes that may need to be modeled, which, in turn, determine whether simple or complex models are needed. The discussion emphasizes ground-water flow and transport.

For the purpose of this discussion, the distinction between simple and complex ground-water modeling is based upon broad classifications of ground-water models as either analytical or numerical. Analytical models are usually approximate or exact solutions to simplified forms of the differential equations for water movement and solute transport. Such models are simpler to use than numerical models and can generally be solved with the aid of a calculator, although computers are also used. Analytical models are limited to simplified representations of the physical situations and generally require only limited site-specific input data. They are useful for screening sites and scoping the problem to determine data needs or the applicability of more detailed numerical models.

Numerical models generally provide solutions to the differential equations describing water movement and solute transport using numerical methods, such as finite differences and finite elements. These methods always require a digital computer, a large quantity of data, and an experienced modeler-hydrologist. The validity of the results from numerical models depends strongly on the quality and quantity of the input data.

In the sections that follow, reference to complex sites and complex models generally means that the processes of interest at a site can be best simulated with numerical models. Reference to simple sites, simple models, or scoping or screening calculations generally means that the processes of interest can be modeled with analytical models. Notwithstanding these definitions, it should be understood that there are also degrees of complexity among both analytical and numerical models. For example, in Section 3.5, which addresses remedial technologies, numerical modeling is generally required to simulate the performance of alternative remedies. However, some remedies require more complex numerical models. The purpose of referring to simple and complex sites and models in this fashion is to alert the RPM or equivalent to circumstances when relatively complex processes may need to be simulated so that the appropriate resources and expertise are included in the planning process.

In general, the site conditions and the processes that need to be modeled, and therefore the complexity of the models, are determined by a combination of the following five factors:

1. the reasons for or objectives of modeling (as discussed in the previous sections, the regulatory requirements and guidelines ultimately establish the reason for modeling),

2. the phase of the remedial process,

3. the chemical and physical form, distribution, and radionuclide composition of the waste,

4. the environmental characteristics of the site, and

5. the site demography and land use.

In general, factors 1, 3, and 4 have the greatest influence on determining the processes that need to be modeled and therefore the required complexity of the models. However, as will be discussed, all five factors in combination influence whether complex or simple models will be needed. Accordingly, the site conditions and the processes that need to be modeled can be defined in terms of a five-dimensional matrix; that is, given the reason for modeling, the phase of the remedial process, the characteristics of the waste, and the environmental and demographic characteristics of the site, the site conditions and the processes that need to be explicitly modeled can be defined.

In the following sections, site conditions and the processes that need to be modeled are discussed in terms of each of the five controlling factors. In each section, the interdependencies among the controlling factors are discussed briefly. Accordingly, the discussion of each factor must include some discussion of each other factor, resulting in some redundancy. Cross-referencing is used to minimize redundancies.

The discussion begins with a listing of the full range of site conditions and processes that may need to be modeled. This is followed by a discussion of how modeling complexity (i.e., modeling needs) is determined, at least in part, by each of the five controlling factors. Bear in mind that it is the combination of the five factors that determines modeling needs.

3.1 SITE CONDITIONS AND PROCESSES THAT NEED TO BE MODELED

Table 3-1 presents an overview of the full range of site conditions, transport processes, doses, and risks from all scenarios and pathways that may need to be modeled during the various phases of the remedial process. These conditions and processes also represent attributes of fate and effects models. That is, if it is determined that a given process needs to be modeled at a given site, and for a given phase of the remedial process, a model or group of models needs to be selected that addresses that process.

3.2 REASONS FOR MODELING

Table 3-2 presents a list of the reasons for modeling and the phases in the remedial process when those reasons are likely to occur. In general, the ground-water flow and contaminant transport processes that need to be modeled are dependent primarily on the modeling objectives and site conditions. However, many of the reasons for modeling listed in Table 3-2 will also affect the processes requiring modeling, and therefore the complexity of the models. For example, the assessment of the onsite intrusion scenarios (item 5) does not require modeling complex flow and transport processes, while modeling the effectiveness of alternative in-situ remedies (item 15) may require modeling complex processes to support the design of the remedy.

As discussed later in Section 3.5, the modeling needs associated with the early phases of the remedial process generally do not require complex modeling. In addition, the detailed site-specific data required to perform complex modeling are usually not available at this early stage in the process. As a result, modeling often consists of screening-level calculations that tend to bound the potential impacts associated with the site and simulate flow and transport using simplifying, conservative assumptions.

The two primary reasons for ground-water modeling in the site characterization phase of the remedial process are to: (1) support the baseline risk assessment and (2) optimize the effectiveness of the site characterization program. Each of these modeling objectives presents distinct modeling needs.

The demands of the baseline risk assessment that are supported by ground-water modeling generally range from determining peak concentrations of radionuclides arriving at the

Table 3-1. Transport Processes

1.	Source Term - Determine routine emissions/leach rate in terms of Ci/yr or accidental emissions in terms of Ci/event as a function of time • Routine Emissions - Waste Form/Waste Container Performance - Natural Barrier Performance - Engineered Barrier Performance • Transient or Accident Emissions - Natural Flood High Winds Tornado Earthquake - Anthropogenic Construction Agriculture Drilling
2.	Environmental Transport - Determine radionuclide concentrations in air (pCi/m^3), soil and sediment (pCi/g), surface and ground water (pCi/L) as a function of time and receptor location • Air Transport Processes - Suspension - Evaporation - Volatilization - Dispersion - Deposition - Radioactive Decay and Buildup • Surface Water Transport in Streams, Rivers, Lakes, Estuary and Marine Environments - Dispersion - Deposition in Sediments - Sediment Transport - Radioactive Decay and Buildup • Ground-Water Transport Processes - Unsaturated Zone Miscible Immiscible Vapor Transport Mass Transport Advection Diffusion Dispersion Physical/Chemical Processes Decay Sorption Dissolution/Precipitation Acid/Base Reactions Complexation Hydrolysis/Substitution Redox Reactions Density Dependent Flow Biologically Mediated Transport

Table 3-1 (Continued)

2.	Environmental Transport (Continued) - Saturated Zone Miscible Mass Transport Advection Diffusion Dispersion Physical/Chemical Processes Decay Sorption Dissolution/Precipitation Acid/Base Reactions Complexation Hydrolysis/Substitution Redox Reactions Density Dependent Flow Biologically Mediated Transport Immiscible - Fractured Zone Nonpercolating Percolating Matrix diffusion effects
3.	Exposure Scenarios • Postulated scenarios causing radiation exposure via various pathways • The no action alternative • Alternative remedies • Trespassers • Inadvertent intruder (construction and agricultural) • Routine and transient emissions • Accidents
4.	Exposure Pathways • The Pathway or Medium to Which Individuals and Populations Are Exposed • External Exposure to Deposited Radionuclides • External Exposures to Airborne, Suspended, and Resuspended Radionuclides • Inhalation Exposures to Airborne, Suspended, and Resuspended Radionuclides • Ingestion of Radionuclides in Food Items and Drinking Water • Ingestion of Contaminated Soil and Sediment • External Exposures from Immersion in Contaminated Water
5.	Doses • mrem/yr EDE to individuals • person rem/yr EDE to population

Table 3-1 (Continued)

6.	<u>Public Health Impacts</u> • Individual Risk (risk per yr and per lifetime) - Acute Effects - Carcinogenic Effects - Mutagenic Effects - Teratogenic Effects • Population Impacts (Effects/yr) - Acute Effects - Carcinogenic Effects - Mutagenic Effects - Teratogenic Effect

ground-water table, which have been derived from an immediately overlying source, to the determination of radionuclide arrival times and concentrations at receptors that may be located miles downgradient. The most acceptable method of predicting peak concentrations of radionuclides emanating from a source and reaching the water table is to model the movement of ground water and radionuclides through the unsaturated zone. A number of ground-water models are available to model flow and transport processes in the unsaturated zone, each with their own strengths and weaknesses (see EPA 88a).

In some instances, the risk assessment may require that radionuclide concentrations be determined at a receptor located at some distance downgradient from the source. In this case, a model that can simulate flow and transport in the saturated zone should be used. Currently, very few ground-water computer codes are available that satisfactorily couple the flow and transport processes occurring in the unsaturated zone with those of the saturated zone. However, it is not essential to use a coupled code to obtain reliable results of ground-water flow and radionuclide transport moving from the unsaturated zone into the saturated zone. Decoupled codes can use the output from the unsaturated flow and transport model (radionuclide concentrations reaching the water table) as input (boundary and/or initial conditions) to the saturated zone flow and transport code. In essence, the codes may be coupled in terms of input and output.

Ground-water modeling during the site characterization phase is also used to: (1) refine the existing site conceptual model; (2) optimize the number and location of monitoring wells; and (3) evaluate the sensitivity of ground-water flow and contaminant transport to various parameters. To accomplish these goals, it is generally necessary to apply relatively complex ground-water models that can simulate flow in the saturated zone as well as transport

Table 3-2. Matrix of Reasons for Modeling[1]

	Opportunities for Modeling	Scoping	Site Characterization	Remediation
1.	When it is not feasible to perform field measurements; i.e., • Cannot get access to sampling locations • Budget is limited • Time is limited	●	○	○
2.	When there is concern that downgradient locations may become contaminated at some time in the future.	●	●	●
3.	When field data alone are not sufficient to fully characterize the nature and extent of the contamination; i.e., • when field sampling is limited in space and time and needs to be supplemented with models • when field sampling results are ambiguous or suspect	●	●	●
4.	When there is concern that conditions at a site may change, thereby changing the fate and transport of the contaminants; i.e., • seasonal changes in environmental conditions • severe weather (floods, tornadoes) • accidents (fire)	○	●	●
5.	When there is concern that institutional control at the site may be lost at some time in the future resulting in unusual exposure scenarios,or a change in the fate and transport of the contaminants; i.e., • trespassers • inadvertent intruder (construction/agriculture) • drilling, mineral exploration, mining • human intervention (drilling, excavations, mining)	○	●	●
6.	When remedial actions are planned and there is a need to predict the effectiveness of alternative remedies.	○	○	●
7.	When there is a need to predict the time when the concentration of specific contaminants at specific locations will decline to acceptable levels.	○	●	●

[1] ● Denotes an important role
○ Denotes a less important role

Table 3-2 (Continued)

	Opportunities for Modeling	Scoping	Site Characterization	Remediation
8.	When there is concern that at some time in the past individuals were exposed to elevated levels of contamination and it is desirable to reconstruct the doses.	○	●	○
9.	When there is concern that contaminants may be present but below the lower limits of detection.	○	●	○
10.	When field measurements reveal the presence of some contaminants and it is desirable to determine if and when other contaminants associated with the source may arrive, and at what levels.	○	●	○
11.	When field measurements reveal the presence of contaminants and it is desirable to identify the source or sources of the contamination.	●	●	○
12.	When there is a need to determine the timing of the remedy; i.e., if the remedy is delayed, is there a potential for environmental or public health impacts in the future.	○	○	●
13.	When there is a need to determine remedial action priorities.	○	○	●
14.	When demonstrating compliance with regulatory requirements.	●	●	●
15.	When estimating the benefit in a cost-benefit analysis of alternative remedies.	○	○	●
16.	When performing a quantitative dose or risk assessment.	○	●	●
17.	When there is uncertainty regarding the proper placement of monitor wells.	●	○	●
18.	When developing a site conceptual model.	●	○	○
19.	When developing a site characterization plan and determining data needs.	●	○	○
20.	When there is a need to anticipate the potential doses to remediation workers.	●	○	●

[1] ● Denotes an important role
○ Denotes a less important role

processes that will affect downgradient radionuclide concentrations. However, the lack of available data throughout much of the site characterization phase will often limit a meaningful analysis to two dimensions.

The objectives of modeling required to support the selection and implementation of alternative remedies are generally more ambitious than those associated with the site characterization phase of the remedial process. Therefore, it is often necessary to select a computer code with more advanced capabilities in order to simulate the more complex conditions inherent in the remedial design. For example, the following specific processes are rarely essential to the baseline risk assessment and site characterization but are often very important to the remedial design:

(1) three-dimensional flow and transport;

(2) matrix diffusion (pump and treat);

(3) resaturation of the nodes (pump and treat);

(4) heat-energy transfer (in-situ vitrification/freezing);

(5) sharp contrasts in hydraulic conductivity (barrier walls);

(6) multiple aquifers (barrier walls);

(7) the capability to move from confined to unconfined conditions (pump and treat); and

(8) ability to simulate complex flow conditions (pumping wells, trenches, injection wells).

If these types of remedies may be employed, complex models will likely be needed to support the selection, design, and implementation of the remedy.

3.3 CHARACTERISTICS OF THE WASTE - MODELING THE SOURCE TERM

Within the context of ground-water modeling, the "source term" refers to the rate at which radionuclides are mobilized from the waste and enter the unsaturated and saturated zones of a site. The following characteristics of the waste will determine the complexity of the models required to simulate realistically the source term:

- Waste container
- Waste form
- Source geometry (e.g., volume, area, depth, homogeneity)
- Types and chemical composition of the radionuclides
- Geochemical environment in the vicinity of the waste

Analytical models for the geosphere can only simulate simple approximations of the source term; therefore, if it is suspected that the source term is transient or that the waste container has a significant impact on the release rates, models that simulate complex source terms, in addition to the more traditional flow and transport computer codes, may be needed.

3.3.1 Waste Form and Containment

As indicated in Appendix B, radioactive contaminants are present in a wide variety of waste forms that may have some influence on their mobility. However, in most cases, the radionuclides of concern are long-lived and the integrity of the waste form or container cannot be relied upon for long periods of time. Therefore, the source term can often be modeled as a uniform point or areal source and no credit taken for waste form or containerization.

If it is desired to model explicitly the performance of the waste form (e.g., rate of degradation of solidified waste or containerized waste) or transport in a complex geochemical environment (changing acidity, presence of chelating agents or organics), more complex geochemical models may be needed. Depending on the waste form and container, such models would need to simulate the degradation rate of concrete, the corrosion rate of steel, and the leaching rate of radionuclides associated with various waste forms (i.e, soil, plastic, paper, wood, spent resin, concrete, glass, etc.). These processes would depend, in part, on the local geochemical setting. However, it is generally acknowledged that the current state-of-the-art does not permit the explicit modeling of geochemical processes responsible for the degradation of the waste containers or the waste itself (NRC 90a). As a result, in order to account for container and waste form performance, the model would need to include terms that provide for a user-defined algorithm which accounts for the delay in release associated with the performance of the barrier or waste form.

3.3.2 Physical and Chemical Properties of the Radionuclides

Certain radionuclides have properties that are difficult to model and may not be adequately simulated with analytical models. For instance, most of the NPL sites are contaminated with thorium and uranium, both of which decay into multiple daughters which may differ from their parents both physically and chemically. Some of the radionuclides (e.g., uranium) exhibit complex geochemistry, and their mobility is dependent upon the redox conditions at the site. The following discusses some of the chemical properties of common radionuclide contaminants found at many NPL and SDMP sites and how these properties can influence radionuclide transport.

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. Similarly, 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.

The radon associated with radium-contaminated sites, as well as sites with tritium, has special considerations in that these radionuclides can move in a gaseous phase. This gaseous phase cannot be simulated with traditional flow and transport models. Furthermore, model calibration of the radionuclide transport may be extremely difficult due to the radionuclide gas or vapor phase moving independently of the ground water.

Transition, Noble Metals, and Lanthanides

These elements (Mn, Ni, Co, Ru, Tc, Eu, and Pm) exist as atoms with one, two, three, 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 that lead to the precipitation of oxides, sulfides, carbonates and sulfates, etc., and ion-exchange will dominate the behavior of these elements. In modeling the transport of these radionuclides, retardation factors are selected based on knowledge of the geochemical environment and whether precipitation reactions are anticipated.

Alkaline Metals and Earths

Cesium, radium, and strontium 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. Radium and strontium will behave similarly to calcium, which controls their behavior in nature, and cesium will tend to follow K and Na in solution. Because of their relatively short half-lives, the retardation factors for Cs-137 and Sr-90 can have a significant effect on the outcome of a modeling exercise. In general, the retardation factors for these radionuclides depend on the composition of the soil (i.e., clay vs. silt vs. sand).

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 site, the possibility exists for transitions within media from reducing to oxidizing conditions on both a macro and micro scale.

While multiple valence states will generally suggest that redox conditions will be a controlling factor in the behavior of radioactive materials, other properties may mask the charge effect. For example, although plutonium can exist in any of five valence states (+3, +4, +5, +6, +7), few of these are, in fact, of geochemical importance. In practice, the property that controls the behavior of plutonium, for example, is the insolubility of Pu(IV) hydrolysis products, which are, in turn, strongly adsorbed to particle surfaces. In general, these processes cannot be reliably modeled. Instead, retardation factors are selected based on an understanding of the site geochemistry and bench scale tests.

Though the chemical form of the radionuclides and the geochemical setting can have a profound effect on the transport of the radionuclides, it is generally acknowledged that the various geochemical processes cannot be modeled reliably. Instead, based on knowledge of the radionuclides, their chemical and physical form, and the local geochemistry, judgments, along with bench scale tests, are used to identify the effective binding coefficients for the radionuclides in that setting.

Decay Chains

Many of the radionuclides discussed in Appendix B have daughters or an entire decay chain (such as uranium and thorium) that must be modeled if exposures over long periods of time are of concern. This necessitates the use of models that explicitly address decay chains.

3.3.3 Geochemical Setting

In addition to the standard chemical properties of radionuclides, it is important to understand the geochemical properties and processes of the radionuclides that are specific to the site. These properties and processes include the following:

- Complexation of radionuclides with other constituents
- Phase transformations of the radionuclides
- Adsorption and desorption
- Radionuclide solubilities at ambient geochemical conditions

To model these processes explicitly, as opposed to using simplifying assumptions such as default or aggregate retardation coefficients, more complex geochemical models may be needed. However, as discussed above, it is generally acknowledged that explicit modeling of complex geochemical processes in conjunction with ground water flow is currently not feasible.

3.4 ENVIRONMENTAL CHARACTERISTICS - MODELING FLOW AND TRANSPORT

In general, the need for complex models increases with increasing complex lithology (i.e., a thick unsaturated zone, and/or streams or other bodies of water on site (i.e., a complex site). However, even at complex sites, complex models may not be needed. For example, if a conservative approach is taken, where transport through the unsaturated zone is assumed to be instantaneous, then the complex processes associated with flow and transport through the unsaturated zone would not need to be modeled. Such an approach would be appropriate at sites that are relatively small and where the extent of the contamination is well defined. Under these conditions, the remedy is likely to be removal of the contaminated surface and near-surface material. Many of the SDMP sites and several of the non-defense NPL sites exhibit such conditions. In these cases, the use of conservative screening models may be sufficient to support remedial decision-making throughout the remedial process.

3.4.1 Sub-Regional Scale Characteristics

At more complex sites, such as many of the defense facilities on the NPL, the remedial process is generally structured so that, as the investigation proceeds, additional data become available to support ground-water modeling. An understanding of the physical system, at least at a sub-regional scale, may allow an early determination of the types of models that may be appropriate for use at the site. Specifically, the following site characteristics may have to be extrapolated from regional-scale information, and will, in part, determine the types and complexity of models required:

- Approximate depth to ground water - A thick unsaturated zone suggests the need for complex models.
- Lithology of the underlying rocks (e.g., limestone, basalt, shale) - Layered, fractured, or heterogenous lithology suggests the need for complex models.
- Presence of surface water bodies - The presence of water bodies on or in the vicinity of the site suggests the need for complex models.
- Land surface topography - Irregular topography suggests the need for complex models.

- Sub-regional recharge and discharge areas may indicate the need for complex models.

- Processes or conditions that vary significantly in time may require complex models.

The NPL sites are distributed more or less randomly across the 48 contiguous United States. However, the SDMP sites are almost all concentrated in the Northeast. The geographic location of the various sites provides some early clues as to the level of sophistication of any required ground-water modeling.

Depth to Ground Water

Sites located in the arid west and southwest (e.g., Pantex, Hanford, and INEL) generally have greater depths to ground water. The simulation of flow and transport through the unsaturated zone may require more complex computer codes due to the non-linearity of the governing equations. Modeling of the unsaturated zone is further hampered because the necessary data are often difficult to obtain.

Sub-Regional Lithology

The lithology of the underlying rocks also provides insight into the expected level of difficulty of modeling. A number of the NPL sites described in Appendix B overlie areas where fractures are probably dominant mechanisms for flow and transport. These sites include Hanford, the Idaho National Engineering Laboratory (INEL), Maxey Flats, Jacksonville, and Pensacola Air Stations. In some cases, such as at Hanford, the fractured zone is deep below the site, and concerns regarding ground-water contamination are limited primarily to the near-surface sedimentary rock.

It is unlikely that analytical models could be used to describe adequately flow and transport in the fractured systems because radionuclide transport and ground-water flow in fractured media are much more complex than in unfractured, granular porous media. This is because of the extreme heterogeneities, as well as anisotropies, in the fractured systems.

Surface Water Bodies

Virtually all of the NPL sites and many of the SDMP sites have surface water bodies at or in the immediate vicinity of the site. Bodies of water often have a significant impact on the ground-water flow and cannot be neglected in the modeling analysis. In general, analytical models are limited in their ability to simulate properly the effect that surface water bodies have on contaminant flow and transport, particularly if the surface water body behaves episodically, such as tidal or wetland areas. Several of the NPL sites are indurated with wetlands, including Oak Ridge, Himco, and Shpack Landfill. At least two sites, Pensacola and Jacksonville, are close to estuaries, which suggests that tidal as well as density-dependent flow and transport may be significant.

Sub-Regional Topography

The land surface topography is often overlooked in the preliminary identification of potential modeling needs but may be an important factor in evaluating the need for, and complexity of, ground-water modeling. Topography may have a significant influence on ground-water flow patterns. For instance, Maxey Flats is situated atop a relatively steep-sided plateau with a stream situated at the bottom of the slope. The steep topography strongly controls the direction of ground-water flow, making it much more predictable. Furthermore, estimating the flux of ground water moving into the system from upgradient sources becomes much simpler if the area of interest is a local recharge area, such as a hill or mountain. Steep topography can also complicate the modeling by making it more difficult to simulate hydraulic heads that are representative of the hydrologic units of interest. To solve this problem, some computer codes have an option to use curvilinear elements.

Regional Recharge/Discharge

The ground-water flow paths will largely be controlled by regional and sub-regional ground-water recharge and discharge areas. It is generally necessary to ensure that the flow and transport simulated by the model on a local scale is consistent with the sub-regional and regional scale. If the site is located in an aquifer recharge area, the potential for widespread aquifer contamination is significantly increased, and reliable modeling is essential.

3.4.2 Detailed Hydrogeological Characteristics of the Site

Detailed knowledge pertaining to the hydrogeology of the site will generally become available during site characterization. Ground-water systems can be grouped into several broad categories. Each category has an associated set of data needed to support ground-water modeling and to determine modeling complexity. These broad classifications are:

- Saturated versus unsaturated systems
- Porous media versus fractured systems
- Complex versus simple hydrologic boundary conditions

In general, sites with relatively simple hydrogeological characteristics pertaining to these parameters may be reliably modeled with relatively simple analytical models.

Unsaturated Zone Properties

The following characteristics of the unsaturated zone determine, in part, whether the unsaturated zone will need to be explicitly modeled. These are also the site-specific parameters required to model transport through the unsaturated zone.

- Recharge through the unsaturated zone (infiltration)
- Thickness and geometry of the unsaturated zone
- Magnitude and distribution of the saturated hydraulic conductivity
- Matric potential and distribution at various soil moisture contents
- Delineation of discrete features
- Degree of isotropy
- Degree of homogeneity
- Distribution coefficients
- Bulk density

- Boundary conditions
- Porosity
- Dispersivity
- Vapor phase transport effects

The sophistication of the unsaturated zone modeling approach will be based not only on the complexity of the hydrogeology but also on the overall modeling objectives. For instance, radionuclide flow and transport through a very thick unsaturated zone may be irrelevant if credit is not taken for it in the baseline risk assessment. On the other hand, if the risk assessment is based solely upon arrival times and peak concentrations of radionuclides arriving at the ground-water table, then consideration of transport through even a thin unsaturated zone is significant.

Situations may arise where reliable simulations of flow and transport of radionuclides through the unsaturated zone may not be possible even with complex ground-water models. In particular, if the unsaturated zone is indurated with fractures or macropores with high permeability, the flow and transport processes become so involved that mathematical formulations of porous media transport are poor representations of the physical phenomena. Furthermore, localized zones of higher permeability may cause the wetting front to advance at highly variable rates, which may introduce significant disparities between the actual and predicted contaminant concentrations. It is also difficult to model saturated zones that are "perched" above fine-grained sediments within the unsaturated zone. These perched-water zones may have a significant impact on the flow and transport of radionuclides.

<u>Saturated Zone Properties</u>

The most frequently performed ground-water modeling is that of the saturated zone. The parameter needs are well defined, and the field data collection activities are relatively straightforward. The characteristics of the site that determine the complexity of saturated zone modeling (and also the site-specific data required to perform saturated zone modeling) include:

- Geometry of the hydrogeologic units
- Specific storage
- Magnitude and distribution of hydraulic conductivity
- Vertical and horizontal hydraulic gradients
- Degree of isotropy
- Degree of homogeneity
- Dispersivity
- Distribution coefficients
- Bulk density
- Diffusion properties
- Effective porosity
- Boundary conditions

Three major hydrogeological factors that provide immediate insight into whether complex ground-water modeling will be necessary are: the transient nature of the flow system; the complexity of the dominant flow and transport processes; and the heterogeneity and anisotropy of the hydrostratigraphic units.

A transient flow system simply means one that fluctuates with time. This fluctuation may be induced by both natural (e.g., tides, rainfall) and manmade influences (e.g., wells, dams). In many instances, transient systems, if observed over the long term, will approach relatively steady-state conditions. If this is the case, it may be possible to undertake a simple modeling approach even with a transient flow system.

Analytical models do not generally account for many of the more complex flow and transport processes that may be occurring. For example, if it is necessary to model multi-phase fluid conditions in order to accomplish the modeling objectives, a more complex modeling approach will be needed.

Hydrogeologic systems that are heterogeneous and/or anisotropic are often associated with complicated flow patterns. Analytical models generally do not allow for the incorporation of varying rock properties. Therefore, heterogeneous conditions are generally simulated with numerical rather than analytical models.

Fracture Zone Properties

A number of the NPL sites described in Appendix B overlie areas where fractures and solution channels are probably dominant mechanisms for flow and transport. These sites include INEL, Maxey Flats, Jacksonville, and Pensacola Air Stations. The uncertainty associated with fracture zone modeling is generally high, and much effort needs to go into the field investigation. The data needs associated with fracture properties to support flow and transport modeling include:

- Aperture
- Porosity
- Orientation
- Length
- Density
- Connectivity
- Roughness coefficient
- Matrix diffusion coefficient
- Effective surface area
- Fracture mineralization

It is unlikely that analytical models could adequately describe flow and transport in most fractured systems because radionuclide transport and ground-water flow in fractured media are much more complex than in unfractured granular porous media. This is due to the extreme heterogeneities, as well as anisotropies, in the fractured systems.

Boundary Conditions

Physical features within the modeled area will be translated into numerical terms as boundary conditions for the ground-water modeling. The following features most commonly constitute boundary conditions and need to be identified and characterized in order to determine the types and level of complexity of ground-water flow and transport models required at a site:

- Surface water bodies
- Ground-water divides
- Fractures and faults
- Areal recharge
- Geologic contacts
- Freshwater-saltwater interface
- Waste source characteristics
- Wells (injection and withdrawal)

Some physical characteristics are more difficult than others to incorporate as boundary conditions into a model and, therefore, will necessitate a more complex modeling approach. In general, flow processes dominated by boundary conditions that are transient in time and/or associated with discrete features (e.g., faults) will require a more complex modeling approach.

3.5 THE PHASE OF THE REMEDIAL PROCESS

The reasons for modeling and the types and complexity of the models required to support remedial decision-making will change as the project matures from scoping and planning (Phase 1), to more detailed site characterization (Phase 2), to remedy selection and implementation (Phase 3). In general, the complexity of modeling will increase as the remedial process proceeds from Phase 1 to Phase 3.

3.5.1 Phase 1 - Planning and Scoping

During Phase 1 (the scoping and planning phase), only limited site-specific data are generally available. Accordingly, modeling during the scoping phase is generally limited to simple one-dimensional or analytical models even if the characteristics of the waste and the site indicate that more complex models may eventually be needed. As a result, modeling in Phase 1 generally consists of screening-level calculations that tend to bound the potential impacts associated with the site and simulate flow and transport using simplifying, conservative assumptions.

3.5.2 Phase 2 - Site Characterization

Phase 2 of the remedial process (the site characterization phase) is designed to characterize the nature and extent of the contamination and the potential risks posed by the site. As indicated in Table 3-2, most of the reasons for modeling present themselves during Phase 2. A properly designed and implemented site characterization program will generate the detailed site-specific information necessary to perform the modeling required to meet the modeling objectives.

Table 3-3 focuses on the various ground-water flow and transport processes at a site that will, in part, determine whether simple or complex models will be needed during Phase 2 of the remedial process. In general, simple models may be adequate under the following combination of conditions: (1) credit is not taken for the waste form or engineered barriers (i.e., it is assumed that the waste is being transported by simple leaching processes), (2) no credit is taken for transport through the unsaturated zone (i.e., it is assumed that the leachate percolates directly into the saturated zone), and (3) the saturated zone is treated as a homogeneous, isotropic medium. Any other assumptions regarding the behavior of the waste or site conditions will likely necessitate the use of more complex models. Additional discussion of the various processes is provided in Sections 3.3 and 3.4, which address how the characteristics of the waste and the characteristics of the site affect modeling needs.

Table 3-3. Ground-water Flow and Transport Processes that May Need to be Modeled and Site-specific Information Needed to Identify the Processes to be Modeled

•	Leach rate of radionuclides - Structural integrity of the source of the waste (i.e., waste form, container, package) - Composition and thickness of the source of the waste - Geochemical environment surrounding the waste - Areal extent and geometry of the waste source - Inventories
•	Transport through the unsaturated zone - Recharge through the unsaturated zone - Thickness of the unsaturated zone - Moisture release curve parameters - Saturated hydraulic conductivity - Matric potential - Soil moisture content - Delineation of discrete features - Degree of isotropy - Degree of homogeneity - Distribution coefficients - Bulk density - Vapor phase transport effects - Porosity
•	Transport through the saturated zone - Geometry of the hydrogeologic units - Specific storage - Hydraulic conductivity - Vertical and horizontal hydraulic gradients - Degree of isotropy - Degree of homogeneity - Dispersivity - Distribution coefficients - Bulk density - Matrix diffusion properties - Effective porosity
•	Fractured media transport - Aperture - Porosity - Orientation - Length - Density - Connectivity - Roughness coefficient - Matrix diffusion coefficients
•	Simple hydrologic boundary conditions

Table 3-3 (Continued)

•	Complex hydrologic boundary conditions - Surface water bodies - Ground-water divides - Fractures and faults - Non-uniform areal recharge - Geologic contacts - Freshwater-saltwater interface
•	Radioactive decay and ingrowth of daughters - Radioisotopes present - Half-life

3.5.3 Phase 3 - Remediation

As the site characterization process proceeds, data are acquired that will help in identifying feasible remedial alternatives. These data, in combination with models, are used to simulate the flow and transport of the radionuclides with and without the feasible alternative remedies. The data and models are used to predict the behavior of the radionuclides and thereby aid in the selection and design of the remedy. The models also help to demonstrate that the selected remedy will achieve the remedial goals.

Each remedial alternative has costs and benefits that must be carefully weighed before a specific remedy or set of remedies is selected and implemented. The benefit of a given remedy is the reduction or elimination of the risks estimated in the risk assessments performed during the site characterization phase. The costs of a given remedy include: (1) the short- and long-term economic costs, (2) the public health impacts on the remediation workers and general public associated with implementing the remedy, and (3) the public health impacts associated with any residual contamination and modifications to the environment associated with the remedy. The various remedial alternatives can be conveniently grouped into the following three categories:

- Immobilization
- Isolation (Containment)
- Removal/Destruction

This section briefly describes each category and the modeling needs that may be associated with each category. In general, most remedies require complex models to support their design and implementation and predict their performance.

Immobilization

Immobilization of the radioactive wastes refers to processes whereby physical or chemical means are used to stabilize the radionuclides and preclude their transport. Biological remedies are not addressed since they are employed primarily to degrade organic contaminants and have limited applicability to sites contaminated with radioactive materials.[1]

The various physical and chemical treatment processes available for relatively long-term immobilization can be grouped as follows:

- Physical
    - water vapor extraction
    - in-situ coating
    - grouting of fissures and pores
    - in-situ vitrification

- Chemical
    - induce secondary mineralization
    - induce complexation
    - alter oxidation-reduction potential

- Physical/Chemical
    - alter surface tension relationships
    - alter surface charges
    - in-situ binding
    - adsorbent injection
    - radionuclide particle size augmentation through clay flocculation

The following are the types of physical and chemical processes that may need to be modeled to support the selection and design of alternative immobilization remedies:

[1] The use of microbes to help stabilize Sr-90 and uranium in waste ponds at Oak Ridge is one exception to this. Another is the use of jimson weed at Los Alamos National Laboratory for the uptake of plutonium in soil.

- Physical Properties and Processes
    - unsaturated zone flow and transport
    - heat energy transfer
    - multiple layers
    - vapor transport
    - density-dependent flow and transport
    - extreme heterogeneity
    - temperature-dependent flow and transport

- Chemical Properties and Processes
    - oxidation-reduction reactions
    - system thermodynamics
    - chemical speciation
    - ion exchange phenomena
    - precipitation
    - natural colloidal formation
    - radiolysis
    - organic complexation
    - anion exclusion

It would be ideal if conventional and available models could reliably describe and model these processes and properties. However, many of these properties and processes are not well understood, and models do not exist that reliably simulate them. Accordingly, treatability studies, as discussed in OSWER Directive 9355.3-01, may be the only reliable method for assessing the performance of a remedy based on immobilization.

The results of the treatability studies can be used to determine aggregate modeling parameters, such as the leach rates of waste stabilized in-situ. These empirically determined parameters can then be used as input to simple or complex ground-water flow and transport models, depending on the other factors discussed above.

Isolation

A common remedial alternative is to emplace protective barriers either to prevent contaminated ground water from migrating away from a contaminated site or to divert incoming (i.e., clean) ground water from the source of contaminants. Several types of materials are being used to construct such barriers, including soil and bentonite, cement and bentonite, concrete, and sheet piling. Examples of potential barriers include the following:

- Physical
  - cutoff curtains, sheet piling, slurry walls
  - covers
  - hydraulic control wells or trenches (injection and/or extraction)

- Chemical
  - ion-exchange barriers

If properly designed and emplaced, such barriers can last for several decades, barring geological disturbances such as tremors, ground settling, significant changes in hydraulic gradients, etc. Accordingly, such barriers can be useful in mitigating the impacts of relatively short-lived radionuclides, or in controlling the migration of long-lived radionuclides until a more permanent remedy can be implemented.

Several mechanisms or processes can affect the long-term integrity of such barriers. Once the installation is complete, cracking, hydrofracturing, tunnelling and piping, and chemical disruption can cause failures. Changes in the site's geological or hydrological characteristics can also lead to catastrophic failures, such as partial collapse, settling, and breaking. If a barrier should fail following installation, water may infiltrate or exfiltrate the site, and contaminated leachate may move beyond the site. This type of failure could result in the dispersion of contaminants in the environment. The risk assessment performed in support of this category of remedial alternative should include an evaluation of the range of radionuclide concentrations in down-gradient wells following such an accident and the associated doses and risks to well users.

The following are the types of physical, chemical, and biological processes that may need to be modeled to support the isolation alternative.

- Physical Properties and Processes
  - unsaturated zone flow and transport
  - runoff
  - transport through multiple layers
  - vegetative cover
  - transient source term
  - extreme heterogeneity
  - areal recharge and zero flux capability

- Chemical Properties and Processes
    - localized ion exchange phenomena
    - oxidation-reduction

Attempts at modeling these processes will have varying degrees of success. Like immobilization techniques, many of these properties and processes are not well understood, especially over the long term, and models do not exist that reliably simulate these processes and properties. Accordingly, prior experience with each remedy, engineering judgment, and conservative design are the principal means for assessing and assuring the performance of an isolation remedy.

The design criteria, such as the hold-up time of barriers and the life expectancy of a barrier, can be used to determine, in part, the transit time to ground-water user locations. These design criteria can then be used as input to simple or complex models appropriate for the site.

Removal

The technologies most commonly used to remove solid, liquid, and vapor (e.g., tritium) radionuclides include:

- soil excavation
- in-situ vaporization
- pump and treat
- soil washing

The following are the types of physical and chemical processes that may need to be modeled to support alternative removal remedies. Most of these processes and properties are readily described in mathematical terms and can be modeled relatively reliably.

- transient source term
- unsaturated and saturated zone flow and transport
- matrix diffusion

- desaturation and resaturation of the aquifer
- vapor transport
- sorption
- mixing
- dilution

The removal alternative is probably the only truly permanent alternative for long-lived radioactive contaminants. However, it is also generally the most expensive. Accordingly, modeling, though expensive and time consuming, can be highly cost-effective if it can convincingly demonstrate that remedies other than removal can be protective of human health and the environment.

3.6 LAND USE AND DEMOGRAPHY

At sites where the ground water is currently being used or may be used in the future as a municipal water supply, complex ground-water models may be needed to gain insight into the plume arrival times and geometries. At sites with multiple user locations, two- and three-dimensional models may be needed to realistically estimate the likelihood that the contaminated plume will be captured by the wells located at different directions, distances, and depths relative to the sources of contamination.

Simple models are typically limited to estimating the radionuclide concentration in the plume centerline. Accordingly, if it is assumed that the receptors are located at the plume centerline, a simple model may be appropriate. Such an assumption is often made even if a receptor isn't currently present at the centerline location because the results are generally conservative. In addition, risk assessments often postulate that a receptor could be located directly down-gradient of the source at some time in the future.

The need for complex models increases if there are a number of municipal water supplies in the vicinity of the source. Under these circumstances, it may be necessary to calculate the cumulative population doses and risks, which require modeling the radionuclide concentrations at a number of specific receptor locations. Accordingly, off-centerline dispersion modeling may be needed.

4. Summary and Conclusions

The EPA Offices of Radiation and Indoor Air (ORIA) and Solid Waste and Emergency Response (OSWER), the DOE Office of Environmental Restoration and Waste Management (EM), and the NRC Office of Nuclear Material Safety and Safeguards (ONMSS) have established an interagency agreement for promoting the appropriate and consistent use of mathematical models in the remediation and restoration process at sites containing, or contaminated with, radioactive materials. This report, which is one of a series of reports prepared under the agreement, specifically addresses the role of, and need for, modeling in support of remedial decision-making. Though the report addresses all pathways, the emphasis is placed on ground-water flow and transport modeling. Other reports in this series will address the selection and application of ground-water models and the evaluation of multimedia models.

This report and the other reports in the series are intended to be used by the Remedial Project Manager (RPM) at National Priorities List (NPL) sites or the equivalent at non-NPL sites containing radioactive materials. They are also intended to be used by geologists and geoscientists responsible for identifying and implementing ground-water flow and transport models at such sites.

This report describes modeling in each of the phases of the remedial process; from scoping and planning, to site characterization and risk assessment, to the selection and implementation of remedial alternatives. The report attempts to address questions regarding why modeling is needed, when it is needed, and when it is not needed. In addition, the report describes when simple versus more complex models may be needed to support remedial decision-making.

Modeling needs are described in terms of the following five interrelated factors:

1. reasons for modeling,
2. waste characteristics,
3. site environmental characteristics,
4. site land use and demography, and
5. phase of the remedial process.

The principal reasons for modeling include: (1) the performance of risk assessments and the evaluation of compliance with applicable health and safety regulations, (2) the design of environmental measurements programs, and (3) the identification, selection, and design of remedial alternatives. Each of these reasons for modeling influences modeling needs and model selection differently.

Risk assessments can be performed with relatively simple models for site screening or may require more advanced models when attempting to quantify risks at particular locations and points in time. The selection of the optimum sampling locations and the identification and design of remedies often require the use of complex 2- and 3-dimensional models to achieve the above objectives. Current regulations and guidelines, which are summarized in Appendix A, do not explicitly require modeling. However, if used appropriately, modeling can be useful in support of remedial decision-making in all phases of the remedial process.

A review of the physical, chemical, and radiological properties of the waste at a number of remedial sites, which are described in Appendix B, reveals that the waste characteristics can be diverse. At sites currently undergoing or scheduled for remediation, over 30 different types of radionuclides have been identified, each with its own radiological and chemical properties. The waste is found in a variety of settings, including contaminated soil, in ponds, in storage piles and landfills, buried in trenches, and in tanks and drums. Each of these settings influences the areal distribution of the contaminants and rate at which they may leach into the underlying aquifer, which, in turn, influences modeling needs.

In a similar manner, the environmental characteristics of remedial sites are highly diverse. The sites containing radioactive materials that are currently undergoing remediation include both humid and dry sites, sites with and without an extensive unsaturated zone, and sites with simple and complex hydrogeological characteristics. These different environmental settings determine the processes that need to be modeled, which, in turn, influence modeling needs.

The land use and demographic patterns at a site, especially the location and extent of ground-water use, affects the types and complexity of the models required to assess the potential impacts of the site on public health. At many of the sites contaminated with radioactive materials, the principal concern is the use of the ground water by present or future residents located close to, and downgradient from, the source of contamination. At other sites, the concern is the use of municipal wells located at some distance and in a variety of directions from the source. Each of these usage patterns influences modeling needs.

Superimposed on these waste and site related issues is the different modeling needs associated with the various phases of the remedial process. The phase of the remedial process from scoping and planning, to site characterization, to remediation, creates widely different opportunities for modeling, which, together with the other factors, influences modeling needs.

Finally, the report also emphasizes that modeling is not always needed or appropriate to support remedial decision-making. If a site is poorly characterized or poorly understood, any simulation of the transport and impacts of contaminants using mathematical models is speculative at best and could be highly misleading. Accordingly, the use of models under such circumstances is limited with regard to the types of decisions they can help to support.

In summary, models are data analysis tools which can be useful in supporting decisions, but are not substitutes for data acquisition and expert judgement. Models should not be used until the specific objectives of the modeling exercise are defined and the limitations of the models fully appreciated. Notwithstanding the limitations of models, it can be concluded that it is difficult to support remedial decisions or the assessment of risks at a site without the use of models.

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APPENDIX A

REGULATORY REQUIREMENTS AND GUIDELINES PERTAINING TO FATE AND EFFECTS MODELING

REGULATORY REQUIREMENTS AND GUIDELINES PERTAINING TO FATE AND EFFECTS MODELING

This appendix summarizes the RCRA/CERCLA requirements and guidelines, DOE Orders, and NRC programs and guidelines that establish the regulatory framework pertinent to fate and effects modeling. Like Section 2, this appendix describes the role of, and need for, modeling; however, the discussion is presented within the context of specific regulations and programs concerned with the remediation of sites contaminated with radioactive material. The summary reveals that though current regulations and guidelines pertaining to site remediation do not explicitly require fate and effects modeling, modeling is needed to support informed decision-making pertinent to site remediation.

A.1 RCRA/CERCLA

Table A-1 presents the overall structure of the RCRA and CERCLA process. This section describes the role of fate and effects modeling in fulfilling the RCRA/CERCLA regulatory requirements.

Fate and effects modeling is not explicitly required by CERCLA or RCRA. However, in many cases, in order to meet CERCLA and RCRA requirements for risk assessments and in support of remedial decision-making, fate and effects modeling is useful. It can be valuable in each of the following phases of the remedial process:

- The scoping and planning phase of the Remedial Investigation/RCRA Facility Investigation (RI/RFI). This early phase of the RI/RFI process is equivalent to the generic Phase 1 defined in Section 2.

- The site characterization phase, including the performance of the baseline risk assessment, of the RI/RFI. This phase of the RI/RFI process is equivalent to the generic Phase 2 defined in Section 2.

- The Feasibility Study/Corrective Measures Assessment (FS/CMA) and remedial implementation phases of the remedial process. These phases of the RCRA/CERCLA processes are equivalent to the generic Phase 3 defined in Section 2.

The following sections describe the RCRA/CERCLA regulations and existing and developing guidelines that effectively require or create opportunities for modeling during each phase of the remedial process.

TABLE A-1*

COMPARISON OF THE RCRA CORRECTIVE ACTION PROCESS AND THE CERCLA RESPONSE PROGRAM

RCRA	CERCLA
RCRA Facility Assessment	CERCLA Preliminary Assessment/Site Inspection (Site Assessment Process)
Performed to identify and gather information on releases at RCRA facilities, make preliminary determinations regarding releases of concern and identify the need for further actions and interim measures at the facility. Performed in three phases: 1) Preliminary Review, 2) Visual Site Inspection, and 3) Sampling Visit (if necessary).	Performed to gather initial information on identified sites in order to complete the Hazard Ranking System to determine whether removal (emergency) actions are required. The Preliminary Assessment and the Site Inspection are performed in two phases and may or may not involve sampling.
RCRA Facility Investigation	CERCLA Remedial Investigation
Defines the presence, magnitude, extent, direction and rate of movement of any hazardous wastes and hazardous constituents within and beyond the facility boundary. The scope is to: a) characterize the potential pathways of contaminant migration, b) characterize the source(s) of contamination, c) define the degree and extent of contamination, d) identify actual or potential receptors, and e) support the development of alternatives from which a corrective measure will be selected by the EPA. The RFI is performed in seven tasks: 1) Description of current conditions 2) Identification of preliminary remedial measures technologies 3) RFI workplan requirements - project management plan - data collection quality assurance plan - data management plan - health and safety plan - community relations plan 4) Facility investigation 5) Investigation analysis 6) Laboratory and bench-scale studies 7) Reports	Performed to characterize the extent and character of release of contaminants. The RI is the mechanism for collecting data to characterize site conditions; determine the nature of the waste; assess risk to human health and the environment; and conduct treatability testing as necessary to evaluate the potential performance and cost of the treatment technologies that are being considered. Although EPA guidance presents a combined RI/FS Model Statement of Work, the RI is generally considered to be performed in seven tasks: 1) Project planning (scoping) - summary of site location - history and nature of problem - history of regulatory and response actions - preliminary site boundary - development of site operations plans 2) Field investigations 3) Sample/analysis validation 4) Data evaluation 5) Assessment of risks 6) Treatability study/pilot testing 7) RI reporting

TABLE A-1 CONTINUED

COMPARISON OF THE RCRA CORRECTIVE ACTION PROCESS
AND THE CERCLA RESPONSE PROGRAM

RCRA

Corrective Measures Study

The purpose of the CMS is to identify, develop, and evaluate potentially applicable corrective measure(s) and to recommend the corrective measure(s) to be taken. The CMS is performed following an RFI and consists of the following four tasks:

1) Identification and development of the corrective measures alternative(s)
2) Evaluation of the corrective measure alternative(s)
3) Justification and recommendations of the corrective measures alternative(s)
4) Reports

Corrective Measures Implementation

The purpose of the CMI is to design, construct, operate, maintain and monitor the performance of the corrective measures selected. The CMI consists of four activities:

1) Corrective Measure Implementation Program Plan
2) Corrective Measure Design, including
   - design plans and specifications
   - operation and maintenance plan
   - cost estimate
   - schedule
   - construction Quality/Assurance Objectives
   - health and safety plan
   - design phases
3) Corrective Measures Construction (including the preparation of a Construction Quality Assurance Program)
4) Reporting

CERCLA

CERCLA Feasibility Study

The FS serves as the mechanism for the development, screening, and detailed evaluation of alternative remedial actions. As noted above, the RI and the FS are intended to be performed concurrently; however, the FS is generally considered to be composed of four general tasks:

1) Remedial alternatives development and screening
2) Detailed analysis of alternatives
3) Community relations
4) FS reporting

CERCLA Remedial Design/Remedial Action

This activity includes the development of the actual design of the selected remedy and implementation of the remedy through construction. A period of operation and maintenance may follow the RA activities. Generally, this aspect of CERCLA response includes:

1) Plans and specifications, including:
   - preliminary design
   - intermediate design
   - prefinal/final design
   - estimated cost
   - correlation of Plans and Specifications
   - selection of appropriate RCRA facilities
   - compliance with requirements of other environmental laws
   - equipment startup and operator training
2) Additional studies
3) Operation and maintenance plan
4) Quality assurance project plan
5) Site safety plan
6) A/E services during construction

* The authors would like to thank Roy F. Weston, Inc. for providing this comparison overview of RCRA and CERCLA requirements.

A.1.1 The National Contingency Plan

The 1990 National Contingency Plan (NCP) (55 Fed. Reg. 8665 - 8865, March 8, 1990) calls for a site-specific baseline risk assessment to be conducted, as appropriate, as part of the remedial investigation [Section 300.430(d)(1)]. Specifically, the NCP states that the baseline risk assessment should "characterize the current and potential threats to human health and the environment that may be posed by contaminants migrating to ground water or surface water, releasing to air, leaching through soil, remaining in the soil, and bioaccumulating in the food chain" [Section 300.430(d)(4)]. The primary purpose of the baseline risk assessment is to provide risk managers with an understanding of the actual and potential risks to human health and the environment posed by the site and any uncertainties associated with the assessment. This information may be useful in determining whether a current or potential threat to human health or the environment exists that warrants remedial action.

In order to satisfy CERCLA requirements regarding the performance of a baseline risk assessment, environmental measurements programs are performed to determine the nature and extent of the contamination in the vicinity of the site. Based on these measurements and other demographic, land use, and environmental data, the actual or potential human health and environmental impacts attributable to the contaminants are assessed. However, environmental measurements alone are not always sufficient to support the performance of a baseline risk assessment because the number and types of samples can be representative only of a limited area in the vicinity of the site. In addition, environmental measurements are sometimes of little use in characterizing past and future conditions at the site and how the conditions at the site may change due to changing environmental conditions, such as severe weather and seasonal weather changes. There may also be questions about data quality and representativeness. Because of these inherent limitations in environmental measurements data, fate and effects modeling is used to supplement field measurements in the performance of baseline risk assessments.

A.1.2 Remedial Investigation (RI)/Feasibility Study (FS) Guidance

As applied to fate and effects modeling, RI/FS guidance can be conveniently discussed from two separate perspectives. The first is RI/FS guidance as it applies to baseline risk assessments and evaluating compliance with ARARs. The second is RI/FS guidance that, though not directly related to modeling, creates opportunities for modeling.

<u>Guidance Pertaining to the Performance of Baseline Risk Assessments and the Assessment of Compliance with Site Specific ARARs</u>

"Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA" (EPA/540/G-89/004, October 1988) describes how the baseline risk assessment fits into the overall RI/FS process. As indicated in the guideline "...the baseline risk assessments provide an evaluation of the potential threat to human health and the environment in the absence of any remedial action. They provide the basis for determining whether or not remedial action is necessary and the justification for performing remedial actions." The guideline also addresses the role of, and need for, fate and effects modeling in evaluating risks and refers to other guidelines describing methods acceptable to the Agency for performing risk assessments.

"Superfund Exposure Assessment Manual" (EPA/540/1-88/001, April 1988) provides the RPMs with the guidance necessary to conduct exposure assessments that meet the needs of the Superfund human health evaluation process. Specifically, the manual "(1) provides an overall description of the integrated exposure assessment process as it applies to uncontrolled hazardous waste sites; and (2) serves as a source of reference concerning the use of estimation procedures and computer modeling techniques for the analysis of uncontrolled sites." The manual includes an overview of air, surface water, and ground-water modeling.

"CERCLA Compliance with Other Laws Manual" (EPA/540/G-89/006, August 1988, referred to as the Other Laws Manual) presents guidance on identifying Applicable or Relevant and Appropriate Regulations (ARARs) that may be used to determine if remedial activities are warranted and for establishing remedial goals. Section 5 of the Other Laws Manual presents a list of potential ARARs for sites contaminated with radioactive materials.

Inspection of the Other Laws Manual and other more recent EPA guidelines pertaining to ARARs (EPA 91, EPA 91a,b) reveals that the ARARs for a site contaminated with radioactive material can be expressed in terms of radionuclide concentrations in water supplies (i.e., pCi/L), radionuclide concentrations in soil (pCi/g), and radiation dose (mrem/yr). Accordingly, field measurements programs and fate and effects models must provide results that have meaning in terms of the media, pathways, and units delineated in the ARARs.

As part of the RI/FS process for the Maxey Flats Disposal Site (MFDS), the EPA defined specific ARARs for radioactivity and required that the baseline risk assessment be performed without taking credit for institutional controls. This requirement effectively defined the types of exposure scenarios, and therefore the types of pathway models, required to evaluate compliance with the ARARs. Specifically, the EPA required that the radiation doses and risks be determined for a broad range of exposure scenarios, including the various intruder and offsite exposure scenarios described in Section 2 (EPA 91d). Although these guidelines apply specifically to the MFDS, they help to establish a regulatory precedent that may apply to other sites contaminated with radioactive material and thereby establish modeling needs.

The "Risk Assessment Guidance for Superfund: Volume I, Human Health Evaluation Manual - Part A" (HHEM) (EPA/540/1-89/002) provides guidance on how to conduct the human health portion of the baseline risk assessment. A separate chapter specifically addresses radiological risk assessment. Part B of this guideline presents methods acceptable to the Agency for establishing remediation goals (EPA 91b). Specific calculational methodologies (i.e., models), along with default assumptions and calculational parameters, are provided for determining remediation goals in terms of contaminant concentrations in specific media.

Volume II of the "Risk Assessment Guidance for Superfund," the "Environmental Evaluation Manual" (EPA/540/1-89/001), and the companion manual "Ecological Assessment of Hazardous Waste Sites: A Field and Laboratory Reference" (EPA/600/3-89/013) provide guidance on conducting the environmental portion of the baseline risk assessment. Other pertinent guidance includes the "Guidance on Preparing Superfund Decision Documents" (ROD guidance) (EPA/624/1-87/001), which provides information on how to document the results of the baseline risk assessment in the ROD.

These documents establish the basic regulatory structure pertaining to the performance of risk assessment in support of remedial decision-making. However, the guidelines are continually being supplemented and refined. For example, additional guidance has been established which further defines cleanup criteria and the assumptions that should be used to perform risk assessments. OSWER Directive 9355.0-03, "Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions," April 1991, presents additional numerical criteria for identifying the risks that warrant remedial action and the criteria to be used in establishing remediation goals. This document effectively supplements the "Other Laws Manual." OSWER Directive 9285.6-03, "Risk Assessment Guidance for Superfund: Volume I, Human Health Evaluation Manual Supplemental Guidance Standard Default Exposure Factors," March 25, 1991, defines the current and future exposure scenarios that should be used to perform risk assessments.

These documents require the performance of risk assessment throughout the remedial process, and define methods generally acceptable to the Agency for performing risk assessments.

Other Opportunities for Modeling

A review of the EPA guidance reveals that, in addition to the obvious need for fate and effects modeling in support of the baseline risk assessment, the RI/FS process offers numerous other opportunities for modeling. Ultimately, all of these opportunities for modeling pertain to the assessment and management of risk. However, throughout the remedial process, specific decisions need to be made in accordance with RI/FS guidance. This section provides an overview of the role of modeling in support of these decisions.

During the early stages of the remedial process, fate and effects modeling may be used to support decisions to implement a time-critical removal action (53 FR 51109, December 21, 1988). Such a decision is appropriately based on environmental measurements or observations. However, if the hazardous material has not yet reached receptor locations, but fate and effects models reveal that the contaminants can reach receptors in the near future, a time-critical response may be appropriate.

During the scoping phase of the RI/FS process, fate and effects modeling may be appropriate as part of the development of the conceptual model of the site and the development of the site characterization plan, both of which are required by EPA/540/1-89/002 (EPA 89b). Preliminary fate and effects modeling will help to identify the critical pathways of exposure and thereby help to define sample types, sample locations, and analytical techniques; i.e., data needs. Data needed to perform more reliable modeling in subsequent phases of the remedial process will also be identified.

At sites with multiple operable units, modeling can be used during planning to establish priorities and determine the potential significance of hydrogeologic connections between adjacent operable units.

Near-field modeling can be used in the preparation of the site health and safety plan by predicting worker exposures associated with intrusive sampling. Models can be used to support health and safety decisions regarding the use of protective clothing, personnel dosimetry, bioassay, and field instrumentation and monitoring for the protection of workers.

During the scoping and site characterization phases of the remedial process, ground-water flow and transport modeling can be used to identify the sources of the contamination observed in an aquifer. Such a modeling need could arise at a site where contamination of an aquifer is observed, but the source of the contamination is unknown or uncertain.

During site characterization, as data are acquired, modeling can be used to refine, in an iterative manner, the design of the field investigation programs. For example, modeling can be used to determine the optimum location of monitor wells for intercepting the plume. Conversely, modeling can be used to justify the elimination of unnecessary monitoring locations and thereby help to control the costs of site characterization.

During the later stages of the remedial process, fate and effects models can be used to identify feasible remedial alternatives and define the performance criteria for alternative remedies required to ensure that the remedial goals are achieved. For example, in-situ remedies based on engineered barriers may be appropriate at sites with relatively short-lived radionuclides. At such sites, models can be used to predict radionuclide concentrations at receptor locations using alternative barrier designs. In a related manner, acceptance criteria for treatability studies can be determined by using fate and effects models. For example, models can be used to define the pump and treat decontamination factors required to ensure that remediation goals at receptor locations are achieved.

Models are also used to predict the impacts on workers, the public, and the environment associated with alternative remedies. For example, excavation can result in the airborne dispersion and transport of radionuclides or the contamination of surface water due to runoff. Fate and effects models can be used to quantify the impacts and evaluate the cost-effectiveness of measures for mitigating these impacts. The use of models in support of the identification and implementation of remedial alternatives is discussed in more detail in Section 3.5.3.

A.2 DOE ORDERS PERTAINING TO THE REMEDIATION OF NPL SITES

DOE Order 5400.4, "Comprehensive Environmental Response, Compensation, and Liability Act Requirements," establishes and implements DOE CERCLA policies and procedures as prescribed by the NCP and under the overall framework established by DOE Order 5400.1, entitled "General Environmental Protection Program Requirements." DOE Order 5400.4 refers to a broad range of laws, DOE orders, and Executive Orders that, in combination, establish the overall DOE regulatory framework for the remediation of sites under CERCLA/SARA. Within this regulatory framework, DOE enters into Interagency Agreements (IAGs) and/or Federal Facility Agreements (FFAs) at both NPL and non-NPL sites, as appropriate, with federal, state, and local entities for the execution of remedial investigation/feasibility studies and remedial actions.

The role of modeling in support of remedial decision-making within this framework is identical to that described above in Section A.1, since the DOE is subject to CERCLA and RCRA. To facilitate the decision-making process for the design and implementation of remedial activities, the DOE has published "A Manual for Implementing Residual Radioactivity Material Guidelines" (DOE 89). The manual adopts the RESRAD computer code as the means for assessing and demonstrating compliance with the applicable regulations and DOE orders. The model employs multi-pathway fate and effects algorithms which are acceptable to the DOE for demonstrating compliance with applicable cleanup criteria.

A.3 NRC PROGRAMS

Under the Atomic Energy Act (AEA), as amended, the NRC has commercial regulatory authority for source, special nuclear, and byproduct material. Though specifically exempt under CERCLA and RCRA (unless mixed waste is present[1]), the technical issues associated with the cleanup of sites licensed by the NRC are in many respects similar to the technical issues associated with the remediation of sites under CERCLA and RCRA. Accordingly, the types of remedial decisions and the role of models used to support these decisions are similar for CERCLA/RCRA and for AEA sites.

This section briefly summarizes the NRC SDMP and the use of fate and effects models in support of remedial decision-making. The technical approaches being used or developed by the NRC have applicability to the modeling needs under CERCLA and RCRA. Conversely, the technical approaches identified and developed in support of CERCLA and RCRA program may be found to be useful to the NRC in meeting its modeling needs.

This section does not address other NRC programs dealing with (1) low-level radioactive waste management under 10 CFR 61, which are the NRC regulations for licensing near

[1] Though materials regulated under the Atomic Energy Act, as amended, are not subject to RCRA, hazardous material, as defined under RCRA, at NRC-regulated sites is subject to RCRA.

surface low-level waste disposal facilities, and (2) high-level radioactive waste management under 10 CFR 60, which are the NRC regulations for licensing a high-level radioactive waste repository. Though these NRC waste programs are concerned primarily with the licensing of radioactive waste treatment and disposal technologies, and not with the remediation of environmental contaminants, they are concerned with technological issues that have a bearing on the characterization and remediation of environmental contaminants.

The Site Decommissioning Management Program (SDMP) (see SECY-90-121, March 29, 1990, and SECY-91-096, April 12, 1991) has identified 46 facilities under the authority of the NRC that have a sufficient level of soil or water contamination to require special attention from the staff. The Office of Nuclear Material Safety and Safeguards (ONMSS) has regulatory responsibility for these sites and cannot terminate the licenses or release these sites for unrestricted use until the sites are decontaminated. Toward this end, the SDMP has the following elements:

- Definition of a project management plan;
- Identification of the sites requiring decontamination;
- Prioritization of efforts;
- Definition of decontamination schedule and resources;
- Resolution of policy issues.

The last item is of particular relevance to this project, since it includes the need to develop residual radioactivity criteria and methods for demonstrating compliance with the criteria. The methods include the application of fate and effects models.

The SDMP makes specific reference to NUREG/CR-5512, entitled "Residual Radioactive Contamination from Decommissioning - Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent" (Ken 92). NUREG/CR-5512 is adopting standard, conservative, multi-pathway exposure scenarios for demonstrating compliance with cleanup criteria. When completed, the document and the accompanying computer code will provide a screening method for determining acceptable levels of residual radioactivity. It is expected that many SDMP sites will fail that screening and require reanalysis using the same models but with site-specific input data and assumptions. Should the site still fail the screening process, more sophisticated modeling may be required.

NUREG/CR-5512 will be used to derive unit concentration total effective dose equivalent (TEDE) factors, which relate a unit concentration of individual radionuclides in the environment, including soil, to a dose. The TEDE factors for soil are being derived using a set of conservative assumptions regarding the transport of residual contamination in multiple pathways, including external exposure, inhalation of suspended dust, ingestion of garden crops, and drinking water. The TEDE factors place an upper bound on the possible doses associated with a unit concentration of residual radioactivity in soil. Once the TEDE factors are adopted, the need to perform site-specific fate and effects modeling at SDMP sites may be reduced.

APPENDIX B

ENVIRONMENTAL CHARACTERISTICS OF NPL SITES CONTAMINATED WITH RADIOACTIVE WASTE AND NRC SITES IN THE SDMP

ENVIRONMENTAL CHARACTERISTICS OF NPL SITES CONTAMINATED WITH RADIOACTIVE WASTE AND NRC SITES IN THE SDMP

This appendix briefly summarizes the overall waste types, waste forms, and site characteristics of the National Priorities List (NPL) sites that are contaminated with radioactive materials and the sites in the NRC's Site Decommissioning Management Program (SDMP). The purpose of this appendix is to describe the range of site conditions and processes that may need to be modeled to support remedial decision-making at sites contaminated with radioactive material.

For each set of sites (i.e., NPL and SDMP sites), the following information is provided:

- a listing of the sites containing radioactive waste materials;
- the types of radionuclides found at each site;
- a description of the physical forms of the waste;
- a description of the physical characteristics of the site itself; and
- demographic characteristics of the region surrounding the site.

B.1 NPL SITES CONTAINING OR CONTAMINATED WITH RADIOACTIVE MATERIALS

Data characterizing the NPL sites were obtained from "Environmental Characteristics of EPA, NRC, and DOE Sites Contaminated with Radioactive Substances," EPA 402-R-93-011, March 1993. The information contained in this report was obtained from readily available EPA, DOE, and NRC publications. No attempt was made to compile and review the large amount of information being gathered as part of the RI/FS process. The intent of the report is to provide survey-level information describing the general types and characteristics of the sites on the NPL and the SDMP contaminated with radioactive materials.

B.1.1 Categories of Sites

The NPL currently includes 45 sites contaminated with radioactive materials (FR 54(134):29820-29825, July 14, 1989)[1]. While each of the sites has specific physical and

[1] At the time of the preparation of this report, there were 45 sites on the NPL containing substantial quantities of radioactive material. The number of sites on the NPL with radioactive contamination has since increased to 48. In addition, DOD sites containing radioactive material have also been identified. It was not possible to revise this report to reflect these recent developments. In addition, since the primary purpose of this appendix is simply to disclose the range of waste types and site characteristics, a detailed description of the most current list of sites is not essential.

environmental characteristics which will be discussed later in this section, and while some sites could be placed in more than one group, it is possible to characterize these sites broadly based on their historical usage. Seven general site types can be identified:

- Defense Plants (all DOE facilities)
- Mill Tailings, Processing, and Disposal Sites
- Radium Sites
- Commercial Landfills
- Research Facilities
- Commercial Manufacturing
- Low-level Waste Disposal

Defense Plants

Of the 45 sites, 15 were involved in operations related to weapons manufacture. Included in this group (all of which are under DOE supervision) are:

Fernald Environmental Remediation Project (FERP)
Hanford (4 sites)
Lawrence Livermore Laboratory (2 sites)
Idaho National Engineering Laboratory
Mound Plant
Oak Ridge Reservation (includes Oak Ridge National Lab)
Pantex Plant
Rocky Flats Plants
Savannah River Site
Weldon Springs (2 sites)

Many of these sites have been in operation since World War II. They were involved in the handling of high levels of actinides, transuranics, and fission products. Each site's involvement with these radioactive materials spans a time during which there was an evolving concern for the environmental consequences of such disposal (see, for example, Eis 63 and Eis 90). The potential risks to health and environment from these sites are high relative to the other categories of sites due to the high level and huge quantity of materials at each of these sites. In addition, the distribution of the contamination tends to be complex. For security reasons, many of these sites are located in sparsely populated regions. They are generally located in arid or semi-arid regions not particularly suitable for agriculture or residential use.

Mill Tailings, Processing, and Disposal

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

Homestake Mining Co.
Kerr-McGee (Kress Creek, Reed-Kepler Park, Residential Areas, Sewage Treatment Plant, Cushing) (4 sites)
Lincoln Park
United Nuclear - Church Rock
Monticello Mill Tailings & Radioactively Contaminated Properties (2 sites)
St. Louis Airport/Hazelwood Interim Storage/Futura Coatings
Uravan Uranium (Union Carbide)
WR Grace/Wayne Internment (DOE)

Common to these sites are very large volumes of wastes containing primarily uranium and thorium along with their daughters. The activity levels, however, are generally low. In some cases, contaminated materials have been widely distributed long after their initial disposal.

Radium Sites

Eleven of the sites fall in this radium processing category:

Denver Radium Site
Glen Ridge Radium Site
Jacksonville Naval Air Station
Lansdowne Radiation Site
Lodi Municipal Well
Maywood Chemical Co.
Montclair/West Orange Radium Site
Ottawa Radiation Sites
Pensacola Naval Air Station
Radium Chemical Corporation
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 its daughters (especially radon), and often located in urban areas. Because of the relatively long history of these sites, contaminated materials have been widely distributed, including incorporation into building materials.

Commercial Landfills

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

Forest Glen Mobile Home
Himco Inc., Dump
Shpack Landfill (DOE)
Westlake Landfill

There is no indication that any special plans were made to isolate or contain radioactive materials, other than routine practices at landfills. The isotopes present at these sites vary widely, as they originated from various medical, research, and defense operations. For these sites, the precise form or original concentration of the radioactive materials present are not known.

Research Facilities

One of the sites, Brookhaven National Laboratory, is a dedicated research facility operated for the Department of Energy. Radioactive materials are employed or produced in various research activities not necessarily related to defense. A wide range of isotopes were disposed of at very low levels in landfills or into ground water, trenches, and other disposal facilities, which has resulted in ground-water contamination.

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.

Low-Level Waste Disposal

One site, the Maxey Flats 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 medium. 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 (Naw 89).

B.1.2 Chemical and Radiological Properties of the Waste

Table B-1 presents the number of sites containing specific radionuclides. The data are based on Par 91. A more exhaustive review of the literature and ongoing RI/FS activities will certainly change this distribution. However, the table provides insight into the relative distribution of the various radionuclides. It is clear that the more prevalent radionuclides are Co-60, Cs-137, H-3, Pu-238/239, Ra-226/228, radon, and the isotopes of thorium and uranium.

Table B-1. Number of Sites Containing Specific Radionuclides

Radionuclide	No. of Sites	Radionuclide	No. of Sites
Actinium-227	2	Protactinium-231	1
Americium-241	3	Plutonium-238	10
Antimony-125	1	Plutonium-239	10
Carbon-14	2	Plutonium-240	5
Cobalt-60	7	Radium-226 (+ progeny)	28
Cerium-144	1	Radium-228	9
Cesium-134	2	Radon-220	5
Cesium-135	1	Radon-222	23
Cesium-137	10	Ruthenium-106	2
Curium-244	1	Selenium-79	1
Europium-152	1	Strontium-90	11
Europium-154	1	Technetium-99	7
Europium-155	1	Thorium-228	3
Hydrogen-3	11	Thorium-230	14
Iodine-129	3	Thorium-232	14
Iodine-131	1	Uranium-234	32
Krypton-85	1	Uranium-235	10
Manganese-54	1	Uranium-238	30
Nickel-63	1		

Chemical Properties of the Radionuclides

The preceding table shows that about 30 isotopes are present, which, for the purposes of this report, can be assigned to the following four chemical groups based on their environmental behavior:

1. Non-metals (C, H, I, Rn, Se)

2. Transition, platinum-group metals, and lanthanides (Mn, Ni, Co, Ru, Tc, Eu, Pm)

3. Alkaline metals and earths (Cs, Ra, Sr)

4. Actinides and transuranics (U, Th, Pu, Am, Ac, Pa)

Section 3.3 describes how the chemistry of these different radionuclides can affect transport and, therefore, influence modeling needs.

Radioactive Properties

Many of the radionuclides have very long half-lives. As a result, they can be assumed to persist indefinitely and, depending on the time period of interest, radioactive decay need not be explicitly modeled. Examples of such long-lived radionuclides are U-238 and Th-232; however, the ingrowth of progeny could be significant.

Among the various radionuclides present at these sites, there are isotopes that 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). Some radionuclides present are associated with 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 that decay to stable daughters through long chains of radioactive daughters are, in fact, the most common materials at the NPL sites contaminated with radioactive material.

B.1.3 Source Types, Containment, and Waste Forms

Hazardous wastes are most often stored or disposed of in a form designed to limit their release to the environment. Even if containment was not deliberate, such as is the case for many of the urban, radium-contaminated sites, soils and manmade materials themselves provide some containment. The form of containment varies widely, but some broad classes can be defined. Table B-2 presents the number of sites associated with specific source types and waste forms, along with a brief description of the general characteristics of the sources and forms of the waste.

Table B-2. Number of Sites Associated with Specific Source Types and Waste Forms

Setting	Number	Description
ponds	16	unlined or lined, excavated into the land surface into which hazardous wastes were originally deposited in fluids, usually water.
surface water	7	deliberate or accidental discharge to streams.
wells	2	deliberate or accidental subsurface injection of waste.
drums	3	usually 55-gallon steel drums.
tanks	5	large surface or buried structures designed to contain waste for long periods.
landfills	14	deliberate 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	12	above-ground heaps of material without controls on leaching or erosion.
burial	27	accidental or indiscriminate burial of wastes above or below ground level.
asphalt & aggregate	3	the use of materials contaminated with radioactivity for construction purposes, generally by those unaware that the materials were contaminated.

Only about a quarter of the containment of radioactive materials at these sites is in a form that might be described as a "point" source. A point source is one in which the area of the source is small compared to the distance to the nearest potential receptor. Section 3.3 discusses how the different waste forms and types of containment may affect modeling needs.

B.1.4 Site Environmental Characteristics

The sites are distributed more or less randomly across the 48 contiguous states (see Figure B-1). They span most of the large-scale physiographic and climatic regions of the North American continent. The terrain where these sites are located is underlain by a wide range of soils and geologic formations. Therefore, no general assumption can be made about the climatic or hydrogeologic characteristics of these sites. Each site 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.

Surface Characteristics

Surface water transport is relevant to the ground-water pathway because surface water can serve as a discharge location for ground-water flow or as a source of ground-water recharge.

Precipitation. The precipitation rate at the 45 NPL sites is as follows:

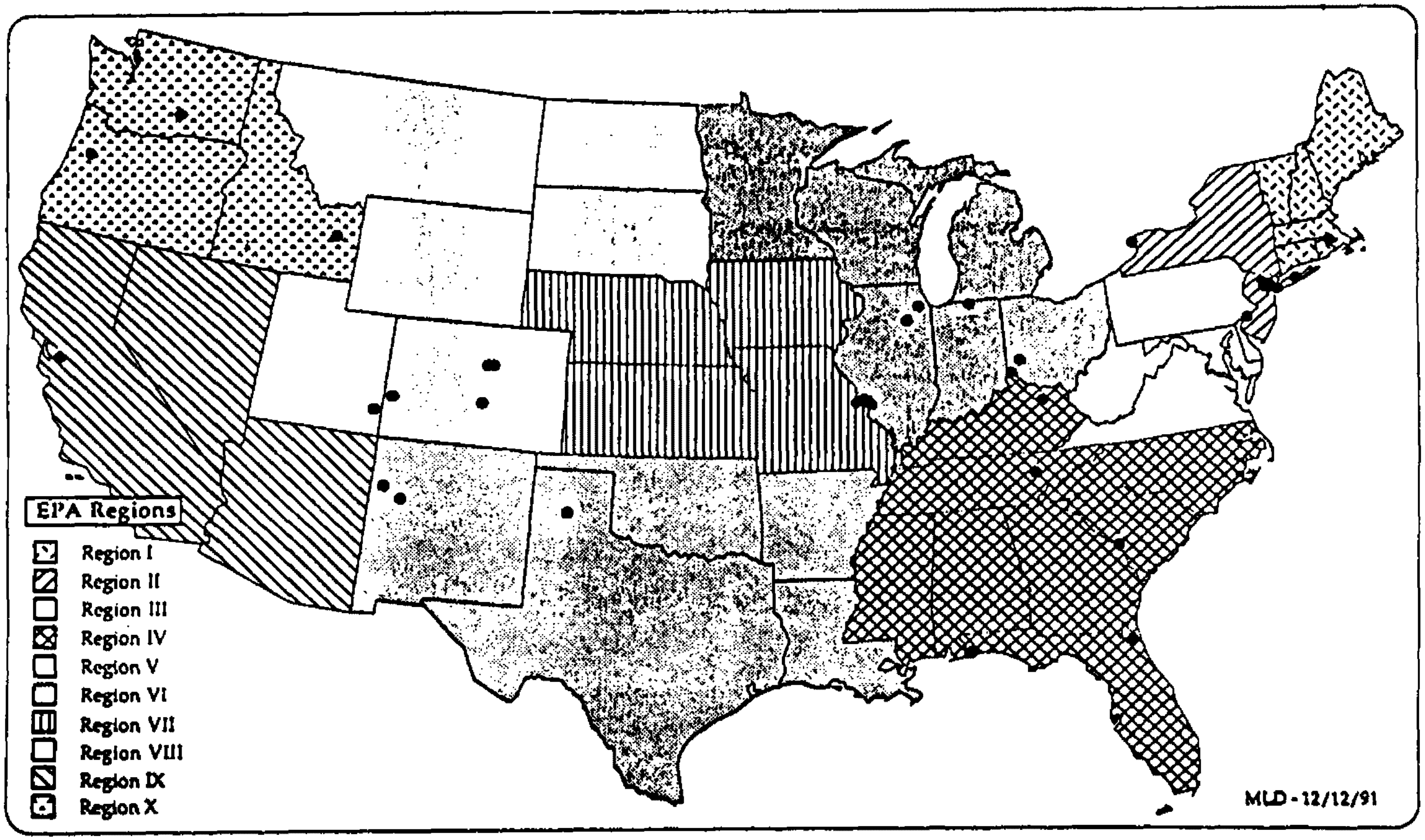
Category	Precipitation (cm/yr)	No. of Sites
Arid	0 - 25	8
Semiarid	25 - 50	8
Semihumid	50 - 100	14
Humid	100 - 200	14
Very Wet	> 200	1

Gross precipitation, total average rainfall for a site, is a rough measure of the relative importance of runoff and infiltration to the overall transport processes. As stated earlier, these sites span a considerable geographic area. 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 less mean evaporation) does not adequately describe that fraction of precipitation which ultimately enters into surface and ground-water systems even in arid regions. On the other hand, an exhaustive analysis of the actual rate of runoff, soil percolation, and ground-water recharge is beyond the scope of this report. For the present purpose, precipitation is used as a general index of runoff and infiltration.

Surface Water Transport. Virtually all of the sites include perennial streams that can or do act as vectors for contaminant transport. In addition, several of the sites contain or are contained within freshwater wetlands. The presence of continuous standing bodies of water

FIGURE B-1

NPL SITES CONTAMINATED WITH RADIOACTIVE MATERIAL



surrounding contaminated materials or of bodies of water that 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, as well as density dependent, flow and transport mechanisms need to be considered. In addition, one site, Idaho National Engineering Laboratory, is flooded with sufficient frequency to suggest that transient flow and transport mechanisms should be given particular attention.

Subsurface Transport

Various attempts have been made to categorize hydrogeologic regions throughout the United States (for a review, see All 85). Figure B-2 presents Heath's 1968 categorization system, which divides the continental United States into 11 hydrogeologic regions (Hea 68). At least one of the 45 NPL radioactively contaminated sites is in each of these regions.

For any given hydrogeologic setting, water movement below the ground surface can be divided into two relatively distinct phases - transport through the vadose zone (subsurface materials not saturated with water) and transport through the phreatic zone (water-saturated). Depth-to-ground water is a measure of the thickness of the vadose zone. Of the 28 NPL sites for which information regarding depth to ground water was readily available, 16 report a relatively thin vadose zone (i.e., $<$ 10 meters), 7 report a 10 to 20 meter vadose zone, and 5 report a vadose zone greater than 20 meters. As discussed in greater detail in Section 3.4, depth-to-ground water is a key factor in determining modeling needs.

B.1.5 Receptor Characteristics

Contamination at a site is important because of the potential for causing harm to people or to the natural environment. Most critical is the risk to the health of the human population in the immediate area surrounding a contaminated site. This section provides data regarding the population distribution and ground water use in the vicinity of the 45 NPL sites containing radioactive material.

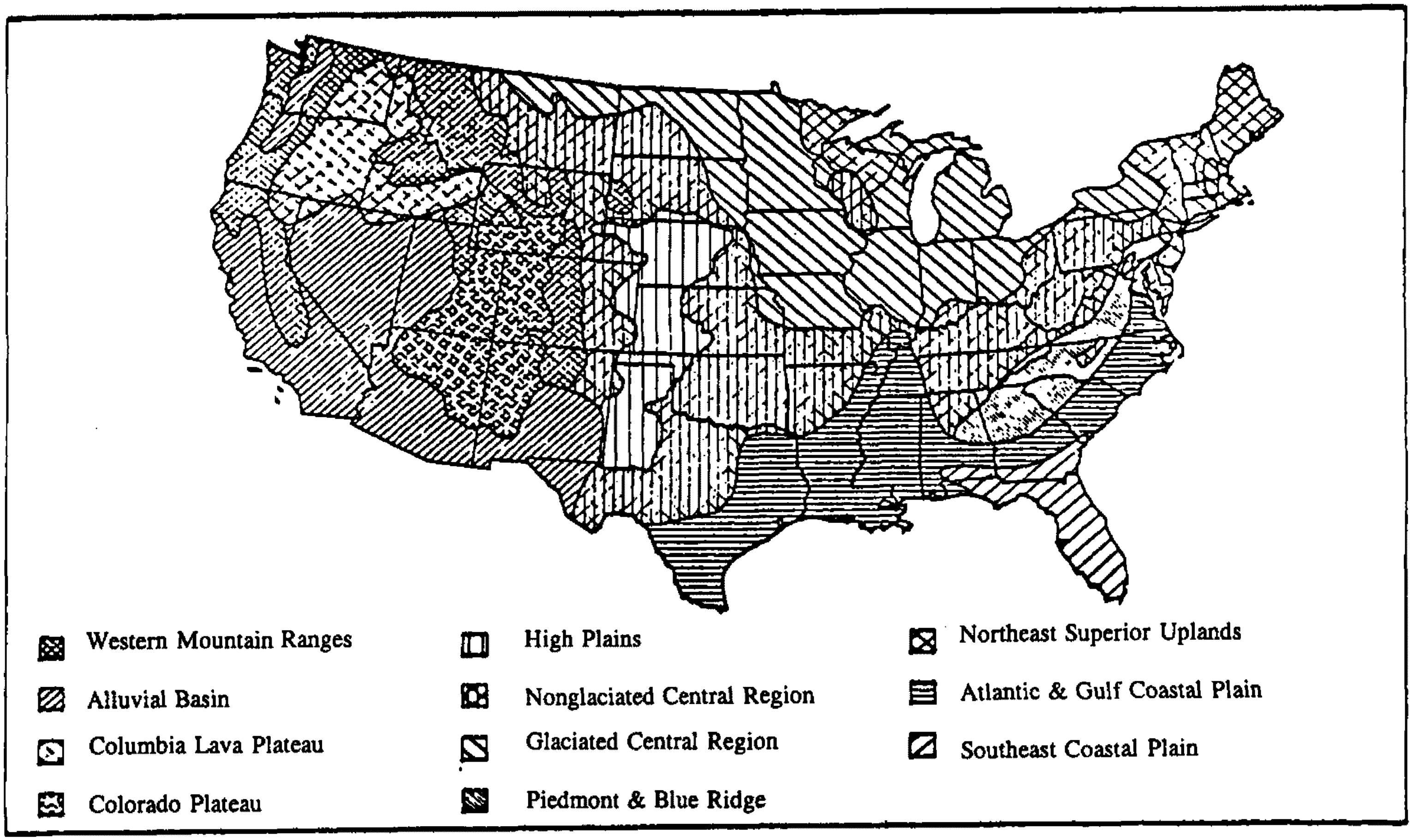
Population Data

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.

The county population densities at the 45 NPL sites tend to fall into four logarithmic groups, as follows:

FIGURE B-2

GROUND-WATER REGIONS IN THE UNITED STATES



(after Heath, 1968)

Population Density (persons/km^2)	Number of NPL Sites (radiological)
0 - 10	7
10 - 100	14
100 - 1,000	17
1,000 - 10,000	7

Where the population is less than 10/km^2, an area may be considered unpopulated. Rural regions are those with a population density of 10-100/km^2. From 100-1,000/km^2 an area is classed as suburban, and population densities of 1,000/km^2 or greater are labeled urban.

Defense plants are generally located in sparsely populated areas, frequently in the western United States, largely for security reasons. For large facilities, like Hanford and Savannah River, the presence of the facility itself may have significantly affected the population density in the area. Even sites in densely populated counties (e.g., FMPC) 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.R. Grace). In contrast, the radium sites are more characteristically located in higher-density urban areas. Other types of sites are less easily categorized.

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, lies 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.

The principal transport media for radioactive contaminants are water and air. Unlike air, water use may vary from site to site. Ground water or surface water in the immediate site area may be used for drinking, irrigation, watering of livestock, or recreational purposes. Water for drinking is obtained from local supplies at 30 of the 45 sites, though this does not necessarily mean that the water supplies are obtained from aquifers interconnected with the sites. Two sites, Brookhaven National Laboratory and the Himco, Inc., Dump, 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.

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. The four population density groupings previously mentioned can 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 nothing at night. Of the primary urban land use groups, industrial areas have the lowest potential population at risk (Mur 66).

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 tend 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 essentially no regular use by human populations. Large areas of desert which were used for nuclear weapons testing are an example of this land "use."

The majority, nearly 70 percent, of the sites are located in rural or suburban areas. Only seven sites are located in urban areas. All are radium sites. Six of the seven are in the greater New York City area; the other (Lansdowne) is near Philadelphia. There are also seven sites in counties classed as unpopulated. These sites are all located in the western United States; all are mill tailings/processing/disposal sites.

B.2 DESCRIPTION OF SITES IN THE NRC SITE DECOMMISSIONING MANAGEMENT PROGRAM

The data in this section were summarized from "Updated Report on the Site Decommissioning Management Plan," SECY-91-096, April 12, 1991, and the database provided in Par 91.

Of the 41 SDMP sites, 30 are contaminated with large volumes of relatively low concentrations of naturally occurring radionuclides associated with the ore and metal processing industries. These residues are typically located in storage piles or ponds and represent an actual or potential source of ground-water contamination. Most of the sites also contain contaminated buildings and structures, which represent a potential risk from direct radiation and airborne particulates in an occupational setting. Several of the sites report the presence of fission products, including Sr-90 and Co-60.

Many of the sites are located in urban or industrialized areas, and the contaminated properties are relatively small compared to many of the defense plants listed on the NPL (see Section B.1.1). The sites have a lot in common with many of the non-defense facilities on the NPL. In fact, some of the SDMP sites are also Superfund sites (i.e., Kerr McGee (Cushing), Westlake, Shpack). Figure B-3 presents the geographical distribution of the sites. The distribution of geohydrological settings, according to Hea 68 (see Figure B-2), is as follows.

Region	Number
Nonglaciated Central Region	15
Glaciated Central Region	10
Northeast and Superior Uplands	12
Piedmont and Blue Ridge	4

Most of the NRC SDMP sites are located in the northeastern United States, 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 used for the NPL sites (Section B.1), with the addition of two categories, Fuel Fabrication and Processing and Scrap Metal Recovery. Though there are no low-level waste disposal sites on the list, many of these and other NRC-licensed sites have waste buried on site in accordance with Part 20.302 of Title 10 of the Code of Federal Regulations. These is also one radium site, the Safety Light Corporation.

Defense Plants

Three NRC sites were involved in weapons manufacture:

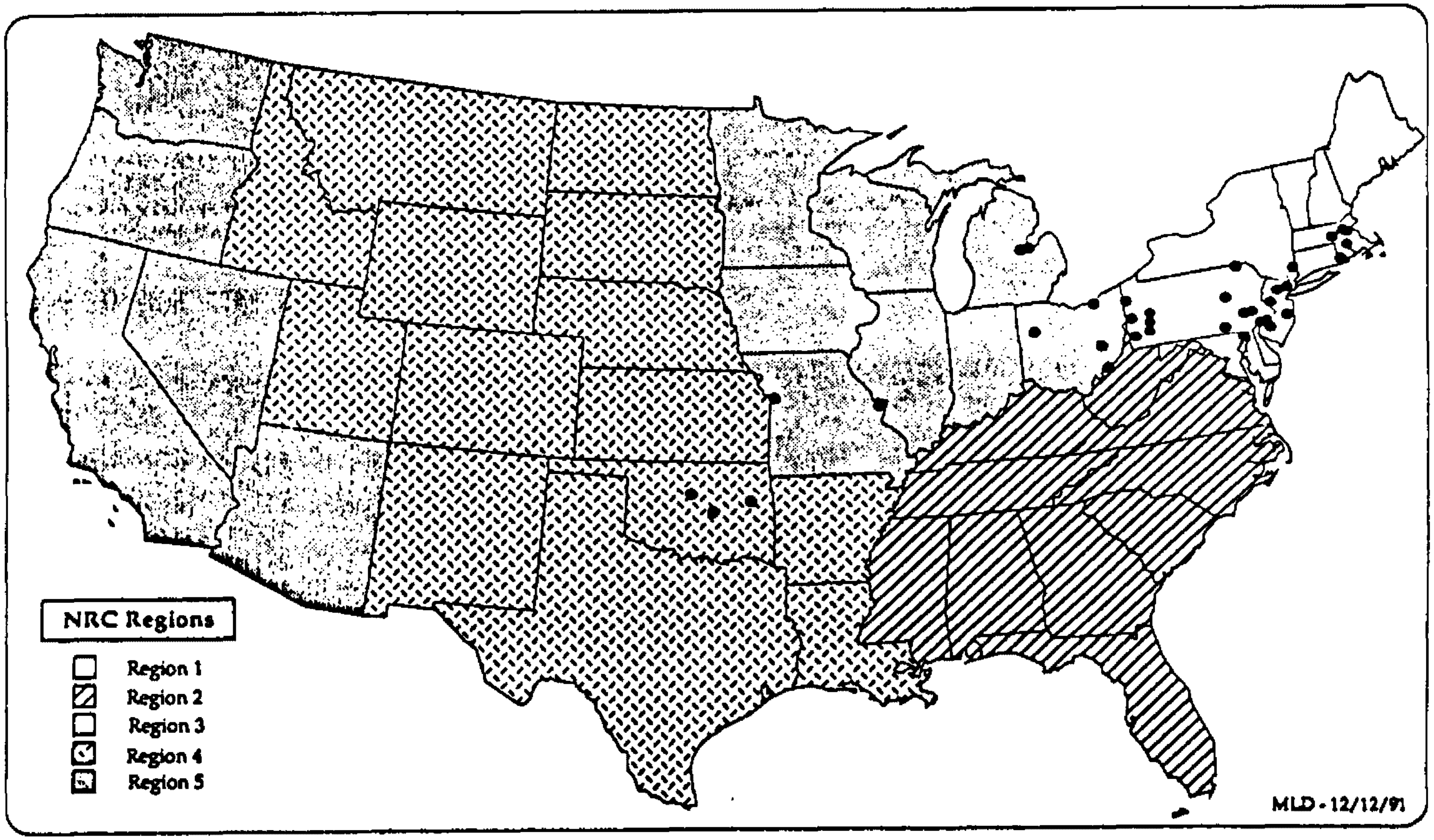
Aberdeen Proving Ground
GSA Watertown Arsenal Site
Remington Arms Co., Inc.

Of these, the Watertown Arsenal (GSA) is currently operated by DOE; the other two are under the control of the Department of Defense (DOD).

Whereas the NPL defense sites are generally located in the western United States, these 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 weapons under the Manhattan Engineering District during World War II. The NRC sites, on the other hand, were involved in the development and testing of ammunition for the U.S. Army and are comparatively smaller.

FIGURE B-3

GEOGRAPHICAL DISTRIBUTION OF THE SDMP SITES



Mill Tailings, Processing, and Disposal

Eleven NRC sites fall into this category:

Cabot Corporation (3 sites)
Fansteel, Inc.
Heritage Minerals
Kerr-McGee Rare Earths Facility (West Chicago)[2]
Magnesium Elektron, Inc.
Molycorp., Inc. (2 sites)
Shieldalloy Metallurgical Corporation (2 sites)

Unlike the NPL sites in this group, not all of these sites deal with uranium ore. Some sites process other ores (tantalum, columbium, zircon, leucoxene) which contain uranium or thorium as a byproduct.

Commercial Landfills

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

Kawkawlin Landfill
Westlake Landfill

The Westlake Landfill is also on the NPL list.

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 carried out nuclear fuels research and development and included both laboratories and reactors. The site was previously decontaminated, but additional contamination was discovered, indicating a need for additional cleanup. 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. Contamination from this site originated from a reactor accident in the 1960s.

[2] Responsibility for this site was recently transferred to Superfund.

Commercial Manufacturing

Twelve NRC/SDMP sites are or were involved in manufacturing processes:

- Advanced Medical
- Allied Signal
- BP Chemicals
- The Budd Company
- Dow Chemical Company
- Mallinckrodt Specialty Chemicals
- Nuclear Metals, Inc.
- Process Technology of New Jersey, Inc.
- Safety Light Corporation
- Schott Glass Technologies
- Whittaker Corporation
- Wyman-Gordon Company

The Dow Chemical site is actually three sites, though they are combined under the SDMP. Two of these, at Midland and Bay City, Michigan, are manufacturing operations; the third, at Salzburg, Michigan, is a landfill owned and operated by Dow, which Dow proposes to use for disposal of low-level radioactive materials from the other two sites.

Fuel Fabrication and Processing

Eight NRC sites are, or have been, involved in uranium fuel fabrication and processing:

- Amax
- Babcock & Wilcox (Apollo)
- Babcock & Wilcox (Parks Township)
- Chemetron (Best Ave.)
- Chemetron (Harvard Ave.)
- Kerr-McGee (Cimmaron)
- Kerr-McGee (Cushing)
- Texas Instruments

One, Babcock & Wilcox (Parks Township), was also used for plutonium fuel fabrication.

Contamination at these sites is usually in the form of enriched and depleted uranium in the soils in the vicinity of burial trenches, occasionally in surface soil around buildings in former processing areas. Thorium, plutonium, and radium are also present.

Scrap Metal Recovery

Two sites are industrial but cannot properly be classified as manufacturing operations:

Pesses Company (METCOA)
UNC Recovery Systems, Wood River

Both were involved in scrap metal recovery from contaminated materials (although contamination may have resulted from other activities), and both have been closed for about a decade. The UNC site is no longer functioning and has been remediated, though some traces of uranium, strontium, and nitrates exist in the ground water. Sources of thorium contamination at the Pesses site include leaking containers and several slag piles.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

This report describes when modeling is neededand the various processes that need to be modeled. Modeling needs are defined in the following terms:

1. Exisitng apllicable regulatory requirements
2. The phase of the remedial process.
3. Site characteristics.

The report presents a generic discussion of the role and purpose of modeling in support of remedial decision-making, with a particular emphasis on ground-water modeling. Descritptions are provided for for various ground-water flow and transport processes that may need to be modeled. A matrix describes ground-water modeling needs as a function of site characteristics and phase in the remedial process.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
ground-water, radionuclide, remediation, computer models, decision-making,environmental		

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