Technical and Regulatory Document

Determining Cleanup Goals at Radioactively Contaminated Sites: Case Studies

April 2002

Prepared by
The Interstate Technology and Regulatory Council
Radionuclides Team

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EXECUTIVE SUMMARY

This document summarizes the various regulatory standards and requirements that dictate the cleanup at radioactively contaminated sites. It discusses processes used to develop cleanup levels and presents case studies from 12 selected sites to demonstrate variations in the decision-making framework and basis:

- Brookhaven National Laboratory, New York
- Enewetak Atoll, Marshall Islands
- Fernald Environmental Management Project, Ohio
- Fort Dix, New Jersey
- Hanford Site, Washington
- Johnston Atoll
- Linde Site, New York
- Nevada Test Site and Associated Ranges, Nevada
- Rocky Flats, Colorado
- Oak Ridge, Tennessee
- Savannah River Site, South Carolina
- Weldon Spring Site, Missouri

An analysis of the case studies has produced conclusions that could prove useful in enhancing consistency of decision making and application of risk assessment approaches at radioactively contaminated sites.

Calculations of cleanup levels vary from site to site due to different physical settings, cleanup authorities, risk assessment methodologies, etc. To compare existing cleanup levels and to help in the development of future cleanup levels, the basis for decision making must be understood. Different cleanup authorities (Comprehensive Environmental Response, Compensation, and Liability Act; Nuclear Regulatory Commission; Department of Energy; state radiation control regulations; etc.) require varying approaches used in radiation risk assessment (e.g., based on dose or on slope factor). Recently, new data and concepts in radiation risk assessment, such as risk coefficients, updated slope factors, and soil screening levels for radionuclides, have been developed that refine these approaches further.

A common understanding among states, stakeholders, sites, and agencies of how various cleanup levels have been or could be derived will make this process more efficient, defensible, and consistent. The use of science-based cleanup criteria reduces the likelihood of delayed cleanup due to litigation and other factors. Decision makers at DOE and other facilities need to be aware of the context used to establish cleanup levels at other sites contaminated with radionuclides. Consistency in decision making for developing cleanup goals will enhance selection and deployment of appropriate environmental remediation and characterization technologies.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

DETERMINING CLEANUP GOALS AT RADIOACTIVELY CONTAMINATED SITES: CASE STUDIES

1.0 INTRODUCTION

Development of cleanup goals is based primarily on the regulatory authority applied and the risk assessment used. Regulations governing radioactively contaminated sites are rather complex and somewhat confusing due to involvement of multiple agencies, overlapping authorities, and multiple categories of radioactive materials. The regulatory system is divided in a manner that does not necessarily assist in accelerating cleanup and disposal decisions. Regulation is committed to three federal agencies (Nuclear Regulatory Commission [NRC], U.S. Environmental Protection Agency [EPA], and U.S. Department of Energy [DOE]) and the states, which have not reached consensus on regulatory standards and approaches.

The need for improvement in consistency and clarity in the development of cleanup goals has been raised in various forums. For instance, the Conference of Radiation Control Program Directors (CRCPD, 1998) has complained that radioactively contaminated sites "are not being cleaned up in a timely manner because there is no uniform cleanup standard applicable to the radioactive materials." In a report to the U.S. Senate, the U.S. General Accounting Office (GAO, 2000) addressed the differences in regulatory strategies resulting from different regulatory authorities. According to the GAO report, NRC and EPA "have continued to use separate approaches in setting standards for cleaning up and decommissioning nuclear sites, especially when groundwater protection is involved. Consequently, perceived dual regulation by EPA and NRC continues to complicate the cleanup and decommissioning process at some sites where both agencies' standards may apply, potentially causing duplication of effort and regulatory delays, adding to facilities' compliance costs, and raising public questions about what cleanup levels are appropriate and safe."

Differences between cleanup levels from site to site are due to variations in one or more of the elements in the cleanup level development process. This process begins with determining which regulatory authority applies. Many sites involving the research, development, processing, assembly, waste disposal, or even deployment of nuclear weapons are being cleaned up under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). According to CERCLA and the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), selected remedies, and therefore cleanup guidelines, must be protective of human health and the environment and must comply with "applicable or relevant and appropriate requirements" (ARARs). Depending on which requirements are determined to be ARARs, preliminary remediation goals (PRGs) are usually established by assessing radiological health effects using a risk-based or dose-based approach. Both approaches require selecting appropriate scenarios, models/equations, and site-specific input parameters. Modifying factors may be applied to PRGs to create final remedial goals (RGs), which are incorporated into decision documents, such as records of decision (RODs). Variations in the elements of this process have led each site to establish different cleanup levels.

This document summarizes the various regulatory standards and requirements that dictate cleanup at radioactively contaminated sites. It reports cleanup levels from various sites and case

studies from 12 selected sites to demonstrate variations in the decision-making framework and basis.

1.1 Purpose of the Report

Against the backdrop of regulatory complexity, site managers are responsible for the efficient development of cleanup goals to facilitate site cleanup. Site managers and state regulators should be able to take advantage of experiences and lessons learned at similarly contaminated sites. Decision makers may find it useful to examine the basis of cleanup level development at other sites. The purpose of this report is to examine the context in which cleanup levels have been developed at various radioactively contaminated sites and identify common themes and lessons that could improve future decision making.

1.2 Organization of the Report

Section 2.0 provides an overview of the regulatory authorities that are the bases for determining cleanup levels. Section 3.0 discusses the risk assessment approaches used to determine cleanup levels. Section 4.0 elaborates on the process of determining the cleanup levels and their application at 12 site case studies. Section 5.0 analyzes the case study data, and Section 6.0 summarizes the conclusions. Selected references used in this report are listed in Section 7.0.

2.0 REGULATORY AUTHORITIES PERTAINING TO REMEDIATION AT RADIOACTIVELY CONTAMINATED SITES

This section summarizes the four major statutes under which radioactively contaminated soils are now being remediated: CERCLA, the Atomic Energy Act (AEA), the Uranium Mill Tailings Radiation Control Act (UMTRCA), and the Resource Conservation and Recovery Act (RCRA) for mixed waste (waste containing both radioactive and hazardous constituents). Additionally, those charged with soil remediation must adhere to a multitude of state, tribal, and local government requirements relative to radioactive materials. Section 2.1 provides the background of radiological standards in effect and the complexity of regulatory requirements. Section 2.2 elaborates on categories of radioactive materials being regulated. Sections 2.3–2.8 provide details of CERCLA, RCRA, AEA, UMTRCA, Defense Nuclear Facility Safety Board (DNFSB) recommendations, and DOE orders.

2.1 Introduction

In developing soil remediation levels, it is necessary to understand the regulatory framework that drives the remedial action. Radioactively contaminated soils are covered under several separate and distinct statutory authorities. Selecting one or more appropriate statutory authorities and associated regulations is fundamental to the development of soil cleanup levels. Table 1 lists major radiological standards in effect in the United States.

Table 1. Major U.S. Radiation Standards

Regulation	Agency[a]	Standard/Numerical limits[b]
General public (10 CFR 20)	NRC	100 mrem/year
Uranium mill tailings (40 CFR 192; 10 CFR 40, App. A)	EPA	Ra-226/228: 5 pCi/g (surface) 15 pCi/g (subsurface) Rn-222: 20 pCi/m^2-sec
High-level waste operations (10 CFR 60)	NRC	100 mrem/year
Low-level waste (10 CFR 61)	NRC	25/75/25 mrem/year
Drinking water (40 CFR 141.15–16)	EPA	Radium: 5 pCi/L Gross alpha: 15 pCi/L (excludes Ra and U) Beta/photon: 4 mrem/year[c] Uranium: 30 µg/L
Uranium fuel cycle (40 CFR 190)	EPA	25/75/25 mrem/year
Air emissions (National Emission Standards for Hazardous Air Pollutants) (40 CFR 61, H)	EPA	10 mrem/year to nearest off-site receptor
Superfund (CERCLA) cleanup (40 CFR 300)	EPA	A risk range of 1:10,000 to 1:1,000,000 (10^{-4}–10^{-6}) excess lifetime risk of getting cancer or ARARs[d]
Decommissioning (10 CFR 20)	NRC	25/100/500 mrem/year
Occupational standards (29 CFR 1910; 10 CFR 20; 10 CFR 835)	OSHA; NRC; DOE	5,000 mrem/year

[a] NRC = Nuclear Regulatory Commission, EPA = Environmental Protection Agency, OSHA = Occupational Safety and Health Administration, DOE = Department of Energy.
[b] A picocurie (pCi) is one-trillionth of a curie, a unit of radioactivity. A millirem (mrem) is one-thousandth of a rem, a unit of dose.
[c] Radioactivity from manmade radionuclides in community drinking water systems.
[d] Any other applicable or relevant and appropriate (ARAR) standards would apply on a site-by-site basis.

The Conference of Radiation Control Program Directors (CRCPD, 1998) has complained that radioactively contaminated sites "are not being cleaned up in a timely manner because there is no uniform cleanup standard applicable to the radioactive materials. . . . [T]he U.S. has a mixed bag of inconsistent annual dose limit fractions (4 mrem/year for water, 10 mrem/year for air, 15 mrem/year for high level waste [proposed], 25/75/25 mrem/year for fuel cycle). Uniformity is not apparent in this melange."

In a report to the U.S. Senate, the U.S. General Accounting Office (GAO, 2000) addressed the differences in regulatory strategies resulting from different regulatory authorities:

- "Lacking conclusive evidence of low-level radiation effects, U.S. regulators have in recent years set sometimes differing exposure limits. In particular, EPA and NRC have disagreed on exposure limits.
- "As applied to nuclear cleanup and decommissioning sites where both EPA and NRC may have jurisdiction, the two agencies' different regulatory approaches have sometimes raised questions of inefficient, conflicting and dual regulation.
- "EPA has historically in many cases implemented a risk-based radiation protection approach, under which the agency addresses individual contamination sources, co-regulates chemicals and radioactive substances, and protects both human health and environmental resources. In accordance with its tradition of regulating chemicals, EPA has generally set a risk of 1 in a million that an individual will develop cancer in a lifetime as a goal for remediation and has considered a risk of greater than 1 in 10,000 to be potentially excessive. EPA's approach has been described as "bottom up," setting a relatively restrictive risk goal to be pursued through the best available technology—but allowing less restrictive limits in site-specific situations. In contrast, NRC favors a dose-based, radiation-specific protection approach. . . . NRC's protection strategy has been described as a 'top down' approach. Compared with EPA, NRC sets a relatively less restrictive dose limit, but reduces doses (and risks) well below the limit in site-specific situations where the reductions are 'reasonably achievable.'
- "The two agencies have continued to use separate approaches in setting standards for cleaning up and decommissioning nuclear sites, especially when groundwater protection is involved. Consequently, perceived dual regulation by EPA and NRC continues to complicate the cleanup and decommissioning process at some sites where both agencies' standards may apply, potentially causing duplication of effort and regulatory delays, adding to facilities' compliance costs, and raising public questions about what cleanup levels are appropriate and safe.
- "The potential acceptable risks, health benefits, and costs of EPA's and NRC's differing regulatory approaches will be of interest to Congress as it continues to focus on nuclear health and safety issues of national importance. . . ."

2.2 Categories of Radioactive Materials

The following major categories of radioactive materials are defined in DOE's *Radioactive Waste Management Manual* (DOE, 2001):

"Source Material—Uranium or thorium, or any combination thereof, in any physical or chemical form, or ores that contain (by weight) 0.05 percent or more of uranium, thorium, or any combination of the two. Unrefined and refined ores from which thorium, uranium, and other elements are extracted; and purified materials or by-products (e.g., depleted uranium) used or produced in the uranium enrichment and fuel fabrication process.

"Special Nuclear Material—Plutonium, uranium-233, uranium enriched in the U-233 or U-235 isotope, and any other material that the NRC, pursuant to the provisions of Section 51 of the AEA, determines to be special nuclear material. Enriched uranium at nuclear fuel fabrication plants, nuclear fuel at reactor sites, nuclear weapons components, and purified radiation sources used in research.

"By-product Material—Any radioactive material (except special nuclear material) yielded in, the process of producing or utilizing special nuclear material; and the tailings or wastes produced by the extraction or concentration of uranium and thorium from ore processed primarily for its source material content.

"Naturally Occurring or Accelerator-Produced Radioactive Material (NARM)—Any radioactive material produced as a result of nuclear transformations in an accelerator, and any nuclide that is radioactive in its natural physical state (i.e., not anthropogenic), excluding source and special nuclear material. Numerous radionuclides produced in accelerators and used for medical and other purposes; and NORM sources. Specific examples include cobalt-60, cobalt-57, manganese-54, sodium-22, and radium-226.

"Naturally Occurring Radioactive Material (NORM)—Naturally occurring radionuclides not regulated under the AEA of 1954, as amended, whose composition, radionuclide concentrations, availability, or proximity to man have been increased by or as a result of human practices. NORM does not include radioactivity of rocks or soil, or background radiation."

Source, special nuclear, and by-product material are given special status under the AEA because they are uniquely associated with atomic energy production. "NARM" is a term used for radioactive materials not defined by the AEA.

2.3 Regulatory Authorities

Various federal and state statutes have provisions that affect the remediation of radionuclides, including CERCLA, RCRA, UMTRCA, and AEA. Besides EPA, NRC, DOE, and DNFSB have responsibilities and enforce regulations pertaining to radionuclides.

2.3.1 Comprehensive Environmental Response, Compensation, and Liability Act

In 1980, Congress passed Public Law 96-510, also known as CERCLA. This act and subsequent reauthorization acts in 1986 and 1990 (i.e., Superfund Amendments and Reauthorization Act of 1986 [SARA] and the Omnibus Budget Reconciliation Act), provided statutory requirements for remediation of sites where hazardous substances have been or might be released into the environment. The statutory authority addresses both private industry and federal facilities. Private industry conducts cleanup utilizing the trust fund ("Superfund") provisions of CERCLA. The lead federal agency for a federal facility is required to enter into an agreement with EPA and

request Congress to appropriate the necessary funds to conduct environmental remediation of the contaminated sites. Many sites involving the research, development, processing, assembly, waste disposal, or even testing and deployment of nuclear weapons are CERCLA sites.

With regard to establishing cleanup levels, CERCLA requires a risk-based approach for selected land use end points (e.g., residential, recreational, and industrial uses). The statute also provides for ecological and habitat protection. This approach culminates in an evaluation of proposed alternatives for remediation screening using the following nine criteria:

Threshold Criteria:
1. overall protection of human health and the environment;
2. compliance with ARARs;

Balancing Criteria:
3. long-term effectiveness or permanence;
4. reduction of toxicity, mobility, or volume through treatment;
5. short-term effectiveness;
6. implementability;
7. cost;

Modifying Criteria:
8. state acceptance; and
9. community acceptance.

A remedy must satisfy the first two criteria to be considered viable. The remaining criteria are used in the decision-making process to select the most appropriate of the proposed alternatives. For those remedies that involve the remediation of radionuclides in the soil or sediments, cleanup levels are generated based upon certain risk assumptions for the intended land use. These cleanup levels are developed using complex models that take into account several factors, such as exposure to an individual, radioactive decay, fate and transport of the radionuclide, and modes of entry (i.e., direct exposure, ingestion, or inhalation, etc.).

National Oil and Hazardous Substances Pollution Contingency Plan

The NCP (40 CFR 300) contains regulations promulgated by EPA to "provide the organizational structure and procedures for preparing for and responding to discharges of oil and releases of hazardous substances, pollutants, and contaminants" (40 CFR 300.1). The NCP provides the requirements for response actions for contaminated media. These requirements are specified in Subpart E (40 CFR 300.400–440). Two types of incident responses are the removal action and the remedial action. These actions differ primarily in the size and scope of the action.

Removal actions are taken to abate, prevent, stabilize, mitigate, or eliminate the release or the threat of release [40 CFR 415(b)(1)]. Removal actions typically consist of an engineering evaluation/cost analysis (EE/CA) and an action memorandum (AM), although there are allowable variations. The following factors are to be considered in determining the appropriateness of a removal action:

- actual or potential exposure to nearby human populations, animals, or the food chain from hazardous substances, pollutants, and contaminants;

- actual or potential contamination of drinking water supplies or sensitive ecosystems;
- hazardous substances or pollutants or contaminants in drums, barrels, tanks, or other bulk storage containers that may pose a threat of release;
- high levels of hazardous substances, pollutants, or contaminants in soils largely at or near the surface, which may migrate;
- weather conditions that may cause hazardous substances or pollutants or contaminants to migrate or be released;
- threat of fire or explosion;
- the availability of other appropriate federal or state response mechanisms to respond to the release; and
- other situations or factors that may pose threats to public health or welfare of the United States or the environment.

The requirements for remedial actions are provided in 40 CFR 300.430. As stated earlier, remedial activities are larger in scope and generally provide a final decision for the remediation of a hazardous substance, pollutant, or contaminant. In addition to describing the organizational aspects of remedial activities (i.e., remedial investigation, feasibility study, proposed plan, ROD, etc.), this section of the NCP describes the methodology for toxicants and the CERCLA acceptable risk range for carcinogens. The risk range is particularly important for radionuclides, since all radionuclides are considered carcinogens.

Acceptable exposures are generally concentration levels that represent an excess upper-bound lifetime cancer risk to an individual between 1 in 10,000 and 1 in 1,000,000 (10^{-4} to 10^{-6}), using information on the relationship between dose and response. In essence, EPA deems excess cancers from exposure to carcinogens that fall between 1 cancer per 10,000 exposed individuals to 1 cancer per 1,000,000 exposed individuals to be protective of human health. The NCP states that the "point of departure" for remedial activities is the 10^{-6} value and that where multiple carcinogens are present, the total risk from all carcinogens should generally not exceed the risk range. EPA guidance further states that where cumulative carcinogenic risk is less than 10^{-4}, "action generally is not warranted" (EPA, 1991).

Applicable or Relevant and Appropriate Requirements

An important aspect of CERCLA is specified in Section 121 of the act, which states that remedial actions for cleanup of hazardous substances must comply with requirements or standards under federal or more stringent state environmental laws and regulations that are determined to be ARARs. Inherent in the interpretation of ARARs is the assumption that the protection of human health and the environment is ensured. The NCP lays out the rationale for identification and use of ARARs.

ARARs are used in conjunction with risk-based goals to govern the conduct of response activities and to establish remediation goals. ARARs form the basis or starting point for determining appropriate remediation levels. In the absence of an ARAR or where the ARAR is

determined to be not sufficiently protective, a site-specific baseline risk assessment is used to determine appropriate remediation levels. ARARs are identified on a site-by-site basis. The lead and support agencies work closely with each other to identify ARARs. Laws and regulations are divided into two primary categories as ARARs: (1) applicable and (2) relevant and appropriate. Additionally, guidance that directly relates to the protectiveness of a particular action is identified as "to be considered" (TBC).

"Applicable" requirements are those cleanup standards, controls, and other substantive environmental protection requirements, criteria, or limitations promulgated under federal or state law that specifically address a hazardous substance, pollutant, or contaminant, remedial action, location, or other circumstance at a remediation site [40 CFR 300.400(g)]. For a requirement to be applicable, the requirement must directly and fully address a CERCLA activity.

"Relevant and appropriate" requirements are those cleanup standards, standards of control, or other substantive environmental provisions that do not directly and fully address site conditions but address similar situations or problems to those encountered at a remediation site. In some cases only a portion of the requirement may be relevant and appropriate. The identification of relevant and appropriate requirements is a two-step process; only those requirements that are considered both relevant and appropriate must be addressed at CERCLA sites.

"To be considered"—Other federal or state policies, guidelines, or proposed rules that pertain directly to the protectiveness of an action, but do not meet the criteria for ARARs may be identified as "TBC." While not legally binding, these TBCs may be used in conjunction with ARARs to achieve an acceptable level of risk. TBCs are evaluated along with ARARs as part of the risk assessment conducted for each CERCLA site to set protective cleanup levels and goals.

Three primary types of ARARs are chemical-specific, location-specific, and action-specific ARARs. Chemical-specific ARARs are usually health- or risk-based restrictions on the amount or concentration of a chemical that may be found in or discharged to the environment. Location-specific ARARs establish restrictions on permissible concentrations of hazardous substances or activities involved in the remediation of those substances because of the special location (e.g., wetlands, floodplains, or critical habitats). Action-specific ARARs include operation, performance, and design requirements or limitations based upon waste type, media, or remedial activities. Some of the more common ARARs that affect radioactively contaminated sites are listed below:

- AEA
- UMTRCA
- Clean Air Act
- Clean Water Act
- Safe Drinking Water Act
- RCRA (mixed waste)

Under certain circumstances, ARARs may be waived in favor of an alternative protective remedy [40 CFR 300.430(f)(1)(ii)(B)]. The following six types of waivers may be invoked during a remedial action:

- Interim Measures—An ARAR may be temporarily waived to implement a short-term alternative, or interim measure, provided that the final remedy will, within a reasonable time, attain all ARARs without causing additional releases, complicating the response process, presenting an immediate threat to public health or the environment, or interfering with the final remedy.
- Greater Risk to Human Health and the Environment—An ARAR may be waived if compliance with the requirement will result in greater risk to human health and the environment than noncompliance.
- Technical Impracticability—An ARAR may be waived if it is technically impracticable from an engineering standpoint, based on the feasibility, reliability, and cost of the engineering methods required.
- Equivalent Standard of Performance—An ARAR may be waived if an alternative design or method of operation can produce equivalent or superior results, in terms of the degree of protection afforded, the level of performance achieved, long-term protectiveness, and the time required to achieve beneficial results.
- Inconsistent Application of State Standard—A state ARAR may be waived if evidence exists that the requirement has not been applied to other sites (National Priorities List [NPL] or non-NPL) or has been applied variably or inconsistently. This waiver is intended to prevent unjustified or unreasonable state restrictions from being imposed at CERCLA sites.
- Fund Balancing—An ARAR may be waived if compliance would be costly relative to the degree of protection or risk reduction likely to be attained and the expenditure would jeopardize remedial actions at other sites.

2.3.2 Resource Conservation and Recovery Act

Contaminants identified as hazardous waste under the provisions of RCRA are often colocated with other hazardous substances as defined by CERCLA. In these cases, the mixed waste can be subject to both RCRA and CERCLA authority. For hazardous wastes, a variety of substantive requirements may be identified as applicable under the CERCLA statute. These requirements pertain to the treatment, storage, and disposal activities regulated under Subtitle C of RCRA. The requirements include design and operating standards for units that treat, store, or dispose of hazardous wastes; treatment standards for wastes that will be placed on the land; groundwater monitoring requirements; and closure standards for treatment, storage, and disposal units.

Mixed waste refers to both currently produced hazardous waste mixed with radioactive materials and legacy waste that is excavated and contains hazardous waste as defined in 40 CFR 264 mixed with radioactive materials.

Several key regulatory provisions of RCRA are described below:

- 40 CFR, Part 264—Among the potentially applicable substantive RCRA standards are design and operating specifications for hazardous waste treatment, storage, and disposal units used

at Superfund sites. For example, RCRA hazardous waste incinerator performance standards (Part 264, Subpart 0), such as destruction and removal efficiency and limits on hydrogen chloride and particulate matter emissions, are applicable to hazardous waste incinerators used during remedial actions. RCRA design and operating standards are also applicable to containers and tanks used to store hazardous wastes at CERCLA sites (Part 264, Subparts I and J). RCRA land disposal unit design and operating standards, known collectively as "minimum technological requirements," apply when permanent on-site disposal of hazardous wastes in landfills, waste piles, surface impoundments, or land treatment units is part of the remedy (Part 264, Subpart N).

- Groundwater Monitoring (Part 264, Subpart F)—Additional RCRA standards may be applicable to hazardous waste land disposal units at CERCLA sites. RCRA groundwater monitoring standards, which involve the use of monitoring wells to detect the presence of contaminants in underlying aquifers, are applicable when a Superfund response involves the creation of a new land disposal unit or the remediation of an existing land disposal unit.
- Land Disposal Restrictions (Part 268)—The temporary or permanent placement of restricted hazardous wastes on the land at a CERCLA site may trigger RCRA land disposal restrictions (LDR) treatment standards as applicable requirements. LDR treatment standards, which vary depending on the type of hazardous waste being treated, are concentration- and technology-based standards designed to reduce the mobility and toxicity of hazardous constituents present in hazardous wastes. For LDR treatment standards to apply, placement of restricted hazardous wastes must occur (not all hazardous wastes are necessarily subject to LDR treatment standards). Placement does not occur when restricted hazardous wastes are moved or treated within an area of contamination, which is essentially a discrete zone of continuous contamination at a Superfund site, but may occur in other cases when hazardous wastes come into contact with the land at a Superfund site. EPA guidance further explains the application of LDRs: *Determining When Land Disposal Restrictions (LDRs) Are Applicable to Response Actions* (OSWER Directive 9347.3-05F5) and *Policy for Superfund compliance With the RCRA Land Disposal Restrictions* (OSWER Directive 9347.1-0).
- Closure and Post-Closure (Part 264 Subpart G)—RCRA closure and post-closure requirements may also be applicable to on-site hazardous waste management units, such as tanks, waste piles, and surface impoundments that are taken out of service at Superfund sites. There are two types of potentially applicable RCRA closure schemes: clean closure and landfill closure. Clean closure involves removing or decontaminating all waste residues, contaminated equipment, and contaminated soils so that no additional care or monitoring is required, either at RCRA or CERCLA sites. Landfill closure involves leaving hazardous wastes and contaminated equipment in place and may trigger applicable requirements, such as the use of a final cap or cover for the unit and continued groundwater monitoring in the post-closure period.

2.3.3 Uranium Mill Tailings Radiation Control Act of 1978

UMTRCA was established to protect human health and the environment from mining and milling activities associated with the nation's nuclear program. In the late 1970s, Congress realized that numerous abandoned uranium mining and milling sites across the country posed a

significant threat to the population and the environment. Signed into law in 1978, UMTRCA established specific cleanup levels for 24 sites that were identified by name in the statute.

Regulations in 40 CFR 192 are applicable to the control of residual radioactive material at designated processing or depository sites under Section 108 of UMTRCA. These regulations identify soil cleanup levels for radium-226 and thorium by-product material pursuant to Section 84 of AEA (5 pCi/g on the surface [upper 15 cm] and 15 pCi/g at depth [deeper than 15 cm]). EPA has provided guidance (EPA, 1998) regarding the circumstances under which these soil cleanup criteria could be considered an ARAR (relevant and appropriate) at other CERCLA sites.

2.3.4 Atomic Energy Act

At the time of enactment, AEA and the statutes that amended it provided a single entity (the Atomic Energy Commission) with regulatory responsibility for radioactive materials. In the years that followed, the use of radioactive material grew rapidly. In the 1970s, separate agencies were established to ensure the safe and responsible use of nuclear energy and materials, including DOE, NRC, and EPA. The purpose of AEA (42 U.S.C. Sects. 2011–2259) is to ensure the proper management of source, special nuclear, and by-product material. AEA and the statutes that amended it delegate the control of nuclear energy primarily to DOE, NRC, and EPA.

DOE authority extends to source material, special nuclear material, and by-product material. DOE has authority over numerous programs, including nuclear weapons production and research related to the nation's national security interests. DOE is also the lead federal agency in the remediation of legacy contamination at federal facilities that were and remain engaged in those types of activities.

NRC has a regulatory responsibility for commercial operations involving radioactive material that are not associated with nuclear weapons development or research. That responsibility extends primarily to the commercial power industry, medical industry, and other industrial uses that require the possession and use of radioactive materials.

EPA has the lion's share of responsibility for ensuring that all other federal agencies remediate hazardous substances to levels that are protective for the public and the environment. Under CERCLA, as opposed to NRC's and DOE's dose-response relationships, potential threats to the public and environment are evaluated in terms of risk.

Because of regulatory differences between the agencies with regard to risk- versus dose-based remediation levels, there are occasional conflicts in selecting appropriate cleanup levels for sites under multiple authorities.

2.3.5 Nuclear Regulatory Commission

NRC's mission is to ensure adequate protection of the public health and safety, the common defense and security, and the environment in the use of nuclear materials in the United States. The NRC scope of responsibility includes regulation of commercial nuclear power reactors;

nonpower research, test, and training reactors; fuel cycle facilities; medical, academic, and industrial uses of nuclear materials; and the transport, storage, and disposal of nuclear materials and waste. NRC and its licensees share a common responsibility to protect the public health and safety. Federal regulations and the NRC regulatory program are important elements in the protection of the public. NRC licensees, however, have the primary responsibility for the safe use of nuclear materials.

NRC has promulgated in 10 CFR 20, "Standards for the Protection of Radiation," regulations establishing standards for protection against ionizing radiation resulting from activities conducted under licenses issued by the commission. These regulations are issued under AEA, as amended, and the Energy Reorganization Act of 1974, as amended. The purpose of the regulations is to control the receipt, possession, use, transfer, and disposal of licensed material by any licensee in such a manner that the total dose to an individual (including doses resulting from licensed and unlicensed radioactive material and from radiation sources other than background radiation) does not exceed the standards for protection against radiation. These regulations incorporate a dose response relationship and describe acceptable levels in millirem units.

NRC's *Radiological Criteria for License Termination* (NRC, 1997) is applicable to NRC-licensed sites but not generally applicable to DOE sites. This rule has been adopted as decommissioning requirements by some authorized states. In at least one example, a state's (Colorado's) decommissioning criteria have been determined to be relevant and appropriate for a site (DOE, 1996c). Therefore, calculations of values based on these decommissioning criteria have been considered in the choice of Rocky Flats cleanup goals.

2.3.6 Department of Energy

DOE traces its origin to 1946, when Congress established the Atomic Energy Commission (AEC) to oversee the nation's nuclear weapons and civilian nuclear reactor programs. In 1974, responding to the national energy crisis, Congress consolidated energy research and development programs housed throughout the federal government and combined them with the nonregulatory activities of the AEC to create the Energy Research and Development Administration (ERDA). In 1977, when ERDA achieved Cabinet status, it was renamed the Department of Energy.

A series of orders was developed to implement measures designed to control exposure from radioactive material associated with the nations nuclear weapons and nuclear research programs. Many of these orders were designed specifically to address threats to human health and the environment. Several of these orders that pertain to environmental remediation of radioactive material are addressed below:

- DOE Order 5400.1—Provides the framework for DOE environmental management by establishing environmental protection program requirements, authorities, and responsibilities for DOE operations for assuring compliance with applicable federal, state and local environmental protection laws and regulations, executive orders, and internal DOE policies. This order includes provisions for an annual site environmental report, monitoring requirements, and development of environmental protection programs.

- DOE Order 5400.5—Establishes standards and requirements for operations of the DOE and DOE contractors with respect to protection of members of the public and the environment against undue risk from radiation. Chapter IV of this order contains information that relates directly to cleanup of radioactively contaminated sites. Additionally, this order includes the concept shared with the NRC of "as low as reasonably achievable" (ALARA). As evident, this concept requires DOE to consider the minimization of exposure to an individual to a level that is as low as can reasonably be achieved.
- DOE Order 435.1—Provides specific requirements related to the management of radioactive waste material, meant to ensure that all DOE radioactive waste is managed in a manner that is protective of worker and public health and safety, and the environment.

2.3.7 Defense Nuclear Facility Safety Board

Through Recommendation 94-2, the DNFSB recommended that DOE carry out performance assessments for disposal facilities. The assessments must consider all inventories of past, present, and future low-level waste in the analysis. DOE committed to address this concern by performing a composite analysis of all sources of radioactivity that may interact with the disposal facility to determine appropriate courses of action. The objective of this requirement is to ensure that a performance assessment be conducted to assess potential exposure dose to hypothetical members of the public from the aggregate of residual radioactive material. This is the material that is likely to remain on a DOE site and to add to the dose from an active or planned low-level waste disposal facility.

The performance measures should be consistent with DOE requirements for protection of public and environment and evaluated for a 1,000-year period following disposal facility closure. The assessment results shall be used for planning, radiation protection activities, and future use commitments to minimize the likelihood that current low-level waste disposal activities will result in the need for future corrective or remedial action to adequately protect the public and the environment.

2.3.8 State Standards and Regulations

In RCRA-authorized states, the RCRA-equivalent regulations are considered ARARs under CERCLA or may be applied directly. Other state regulations may be considered relevant and appropriate, such as New Jersey's Soil Remediation Standards for Radioactive Materials and Colorado's decommissioning criteria. Colorado's surface water standards are applied to the Rocky Flats facility through that site's Federal Facility Agreement (DOE, 1996a).

3.0 ASSESSING RADIATION RISK AT CONTAMINATED SITES

Since this study is focused on learning about factors that influence the cleanup levels determined at various sites, it is important to understand the main factors that could potentially vary among sites during the risk assessment process. For this purpose, the following subsections describe the variations due to selection of

- risk assessment approaches (Section 3.1),
- exposure scenarios (Section 3.2),
- computer codes/models (Section 3.3), and
- input parameters (Section 3.4).

In addition, Section 3.5 and 3.6 discuss the selection of cleanup goals and their application during remedial projects. Relevant examples of data collected for the case studies provided in Section 4.0 are also used.

3.1 Risk Assessment Approaches

The methodology used to evaluate health effects due to radiation at contaminated sites depends on the regulatory authority. The two methods for calculating adverse health effects associated with radiation exposure are as follows:

- Dose assessment—where a dose is calculated by multiplying a dose conversion factor (expressed in terms of unit dose/unit intake) for a given radionuclide by the total intake/exposure to that radionuclide (i.e., ingestion, inhalation, or external exposure). The calculated dose can also be multiplied by a probability coefficient to arrive at a risk value.
- Risk assessment (cancer slope factor approach)—where risk is calculated directly by assigning a unit of risk for every unit of exposure (i.e., probability of adverse effect/pCi), and multiplying by the total exposure.

The use of two different methods can be traced back to the different missions of EPA and NRC. Sites regulated by NRC and DOE orders have followed the International Commission on Radiological Protection (ICRP) effective dose equivalent approach. This dose approach originated with the need to protect workers and the public from ongoing nuclear operations. Since dose can be directly measured in the workplace, while cancer risk cannot, it was natural to adopt the dose approach. ICRP methods are based on a "safe dose" below which the exposure to radioactivity is protective of workers and the exposed public. When the NRC began developing criteria for license termination, it simply extended the dose approach to cover cleanup. Cleanup levels were derived using dose conversion factors to back-calculate radionuclide concentrations (activity per mass) corresponding to a target dose. While ongoing doses can be directly measured, future doses to the public must be modeled.

EPA approached the cleanup of radioactively contaminated sites from the perspective of having studied many cancer-causing chemicals. EPA was used to expressing future risks in terms of excess cancer probabilities. This method was simply extended to radionuclides, and an external radiation pathway was added. Low-level exposure to radionuclides can result in noncarcinogenic

risk and well as carcinogenic risk. However, in evaluating exposure to radioactive materials at contaminated sites, only carcinogenic risk is considered for most radionuclides. The noncarcinogenic health effects associated with exposure to ionizing radiation include mutagenic, teratogenic, and acute toxicity effects. However, these effects are generally less significant for doses associated with environmental exposures. Therefore, carcinogenic risk is considered to be a sufficient basis for assessing radiation related to human health risk at sites. The EPA CERCLA approach for risk assessment is the cancer slope factor approach.

The two methods both require exposures to be modeled. Using site conceptual models and exposure scenarios, as described later, the pathways by which radiation can affect the body are determined. These are external exposure, inhalation, direct ingestion of soil, ingestion of contaminated food (plant, meat, milk, or aquatic), and ingestion of drinking water. Using appropriate transfer equations, the quantity of external gamma exposure or intake of internal radionuclides is calculated over a period of time.

Sections 3.1.1 and 3.1.2 provide overviews of the dose and risk assessment methods. Section 3.1.3 compares the two approaches and discusses the divergence in methodology and policies.

3.1.1 Dose Assessment Approach

The dose approach is based on an annual exposure to radiation. "Dose" generally refers to the effective dose equivalent (EDE), a unit of measure developed by ICRP to normalize radiation doses by considering the adverse effects on a total body basis for the purpose of regulation of occupational exposure. EDE is derived by multiplying a dose conversion factor (DCF) for a given radionuclide by the unit intake of exposure to that radionuclide (i.e., ingestion, inhalation, or external exposure). For instance, the standard equation for an inhalation pathway is

Annual Dose (inhalation pathway) = (DCF) x (radionuclide concentration in air) x (breathing rate) x (exposure duration)

DCFs are set by ICRP and expressed as dose per unit exposure. Most workplace standards are based on DCFs in ICRP Publication 30 (ICRP, 1979). However, the newer DCFs in ICRP Publications 72 (ICRP, 1996) have been utilized recently at some sites since they are based on additional scientific data, they are more applicable to the general public, and they correspond to current cancer slope factors. The newer DCFs place more emphasis on the ingestion pathway at the expense of the inhalation pathway. The following factors are considered in the development of DCFs for radionuclides:

- type of radiation,
- relative strength (or energy) of the radiation,
- different radionuclides will target different organs or tissues, and
- different organs or tissues will exhibit different cancer induction rates.

Each radionuclide has a unique DCF and therefore produces different doses. A total dose is the sum of doses from all applicable pathways (ingestion of contaminated soil, water, and plants, inhalation, and external exposure).

Most health physicists are concerned with radiological doses and do not calculate the risk associated with a given dose. They simply compare the dose to an appropriate dose-based standard, e.g., 100 mrem/year for public exposure or 5,000 mrem/year for occupational exposure. However, the risk associated with a given dose can be calculated using a probability coefficient. According to the 1990 recommendations of the ICRP, the probability coefficient from fatal cancers, nonfatal cancers, and severe hereditary effects is 7.3×10^{-2}/sievert (1 sievert = 100,000 mrem). This risk coefficient is based on low, linear energy transfer (LET) (gamma) radiation (clearly not appropriate for some radionuclides) and considers all cancers. The calculation to derive risk from a given dose is

Risk = (total dose) x (probability coefficient in risk/unit dose)

In a position statement, the CRCPD (1998) recommends using the total effective dose equivalent (TEDE) as the basis for uniform criteria for regulating the risk from exposure to radiation. This statement agrees with the National Council on Radiation Protection and Measurements (NCRP) and the ICRP that the dose limit for members of the public should be 100-mrem/year TEDE:

> "This value—100 mrem/year—should be the basis of the standard. The only technical reason for discussion of constraints to lower levels is for the members of the public who may be exposed to more than one such source of radiation at the same time. The CRCPD agrees with the NCRP's opinion that the potential for exposure to multiple exposures is remote. Using currently available instrumentation, it is feasible to measure radiation levels that correspond to a dose level of 25 to 30 mrem/year. A value in this range is sufficient to allow an adequate margin of safety to account for the possibility of exposure to multiple sources of radiation. The meaningful issue is: how far below 100 mrem/year do regulators need to push limits for individual sites to account for the possibility of a person's exposure to multiple sources. . . . Based on widely accepted technical and scientific information, a standard higher than 25 mrem/year would not likely result in a member of the public receiving a dose exceeding 100 mrem/year and would be acceptable."

The CRCPD believes that an all pathways cleanup standard of 25 mrem/year (the NRC promulgated standard) "provides a more than adequate margin of safety below the public dose limit."

The Health Physics Society Position Statement "Return to Background" (Health Physics Society, 1994) states:

> "Cleanup standards should assure that no individual will experience an increased lifetime risk as a result of the residual conditions at a specific site. This goal is achievable by ensuring that the potential dose rates from all residual sources and pathways are within the regional distribution of doses from natural sources. . . . For purposes of limiting lifetime risk, a site-specific dose rate of 10–30 mrem/yr greater than the regional average is well within the natural variations of background and should be considered equivalent to background without demonstrable increased risk."

3.1.2 Cancer Slope Factor Approach

EPA has developed guidance for evaluating risks to human health and the environment from exposure to radioactive substances at sites regulated under CERCLA. This guidance is documented in EPA's *Risk Assessment Guidance for Superfund (RAGS): Part A* (EPA, 1989). The RAGS methodology was developed for use in the remedial investigation/feasibility study (RI/FS) process at the CERCLA sites. This process is specified in the NCP, the implementing regulation for CERCLA (40 CFR 300). The RAGS methodology provides the framework for assessing baseline risks, developing and refining preliminary remediation goals, and evaluating risks associated with various remedial action alternatives. Only cancer risks are considered for most radionuclides; for uranium, noncancer toxicity hazards are also considered. These methods are confirmed and extended in the recently published *Soil Screening Guidance for Radionuclides* (EPA, 2000d). The soil screening levels are not cleanup goals but are risk-based concentrations associated with 10^{-6} risk level, below which the sites do not require further federal attention.

The risks to potentially exposed human receptors is computed as the product of the estimated lifetime intake or external exposure for a contaminant of concern times a measure of the likelihood of incremental cancer induction per unit exposure for that contaminant, termed the "slope factor." A slope factor is similar to a dose conversion factor, but instead of assigning a unit dose for every unit of exposure (i.e., mrem/pCi), a unit of risk is assigned for every unit of exposure (i.e., probability of adverse effect/pCi). The slope factor is an estimate of the probability of a response, i.e., the probability of an individual developing cancer per unit intake of, or external exposure to, a carcinogen over a lifetime. The slope factor multiplied by an estimate of the total lifetime exposure is used to estimate the probability of an individual developing cancer as a result of that exposure. For instance, the standard equation for an inhalation pathway is

Risk (inhalation pathway) = (inhalation slope factor) x (radionuclide concentration in air) x (breathing rate) x (exposure duration) .

Calculating risk directly in this way yields a lower result than calculating risk using the dose conversion method. EPA believes that for internal exposures to alpha and beta emitters, the slope factor method produces a more reliable estimate of risk. In a report developed by the Committee on Evaluation of EPA Guidelines for Exposure to Naturally Occurring Radioactive Materials, the National Research Council (1999) explains how EPA's risk assessment guidance for radionuclides differs from other agencies in terms of scientific basis and policy. The report concludes that "EPA has developed a methodologically more rigorous approach to assessing risk posed by chronic lifetime exposure to radionuclides. . ." and "EPA's approach should provide more realistic estimates of risk than the approach used by the Nuclear Regulatory Commission."

EPA has calculated slope factors for most radionuclides, and—just as different radionuclides have different DCFs—different radionuclides generally have different slope factors. The slope factors also vary depending on route of exposure. Therefore, risk associated with inhaling 1,000 pCi of uranium is different from that of inhaling 1,000 pCi of cesium. Also, the risk associated with inhaling 1,000 pCi of radium is different from that of ingesting 1,000 pCi of radium via drinking water.

Federal Guidance Report No. 13 (EPA, 1999a) provides updated and improved radiation risk coefficients for cancer incidence and mortality. These updated risk coefficients are the basis for new slope factors in the Health Effects Assessment Summary Tables (HEAST) (EPA, 2001b). The risk coefficients were revised because there have been significant developments in the scientific information concerning radiation risk and dosimetry, including

- the most recent epidemiological evidence for cancer risk,
- updated vital statistics,
- improved ICRP biokinetic and dosimetry models (increased the predicted quantities for ingestion and decreased the predicted quantities for inhalation),
- more relevance to the general public, and
- the most recent external dosimetry.

Table 2 shows the major improvements resulting from the new slope factor values.

Table 2. Major Differences Between the New Risk Coefficients/New HEAST Slope Factors and Previous HEAST Slope Factors (Boyd, 2000)

	***Federal Guidance Report No. 13* and 2001 HEAST Radionuclide Slope Factors**	**Previous HEAST Radionuclide Slope Factors**
Cancer risk model	Vital statistics—1989–91, Updated risk model	Vital statistics—1979–81, 1994 risk model
Biokinetic and dosimetry models	Lung model—ICRP 1994 Gut f1—ICRP 1989, 1993, 1995b, and 1996 Systemic models—ICRP 1989, 1993, 1995a, and 1995b Intake rates—age and gender specific Organ mass—age and gender specific	Lung model—ICRP 1979 Gut f1—ICRP 1979 Systemic Models—ICRP 1979 Intake rates—not specified Organ mass—reference adult
External dosimetry models	Based on *Federal Guidance Report No. 12* (EPA, 1993)	Based on MMSOILS and DLSOILS models
Exposure pathways	External Inhalation Ingestion—tap water, food, milk (radioiodine)	External Inhalation Ingestion
Population group	Average member of general public	Adult worker

These updated slope factors are incorporated into EPA's radionuclide PRG electronic calculator (EPA, 2002a), which provides information on developing PRGs for CERCLA sites contaminated with radionuclides. This new tool uses standardized exposure parameters and equations for calculating radionuclide PRGs for residential, commercial/industrial, and agricultural land use exposures, tap water and fish ingestion exposures, and migration of radionuclides through the unsaturated zone.

3.1.3 Comparison of Radiation Risk Assessment Approaches

Traditionally, impacts from exposure to radioactive materials have been expressed in terms of dose. Most radiation protection standards and requirements are specified in terms of a radiation dose limit (e.g., mrem/year). Prior to the development of radionuclide slope factors, cancer risk from radiation exposure was traditionally estimated by multiplying the radiation dose, computed using the DCFs, by an estimate of the cancer risk per unit dose, which is averaged over all organs and tissues. The magnitude of discrepancy in the two methods depends on the particular radionuclide and exposure pathways for the site-specific conditions. These differences may be attributed to factors such as the consideration of competing mortality risks and age-dependent radiation risk models in the development of slope factors, different distribution of relative weights assigned to individual organ risks in the two methods, and differences in dosimetric and toxicological assumptions. The comparison between the bases of the two methods is summarized in Table 3, adopted from EPA's *Radiation Exposure and Risk Assessment Manual* (EPA, 1996a) with additional data from a National Research Council report stating that "many of the differences between EPA and Nuclear Regulatory Commission approaches to risk assessment . . . result from the use by the Nuclear Regulatory Commission, and other federal and state agencies, of the now outdated effective dose equivalent."

EPA believes that dose calculations using DCFs are adequate for assessing the risks of exposure to low-LET radiation (i.e., gamma radiation) but not for assessing risks of internal exposure to alpha- and beta-emitting radionuclides. In the case of internal exposure, the dose assessment methodology generally overestimates the risk. EPA guidance documents have stated that a 15-mrem annual dose corresponds to a 3×10^{-4} risk (EPA, 1997a; EPA, 1999b; EPA 1999c; EPA, 2000b; EPA, 2000d), which it considers essentially the same as a 10^{-4} risk. This conversion is based on the ICRP risk coefficient of 0.073/Sv for external low-LET radiation. The calculation for deriving the 3×10^{-4} risk number is

$$(15\ \text{mrem/year})(30\ \text{years})(7.3 \times 10^{-2}/\text{sievert})(10^{-5}\ \text{sievert/mrem}) \quad = \quad 3 \times 10^{-4}$$

EPA, therefore, has felt that the NRC's 25-mrem/year dose standard allows risks outside the CERCLA risk range. However, EPA has stated in its policy for evaluating whether or not NRC facilities would meet CERCLA protectiveness standards that "EPA expects that the vast majority of facilities decommissioned under NRC authority will be protective of human health and the environment" (EPA, 2000a). For example, in correspondence to the NRC, EPA Region 2 stated that a 25-mrem/year dose limit would be protective of unrestricted use at the West Valley Demonstration Project (EPA, 2001a). EPA states that "Derived Concentration Guideline Limits (DCGLs), that are developed consistent with NRC's guidance for deriving concentration limits to meet the NRC's annual limit of 25-mrem TEDE (total effective dose equivalent), result in a residual risk within the CERCLA risk range of 10^{-4} to 10^{-6}, when calculated in accordance with EPA's Risk Assessment Guidance for Superfund." EPA and NRC also agreed in this case that if residual levels of contamination require restricted release (100 mrem/year and 500 mrem/year), imposing institutional controls would still allow the site to remain within the CERCLA risk range.

Table 3. Comparison of Radiation Risk Estimation Methodologies (modified from EPA, 1996a and National Research Council, 1999)

Parameter	Risk Assessment	Dose Assessment
Competing risks	Persons dying from competing causes of death (e.g., disease, accident) are not considered susceptible to radiation-induced cancer. Probability of dying at a particular age from competing risks is considered based on the mortality rate from all causes at that age in the 1979–81 U.S. population.	Competing risks are not considered explicitly.
Risk models	Age-dependent and sex-dependent risk models for 14 cancer sites are considered individually and integrated into the slope factor estimate.	Separate dose conversion factors for infants, children, and adults. Annual dose requires that infants and children be considered separately.
Genetic risk	Genetic risk is not considered in the slope factor estimate.	Effective dose equivalent value includes genetic risk component.
Dose estimate	Low-LET and high-LET dose estimates considered separately for each target organ.	Dose equivalent includes both low-LET and high-LET radiation multiplied by appropriate relative biological effectiveness (RBE) factors (see below).
Relative biological effectiveness (RBE) for alpha radiation	20 for most sites (8 prior to 1994) 10 for breast (8 prior to 1994) 1 for leukemia (1.117 prior to 1994)	20 (all sites)
Organs considered	Estimates of absorbed dose to 16 target organs/tissues considered for 13 specific cancer sites plus residual cancers.	Effective dose equivalent ICRP 1979 considers dose estimates to 6 specified target organs plus remainder (weighted average of 5 other organs). Effective dose ICRP 1991 considers dose estimates to 12 specified target organs plus remainder (average of 10 other organs).
Lung dose definition	Absorbed dose used to estimate lung cancer risk computed as weighted sum of dose to tracheobronchial region (80%) and pulmonary lung (20%).	Average dose to total lung (mass-weighted sum of nasopharyngeal, tracheobronchial, and pulmonary regions).
Integration period	Variable length (depending on organ-specific risk models and considerations of competing risks) not to exceed 110 years.	Fixed integration period of 50 years typically considered.
Domestic/metabolic models	Metabolic model parameters for dose estimates generally follow ICRP 1979 recommendations; exceptions include transuranic radionuclides.	Typically employ ICRP 1979 and ICRP 1991 models and parameters for radionuclide uptake, distribution, and retention.
Standards	Expressed as a target risk of lifetime excess cancer incidence.	Generally expressed as an annual dose limit.

3.2 Selecting Exposure Scenarios

Selecting appropriate current and future land use scenarios is a critical step in calculating cleanup levels. Scenarios are descriptions of various lifestyles and activity patterns that approximate an individual's exposure to contaminants in environmental media. Conceptual site models display the exposure pathways inherent in a scenario and are useful tools to convey which pathways are reasonable and complete, i.e., capable of transferring harmful effects from radionuclides in surface soil to exposed individuals. By developing conceptual site models, it is possible to estimate representative modes of exposure for target populations, allowing those exposures to be quantified. Figure 1 shows an example of a conceptual site model developed for Rocky Flats.

Depending on the regulatory framework, risk assessors are directed to construct a "reasonable maximum exposure" or the "average member of the critical group" (see Section 3.4). Regulatory guidance directs using current land use as a starting point for establishing exposure scenarios. Alternative future land uses may be considered if they seem possible or likely "based on available information and professional judgment" (EPA, 1989). EPA's withdrawn Radiation Site Cleanup Regulation [40 CFR 196.23(c)] also explained that, to ensure compliance with that section, the implementing agency should not assume catastrophic events, but rather should ". . . assume that the current physical characteristics (i.e., important surface features, soils, geology, hydrogeology, meteorology, and ecology) will exist at the site for the next 1,000 years. . . ." NRC guidance also addresses future land use assumptions. "Site-specific scenarios to calculate doses from residual radioactivity in soil should describe the reasonable land uses and human activities for the future, following license termination. It is reasonable to assume that current land uses in the area will be continued for the period of the dose assessment (1,000 years)." (NRC, 1998).

Generally, cleanup based on a residential scenario (suburban resident, rural resident, resident farmer, or rancher) will allow unres7tricted use of a site. Choosing a less conservative scenario invokes institutional controls and inherent long-term stewardship issues. The considerable difference in half-lives among various radionuclides is an important consideration in deciding whether long-term controls are feasible and therefore may affect exposure scenario selection.

Guidance, including EPA's *Exposure Factors Handbook* (EPA, 1997b), does not prescribe or describe many of the potential scenarios. For example, data on many of the elements pertinent to a Native American lifestyle (e.g., ingestion of wild game, roots, berries, and herbs) may not be readily available. The exposure scenarios of Native American are unique and different from residential or rural residential scenarios. Their food habits and duration of exposure to soil, surface water, and groundwater are different and must be incorporated in the calculation of allowable risk and dose. In the food habit, the reliable assumption must be to quantify consumption of crops, meat, and milk from plant and animals raised upon the waste site; use of medicinal plants; and consumption of fish from ponds/river downgradient from the waste sites. The water used by the Native American for religious ceremonies, drinking, bathing, swimming, watering livestock, and fish production, etc. must be carefully assessed. Depending on the nature of the environment they live in, the site-specific conditions would play an important role.

Table 4 shows the various scenarios selected for risk assessment at selected case study sites.

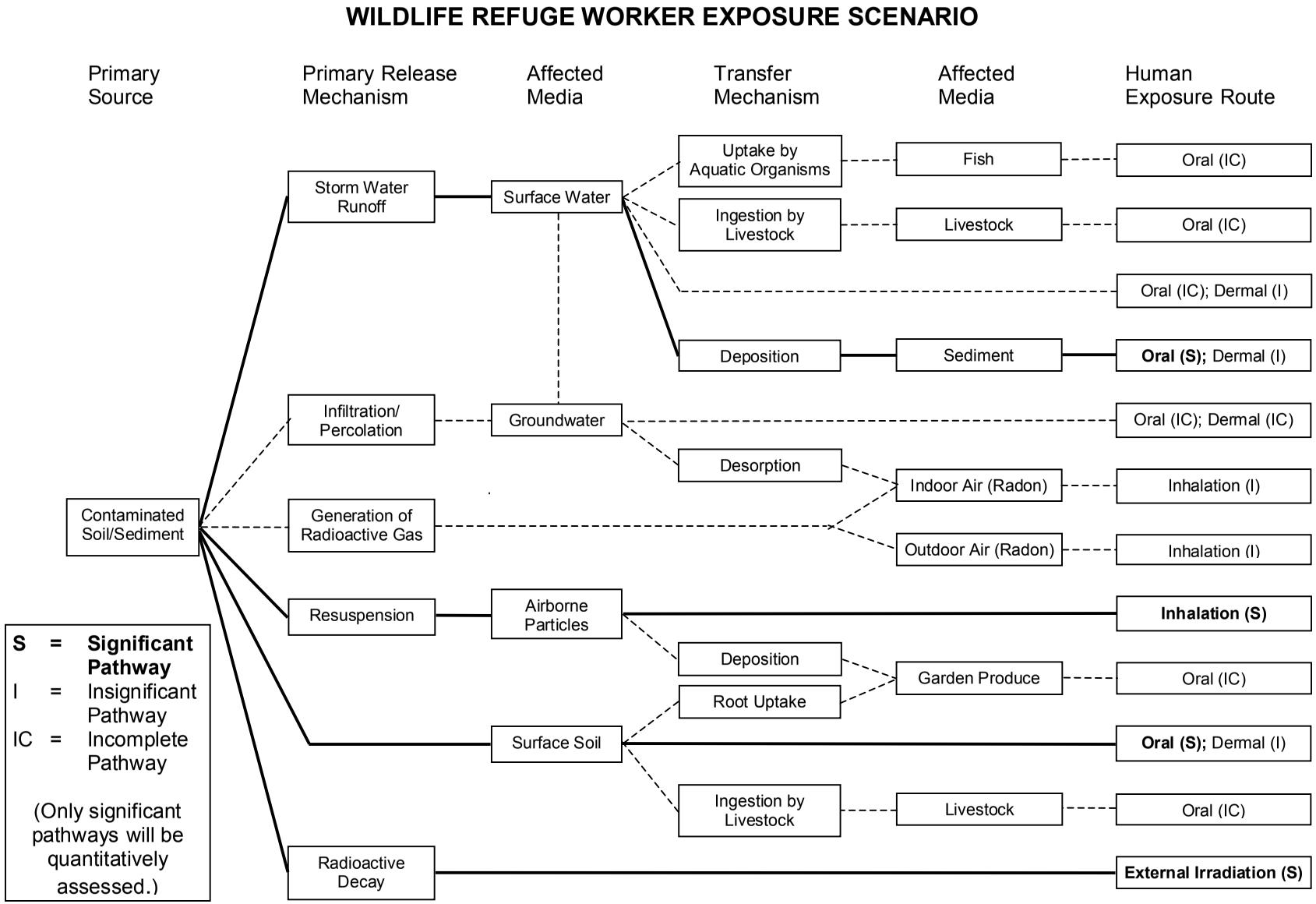

Figure 1. A Conceptual Site Model Developed for Rocky Flats

Table 4. Selection of Exposure Scenarios at Case Study Sites

Site	Scenario								
	Resident	Rancher	Farmer	Park/Open Space User	Commercial/ Industrial	Fish & Wildlife Service	Ecotourist	Homesteader	Subsurface
Brookhaven	✓				✓				
Enewetak	✓		✓						✓
Fernald			✓	✓					
Ft. Dix	✓				✓				
Hanford	✓								
Johnston Atoll	✓					✓	✓	✓	
Linde Site					✓				
Nevada	✓	✓	✓		✓				
Oak Ridge					✓				
Savannah River					✓				
Rocky Flats	✓			✓	✓	✓			
Weldon Spring	✓		✓	✓		✓			

3.3 Selecting Computer Models

Mathematical models are used to approximate human and ecological exposure at a site. The basic equations used to assess health effects due to radiological exposure are relatively straightforward and can be computed with a hand calculator or a spreadsheet. These equations generally sum the exposure from the ingestion, inhalation, and external irradiation pathways, each of which has an intake or source term, an exposure period, and either a dose conversion factor or a cancer slope factor. Modifying factors can be added, which adjust exposure periods and account for fate and transport of radionuclides in the environment. These factors may add considerably to the number of interacting terms and therefore to the complexity of the calculations. Several multimedia/multiple-pathway computer models have been developed to handle these more complex calculations:

- RESRAD family of codes (DOE-Argonne National Laboratory)
- MEPAS (Multimedia Environmental Pollutant Assessment Systems)/ GENII/FRAMES/SUM3 set of codes (Pacific Northwest Laboratories)
- MMSOILS (EPA)
- DandD (NRC)
- Presto-EPA-CPG (EPA)
- PATHRAE-EPA (EPA)

RESRAD (RESidual RADiation) has emerged as the leading computer code for calculating dose. RESRAD is capable of computing activity levels associated with either a dose limit or a target risk level. Seven of the case study sites (Brookhaven, Hanford, Johnston Atoll, Nevada Test Site,

Oak Ridge, Rocky Flats, Weldon Spring) used the RESRAD code to develop either dose-based or risk-based cleanup levels. The RESRAD code implements DOE and NRC guidelines and is endorsed by both agencies as acceptable for evaluating residual radioactivity. Recent improvements include a new air model (Version 5.82). The RESRAD 6.0 version of the code was released in 2000 and offers the ability to enter input parameters as probability distributions rather than discrete values (Yu, et al., 2000).

Various computer codes can be evaluated or compared through processes known as "benchmarking," "verification," and "validation." Benchmarking compares the results from several different computer codes using the same set of problems. Verification is the procedure that tests for internal mathematical consistency and accuracy. Validation is the process that tests a mathematical model against actual field measurements.

Several criteria can be considered during the computer code selection process:

- Does the code incorporate key processes from the conceptual site model?
- Does the code satisfy study objectives?
- Has the code been verified using published analytical equations in scientific and technical journals?
- Has the code been validated against known site conditions?
- Does the code have the capability of inputting probabilistic analyses?
- Is the code well documented?
- Is the model available in the public domain?

While models are extensively used in risk assessment, their selection and interpretation of results need close examination. A National Academy of Science report (Neuman and Ross, 2000) concluded that "There has been a tendency by the DOE and some other agencies to rely excessively on models in the context of waste disposal and site contamination issues." The report's conclusions include the following:

- The model comparison indicated that . . . existing major differences between models are due to their differing objectives—where the capabilities of the models overlap, such differences are due to the formulation of transport components.
- Spreadsheets (or pen-and-pencil calculations) are much more flexible than computer models. The effect of using a computer program rather than a spreadsheet to do the risk assessment is that the assumptions that most need review are hidden where they are not accessible.
- Deterministic models are unable to account for uncertainties in input data and therefore yield outputs (such as contaminant concentrations, exposure doses and risks) of unknown reliability.
- The principle of parsimony should be used to differentiate between alternative operational models. This principle states that among all operational models that one can use to explain a given set of experimental data, one should select the model that is conceptually least complex and involves the smallest number of unknown (fitting) parameters.

- Models are appropriate, often essential, tools for risk assessment and decision-making concerning cleanup and management of contaminated, or potentially contaminated, sites. However, it is inappropriate to use models as "black boxes" without tailoring them to site conditions and basing them firmly on-site data. Neither disregard of models nor overreliance on them is desirable.
- The environment constitutes a complex system that can be described neither with perfect accuracy nor with complete certainty. It is imperative that uncertainties in system conceptualization and model parameters and inputs be properly assessed and translated into corresponding uncertainties in risk and decisions concerning risk management. The quantification of uncertainties requires a statistically meaningful amount of quality site data. Where sufficient site data are not obtainable, uncertainty must be assessed through a rigorous critical review and sensitivity analyses.
- Models and their applications must be transparent to avoid hidden assumptions. Model results must not be accepted at face value, because hidden assumptions are easily manipulated to achieve desired outcomes.
- Decisions concerning site disposition and risk management should account explicitly and realistically for lack of information and uncertainty.
- The monitoring of site conditions and contamination is an imperfect art. It is important that uncertainty associated with monitoring results be assessed a priori and factored explicitly into site remedial design and post-closure management.
- Where effective and affordable science and technology are not readily available for site characterization, remediation, monitoring, and analyses, the DOE should initiate and pursue vigorously a suitable research and development program. The goals of this program should be both short- and long-term. The program should engage a broad array of talents and specialties from government, industry, and academia in order to maintain a proper balance between disciplines.

3.4 Selecting Input Parameters

Many of the key parameters used in calculating cleanup levels are bounded within certain ranges once an exposure scenario is established. For example, typical exposure periods and breathing and ingestion rates for various scenarios have been determined for use in risk or dose calculations (EPA, 1989). In some cases, especially for sensitive parameters, distributions may be available and used in place of discrete values. Using distributions enables the entire range of possible values to be considered for a parameter and helps to account for the uncertainty and variability inherent in parameter selection (EPA, 2001c). Relatively few input parameters used in computer codes or risk equations have significant influence on the resultant cleanup level. These include inhalation rate, dose conversion factors, soil ingestion rate, mass loading for inhalation, and others. Table 5 compares the various input parameters used in calculating risk at some of the sites that are examined in this report.

Table 5. Comparison of Key Residential RESRAD Input Parameters

Parameter	Units	Hanford Site[a]	Johnston Atoll[b]	Clean Slate Sites, Nevada[c]	Rocky Flats Cleanup Agreement[d]	Rocky Flats Oversight Panel[e]	Rocky Flats Revised Soil Action Levels (draft)[f]
Dose limit [or risk range]	mrem/yr	15	[10^{-4}–10^{-6}]	100	15	15	25 [10^{-4} – 10^{-6}]
RESRAD version		5.7	5.82	5.61	5.61	5.82	6.0
Exposure pathways:							
External gamma		Active	Active	Active	Active	Active	Active
Inhalation		Active	Active	Active	Active	Active	Active
Plant ingestion		Active	Active	Active	Active	Active	Active
Meat ingestion		Active	Suppressed	Active	Suppressed	Active	Suppressed
Milk ingestion		Active	Suppressed	Active	Suppressed	Active	Suppressed
Aquatic foods		Active	Suppressed	Suppressed	Suppressed	Suppressed	Suppressed
Drinking water		Active	Suppressed	Active	Suppressed	Active	Suppressed
Soil ingestion		Active	Active	Active	Active	Active	Active
Radon		Suppressed	Active	Active	Suppressed	Suppressed	Suppressed
Plutonium form		Soluble	Insoluble	Soluble	Insoluble	Insoluble	Insoluble
Distribution coefficients (Kd):	cm^3/g						
Americium		200	10,000	1900	76	2300*	1800
Plutonium		200	230,000	550	218	218*	2300
Uranium		2	50	35	50	218*	2.3
Area-contaminated zone	m^2	10,000	98,000	248,000	40,000	*	1,400,000
Thickness-contaminated zone	m	4.6	0.61	0.05	0.15	0.2	0.15
Inhalation rate	m^3/year	7,300	8,400	6,820	7,000	10,800	8,400*
Mass loading (inhalation)	g/m^3	0.0001	0.0002	0.000015	0.000026	0.007*	0.000058*
Exposure duration	year	30	10	30	30	70	30
Inhalation shielding factor		0.4	1	1	1	1	0.7
External gamma shielding factor		0.8	0.5	0.7	0.8	0.7	0.4
Indoor time fraction		0.6	0.25	0.58	1	0.6	0.82*
Outdoor time fraction		0.2	0.75	0.0155	0	0.4	0.14*
Wind speed	m/s	--	9	--	--	4	4.2
Fruits, vegetables, grain ingestion	kg/year	110	1	120.5	40.1	190	85*
Leafy vegetable ingestion	kg/year	2.7	1	10	--	64	6.4*
Soil ingestion	g/year	36.5	73	37.4	70	75	36.5
Drinking water intake	L/year	510		444.6	--	730	--

Parameter	Units	Hanford Site[a]	Johnston Atoll[b]	Clean Slate Sites, Nevada[c]	Rocky Flats Cleanup Agreement[d]	Rocky Flats Oversight Panel[e]	Rocky Flats Revised Soil Action Levels (draft)[f]
Drinking water fraction from groundwater		1	--	1	--	1	--
Depth – soil mixing layer	m	0.15	--	0.15	0.15	0.03	0.15
GI absorption factor (f_1):							
Am-241			1E-3			5E-4	
Pu-239			1E-3			5E-4	
U-238 + D			5E-2			2E-2	
Ingestion slope factor:	risk/pCi						
Am-241			3.28E-10				
Pu-239			3.16E-10				
U-238 + D			6.20E-11				
Inhalation slope factor:	risk/pCi						
Am-241			3.85E-8				
Pu-239			2.78E-8				
U-238 + D			1.24E-8				
External exposure:	risk/year						
Am-241	per pCi/g		4.59E-9				
Pu-239			1.26E-11				
U-238 + D			5.25E-8				
Dose conversion factors:	mrem/pCi						
Inhalation:							
Am-241				4.40E-1	4.44E-1	1.55E-1	
Pu-239				4.29E-1	3.08E-1	5.9E-2	
U-234				1.32E-1	1.32E-1	3.5E-2	
U-235 + D				1.23E-1	1.23E-1	3.1E-2	
U-238 + D				1.18E-1	1.18E-1	3.0E-2	
Ingestion:							
Am-241				3.64E-3	3.64E-3	7.4E-4	
Pu-239				3.54E-3	5.18E-5	9.3E-4	
U-234				2.83E-4	2.83E-4	1.8E-4	
U-235 + D				2.67E-4	2.67E-1	1.7E-4	
U-238 + D				2.69E-4	2.69E-4	1.7E-4	

[a] WDOH, 1997
[b] Uncapher et al., 2000
[c] DOE, 1997
[d] DOE, 1996a
[e] RAC, 2000
[f] EPA et al., 2001

* Derived probabilistically using distributions of data.

When assessing human exposure, EPA guidance (RAGS, Part A) prescribes selecting input parameters so that the combination of all intake variables results in an estimate of the "reasonable maximum exposure" (RME) expected to occur at a site for a given scenario. NRC regulations and guidance (NRC, 1997, 1998) address exposure in terms of the "average member of the critical group," which means "the group of individuals reasonably expected to receive the greatest exposure to residual radioactivity for any applicable set of circumstances."

Behavioral parameters are generally determined, or at least bounded, by the selected exposure scenario. Physical parameters are determined by measurements at or near a particular site, if available. Guidance emphasizes that site-specific values should always be used whenever possible (Yu, et al., 2000). Differences in physical settings from site to site, or between site-specific and default values, account for some of the variations in calculated risk levels.

3.5 Selection of Cleanup Goals

In a risk assessment process, dose-based and/or risk-based values are calculated as described in Section 3.1. In a subsequent risk management process, cleanup goals are established using these calculated soil concentrations as a basis.

Various terms are used, sometimes interchangeably, to describe numbers that guide remedial actions at radioactively contaminated sites. Terms used in the case studies in this report include "action levels," "ALARA goal levels," "allowable residual soil concentrations," "cleanup levels," "cleanup standards," "derived concentration guideline levels," "guideline concentrations," "remedial goal options," "remedial goals," "remediation levels," "risk-based concentrations," "soil cleanup concentrations," and "soil cleanup criteria." Cleanup levels from site to site, or even at a single site, cannot be compared without knowing their purpose, how they were derived, and how they will be applied.

An "action level" in the Superfund program refers to the existence of a contaminant concentration in the environment high enough to warrant action or trigger a response under SARA and NCP. Responses triggered may include actions such as removal, treatment, containment, stabilization, or institutionally controlling exposure. The term can be used similarly in other regulatory programs (EPA, 2002b). An action level is referred to as an "investigation level" in *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)* (EPA, et al., 2000). MARSSIM's "derived concentration guideline levels" are examples of specific investigation levels derived by converting dose or risk from a release criterion into concentration or activity levels that are directly measurable.

"Preliminary remediation goals" (PRGs) are the initial remedial guidelines usually developed early in the RI phase to provide risk-reduction targets. PRGs based on ARARs are generally considered protective for single pathways or contaminants. Risk-based PRGs are developed when multiple pathways or contaminants are present. Numerical PRGs for radionuclides are typically based on the upper-bound carcinogenic risk of one in a million (10^{-6}). Until the final remedy is selected and documented in a ROD or other decision document, PRGs constitute initial guidelines, not final cleanup goals [40 CFR 300.430 (e)(2)(i)].

"Remediation goals" (RGs) are media-specific cleanup goals for a selected remedial action. CERCLA requires the development of ". . . methods and criteria for determining the appropriate extent of removal, remedy, and other measures . . ." for responding to releases of hazardous pollutants and contaminants. [CERCLA Section 105(a)(3)] To meet this requirement, a process defined in the revised NCP evaluates potential remedial alternatives once it has been determined that remediation is warranted. The development of remedial action objectives is directly tied to this alternative evaluation. Numerical RGs, which are part of the remedial action objectives, can be based on existing standards that are ARARs or on risk calculations [40 CFR 300.430(e)]. These two criteria are the "threshold criteria" for evaluating both remedial alternatives and remedial action objectives. Final RGs, along with the final remedy, are selected and documented in a ROD.

Because risk-based PRGs do not necessarily represent realistic exposure and risk, those numbers may not be appropriate cleanup levels. PRGs can be proportionally adjusted upward to become RGs using a level higher in the acceptable carcinogenic risk range to account for the conservatism inherent in the PRGs. Other factors related to technical limitations (e.g., detection or quantification limits) can also be applied. In addition, the "balancing criteria" and the "modifying criteria" for analyzing remedial alternatives, such as cost and state and community acceptance, should also be considered [40 CFR 300.430(e)(2)(i)(A)]. In some cases, RGs may be adjusted downward to account for multiple radionuclides or co-occurring nonradionuclide chemicals. Final RGs are documented in the decision summary section of the ROD as radionuclide-specific "remediation levels" [40 CFR 300.430(f)(5)] or qualitative definition of the risk-reduction cleanup objective to be achieved for the nonnumerical RGs [40CFR 300.430 (Subpart E)].

3.6 Application of Cleanup Goals

Once a cleanup level has been established, differences may still remain in how the value is applied. The application of a cleanup level, whether risk- or dose-based, must be tied in some way to characterization data points. The location and density of these data points may be determined by a variety of characterization sampling schemes:

- Biased sampling—locations where process knowledge, limited analytical data, visible staining, topography, vegetation, etc. suggest the possibility of contamination.
- Standard statistical sampling—a regular, systematic plot of locations in areas of little or no data; MARSSIM (EPA et al., 2000) recommends triangular grids and provides protocols for determining appropriate grid spacing.
- Geostatistical sampling—an iterative process based on a remediating a contaminated area to a required cleanup level at a specified level of confidence; sampling results are used to determine the optimal number and locations of samples to be collected in the next iteration, if necessary.

If multiple radionuclides are present in the environment, the sum-of-ratios (or sum-of-fractions) method is typically used to account for the contribution of each single isotope towards the dose- or risk-based limit. Measured values of all radionuclides present are compared to cleanup levels

by dividing the measured value of each radionuclide by its respective cleanup level, then adding the ratios. If the sum of the individual ratios is greater than 1, then the limit is exceeded:

$$Sum-of-Ratios = \sum_j \frac{C_j \ (pCi/g)}{CG_j \ (pCi/g)} \leq 1 \ ,$$

where

C_j = soil concentration of radionuclide j,
CG_j = cleanup goal for radionuclide j.

Typically, exceedances of cleanup levels are determined by comparing those levels to aggregations of sampling data over specified areas of concern or exposure units. Cleanup criteria at most sites also include hot-spot methodologies, which require evaluation of small areas of elevated sample results within larger areas, which have been determined to require no further remedial action. These hot spot methodologies usually incorporate an area-weighted factor, which—when applied to cleanup levels—provides an upper limit on the amount of activity that can be left in these small isolated spots. Hot-spot criteria are found in DOE Order 5400.5 and in the RESRAD User's Manual (Yu et al., 2000); the hot-spot methodology in MARSSIM is termed "elevated measurement comparison" (EPA et al., 2000).

Setting more restrictive cleanup levels will necessarily lead to more cleanup at a higher cost, but for specific projects at some sites, those increased costs may be incrementally small or may reduce long-term stewardship costs. A study by GAO (2000) examined several EPA, NRC, and DOE analyses of different radionuclide cleanup options and costs. The study concludes that an "examination of DOE's and NRC's analyses showed potential site-specific cost differences of millions of dollars, in some cases, between cleaning up radioactively contaminated soil to 15 millirem a year and cleaning it up to 25 millirem a year, under various scenarios. EPA's analysis showed potential nationwide incremental costs in the low billion dollars to achieve more restrictive cleanup levels." DOE, however, believes that EPA may have significantly underestimated the potential costs of implementing EPA's drinking water standards for groundwater at DOE sites.

4.0 CASE STUDIES

Case studies from 12 radioactively contaminated sites present a background of each site including the site history and nature of contamination. These case studies then discuss the unique manner in which each site developed cleanup levels—the regulatory basis, models, and inputs used and what factors may have been applied to derive a final cleanup number. If actual cleanup has taken place at the site, the status of those activities is reported. Contact information is listed for most sites, including persons who are knowledgeable about the site and Web sites, if available. Data availability varied from site to site. The sites reported are as follows:

1. Brookhaven National Laboratory, New York
2. Enewetak Atoll, Marshall Islands
3. Fernald Environmental Management Project, Ohio
4. Fort Dix, New Jersey
5. Hanford Site, Washington
6. Johnston Atoll
7. Linde Site, New York
8. Nevada Test Site and Associated Ranges, Nevada
9. Rocky Flats, Colorado
10. Oak Ridge, Tennessee
11. Savannah River Site, South Carolina
12. Weldon Spring Site, Missouri

Cleanup levels have been identified for several other sites besides those included in this report. Without the background and context for these values, however, they will not be reported here.

Sections 4.1 through 4.12 describe the case studies in turn, as mapped in Figure 2.

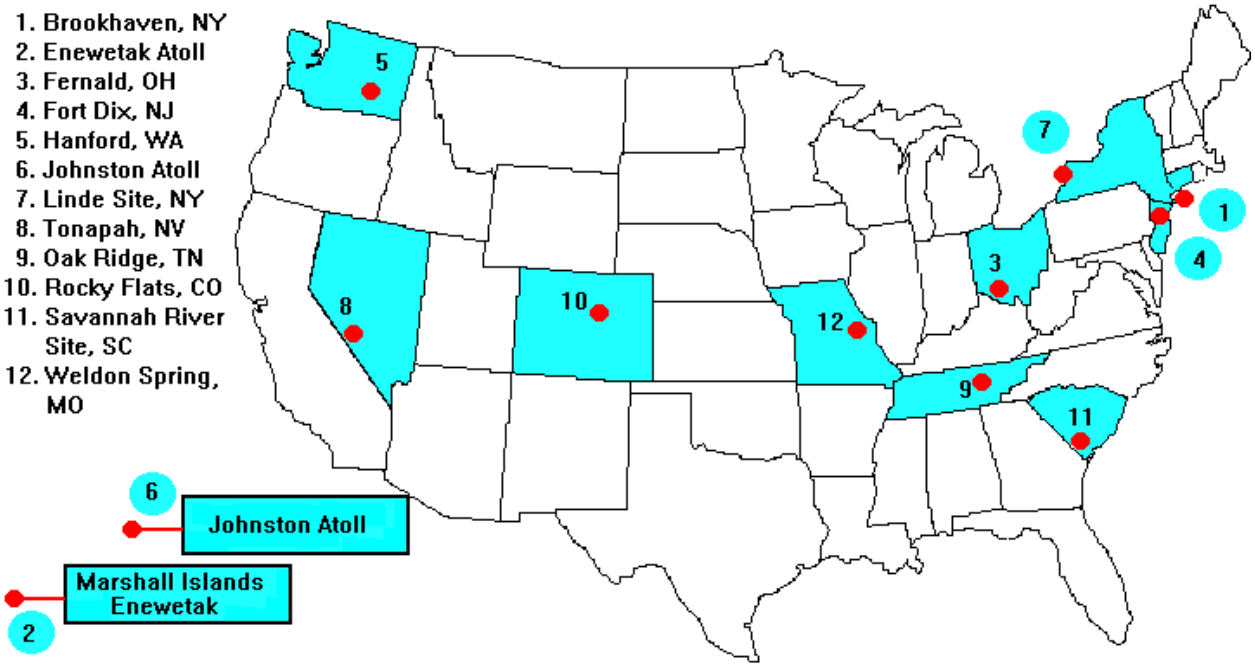

Figure 2. Index Map of Case Study Sites

4.1 Brookhaven National Laboratory, New York

Background

Brookhaven National Laboratory (BNL) consists of 5,320 acres and is about 60 miles east of New York City. Formerly Camp Upton, BNL was administered by the U.S. Army during the World Wars and has been operated by DOE and its predecessors since 1947. This facility processed, treated, and stored radioactive and hazardous waste. The BNL site was placed on New York State's Department of Environmental Conservation (NYDEC) list of inactive hazardous waste sites in 1980 and on the NPL in 1989. Remediation at this site is being done under CERCLA, 40 CFR Part 300. Soils in several areas were contaminated with radionuclides from past waste handling operations, spills, or inadvertent use of contaminated soils for landscaping. Most of the radioactively contaminated soils are at the former Hazardous Waste Management Facility.

Cleanup Level Development

The radionuclide soil cleanup level is based on a total dose limit of 15 mrem/year above background, considering 50 years of institutional controls for the selected land use. This dose limit was based on EPA's draft proposed cleanup rule and is contained in a decision document finalized in October 1999. Residual radiological contamination following remediation will also be within the CERCLA risk range. Specific cleanup levels for individual radionuclides (Table 6) were determined for both residential and industrial land use scenarios, using the RESRAD computer code. Cesium cleanup levels within the former Hazardous Waste Management Facility assumes industrial land use with 50 years of institutional controls and residential land use with 100 years of institutional controls. Outside the facility, cleanup levels for cesium are based on residential land use with 50 years of institutional controls. The cleanup level for strontium-90 is based on impacts to groundwater and is protective of residential and industrial use as well. DOE Order 5400.5 is the basis for the cleanup level chosen for radium-226. NYDEC's guidance of 10 mrem/year above background is an ALARA goal to be considered during remedial design.

Table 6. Brookhaven National Lab Site Cleanup Levels, in pCi/g

Radionuclide	Residential Land Use	Industrial Land Use
Cesium-137	23	67
Strontium-90	15	15
Radium-226	5	5

Remedial Actions

Operable Unit I includes soils at the site contaminated with radionuclides. Over 2,500 cubic yards of landscaping soils with low levels of radionuclides have been excavated and shipped to a disposal facility in Utah. Soil cleanup at Operable Unit I is expected to be completed by 2005. Other areas of radioactively contaminated soils include the Hazardous Waste Management Facility, the Waste Concentration Facility, the Reclamation Facility sump, and tanks at Building 811. Post-remedial sampling will ensure that the dose from all residual radionuclides will not exceed 15 mrem/year (considering 50 years of institutional control for the specified land use).

Contacts

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4.2 Enewetak Atoll

Background

Enewetak Atoll is a ring of 40 islands surrounding a lagoon about 20 miles in diameter. The total area of the islands is about 1800 acres. Before World War II, Enewetak was used as a military base by the Japanese. It was attacked and taken by the United States in February 1944. After the war, AEC required a site for nuclear weapons tests. Enewetak Atoll was selected, and in December 1947 its 136 inhabitants were transported to Ujelang, a nearby atoll. Between 1948 and 1957, forty-three different nuclear devices were detonated on Enewetak, including the largest device tested by the United States. These tests left much of the atoll contaminated with short-lived fission products as well as longer lasting isotopes of plutonium (Pu). In 1971, the U.S. government made the decision to return the atoll to the Trust Territory of the Pacific Islands, and planning for the cleanup was started.

Cleanup Level Development

The remediation of Enewetak represents the first time that the United States attempted to set cleanup standards for Pu. Many different agencies were involved. From the published sources it is not clear how the first standards were derived. It appears that 400 pCi/g was chosen by AEC in 1974 as the maximum exposure and that 1/10 of that level, 40 pCi/g, was considered safe. It was then decided to remove all soil over 400 pCi/g and leave soil below 40 pCi/g. Soil with Pu between 40 pCi/g and 400 pCi/g would be considered on a case-by-case basis. In September 1974, a draft environmental impact statement (EIS) was published that recommended the 40–400 pCi/g standards and rejected cleanup of fission products due to their short half-life and the extreme disruption of islands that removing them would cause. One interesting concept discussed in the EIS is that once a cleanup action was initiated, the Pu concentrations should be reduced to the lowest possible levels, a concept similar to ALARA. During the comment period on the draft EIS, numerous objections were brought up both about the standards and the placement of the waste; nevertheless, the final EIS was nearly identical to the draft.

Although demolition of the buildings and cleanup of the debris were started, controversy over the soil cleanup continued. In August 1977 an independent committee chaired by Dr. W. Blair (the Blair Committee) was formed to recommend a course of action. EPA had recently released its draft guidance on Pu cleanup, which contained a 15-pCi/g cleanup recommendation. This value was rejected as being not applicable to Enewetak. Also planning and budgeting were

already too advanced to allow the project to be delayed by more studies. The Blair Committee generally endorsed the standards in the EIS; meanwhile the short-lived ERDA, successor to the AEC, objected that the new EPA Pu soil standard should apply. The project was again put on hold until a decision could be made. In the meantime the DOE replaced ERDA. In January 1978, the Blair committee was again asked to recommend cleanup levels and made the following recommendations:

- Residential islands should be cleaned up if the average concentration exceeded 40 pCi/g.
- Agriculture islands should be given second priority and should be cleaned up if the average is greater than 80 pCi/g.
- Third priority should be given to the other islands, and they should be cleaned up if the average is greater than 160 pCi/g.

The committee reaffirmed that once the cleanup began, it should continue until a level of at least 40 pCi/g was achieved. The committee recognized that because of the fixed cleanup budget, this standard could result in some islands not being cleaned up and that they may have to be quarantined. This recommendation essentially formed the basis for the soil cleanup.

Remedial Actions

During 1977 and 1978 a total of 253 thousand cubic yards of debris was removed, including nearly 6000 cubic yards of contaminated debris. The soil cleanup went much better than planned, and in the end only one island, Runit, was quarantined due the disposal cell being on the island, even though the surface soil was cleaned up. All the other islands were cleaned to at least the 160 pCi/g standard, and most did not exceed 40 pCi/g (Defense Nuclear Agency, 1981).

Contacts

According to the Defense Threat Reduction Agency, no U.S. agency currently has jurisdiction for any further remediation, per the request of the inhabitants of the island.

4.3 Fernald Environmental Management Project, Ohio

Background

The Fernald Environmental Management Project (Fernald) is a 1500-acre DOE facility about 17 miles northwest of Cincinnati, near the village of Fernald, Ohio. Fernald operated from 1952 to 1989 as the Feed Materials Production Center, a large-scale production facility extracting uranium from ores and ore concentrates to yield high-purity metal products in support of U.S. defense programs. During this period, over 500 million pounds of slightly enriched and depleted uranium metal products was shipped to other DOE sites across the country. Smaller amounts of thorium were also produced. Production stopped in 1989, and the site was added to the NPL. In 1991 the site was officially closed and renamed to reflect its new cleanup mission.

Topography in the area consists of gently rolling uplands with steep hillsides along a major stream. Surface drainage at Fernald is from east to west and south into Paddy's Run, with the

exception of the northeast corner, which drains east toward the Great Miami River. Groundwater is contained in two geologic units: glacial overburden ranging in thickness 0–50 feet and sand and gravel of the Great Miami Aquifer. Groundwater in the glacial overburden is considered perched, since it is contained within silty sand lenses within a low-permeability, clay-rich soil. The underlying Great Miami Aquifer is the principal drinking water supply for the region and is regulated as a sole-source aquifer under the Safe Drinking Water Act.

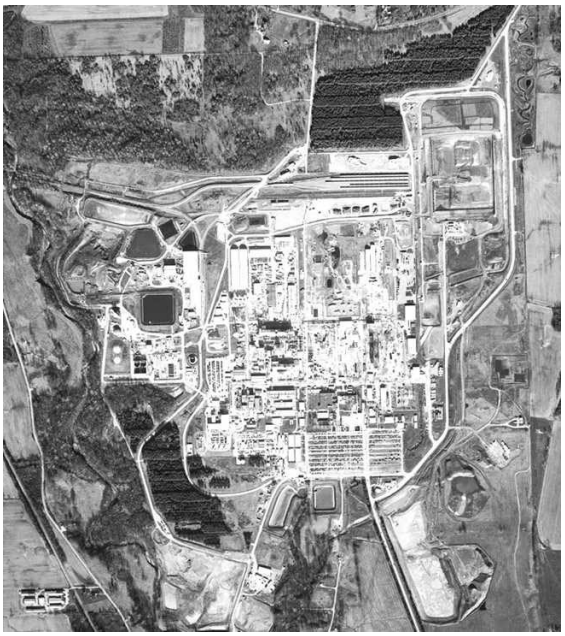

Figure 3. Aerial View of the Fernald Site

Six waste pits used during past operations contain approximately 475,000 tons of waste, including uranium, thorium, and other radioactive and chemical contaminants. The pits range in size from a football field to a baseball diamond, and vary in depth 13–30 feet. Two of the pits have a water cover, one has a synthetic cap, and the others have a soil cover. The waste pits are either in close proximity to, or in contact with, the Great Miami Aquifer and are contributing to contamination of the groundwater.

There are four concrete silos at Fernald that were constructed to store radioactive materials. Two of them, referred to as the K-65 silos, contain high radium-bearing residues, one contains lower-level dried uranium residues, and one has never been used. To reinforce the K-65 silos, a soil berm was added in the 1960s and enlarged in the early 1980s. In 1991, bentonite clay was injected into the tops of the two K-65 silos to cap the high-radium residues and reduce radon emissions from the silos.

Large volumes of contaminated soil exist on site as a result of dumping, spilling, and fugitive emissions during site operations. Disposal areas include the Southern Waste Units, Solid Waste Landfill, and Lime Sludge Ponds. Soil underlying the current production area is contaminated as a result of leaks and spills.

EPA and DOE have a federal facility agreement covering CERCLA remediation and National Emissions Standards for Hazardous Air Pollutants (NESHAPs) activities. The state of Ohio and DOE have a consent order covering hazardous waste, surface water, and natural resource restoration.

Cleanup Level Development

Cleanup levels for the entire site have been established through CERCLA RODs for the five operable units that encompass the site. Soil cleanup levels are risk based using EPA risk assessment guidance and land uses consisting of an on-site undeveloped park and an off-site resident farmer. Groundwater cleanup levels are based upon EPA drinking water maximum contaminant levels (MCLs), proposed MCLs, or risk-based numbers. Table 7 lists cleanup values

presented in the Operable Unit 5 ROD (DOE, 1996c), which addresses the large majority of the site. Cleanup values differ in other portions of the site based upon proximity to groundwater and contaminant type, but are generally similar.

Table 7. Fernald Site Final Remediation Levels (FRLs)

Contaminant	On-Property FRL[a] (pCi/g)	Off-Property FRL[b] (pCi/g)
Cesium-137+1D	1.4×10^{0}	8.2×10^{-1}
Neptunium+1D	3.2×10^{0}	4.9×10^{-1}
Lead-210	3.8×10^{1}	2.2×10^{0}
Plutonium-238	7.8×10^{1}	9.3×10^{0}
Plutonium-239/240	7.7×10^{1}	9.0×10^{0}
Radium-226+8D	1.7×10^{0}	1.5×10^{0}
Radium-228+1D	1.8×10^{0}	1.4×10^{0}
Strontium-90	1.4×10^{1}	6.1×10^{-1}
Technetium-99	3.0×10^{1}	1.0×10^{0}
Thorium-228+7D	1.7×10^{0}	1.5×10^{0}
Thorium-230	2.8×10^{2}	8.0×10^{1}
Thorium-232+10D	1.5×10^{0}	1.4×10^{0}
Uranium, total (K_l = 325 L/kg) (ppm)	8.2×10^{1}	5.0×10^{1}
Uranium, total (K_l = 15 L/kg) (ppm)	2.0×10^{1}	NA

[a] Undeveloped park user scenario at 10^{-6} excess cancer risk.
[b] Resident farmer scenario at 10^{-5} excess cancer risk.

Remedial Actions

- Waste Pits Remedial Action Project (waste storage area, including six waste pits, clear well, and burn pit)—The waste pit contents are being excavated, thermally dried, and shipped by rail to a permitted commercial disposal facility. Significant effort has been put into upgrading on- and off- site rail systems.
- On-Site Disposal Facility (OSDF)—Contaminated soil and debris are being excavated and disposed of in the on-site engineered disposal cell. Any waste that exceeds the waste acceptance criteria will be disposed of off site. No off-site waste will be allowed in the disposal cell. The first waste placement occurred in December 1997. The OSDF is designed to hold 2.5 million yards of waste.
- Facilities Closure and Demolition Project (former production area, including all buildings, equipment, inventoried hazardous material, and scrap metal piles)—All on-site buildings will be decontaminated and dismantled. Debris within the waste acceptance criteria will go in the on-site disposal facility, with higher-level materials going off site. Significant progress has been made in the safe shutdown of nuclear materials by decontamination and dismantling of production facilities. A number of innovative technologies have been deployed during the

decontamination and decommissioning activities, including oxygasoline torch, insulation removal, decontamination equipment, and scanning equipment.

- Silos Project (Silos 1–4, including the K-65 silos, their contents and associated piping and soils)—Due to the 1996 failure in the Vitrification Pilot Plant, an "explanation of significant difference" was completed for Silo 3, and a ROD amendment will be completed for Silos 1 and 2.
- Soils Characterization and Excavation Project (formerly Operating Units [OU] 2 and 5)—Contaminated soils are excavated, and those meeting the waste acceptance criteria are disposed of in the on-site disposal facility. Excavation of the first contaminated soils area was completed in 1997. Technologies being used include a number of field-deployed analytical devices for quick assessment of radionuclide concentrations.
- Aquifer Restoration and Waste Water Project (formerly OU5)—The Great Miami Aquifer will be remediated by a combination of treatment, extraction, and injection of the groundwater. The Advanced Waste Water Treatment Facility was completed in 1994 with additional capacity added in 1998. The South Plume extraction system removal action began pumping in August 1993. The South Field extraction and injection system became operational in the summer of 1998.

The future land use will include natural resource restoration on the majority of the site. Natural resource restoration is part of ongoing negotiations to settle the state of Ohio's natural resource damages claim against DOE. Restoration will include development of wetlands, forests, and prairie areas. Low-impact public access will be allowed. The OSDF will remain and be managed/monitored.

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4.4 Fort Dix, New Jersey

Background

In June 1960, a large fire in an antiaircraft bunker melted the warhead of a Boeing Michigan Aeronautical Research Center (BOMARC) missile, releasing plutonium to the environment. Water used to fight the fire spread the plutonium over the land surface and into the subsurface. Some equipment was eventually removed and the area of contamination covered with layers of concrete. Many of the details regarding this accident and subsequent response remain classified.

Cleanup Level Development

On August 7, 2000, the New Jersey Commission on Radiation Standards promulgated Soil Remediation Standards for Radioactive Materials (N.J.A.C. 7:28-12), intended to apply as an ARAR at radioactively contaminated CERCLA sites. Minimum remediation standards are based on a 15-mrem TEDE limit. This annual dose limit includes the groundwater pathway and equates to 1 standard deviation of the background levels in the state. This dose limit was translated to soil concentration limits using an all-pathways approach. These soil remediation standards are increments above background. Average background concentrations of the radionuclides at a site are determined using MARSSIM methodologies or other approved methods. The sum of fractions rule applies to sites with multiple radionuclides.

DCGLs have been calculated using a spreadsheet for several individual radionuclides (U-234, U-235, U-238, Ra-226, Ac-227, and Th-232). These dose-based DCGLs have been derived for unrestricted use (residential), limited restricted use (institutional controls required), and restricted use (institutional controls and engineering controls required) using parameters from EPA's *Exposure Factors Handbook* (EPA, 1997b) and NRC's NUREG 5512 (NRC, 1992). Table 8 shows the values for 1 foot of contaminated soil.

Table 8. Fort Dix Soil Remediation Standards for Radionuclides, in pCi/g

Radionuclide	Unrestricted Use[a]	Limited Restricted Use[b]	Restricted Use[c] (1-foot cover)
Ac-227	3	5	17
Ra-226	3	5	7
Th-232	2	3	15
U-234	62	69	81
U-235	29	37	62
U-238	54	64	82

[a] Residential use.
[b] Institutional controls required.
[c] Commercial use; institutional and engineering controls required; cover must be maintained

Sites may petition for alternative remediation standards in lieu of the DCGL tables using RESRAD or the spreadsheet RaSoRS. These alternative soil cleanup standards must

- not exceed 15-mrem/year TEDE,
- not exceed 3 pCi/L of radon in indoor air, and
- not exceed New Jersey Groundwater Quality Standards.

Table 9 shows the input values for alternative remediation standards and how they differ for the unrestricted and restricted land use.

Table 9. Standard Input Values for Certain Parameters for Calculating Alternative Soil Standards for Radionuclides at Fort Dix

Parameter	Unrestricted Use	Limited or Restricted Use
Indoor on-site breathing rate (m^3/h)	0.63	1.4
Outdoor on-site breathing rate (m^3/h)	1.40	1.4
Soil ingestion rate (g/year)	70	12.5
Homegrown crop ingestion rate (g/year)	17,136	0
Drinking water consumption rate (L/year)	700	700
Shielding factor through building or slab	0.20	0.20
Shielding factor through wall	0.80	0.80
Shielding factor outside	1	1
Fraction of time spent indoors on site	0.70	0.18
Fraction of time spent outdoors on site	0.05	0.05
Soil-to-vegetation transfer factors (pCi/g wet plant to pCi/g dry soil):		
Thorium	1×10^{-3}	1×10^{-3}
Radium	4×10^{-2}	4×10^{-2}
Lead	1×10^{-2}	1×10^{-2}
Polonium	1×10^{-3}	1×10^{-3}
Uranium	2.5×10^{-3}	2.5×10^{-3}
Actinium	2.5×10^{-3}	2.5×10^{-3}
Protactinium	1×10^{-2}	1×10^{-2}
Bismuth	1×10^{-1}	1×10^{-1}

The U.S. Air Force, which is responsible for the cleanup at Ft. Dix, derived a cleanup level of 8 pCi/g of plutonium for a ROD, which was signed in 1992. This activity level was originally designed to represent a 4-mrem annual dose. Even though this value has not been reduced to account for other radionculides such as americium in-growth, it is acceptable to the New Jersey Department of Environmental Protection since it is considerably lower than an unrestricted cleanup level based on the state's current dose criterion of 15 mrem/year (approximately 25 pCi/g of Pu). The ROD requires the removal and off-site disposition of concrete and soils that exceed the 8 pCi/g cleanup level.

The New Jersey Soil Remediation Standards include a section pertaining to changes in land use. These requirements state that a "subsequent proposed use of a property that is different from the intended use (other than unrestricted use remedial actions) described in the original remediation proposal shall require a prior review and prior approval by the Department [of Environmental Protection]." The department and affected cities must be informed of the following:

- the new land use compared to the original use;
- additional remedial actions, or engineering or institutional controls to be implemented;

- a dose assessment analysis; and
- new characterization data, such as soil concentrations.

Remedial Actions

Remediation of the BOMARC missile site at Ft. Dix is anticipated for 2002. The U.S. Air Force will begin by rebuilding a rail line entirely on federal property, a task expected to be completed by the end of March. Based on characterization data, the Air Force expects to remove approximately 8,000–10,000 cubic yards of soil. Excavation will begin in April and is scheduled for completion in October 2002.

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4.5 Hanford Site, Washington

Background

The DOE Hanford Site occupies 586 square miles in the southeastern portion of Washington state. The site is adjacent to the Columbia River in a semiarid region and constitutes one of the prime remaining examples of shrub-steppe habitat. The site is divided into four different sites listed on the NPL, the 100 Area (nine former production reactors), 200 Area (fuel reprocessing and waste management), 300 Area (fuel fabrication), and 1100 Area (support and outlying areas).

Hanford, a government-owned, contractor-operated facility, is part of the nationwide nuclear weapons complex. Previous operations at the site consisted of fabrication of uranium fuel for irradiation in production reactors (300 Area), irradiation of fuel in eight single-pass and one closed-loop nuclear reactors (100 Area), and recovery of plutonium and uranium from irradiated fuel (200 Area). Each of the primary environmental issues has an estimated cost of $500–5,000 million:

- interim stabilization of the production reactors (100 Area);
- cleanup of burial grounds and liquid waste disposal sites adjacent to the reactors (100 Area);
- retrieval and repackaging of spent nuclear fuel (100 Area);
- disposition of the “canyon”-type reprocessing buildings (200 Area);

- closure of 177 waste tanks, including vitrification of the tank wastes (200 Area);
- environmental restoration of waste treatment, storage, and disposal areas in the former fuel reprocessing (200 Area); and
- environmental restoration of the former fuel fabrication area, including retrieval and treatment of remotely-handled transuranic (TRU) waste from two burial grounds (300 Area).

Cleanup Level Development

DOE, EPA, and the Washington Department of Ecology signed a comprehensive cleanup and compliance agreement, the Tri-Party Agreement (TPA) on May 15, 1989. The TPA prescribes numerous milestones for interim remedial actions (IRAs), including IRA RODs. The RODs typically present chemical-specific remediation levels based on the most restrictive number from different pathways, e.g., (1) protection from direct exposure, (2) contaminant-specific concentration in soil, protective of groundwater, and (3) contaminant-specific concentration in soil, protective of the Columbia River.

Washington's Model Toxics Control Act (MTCA), Washington Administrative Code 173-340 (WDOE, 1996), is an ARAR under CERCLA. Typically, the critical pathway is contaminant-specific concentration in soil, protective of the Columbia River, and is based on (1) a provision in MTCA establishing the relationship that concentrations in soil shall be "equal to less than one hundred times the groundwater cleanup level" and (2) an assumed dilution factor from groundwater into the Columbia River.

MTCA tabulates soil cleanup standards and groundwater cleanup levels under method A (tabulated/routine), and cleanup levels can be calculated using the Cleanup Levels and Risk Calculation (CLARC) risk assessment model for method B (standard/industrial) and method C (conditional application). MTCA requires cleanup to 10^{-5} excess risk for all carcinogens (10^{-6} per contaminant). Proposed revisions to MTCA include methods for assessing impact to terrestrial ecology.

The MTCA risk assessment model is not appropriate for calculating risk due to direct exposure to radionuclides, and the state of Washington has not issued a policy statement regarding the use of MTCA for regulating radionuclides. The Washington Department of Health administers radiation protection standards as an "agreement state" with NRC, but current usage of those regulations is limited to radionuclides in air. The IRA RODs at Hanford generally default to a remediation level of 15 mrem for soil and 4 mrem for groundwater. The RESRAD code is used to calculate dose.

The Hanford Site Risk Assessment Methodology (HSRAM), published in May 1995, ensures the use of consistent exposure scenarios, exposure parameters, and computer models for IRA risk assessments. However, it is only guidance, and it needs to be updated because it was based on then-current EPA risk assessment guidance for Superfund. The methodology is typically applied on an action-specific (IRA-specific) basis and is used to compute remediation levels for particular contaminants of concern. The Native American lifestyle is an important risk scenario for Hanford because of the expectation that, after remediation, Native Americans will resume hunting, fishing, and cultural practices at usual and accustomed places. The HSRAM is weak in

its treatment of ecological risk assessment. Typically, ecological risk assessment has been addressed on either a qualitative basis for particular actions or has been focused on a specific contaminant of concern and specific receptor. Again, the proposed revisions to MTCA include additional tools for ecological risk assessment.

Remediation in the 100 Area provides an example of how cleanup levels have been developed at Hanford. The *Remedial Design Report/Remedial Action Work Plan for the 100 Area* (DOE, 1998) presents RAGs for radionuclide contaminants in soil at the 100-Area liquid-waste disposal sites. These RAGs are intended to support a cleanup that achieves both the remedial action objective (RAO) for direct exposure and the RAO for protection of groundwater and the Columbia River.

A primary goal of the ROD (EPA, 1995), signed in September 1995, is to achieve cleanup levels that would not restrict future land use in the 100 Area. Unrestricted use is represented by a rural residential scenario, and RAGs are based on a 15-mrem annual dose as calculated by the RESRAD code. This dose limit had EPA's draft proposed cleanup rule as its basis. The direct exposure pathways considered in estimating dose from radionuclides in soil are inhalation; soil ingestion; ingestion of homegrown crops, meat, fish, drinking water, and milk; and external gamma exposure. The resident is assumed to live in a house with a basement 3.7 m (12 feet) below grade and to spend 25% of the time in the basement. Doses are calculated separately for fill soil 0–4.6 m (0–15 feet) below grade and for residual contaminants at the bottom of the basement excavation. For most of the radionuclide contaminants of concern in the 100 Area, external gamma exposure is the dominant modeled pathway (inhalation and ingestion contribute little to the total dose). Ingestion pathways dominate for strontium-90, however.

Figure 4. Remedial Activity at the Hanford Site

The single radionuclide values in Table 10 are "intended for use in estimating contamination volumes, screening field sampling and analytical data, and guiding remediation. They are not intended to represent final cleanup concentrations to be achieved by remedial action at a particular site" (DOE, 1998). The most limiting among the RAGs calculated for protection from direct exposure, protection of groundwater, or protection of the Columbia River, is selected as a "look-up" value. Since most sites will have multiple radionuclides driving cleanup, the dose limit would result in individual radionuclide concentrations that are lower than these values. Generic input parameters have been assumed for the purpose of developing the look-up values in this table; many of the important parameters used are listed in Table 4. These parameters are essentially the same developed in guidance by the Washington Department of Health (WDOH,

1997). Final cleanup levels for specific site closeout verification will be determined using site-specific parameters. Deed restrictions are required to prohibit excavation in areas where concentrations below the 4.6-m (15-foot) level exceed the direct-exposure RAGs.

Table 10. Remedial Action Goals for the 100 Area at the Hanford Site (DOE, 1998)

Radionuclide	Remedial Action Goal for Direct Exposure[a] (pCi/g)	Soil Concentration Protective of Groundwater/ Columbia River[b] (pCi/g)	Remedial Action Goals—Look-Up Values (pCi/g)	
			Shallow Zone[c] <4.6 m (15 feet)	Deep Zone[d] >4.6 m (15 feet)
Americium-241	31.1	1,577,000	31.1	1,577,000
Cesium-137	6.2	[e]	6.2	NA
Cobalt-60	1.4	[e]	1.4	NA
Europium-152	3.3	[e]	3.3	NA
Europium-154	3.0	[e]	3.0	NA
Europium-155	125	[e]	125	NA
Nickel-63	4,026	[e]	4,026	NA
Plutonium-238	37.2	1,123	37.2	1,123
Plutonium-239/240	33.9	718,600	33.9	718,600
Strontium-90	4.5	[e]	4.5	NA
Technetium-99	15	15[f]	15[f]	15[f]
Thorium-232	1.3	[e]	1.3	NA
Tritium (H-3)	510	35.5	510	35.5
Uranium-233/234	1.1	1.1[g]	1.1[g]	1.1[g]
Uranium-235	1.0	1.0[f]	1.0[f]	1.0[f]
Uranium-238	1.1	1.1[g]	1.1[g]	1.1[g]

[a] 15-mrem dose to a rural resident.
[b] Soil concentration that either corresponds to a 4-mrem annual dose or achieves the groundwater/river protection RAGs per RESRAD calculations.
[c] In the shallow zone, cleanup must achieve the direct exposure RAO and the groundwater/Columbia River RAO; therefore, the lowest value associated with those RAOs is the applicable look-up value.
[d] In the deep zone, cleanup must achieve the groundwater/Columbia River RAO; therefore, the lowest value associated with that RAO is the applicable look-up value.
[e] RESRAD predicts the radionuclide will not reach groundwater within a 1,000-year timeframe.
[f] The RAG is below the practical quantitation limit (PQL); the value presented is the PQL.
[g] The RAG is below background; the value presented is background.

Remedial Actions

Remedial actions are scheduled over multiple decades ending in 2050:

- Interim stabilization of the production reactors (100 Area) is required by 2018, but negotiations in progress (as of December 2001) projected completion by 2012. The reactors will be allowed to "decay in place" for 70 years to allow short-lived radionuclides to decay to inconsequential concentrations. DOE plans to make final disposition of the reactors after that.
- Cleanup of burial grounds and liquid waste disposal sites adjacent to the reactors (100 Area) is 30% complete and will finish by 2012.

- Retrieval and repackaging of spent nuclear fuel (100 Area) is in progress and will finish by 2006. Waste residuals—fuel packed in canisters—will be stored in the 200 Area pending construction of the national high-level waste repository.
- Options for disposition of the "canyon"-type reprocessing buildings (200 Area) are being evaluated and may dovetail with soil remediation schedules. One option is use of the canyons for waste disposal.
- Closure of 177 waste tanks, including vitrification of the tank wastes (200 Area) is on a multiple-decade schedule. DOE has an enforceable milestone to construct and operate a waste treatment plant (vitrification plant).
- RI/FS for environmental restoration of waste treatment, storage, and disposal areas in the former fuel reprocessing (200) area will be completed by 2008. Schedules for remedial actions are being negotiated (as of December 2001).
- Environmental restoration of the former fuel fabrication area, including retrieval and treatment of remotely handled TRU waste from two burial grounds (300 Area) will be completed by 2018.

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4.6 Johnston Atoll

Background

Johnston Atoll is located between Hawaii and the Marshall Islands. Oahu, 720 nautical miles northwest of the atoll, is the closest inhabited island. The atoll originated as a volcanic island but is now composed exclusively of coral. There were no indigenous people on the islands, and until World War II the islands were only occasionally inhabited. Since 1941, the atoll has been used as a military reservation. The atoll is composed of two islands, Johnston Island and Sand Island. Johnston Island was originally about 46 acres, but after several periods of dredging, the area at the time of the nuclear tests was 185 acres. Since the tests, the island has been further enlarged to 625 acres. The atoll has been determined to have no further defense mission and remains an unincorporated territory of the United States. Operational control is currently held by the Defense Threat Reduction Agency (DTRA) of the Department of Defense. After cleanup, the

island will be declared a wildlife refuge under the administration of the U.S. Fish and Wildlife Service.

The contamination on Johnston Atoll was caused by three separate accidents involving THOR rockets during high-altitude tests of nuclear devices during the summer and fall of 1962. None of the accidents resulted in an accidental detonation of a nuclear device. One rocket exploded on the pad on Johnston Island, distributing coarse plutonium particles over the immediate area around the launch pad. Two rockets were destroyed by the range safety officer at altitudes of 30,000 and 109,000 feet over Johnston Atoll. The explosion at 30,000 feet definitely contaminated large areas of the atoll. The higher-altitude explosion may also have contaminated the atoll. The most serious contamination was in the immediate area of the launch pad. During cleanup, some of the material was placed in the lagoon, along with some debris from the high-altitude rocket explosions, which rained down on the lagoon. Later dredging efforts to expand the island resulted in some of this contamination being spread over other areas on the island.

Cleanup Level Development

In the late 1980s a cleanup level of 13.5 pCi/g was adopted for plutonium. This level was derived for a 10-mrem dose based on EPA draft guidance for dose limits for exposure (EPA, 1977). That guidance has now been superseded by the current EPA guidance using lifetime cancer risk (EPA, 1989).

The DTRA issued the *Johnston Atoll Radiological Survey* (Uncapher, et al., 2000) in January 2000. Appendix C, "An Assessment of the Risks on Johnston Island," describes how cleanup levels were developed. RESRAD Version 5.82 program was used to determine cleanup levels that correspond to specific risk levels in the CERCLA risk range. Instead of entering a dose limit, the program was run in the cancer risk mode. This mode is not documented, but the program is fully capable of utilizing cancer slope factors to set a soil action level. Key model input parameters are listed in Table 5, where they are compared to parameters used by other sites.

Four separate scenarios were investigated. Two of these are similar in that they involve a cleanup worker and a Fish and Wildlife Service worker. The difference between the two is that, although both work outdoors in a dusty environment and ingest a large amount of soil, the cleanup worker also grows a modest amount of vegetables and, because of the soil disturbance, breaths twice the dust (0.0002 g/m^{-3}). The third scenario is an ecotourist who visits the island for two weeks a year to observe seabirds; therefore, his exposure is less. The last scenario is a homesteader that surreptitiously lives on the island. The study used a soil ingestion rate of 73 g/year for the two worker scenarios and 36 g/year for the homesteader. The *EPA Exposure Factors Handbook* recommends 18 g/year for adults, while the RESRAD default value is 36 g/year. On this basis, the values are conservative. Total excess cancer risk was calculated by the RESRAD code using cancer risk factors from the 1997 HEAST (EPA, 1997c). The risk is greatest in the first year for all exposure scenarios. The estimated total excess lifetime risk per pCi/g of TRU alpha exposure results are given in Table 11.

Table 11. Allowable Residual Soil Concentrations at Johnson Atoll, in pCi/g of TRU alpha

Cancer Risk	Fish and Wildlife Worker	Resident	Ecotourist	Homesteader
10^{-6}	2.1	1.9	38	0.32
10^{-5}	21	19	380	3.2
10^{-4}	210	190	3800	32

If the pathways that produced the risks are examined, the ingestion pathway, especially soil ingestion, dominates, as shown in Table 12.

Table 12. Contribution of Exposure Pathways to Calculated Risk at Johnson Atoll, in percent

Pathway	Fish and Wildlife Worker	Resident	Ecotourist	Homesteader
Inhalation	4.9	9.3	1.8	3.7
Soil ingestion	86.9	82.2	16.1	34.9
Plant ingestion	0	0.7	0	56.6
External exposure	8.2	7.7	82.1	4.6

Following release of its *Johnston Atoll Radiological Survey*, DTRA proposed a cleanup standard of 40 pCi/g, which is an estimated 2.1×10^{-5} risk to a hypothetical resident.

In September 2000, EPA Region 9 responded to DTRA's proposed cleanup standard and risk assessment (EPA, 2000a), concluding that "the Johnston Atoll radiological risk assessment conforms with the standard and uniform methods for the evaluation of site-specific risk" and that the exposure parameters used are reasonable and appropriate. Any of the values calculated for the three risk levels are consistent with EPA's policies. In determining an RME, EPA rejected the homesteader scenario as overly conservative because of the 70-year exposure duration, the remote location, and the lack of potable water and productive soils. The ecotourist was considered insufficiently conservative, since the Fish and Wildlife Service planned to remain on the atoll. The other two scenarios are nearly identical, and EPA selected the resident to represent the RME for an individual.

EPA recommended a cleanup level of 13.5 pCi/g, the historically used value, which equates to a 7.1×10^{-6} risk to a resident. EPA considers this value ALARA, since DTRA had previously achieved this level, and believes this lower level will help to account for the presence of other contaminants, such as dioxins, polychlorinated biphenyls, and lead.

Remedial Actions

The island has undergone several previous cleanup attempts. In 1962, the debris from the destroyed rockets and some surface coral were loaded into landing craft and disposed of at sea. The less-contaminated soil was dumped into the lagoon. No formal cleanup standard was used to determine the extent of the cleanup. Two years later the lagoon was dredged, and most of the contaminated soil was incorporated into the island. At the end of November 2000, the U.S. Army

announced that all of the 400,000 chemical weapons that had been stockpiled on Johnston Atoll had been destroyed. The disposal facility used for the project will be shut down, and the islands turned over to the Fish and Wildlife Service.

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4.7 Linde Site, New York

Background

The Linde Site is located in the town of Tonawanda, New York, near Buffalo. From 1942 to 1946 (or 1948 according to some records), this site was used for separation of uranium ores from Colorado and the Congo under the Manhattan Engineering District. Ores were processed in three phases: uranium separation from the ore, conversion of U_3O_8 to uranium dioxide, and conversion of UO_2 to UF_4. The principal contaminants of concern resulted from the first processing phase; residues from the other phases were recycled. Disposal of processing wastes from the Linde property also contaminated three other sites in Tonawanda. Radioactive contamination occurs in processing buildings, surface and subsurface soils, and sediments in sumps and storm and sanitary sewers. Also, approximately 55 million gallons of waste effluent containing dissolved uranium dioxide was injected into the subsurface through seven wells during a three-year period. The RI (BNI, 1993) concluded that subsurface radioactive contamination probably occurs as minor amounts of immobile uranyl sulfates and carbonates precipitate in the underlying shale.

Cleanup Level Development

The Army Corps of Engineers became the lead regulatory agency for the Linde site in 1998, when Congress handed the Formerly Utilized Sites Remedial Action Program (FUSRAP) to the Corps. DOE had previously handled the cleanup effort and had issued a proposed plan in 1993, calling for a cleanup level of 60 pCi/g for total uranium. In accordance with the NCP requirement that selected remedies comply with ARARs, the Corps reviewed UMTRCA for applicability. Standards in UMTRCA (40 CFR Part 192) are not considered applicable since the

regulation applies only to specific sites designated in the act. The Corps, however, determined that UMTRCA is relevant and appropriate to the Linde Site cleanup since the processing activities and radionuclides in the resulting wastes are similar to those at uranium mill sites. In a new proposed plan (USACE, 1999) issued in March 1999 and in a ROD (USACE, 2000) signed in June 2000, the Corps calculated new cleanup levels based on UMTRCA.

Subpart A of 40 CFR 192 establishes groundwater standards including maximum radionuclide concentrations:

- combined Ra-226 and Ra-228: 5 pCi/L,
- combined U-234 and U-238: 30 pCi/L, and
- gross alpha particle activity (excluding radon and uranium): 15 pCi/L.

A review by the Corps of previous groundwater sampling results shows that these standards are not exceeded. Based on these results and information that showed that groundwater at the site is not potable, the Corps concluded that groundwater at the Linde Site does not need to be remedied.

Subpart B of 40 CFR 192 addresses cleanup of soil and buildings and sets standards for residual concentrations of Ra-226 in soil. Radium concentrations cannot exceed background by more than 5 pCi/g in the upper 15 cm of soil or 15 pCi/g in any 15-cm layer below the upper layer, averaged over an area of 100 m^2.

Subpart D of 40 CFR 192 requires that releases of Rn-222 and Rn-220 into the atmosphere cannot exceed an average rate of 20 pCi/m^2-sec. The proposed plan concludes that implementation of the proposed remedy will result in releases that are below this limit.

In addition to UMTRCA requirements, the Corps also developed cleanup levels for various risks and doses (USACE, 1999). This cleanup guideline for total uranium applies to areas of the Linde site where soils are predominantly contaminated with uranium and very little radium and thorium. A risk assessment conducted by the Corps considered the radiological risk as well as the chemical toxicity of uranium. That assessment used the RESRAD computer code (Version 5.782) and considered the most likely future land use to be the site's current industrial/commercial use. A cleanup level of 600 pCi/g for uranium was calculated based on limiting potential radiological risks to 10^{-5}. This 600-pCi/g cleanup level for uranium, together with the UMTRCA criteria, form the cleanup requirements for the Linde Site. The calculated values shown in Table 13 used the input parameters given in Table 14.

Table 13. RESRAD-Calculated Estimates for the Commercial/Industrial Exposure Scenario to Meet Acceptable Dose and Risk Limits at the Linde Site

Radionuclide	Residual Concentration (pCi/g)					
	10 mrem/year		25 mrem/year		10^{-4} risk	
	6-inch cover	No cover	6-inch cover	No cover	6-inch cover	No cover
Ra-226	37	5.7	92	14	25	6.1
Th-230	107	16	267	41	71	11
Th-232	23	3.9	58	9.8	16	2.8
Total U[a]	1,888	629	4,720	1,572	7,400	6,200

[a] Total uranium includes U-238, U-235, and U-234 at natural concentration ratios (1.0/0.05/1.0, respectively).

Table 14. Future Industrial/Commercial Worker Parameters—Linde Site

RESRAD Parameter	Value
Area of impacted zone	2,000 m^2
Thickness of impacted zone	3 m
Cover depth	0–0.15 m
Inhalation rate	8,400 m^3/year
Mass loading for inhalation	0.0001 g/m^3
Exposure duration	25 years
Shielding factor, inhalation	0.4
Shielding factor, external gamma	0.7
Fraction of time indoors	0.2
Fraction of time outdoors	0.03
Soil ingestion rate	18.25 g/year
Drinking water intake	0 L/year

In response to public comments, the Corps redefined how cleanup levels were derived. Subsequent to the cleanup levels calculated for the radiological assessment, a new amendment to 10 CFR 40, Appendix A, Criterion 6(6) was promulgated, which addressed areas contaminated with radionuclides in addition to radium. This criterion states that post-remedial radioactive contamination, considering all radionuclides including radium, cannot result in a TEDE to the average member of the critical group exceeding the benchmark dose after cleanup to the 40 CFR Part 192 standards for soils contaminated with radium only. The benchmark dose for surface cleanup was derived by dividing the 10 mrem/year (with no cover) by the 5.7 pCi/g of Ra-226 associated with that dose, and then multiplying the result by 5 pCi/g of Ra-226, resulting in a benchmark dose of 8.8 mrem/year for surface cleanups. The 10-mrem values for Th-230 and total uranium were used to calculate allowable concentrations for those radionuclides. The same methodology was used to derive a benchmark dose for subsurface cleanup levels as well. These calculated benchmark dose values are shown in Table 15.

Table 15. Allowable Residual Concentration Limit for Indicated Benchmark Dose—Linde Site, in pCi/g

Radionuclide	Surface Soil 8.8 mrem/year	Subsurface Soil 4.1 mrem/year
Ra-226	5.0	15
Th-230	14	44
U-total	554	3,021

This new method of deriving cleanup levels resulted in a more stringent cleanup for total uranium than was required in the proposed plan. Radionuclide concentrations remaining in soils averaged over 100 m^2 must be below these levels. If more than one residual radionuclide is present in a 100-m^2 area, the sum-of-the-ratios methodology will be applied. The ROD also commits that no concentration (hotspots) of total uranium greater than 600 pCi/g above background will remain in site soils.

The ROD for the Linde site was signed in March 2000 by the Corps' Deputy Commanding General for Civil Works. EPA Region 2 and the New York Department of Environmental Conservation and Department of Health, however, have refused to support the cleanup levels designated in the ROD. The agencies disagree with these levels for several reasons:

- Since the site will not be government owned, only a residential-based assessment will protect against future changes in ownership.
- The current industrial/commercial use is not sufficiently protective of future uses.
- The cleanup level calculations exclude a groundwater pathway.
- The ALARA concept was not incorporated.
- The calculations are not consistent with NRC guidance.
- The calculations do not consider state guidance in Technical and Administrative Guidance Memorandum #4003, which limits exposure of maximally exposed individuals to 10 mrem/year.

The Corps expects that its remedial actions will lower the average activity levels due to residual contamination to about 60 pCi/g for uranium and 5 pCi/g for radium. The state would accept this level of cleanup, which is the level originally presented in the 1993 proposed plan. The state plans to require a radioactive materials license for any future landowner if the residual radiation is greater than 0.05% by weight. EPA's position is that the cleanup level should be below 100 pCi/g, a level "consistent with cleanup levels at other CERCLA radiation sites."

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4.8 Nevada Test Site and Associated Test Ranges, Nevada

Background

The Nevada Test Site (NTS) is a DOE, National Nuclear Security Administration Nevada Operations Office (NNSA/NV) installation occupying approximately 1,505 square miles in southeastern Nye County, Nevada. The site is situated about 65 miles northwest of Las Vegas, home to 1.2 million residents and annual visitor counts now exceeding 30 million. NTS is larger than the state of Rhode Island, and site features include deserts, playas, and mountainous terrain. NTS was established in 1951 as the nation's proving ground for testing and development of nuclear weapons. Between 1951 and 1992, the federal government conducted just over 900 nuclear tests at the site. One hundred of these tests were conducted above ground. NTS is surrounded by thousands of additional acres withdrawn from the public domain for use as a protected wildlife refuge and for military gunnery ranges, creating an unpopulated land area comprising some 5,470 square miles.

NNSA/NV also conducted numerous safety experiments at NTS and on the Nellis Air Force Range (NAFR) complex. These experiments were conducted at five NAFR locations—Double Tracks; Clean Slates 1, 2, and 3; and Project 57—to determine the behavior of nuclear weapons in conventional explosive accident scenarios during handling, storage, and transportation operations and to determine the biological uptake of plutonium by various species of animals and plants. These experiments did not produce nuclear explosions; however, they did create significant surface contamination. The depth of contamination at these soil sites varies, and NNSA/NV has estimated that about 2,885 acres is contaminated with plutonium at levels in excess of 40 pCi/g.

In May 1996, the Nevada Division of Environmental Protection (NDEP) and the NNSA/NV signed a federal facilities agreement and consent order that, in part, authorized NDEP to oversee NNSA/NV's remediation of radiologically contaminated surface soil sites in the state. "Clean Slate" sites will be the focus of this remediation effort, Operation Roller Coaster. Operation Roller Coaster was a series of tests conducted to determine the effects of plutonium dispersion. Concentrations of these radioactive materials at the Clean Slate sites range from background to more than 12,800 pCi/g. The sites are located on the Tonopah Test Range, approximately 130

miles northwest of Las Vegas and 40 miles southeast of Tonopah, Nevada, in the high desert region of south central Nevada at an elevation of 5,380 feet.

Cleanup Level Development

Proposed interim cleanup actions by DOE at the Clean Slate 1, 2, and 3; Double Tracks; and Project 57 sites were based on a 200-mrem cleanup level established in *Radiological Dose Assessment for Residual Radioactive Material in Soil at the Clean Slate Sites 1, 2, and 3, Tonapah Test Range* (DOE, 1997). This assessment reviewed several dose analyses previously performed in the area of NTS. Each of these analyses used different exposure scenarios and parameter values. Although these analyses varied in their assumptions, the general conclusion reached by the dose assessment was that an average activity level of 200 pCi/g would ensure that the public dose limit of 100 mrem/year in DOE Order 5400.5 would be met. The RESRAD computer code evaluated four human exposure scenarios by means of an environmental pathway analysis performed by a forward calculation of the RESRAD computer code for the following receptors: rancher, farmer, rural resident, and industrial worker.

The two agricultural scenarios were considered implausible by DOE but were included for completeness. The maximum committed effective dose equivalent (CEDE) calculated in the dose assessment, 47 mrem/year to a rancher, is less than half the basic dose limit in DOE Order 5400.5. The rural residential and industrial worker scenarios were included because they were established as part of EPA's draft proposed cleanup regulations (EPA, 1996b). This proposed regulation was not considered applicable to DOE operations, but the scenarios were included for comparison. Calculated CEDE values for both these scenarios were less than the 15-mrem/year dose limit in the draft proposed EPA regulations. For the purpose of calculating "guideline concentrations," the Pu-239/240:Am-241 ratio was assumed be 14:1, and the depth of contamination was assumed to be 5 cm. These guideline concentrations were never accepted by NDEP as cleanup levels. Tables 16 and 17 show the calculated dose and key parameters used for different receptors at the site.

Table 16. DOE-Calculated Dose to Hypothetical Individuals Exposed to 200 pCi/g at the Clean Slate Sites, in mrem/year

Scenario	Clean Slate 1	Clean Slate 2	Clean Slate 3
Rancher	47	47	46
Rancher child	23	23	22
Farmer	12	12	12
Rural resident	13	13	13
Industrial worker	4.5	4.4	4.4

Table 17. Key Parameter Values Used for Exposure Scenarios in the Clean Slate Sites Dose Assessment

Parameter	Rural Resident	Rancher	Farmer	Industrial Worker	Child
Exposure frequency (day/year)	341	341	341	250	330
Inhalation (m^3/d)	20	22	22	12.6	12.3
Soil ingestion (mg/d)	120	131	129	50	24
Exposure time indoors (h/d)	14.9	9	9	8	18.4
Exposure time outdoors(h/d)	0.4	15	15	2	5.6
Shielding factor—indoor inhalation	0.4	1	1	0.4	0.4
Drinking water ingestion (L/d)	1.4	1.86	1.86	0.875	0.32
Leafy vegetable ingestion (g/d)	29.5	29.5	29.5	0	18.5
Plant ingestion (g/d)	354	354	353	0	397
Milk ingestion (L/d)	0.61	0.61	0.61	0	1.18
Meat/egg ingestion (g/d)	274	274	274	0	153

NNSA/NV proposed interim remediation requirements for the Clean Slate 1, 2, and 3; Double Tracks; and Project 57 sites were

- average soil concentrations over any 100-m^2 area must not exceed 200 pCi/g;
- plutonium hotspot concentrations averaged over an area of 25 m^2 or less must not exceed the guideline concentration by a factor of (100/hotspot area in meters)$^{0.5}$ [DOE Order 5400.5, Chapter IV, Section 4.a.(1)]; and
- reasonable efforts must be made to remove any source of radionuclides that exceeds 30 times the guideline levels, regardless of the average concentrations.

This interim action, however, did not achieve this guideline concentration level. NNSA/NV did some ground-zero remediation and used the KIWI system, which consists of a Chevrolet Suburban with six $2 \times 4 \times 16$–inch sodium iodide detectors mounted in a frame at the rear of the vehicle, to verify that cleanup levels were reached. NNSA/NV then decided to have a segmented gate technology demonstration conducted at Clean Slate I to see whether soil reduction could be achieved. A comparison of data collected during the segmented gate technology demonstration and revalidated KIWI data showed that the residual soil values were as much as 75% higher than originally reported. NNSA/NV determined that the KIWI system did not provide accurate data (initially shown to be low by up to 75%), and NNSA/NV has not conducted any further termination under the NRC based on total dose received by all sources on site.

Remedial Actions

Presently, there are no established regulations for amounts of plutonium that can be left in the soil at DOE-managed sites that are undergoing remediation. However, there are NRC regulations and guidelines for commercial license termination that may be applicable, which are based on total dose received by all sources on site. Therefore, an integrated evaluation of all potentially

appropriate and/or applicable release criteria, utilizing professional judgment, must still be conducted.

Ongoing negotiations between NDEP, the Department of Defense (DOD), and NNSA/NV indicate that these soil contamination areas should be remediated to a dose receptor limit of 25 mrem/year.

NDEP has concerns that the RESRAD model may not provide an adequate or appropriate evaluation based on current utilization of the land. NDEP accepts that the residential rancher/farmer scenario is the most conservative approach allowed in the RESRAD model. The RESRAD model does not provide for a risk evaluation of the area as an active military installation under the current possible use scenarios. While potential exposure risks associated with this type of activity may or may not be as significant as a rancher/farmer, NDEP contends that the current and anticipated future land use scenario must be evaluated.

NNSA/NV and the Air Force are currently working together to determine present land use scenarios to define appropriate exposure concerns. It should be noted that the Air Force would be required to address any residual radioactive soil contamination remaining at these sites based in accordance with the withdrawal legislation, which requires the land to be returned acceptable for unrestricted use. This requirement may compel the Air Force to permanently withdraw the land and provide institutional control as well as constrain future mission activity in these areas. Should mission activities require use of the land, the Air Force will be responsible for future remediation of these areas prior to use.

NDEP has disputed some aspects of the most recent RESRAD calculations NNSA/NV has made, including the use of ICRP-68/72 DCFs. NNSA/NV has also used model assumptions and default parameters, not current field data. While historic information may be appropriate, NDEP asserts that verification of current conditions at the sites must occur. No validation or confirmation of the characterization and remediation activities has been conducted other than a surface radiation survey, averaging residual contamination for activity level verification. As reported above, comparison of data collected during a segmented gate technology demonstration and revalidated KIWI data showed that the residual soil values were as much as 75% higher than originally reported. Upon the initial review of documentation, it appears to NDEP that historic sampling may not be sufficient to distinguish the variability in the distribution of contaminated particles over the site. Additional sampling may be required to fill these data gaps and adequately characterize the site. As part of the characterization and remediation of all radiologically contaminated soil sites, NDEP will require NNSA/NV to provide current validation of particulate size, particle distribution, depth profiling, and chemical form, as well as verification that contaminants are not a concern outside of the fenced zone. The Air Force has proposed to do its own sampling event within federal fiscal year 2002 to validate NNSA/NV historic data and to obtain current site conditions.

The Air Force is also currently conducting its own evaluation of what future land use scenarios would be credible for Air Force activities and what action level will need to be established for these uses. NDEP maintains that, if the scenario allows greater contamination to be left in place for proposed Air Force use, action levels and the cost for unrestricted use (resident rancher

farmer) must still be evaluated, as this is a congressional requirement contained in the withdrawal legislation.

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4.9 Oak Ridge Reservation—Melton Valley Watershed, Tennessee

Background

The Melton Valley area of the Oak Ridge Reservation encompasses 1062 acres and contains numerous radioactive and hazardous waste units. These units include low-level waste (LLW) trenches and pits, active waste storage areas, construction landfills, underground and above-grade tanks, impoundments, deep well injection (hydrofracture), buried pipelines, and

contaminated buildings. From 1943 to 1986, the valley was used for radioactive waste disposal, and as the southern regional burial ground from 1955 to 1963, received waste from across the complex. Since 1986, the area has been used for active waste management. A brief description of these units is provided below:

- LLW—Areas of Melton Valley were used as early as 1943 for the shallow land burial of LLW. Early procedures used unlined trenches and auger holes for waste disposal. When filled, these areas were covered with soil or, in some cases, concrete. Burial in the unlined trenches and auger holes was discontinued in 1986.
- Active waste—A portion of the valley is being used for storage of active waste management materials, including TRU waste, LLW, and spent nuclear fuel. The materials are stored in concrete silos; above-grade storage units, buildings, tents; and above-grade tanks.
- Landfills—There are several construction debris landfills in Melton Valley. These areas received bulk material and equipment that was not considered LLW.
- Tanks—All tanks in Melton Valley are constructed of steel. The newer tanks have cathodic protection to prevent corrosion and have secondary containment. Older tanks are single-walled steel tanks. These tanks received concentrated liquid LLW for underground storage. Several of the tanks have already been remediated, and a few are scheduled for early action under the Bethel Valley ROD.
- Impoundments—Several impoundments are located in Melton Valley, used to store wastewater and for direct storage of liquid LLW. Most are unlined.

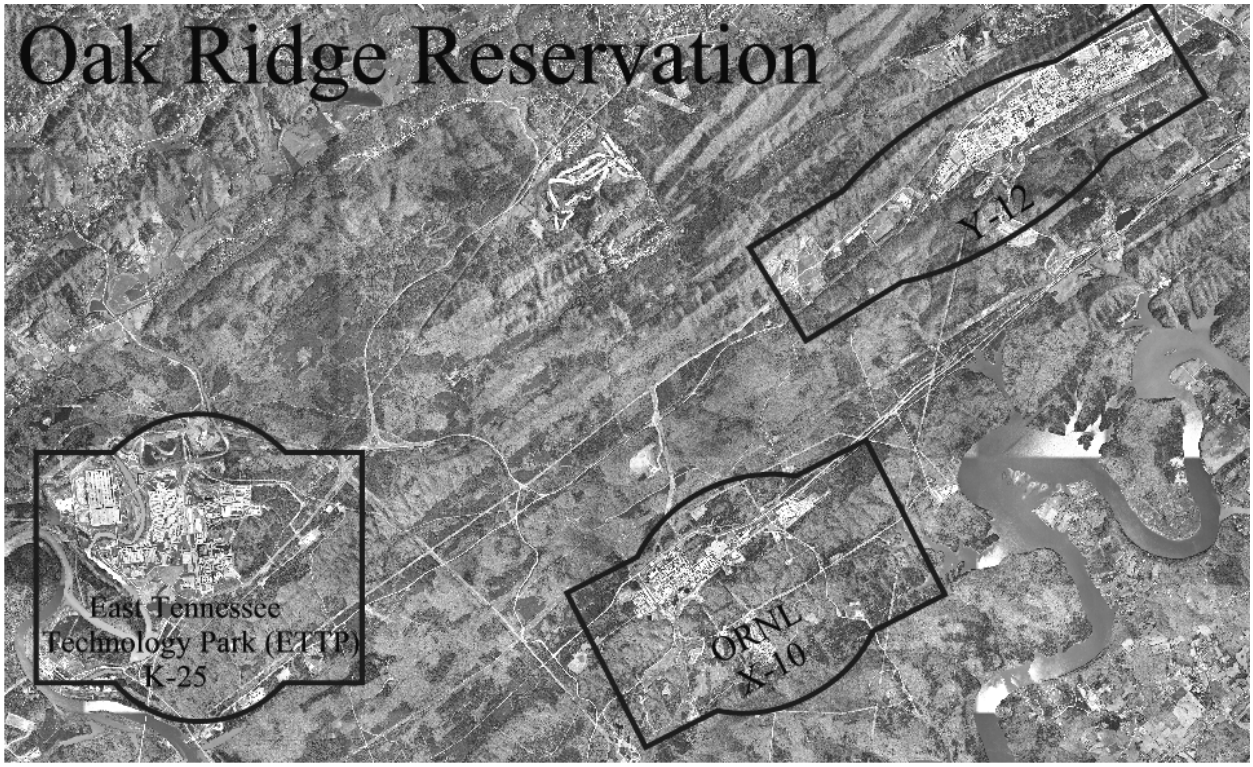

Figure 5. The Three Oak Ridge Sites (Photo courtesy of the Geographic Information Science and Technology Group, Oak Ridge National Laboratory)

- Deep Well Injection—The Hydrofracture facility pumped over 1.5 million curies of radioactive material (primarily cesium-137 and strontium-90) into hydraulically fractured rock 800–1000 feet deep. Monitoring wells that were installed during operation are scheduled to be plugged to prevent upward migration of highly contaminated liquids.

Contaminants of concern cover the entire radionuclide spectrum. From a soils cleanup perspective, cesium-137 and cobalt-60 are regarded as the most significant radionuclides because of the high energy of gamma radiation that these radionuclides emit.

Cleanup Level Development

The Melton Valley ROD incorporates a concept of aggregating risk over an entire exposure unit. DOE proposed, and the state of Tennessee and EPA have agreed, to identify exposure units and corresponding risk assumptions within the boundary of Melton Valley over which the receptor is assumed to roam.

For the industrial areas of Melton Valley, two important assumptions are made in the industrial worker exposure scenario with regard to time. The first calculation is based on the industrial worker's risk aggregated over the exposure unit for an entire working year (2000 hours per year). The second calculation is based upon the receptor being exposed to a particular location or hotspot (200 hours per year). The remediation level (soil cleanup level) is determined by the more protective of the two calculations.

Soil concentration limits were calculated in three ways:

- risk-based limits derived using the RAGS PRG equations (10^{-4} incremental lifetime cancer risk [ILCR]),
- RESRAD-derived risk-based limits (10^{-4} ILCR), and
- RESRAD-derived dose-based limits (25-mrem/year).

Values were derived using the RAGS PRG equations for an industrial worker scenario with a target risk goal of 10^{-4} ILCR. The only deviation from the standard RAGS equations and default parameters was the addition of a "decay factor" to account for radioactive decay and in-growth of daughter radionuclides over the 25-year exposure duration. This decay factor was incorporated into the calculations with the concurrence of EPA Region 4 and the Tennessee Department of Environment and Conservation:

$$RL_{industrial} = 10^{-4} / ((SF_{oral})(12.5) + (SF_{ext})(0.183) + (SF_{inhal})(0.00379))\ (25)\ (DF)\ ,$$

where

$RL_{industrial}$ = remediation level for soil under the industrial land use scenario,
SF_{oral} = oral slope factor,
SF_{ext} = external radiation slope factor,
SF_{inhal} = inhalation slope factor,
DF = radioactive decay factor (calculated as 25-year integrated average, using the midpoint (arithmetic average) activity for each 5-year time interval).

The RESRAD-derived concentration limits were originally developed using RESRAD Version 5.82, but Version 6.0 produces equivalent results. Key RESRAD input parameter assumptions were selected to mimic RAGS-PRG calculations for the same industrial worker scenario for each of the pertinent exposure pathways (direct external radiation, particulate inhalation, incidental soil ingestion).

- *External exposure pathway*:

  Indoor occupancy factor = 0
  Outdoor occupancy factor = 0
  Area of contaminated zone = 125 m^2 (yields area factor = 0.8, same as RAGS (1-Se))
  (product of occupancy factor and external area factor and depth factor of 1 yields 0.184, corresponding to 0.183 in RAGS-PRG)

- *Inhalation exposure pathway*:

  Inhalation rate = 21,900 m^3/year (equivalent to RAGS 20 m^3 per 8-h workday for 8760 h/year)
  Dust loading = 7.5 x 10^{-6} g/m^3
  (product of inhalation rate, mass loading, occupancy factor, and inhalation area factor yields an annual inhaled mass of 0.004 g/year, corresponding to 0.0038 g/year in RAGS-PRG)

- *Soil ingestion pathway*:

  Soil ingestion rate = 435 g/year (when adjusted by occupancy factor (0.23) and ingestion area factor, yields 12.5 g/year soil ingested, equivalent to RAGS)

Other parameter values were set at RESRAD default values, since they do not significantly impact dose and risk estimates for the industrial scenario. Table 18 presents the values for various individual radionuclides.

The final remediation level for each radionuclide was selected as the most limiting (lowest) soil concentration limit from the RAGS calculation or the two RESRAD-derived concentration limits. The risk-based limits were selected for most radionuclides and, with the exception of Sr-90+D, risk-based limits derived using the RAGS-PRG equations and RESRAD were essentially equivalent (for Sr-90+D, the RESRAD-derived concentration was lower due to the use of a different slope factor for external radiation). Thus, all values selected were derived to achieve both the target risk of 10^{-4} and the dose limit of 25 mrem/year. For Melton Valley, the radionuclides Cs-137 and Co-60 are expected to be limiting in virtually all cases.

Table 18. Oak Ridge—Melton Valley Remediation Levels (Industrial Worker)

Radionuclide	RAGS-PRGs 10^{-4} Risk[a] (pCi/g)	RESRAD-Derived		Selected Cleanup Level (pCi/g)	Basis of Selection
		10^{-4} Risk[a] (pCi/g)	25-mrem/year dose (EDE) (pCi/g)		
Cesium-137	13.7	13.7	39.8	14	Risk
Cobalt-60	7.39	7.56	8.37	7.4	Risk
Curium-244	2260	2280	951	950	Dose
Europium-154	10.6	10.6	17.6	11	Risk
Lead-210	453	475	271	270	Dose
Radium-226	Alternative concentration[b]			5	Note b
Radium-228	Alternative concentration[b]			5	Note b
Strontium-90	7580	1230	3400	1200	Risk
Thorium-228	Alternative concentration[b]			5	Note b
Thorium-232	Alternative concentration[b]			5	Note b
Uranium-233	5050	5370	5510	5100	Risk
Uranium-234	6540	7100	6020	6000	Dose
Uranium-235	81.4	82.4	167	81	Risk
Uranium-238	311	331	852	310	Risk

[a] Incremental lifetime cancer risk.
[b] Alternative concentration.

Where multiple radionuclides are encountered, the sum of fractions will be applied to develop appropriate cleanup numbers for each contaminant. In addition, any source, regardless of depth, which regulators determine is causing a significant impact to groundwater or surface water will be remediated. This approach provides for risk-based decisions on soil cleanup that can be adapted to a variety of sites with differing land uses and contaminants. Consideration must be given to the fact that under this approach, cleanup numbers for a particular radionuclide may vary from one exposure unit to the next, but aggregate risk levels will be the same or similar.

Issues associated with implementation of field remediation of soils using this approach will require more work between the state, EPA, and DOE. Work plans will have to contain information on the field techniques that will be used to verify that cleanup has been achieved without imposing significant delays in the remedial actions. Subsequent CERCLA documents at Oak Ridge are adopting variations of this approach for remediation of radioactively contaminated soils.

Remedial Actions

The Melton Valley ROD, signed on September 21, 2000, requires approximately $164 million of remediation over the next decade. The remediation of Melton Valley includes a complex mix of protective caps, hydraulic isolation, decontamination and decommissioning, and soils removal.

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4.10 Rocky Flats Environmental Technology Site, Colorado

Background

Rocky Flats Environmental Technology Site (Rocky Flats) is located adjacent to the Colorado Front Range about 16 miles northwest of Denver. Most structures are within an industrial area occupying approximately 400 acres and surrounded by a buffer zone of about 6,150 acres. The site sits on an alluvial-covered pediment surface dissected by a series of east-northeast trending stream-cut valleys.

Rocky Flats, a government-owned, contractor-operated facility, was part of the nationwide nuclear weapons complex. Previous operations at the site consisted of fabrication of nuclear weapons components from plutonium, uranium, and non-radioactive metals (e.g., stainless steel and beryllium). Major releases of radionuclides to the environment include fires in processing buildings in 1957 and 1969. The largest release occurred when plutonium-contaminated oils leaked from drums at a waste storage site, allowing high winds to distribute contaminated soils over a broad area east of the industrial area. Several hundred curies of tritium were released when treated liquid wastes were discharged to surface water.

Figure 6. The Rocky Flats Site

Cleanup Level Development

In 1972, the Colorado Board of Health was asked to determine levels of plutonium in soil below which construction activities could safely occur. In response, the board approved a standard that requires "special techniques of construction" in areas where plutonium contamination exceeds 2 disintegrations per minute per gram of dry soil (0.9 pCi/g). This is a substantive requirement that would be relevant and appropriate to any proposed construction activities that may be implemented at or near Rocky Flats, including excavation.

In 1996, DOE, EPA Region 8, and the Colorado Department of Public Health and Environment signed the *Rocky Flats Cleanup Agreement* (RFCA) (DOE, 1996b), which replaced an earlier interagency agreement signed in 1991. An enforceable attachment of this agreement, the Action Levels and Standards Framework (ALF), includes lists of soil contaminant levels that trigger remedial or management actions. Surface soil action levels for nonradionuclides in the ALF are risk-based PRGs. An upper level (Tier I) corresponds to a 10^{-4} risk, and exceedances generally require remedial actions; a lower level (Tier II) corresponds to a 10^{-6} risk, which requires an evaluation to determine whether potential impacts to surface water or ecological resources would require an action.

The radionuclide soil action levels were by far the most difficult to derive and the most contentious. Risk-based PRGs had already been developed, but it was decided during the negotiations for the RFCA that dose-based values would be more appropriate and useful. EPA's proposed rule for *Radiation Site Cleanup Regulations* (draft 40 CFR 196) was out for public comment at the time, and this rule was used as the basis for developing action levels. The Part 196 methodology also seemed to be consistent with DOE's *Radiation Protection of the Public and the Environment* (DOE Order 5400.5), DOE's proposed 10 CFR 834, and the NRC's proposed *Radiological Criteria for Decommissioning* (proposed 10 CFR-NRC).

The RFCA prescribes two future land users: an office worker to represent potential reuse of the industrial area and an open-space user. The soil activity equivalent to a 15-mrem annual dose was back-calculated for these two scenarios using the latest RESRAD code at the time, Version 5.61. As described in the proposed Part 196, these levels are then compared to an activity level calculated for an 85-mrem annual dose to a resident to provide a safety net level in case institutional controls failed. A 15-mrem dose to an office worker was calculated to be more conservative than 85 mrem to a suburban resident, so that level became the Tier I action level for industrial reuse. In the case of the open-space user, the 85-mrem dose to a resident proved more restrictive, so that level became the Tier I value for open-space use. The Tier II value for radionuclides was calculated from a 15-mrem annual dose to a resident. Table 19 shows the calculated levels for various land use receptors: the input parameters chosen to represent these exposure scenarios are listed in Table 5.

Table 19. 1996 Radionuclide Surface Soil Action Levels for Rocky Flats, in pCi/g

Radionuclide	Rural Resident		Office Worker	Open-Space User
	15 mrem[a]	85 mrem[b]	15 mrem[c]	15 mrem
Americium-241	38	215	209	1,283
Plutonium-239/240	252	1,429	1,088	9,906
Uranium-234	307	1,738	1,627	11,500
Uranium-235	24	135	113	1,314
Uranium-238	103	586	506	5,079

[a] Applied as Tier II action levels.
[b] Applied as Tier I action levels.
[c] Applied as Tier I action levels for industrial reuse.

Soon after the interim action levels in 1996, a number of stakeholders requested a review of the calculations since the values were higher than cleanup levels at several other sites. A Radionuclide Soil Action Level Oversight Panel was formed from among stakeholders, and a consultant was chosen to perform the DOE-funded review. The consultant, Risk Assessment Corporation (RAC) recalculated the action levels, making several significant changes (RAC, 1999), including using probability distributions and a much higher mass-loading value to account for prairie fires.

The RFCA requires an annual review of soil action levels by the three agencies. In particular, revisions must be considered if new regulations or new scientific information warrant it. As an example, once NRC's *Radiological Criteria for Decommissioning* were promulgated, they were adopted as decommissioning criteria by the state of Colorado. The parties have agreed that, while this regulation is not applicable to a DOE-owned site, certain sections, including the ALARA provisions, are relevant and appropriate. Therefore, in addition to risk calculations bounding the CERCLA risk range, radionuclide concentrations for a 25-mrem annual dose limit have been calculated for comparison (see Tables 20 and 21). A new receptor, the wildlife refuge worker, has been added and is considered the most likely future land user since the passage of the Rocky Flats National Wildlife Refuge Act in December 2001. A newer version of the RESRAD computer code (6.0) allows probability distributions as input and incorporates an updated air model. Many of the input parameters have been revised based on newly available data. Probability distributions have been developed and used for the most sensitive input parameters in the refuge worker and rural resident scenarios. A distribution developed for the mass-loading value accounts for decreased vegetation due to drought conditions or periodic fires. New dose conversion and slope factors and new data pertaining to the migration of radionuclides have also been incorporated.

The sum-of-ratios method is used to account for the contribution of each individual isotope towards the dose- or risk-based limit. For example, the coexistence of americium and plutonium reduces the allowable concentrations from the levels listed in the tables above. Using an Am:Pu activity ratio of 0.182 (representing maximum americium ingrowth), the concentration producing a 10^{-4} risk to a wildlife refuge worker, 1150 pCi/g, is adjusted to 738 pCi/g.

Table 20. 2002 Dose and Risk Calculations for Plutonium in Surface Soil at Rocky Flats, in pCi/g—PRELIMINARY

Land Use Scenario	25-mrem/year Dose	Target Risk Levels		
		10^{-4}	10^{-5}	10^{-6}
Wildlife refuge worker[a]	780	1150	115	11.5
Rural resident—adult[a]	232	306	31	3.1
Rural resident—child[a]	251			
Open-space user—adult	3617	1126	113	11.3
Open-space user—child	1205			
Office worker	1598	800	80	8

[a] Reported at 5th percentile of concentration distribution (corresponds to 95th percentile of risk distribution).

Table 21. 2002 Dose and Risk Calculations for Americium in Surface Soil at Rocky Flats, in pCi/g—PRELIMINARY

Land Use Scenario	25-mrem/year Dose	Target Risk Levels		
		10^{-4}	10^{-5}	10^{-6}
Wildlife refuge worker[a]	142	376	38	3.8
Rural resident—adult[a]	42	93	9	0.9
Rural resident—child[a]	46			
Open-space user—adult	658	364	36	3.6
Open-space user—child	219			
Office worker	290	369	37	3.7

[a] Reported at 5th percentile of concentration distribution (corresponds to 95th percentile of risk distribution).

Table 22. 2002 Dose and Risk Calculations for Uranium-238 in Surface Soil at Rocky Flats, in pCi/g—PRELIMINARY

Land-Use Scenario	25-mrem/year Dose	Target Risk Levels		
		10^{-4}	10^{-5}	10^{-6}
Wildlife refuge worker[a]	1059	3510	351	35.1
Rural resident—adult[a]	227	122	12	1.2
Rural resident—child[a]	254			
Open-space user—adult	--	2732	273	27.3
Open-space user—child	--			
Office worker	--	2570	257	25.7

[a] Reported at 5th percentile of concentration distribution (corresponds to 95th percentile of risk distribution)

Values were also calculated for uranium-234 and uranium-235. Sum-of-ratio values for uranium isotopes will be based on isotopic ratios for depleted and enriched uranium. In addition, uranium toxicity values have been calculated, based on a hazard index of 1.0 for total uranium. The most restrictive action levels for total uranium are based on enriched uranium—31 μg/g for an adult resident and 225 μg/g for a wildlife refuge worker.

Using these calculated concentrations for americium, plutonium, and uranium, risk managers will choose revised radionuclide action levels, which will guide interim remedial actions. Final cleanup levels will be established in subsequent decision documents.

Protection of state surface water standards is inherent in the soil cleanup level concept in RFCA. The direct exposure dose and risk calculations, however, do not account for contamination of surface water. Therefore, an ongoing effort called the Actinide Migration Evaluation has been studying the mobility of radionuclides. Major conclusions of this study include the following:

- The forms of plutonium expected and observed at Rocky Flats are essentially insoluble, and soluble transport is not evident at Rocky Flats or elsewhere.
- Pu is nearly always transported as colloids (<2 : m) or attached to mineral particles.
- Mixing, erosion, and chemical processes all reduce the amount of Pu activity in the environment; chemical processes are the least important.
- In certain watershed segments, the calculated soil action levels may not be sufficiently conservative to ensure that the surface water standards for radionuclides will be met.

Remedial Actions

RFCA assumes that individual contaminated sites will be cleaned up by means of interim actions, so that the final sitewide ROD will require no further remedial action. The agreement establishes Tier I action levels as "interim cleanup levels" unless a greater level of cleanup is required by another provision of ALF (e.g., protection of surface water). Final cleanup levels will be established in a sitewide Corrective Action Decision/ROD.

The 1996 cleanup levels have been used as the basis for remediating several sites contaminated with plutonium, americium, and depleted uranium, including burial trenches and waste storage sites where excavation and off-site disposal were the selected remedy.

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4.11 Savannah River Site, South Carolina—Seepage Basins Operable Unit

Background

The Savannah River Site (SRS) is one of several government-owned, contractor-operated sites in DOE's nuclear defense complex. Construction of SRS began in February 1951, and the first facility, the heavy-water plant, began operating in August 1952. The first production reactor started operating in December 1953. SRS was constructed to produce basic materials used in nuclear weapons, primarily tritium and plutonium-239. Five reactors were built to produce these materials by irradiating target materials with neutrons. Support facilities, including two chemical separations facilities, a heavy-water production plant, a nuclear fuel and target fabrication facility, and waste management facilities, were also built. SRS produced about 36 metric tons of plutonium from 1953 to 1988. All five reactors are now shut down due to declining defense requirements. However, until fresh supplies of tritium are available, recycling and reloading of tritium will continue.

The SRS is located in south central South Carolina and occupies an area of approximately 310 square miles in Aiken, Barnwell, and Allendale counties. A marked property line establishes the site's boundary to the north, south, and east. The Savannah River forms the site's western boundary for approximately 35 miles along the South Carolina/Georgia border.

Four unlined basins comprise the SRL [Savannah River Laboratory] Seepage Basins, located in the northwestern portion of SRS near the Savannah River Technology Center in the Administration and Management Area. The seepage basins received low-level radioactive wastewater 1954–1982. Basins 1 and 2 began operation in 1954; Basins 3 and 4 were added in 1958 and 1960, respectively. The basins are rectangular in shape and are connected by a series of sequential overflow channels designed to receive wastewater by overflow from Basin 1 to Basin 4. Wastewater entered the western end of Basin 1 via the 10-inch-diameter vitrified clay process sewer line. Wastewater seldom reached Basin 4 because evaporation and infiltration in Basins 1 through 3 were high enough to maintain the level of wastewater in the basins below the overflow channel to Basin 4. Wastewater discharged to the basins included uranium, plutonium, cesium, strontium, thorium, radium, cobalt, americium, curium, ruthenium, alpha (unidentified), beta-gamma (unidentified), and tritium; tritium was the most abundant radionuclide discharged to the basins. Nitrate, sodium, chlorine, calcium, and nickel were the primary inorganic constituents discharged to the basins. Process knowledge suggests that no significant quantities of chlorinated organic compounds were discharged to the seepage basins. Subsequent to the

termination of operations in 1982, weeds, grasses, brush, and trees became established in the basins. This vegetation underwent a volume reduction process by chipping and was bagged and staged within the basins pending disposition consistent with the basin soils. This early action achieved the removal objective of limiting the spread of contamination due to foliage drop and wind dispersion.

The conceptual site model for the SRL Seepage Basins OU identified several pathways for potential exposure to constituents released from the unit. Mechanisms identified for constituents to reach receptors were ingestion of contaminated media, inhalation of airborne dust and/or volatile emissions, biotic uptake, dermal contact with contaminated media, and external radiation dose. Four exposure pathways were identified in the conceptual site model: airborne (volatiles and dust), biota (biotic uptake), surface soil (direct contact with excavated subsurface soil), and groundwater (leaching). Soil, surface water and sediment, and groundwater sample results were used to evaluate potential exposures and risks for each of these.

Cleanup Level Development

On December 21, 1989, SRS was included on the NPL. This inclusion created a need to integrate the established RCRA Facility Investigation program with the CERCLA requirements to provide for a focused environmental program. In accordance with Section 120 of CERCLA, 42 USC Section 9620, DOE negotiated a federal facility agreement with EPA and the South Carolina Department of Health and Environmental Control (SCDHEC) to coordinate remedial activities at SRS as one comprehensive strategy which fulfills these dual regulatory requirements. DOE functions as the lead agency for remedial activities at SRS, with concurrence EPA Region 4 and SCDHEC.

The SRL Seepage Basins OU was identified as a solid waste management unit requiring investigation in the Natural Resources Defense Council consent agreement. This decree required SRS to submit various documents, including a closure plan for the units. A closure plan proposing the installation of a RCRA cap was written and submitted in 1993, using procedural requirements applicable to RCRA closure plans. Revision 0 of the closure plan received a notice of deficiencies/warning from SCDHEC and was revised and reissued. Revision 1 received considerable comment from public stakeholders. After consideration of comments, SCDHEC determined that a more comprehensive evaluation of the unit and closure alternatives was warranted. DOE and SCDHEC decided that the SRL Seepage Basins OU should be evaluated under the RCRA/CERCLA process, which considers remedial alternatives against the nine CERCLA criteria to select a remedy protective of human health and the environment.

As the investigation/assessment process for the SRL Seepage Basins OU, a baseline risk assessment was performed using data generated during the investigation phase. This evaluation identified the contaminants of concern (COCs) and the presence of principal threat source material (PTSM) and therefore provided the basis for remedial action. PTSM is defined as source material that is highly toxic and/or mobile at levels that pose a risk to human health greater than 1×10^{-3} (industrial worker scenario) should exposure occur.

RAOs are established to identify the cleanup objectives for a given waste unit. The RAO for the SRL Seepage Basins is to ensure the protection of human health and the environment. This objective will be achieved by eliminating surficial soil exposure and potential leachability to groundwater and removing or treating all PTSM. Remedial goal options (RGOs) are developed to achieve the RAOs. RGOs are concentration goals for individual chemicals in specific media and land use combinations. They are designed to provide conservative, long-term targets for the selection and analysis of remedial alternatives. Human health RGOs estimate protective remedial levels for COCs based on risk to human receptors. In a similar manner, ecological RGOs are based on risks to ecological receptors. Contaminant migration RGOs are based on risk from contaminants in soil leaching to groundwater above an MCL. Final remedial levels for the COCs, which will be selected by risk managers, are to be protective of human health and ecological receptors and comply with federal and South Carolina ARARs.

Excess lifetime cancer risk was calculated for unit-related radionuclides using EPA exposure factors and slope factors from HEAST. Total media risk (TMR, e.g., total carcinogenic risk for surface soil) was determined by summing the individual constituent risks within the particular media. This TMR value was then used to determine the need for remedial action. Since human health and PTSM COCs were identified at the SRL Seepage Basins and the TMR for surface soils was 2×10^{-1} for the industrial scenario, RGOs were then back-calculated for the respective risk levels (10^{-6}, 10^{-5}, 10^{-4} and 10^{-3} industrial for PTSM), shown in Table 23. Based on risk-management decisions, remedial goals were then determined from the RGOs.

Table 23. Soil Remediation Goals for the SRL Seepage Basin, in pCi/g

Contaminant of Concern (Radionuclide)	Remedial Goals for Human Health Criteria[a]	Remedial Goals for PSTM Criteria[b]
Actinium-228	0.07	70
Americium-241	8.08	8,080
Cesium-137	0.11	110
Cobalt-60	0.02	20
Curium-243/244	1.6	1,600
Lead-212	0.7	700
Neptunium-239	0.9	900
Plutonium-238	10.857	10,857
Plutonium-239/240	10.130	10,130
Radium-228	0.067	67
Strontium-90	57.130	57,130
Thorium-228	0.035	35
Thorium-230	85.38	85,380
Thorium-232	98.0	98,000
Uranium-233/234	71.0	71,000
Uranium-235	0.83	830
Uranium-238	3.1	3,100

[a] Industrial worker, 10^{-6} excess lifetime cancer risk.
[b] Industrial worker, 10^{-3} excess lifetime cancer risk.

Remedial Actions

The preferred remedial response/technology was removal of soil with off-SRS disposal and backfilling the basins with an earthen cover. Details are as follows:

- Estimated cost: $3,550,000.
- Estimated construction time to complete: 18 months.
- Excavation, removal, and disposal of all PTSM (soil above 1×10^{-3} industrial risk) at a licensed off-SRS facility. Approximately 3207 m^3 of soil would be removed.
- Earthen cover placed over open basins and graded to provide a structural fill barrier (minimum of 9 feet, measured from waste remaining in basin to ground surface). The cover would eliminate risk due to residual contamination left in place greater than 1×10^{-6} but less than PTSM levels.
- Institutional controls would remain in place and preclude residential development and disturbance of the cover.

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4.12 Weldon Spring Site, Missouri—Chemical Plant Area

Background

From 1941 to 1945, as part of the World War II defense effort, the U.S. Army produced explosives at the Weldon Spring Ordnance Works, a 17,000-acre facility in St. Charles County, Missouri, northwest of St. Louis. After the war, the government transferred ownership of some of this land to the state of Missouri and the University of Missouri, with the Army retaining most of the remainder for use as a training area.

In 1955, the Army transferred 205 acres to AEC for construction of the Weldon Spring Uranium Feed Materials Plant. From 1957 to 1966, the feed materials plant processed uranium ore concentrates and a small amount of thorium. Wastes generated during these operations were stored in four open-air lagoons called the “raffinate pits.” From 1963 to 1969, AEC disposed of

uranium residues and a small amount of thorium residue in the Weldon Spring Quarry. Material placed in the quarry during this time includes uranium- and radium-contaminated building rubble and soils from the demolition of a uranium ore processing facility in St. Louis. Other radioactive materials in the quarry included drummed wastes, uncontained wastes, and contaminated pieces of manufacturing equipment.

The feed materials plant was shut down in 1966, and in 1967 AEC returned the facility to the Army for use as a defoliant production plant to be known as the Weldon Spring Chemical Plant. In 1968, the Army started removing equipment and decontaminating several buildings. However, the defoliant project was canceled in 1969 before any process equipment was installed. The Army retained responsibility for the land and facilities of the chemical plant, but the raffinate pits were transferred back to AEC. By direction of the Office of Management and Budget, DOE was to assume responsibility for custody and control of the site, and in 1985 custody was transferred from the Army to DOE. In 1985, DOE proposed designating control and decontamination of the chemical plant, raffinate pits, and quarry as a major project to be called the Weldon Spring Site Remedial Action Project (WSSRAP). The quarry was placed on the NPL in July 1987; the chemical plant and raffinate pits were added in March 1989.

Cleanup Level Development

Cleanup at the Weldon Spring Site is being conducted in accordance with both CERCLA and the National Environmental Policy Act (NEPA). In addition, other standards and guidelines are considered ARAR. Nonspecific radiological dose standards, such as the 100-mrem/year CEDE limit to the general public in DOE Order 5400.5, are considered applicable. National Emission Standards for Hazardous Air Pollutants (NESHAPs) restrict airborne emissions to an effective dose equivalent of 10 mrem/year. Missouri radiation regulations limit the maximum whole-body dose to an individual in uncontrolled areas to 2 mrem/h, 100 mrem in any 7 consecutive days, and 500 mrem/year. The greatest dose at the site is associated with radium-226 because this radionuclide and its decay products account for most of the total dose at the site from both external gamma irradiation and inhalation of radon.

Although the EPA-promulgated standards in the UMTRCA do not apply to the site, they are considered relevant and appropriate since the material at the site is similar to mill tailings. DOE guidelines include the EPA standards for radium and establish similar standards for the thorium isotopes for soil in areas of unrestricted access. These radionuclides are not to exceed background concentrations by more than 5 pCi/g in the upper 15 cm (6 inches) of soil or 15 pCi/g in each 15-cm layer beneath the surface, averaged over an area of 100 m^2. Since the background concentration of these radionuclides in the vicinity of the site is 1.2 pCi/g, the surface and subsurface standards for radium and thorium are 6.3 pCi/g and 16.2 pCi/g, respectively.

No federal or state ARARs were identified for uranium in soil. Results of a site-specific risk assessment were used in conjunction with a preliminary ALARA analysis to develop a site-specific cleanup criterion. Soil cleanup criteria (or risk-based remediation goals) were developed, assuming failure of institutional controls in the future. A recreational visitor, wildlife area ranger in an on-site station, resident, and resident farmer are considered potential future land users.

Health-based criteria were developed for a resident and farmer since these uses represent maximum exposures and constitute a comprehensive application of the ALARA process. Table 24 shows the surface and subsurface cleanup levels developed at the site.

Table 24. Weldon Springs Site Cleanup Levels, in pCi/g

Radionuclide	Surface[a]		Subsurface[b]	
	Criteria	ALARA goals	Criteria	ALARA goals
Radium-226[c,d]	6.2	5.0	16.2	5.0
Radium-228[c,d]	6.2	5.0	16.2	5.0
Thorium-230[c,d]	6.2	5.0	16.2	5.0
Thorium-232[c,d]	6.2	5.0	16.2	5.0
Uranium-238	120	30.0	120	30.0

[a] Surface soil values apply to contamination within the upper 15 cm (6 inches) of soil.
[b] Subsurface soil values apply to contamination in each 15-cm (6-inch) layer of soil more than 15 cm below the surface.
[c] If both Th-230 and Ra-226 or both Th-232 and Ra-228 are present and not in secular equilibrium, the cleanup criterion applies for the radionuclide with the higher concentration.
[d] At locations where both Ra-226 and Ra-228 are present, the cleanup criteria for both surface and subsurface soil applies to the sum of the concentrations of these two radionuclides.

A ROD for the management of the quarry bulk wastes was established in 1990. DOE developed this ROD in consultation with and with the concurrence of the EPA Region 7 and the state of Missouri.

These cleanup standards trigger remedial actions and guide confirmation sampling decisions following remediation. Confirmation samples are collected from the upper 6 inches of soil, and these surface soil samples are considered representative of the subsurface as well. Areas that are potentially contaminated or have been remediated are divided into confirmation units. These units are 2,000 m^2, a size approximately the same as the exposure units used in the risk assessment for a future residential lot. The mean of the samples across each confirmation unit is compared to the ALARA goals. The mean is used since average exposure is the guiding principle for the risk assessment and because there should be little spread in the data after remediation. A second decision rule evaluates hotspots. The average radiological contaminant concentration in each 100-m^2 area will be compared to the cleanup criteria according to the formula

$$\textit{maximum concentration} = \textit{cleanup criteria} \times (100/\mathrm{A})^{1/2},$$

where A is the area of the hotspot in square meters. In addition, a minimum hotspot size (25 m^2), uncertainty parameters, and minimum sample sizes are all established.

Remedial Actions

The resulting remedy includes an on-site disposal cell. The mission of the project is to eliminate potential hazards to the public and environment and to make surplus real property available for other uses to the extent possible. The scope of work includes dismantling 44 chemical plant buildings and structures and disposing of both radiologically and chemically contaminated structural materials and soils. It also includes disposing of as much material as possible from the

raffinate pits, quarry, and nearby properties (including water, sludge, abandoned waste materials, and structural materials). Capping of the on-site disposal cell was completed during 2001.

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5.0 ANALYSIS OF CASE STUDIES

This study has examined the cleanup level development process across several sites. This analysis of case studies and background information is intended to deduce some common observations and lessons learned that could enhance future cleanup efforts at radioactively contaminated facilities. Although the data available for each case varies, it is sufficient to draw the following observations related to the cleanup decisions at these sites.

- **Observation 1—Regulations and guidance pertaining to radioactive contamination have evolved and have become rather complex.**

Several government agencies apply somewhat overlapping authority over multiple categories of radioactive materials and have not reached consensus on regulatory standards and approaches (see Table 1). Thus, sites have to keep up with the evolving requirements. The result is that the regulators at sites have a great deal of flexibility in how they approach the cleanup problem.

- **Observation 2—Different risk assessment approaches (dose and cancer risk) lead to differences in derived cleanup values. Neither approach necessarily leads to more conservative cleanup values than the other.**

Some sites have developed both dose-based and risk-based soil concentrations. Oak Ridge used both approaches to calculate soil concentrations for the Melton Valley ROD using input parameters for each that were as equivalent as possible. The more conservative resulting value was then applied as the cleanup level for each radionuclide (see Table 18). At Rocky Flats, the 1996 dose calculations (15 mrem/year) were compared to the existing risk-based PRGs to decide which should apply as action levels (see Table 19). The recalculations done at Rocky Flats in 2001 again compared dose-based concentrations (25 mrem) with risk-based concentrations (see Table 20). Interestingly, neither approach seems to lead consistently to a more conservative value than the other.

- **Observation 3—Dose-based cleanup levels derived at several sites predate EPA's guidance against applying dose-based requirements rather than the CERCLA risk range in developing cleanup levels.**

Historically, there has been a trend from using ICRP 1979 in the 1970s and 1980s to using a dose-based risk approach in early 1990s (e.g., Nevada Test Site), and currently we see an increasing use of the CERCLA slope factor risk approach (e.g., Fernald) to develop cleanup numbers. Sites are increasingly assessing risks by applying both the dose-based approach and the slope factor approach for risk assessment and then using the lower one to determine the site cleanup levels (e.g., Oak Ridge Reservation and Rocky Flats).

- **Observation 4—Dose conversion factors and cancer slope factors continue to be revised, potentially requiring modifications to cleanup levels.**

Fundamental components of the two risk assessment approaches—dose conversion factors and cancer slope factors—have been updated over the years in response to new scientific evidence.

For instance, data from the recent Japanese atomic bomb survivors has been added to deriving the latest risk coefficients published in *Federal Guidance Report No. 13* (EPA, 1999a), and data from new studies have been incorporated in new DCFs developed by ICRP and NCRP. Regulatory changes typically lag behind scientific advances, which may require risk assessors and project managers to stay updated about new guidance and approaches. Consideration of these periodic changes may impact five-year reviews of ROD-driven remedial actions.

- **Observation 5—The selection of exposure scenarios is influenced by future land use assumptions and significantly influences the derivation of soil cleanup levels.**

Tables 25 and 26 demonstrate how cleanup levels at the same site vary depending on land use assumptions. Table 4 shows which exposure scenarios were assessed by various sites. A residential scenario of one type or another is most commonly assessed and usually represents unrestricted release criteria. An industrial or commercial land use is the next most common. A comparison of cleanup levels for residential vs. commercial/ industrial scenarios at sites where both were calculated shows that a residential scenario yields a cleanup level that is about 4–7 times more conservative.

The land use assumed for risk assessment is important at these sites, for not only cleanup but also for the long-term stewardship of these sites by the communities/states. Long-term stewardship will be required unless the cleanup levels are protective for all future land uses.

Table 25. Derived Soil Concentrations for Plutonium-239

Site	Exposure Scenario	Soil Concen-trations (pCi/g)	Date	Comments (Regulatory Standards, Dose Assumptions, and Models Used)
Enewetak	Residential Agricultural Food-gathering Subsurface	40 80 160 400	1973	DOD-DNA/DOE[a]
Erwin, Tennessee	Suburban resident	140	2001	NRC; 25 mrem/year (100 mrem/year if institutional controls are lost); used RESRAD; groundwater ingestion not included; (Nuclear Fuel Services facility)
Fernald	Park user (on site) Resident farmer (off site)	77 9	1995	DOE/EPA/OEPA; 10^{-6} risk (on site); 10^{-5} risk (off site)
Ft. Dix		8	1992	USAF; BOMARC missile accident; 4 mrem/year
Hanford Reservation	Rural resident Commercial/Industrial	34 245	1995	WDOH; 15 mrem/year; used RESRAD Version 5.7
Johnston Atoll	 Fish & wildlife researcher Resident Ecotourist Homesteader	13.5 2.1–210 1.9–190 38–3800 0.32–0 32	1988 2000	Derived as soil screening level; established as ALARA cleanup level by EPA Reg. 9; equivalent to 7.1×10^{-6} residential risk DOD-DTRA; 10^{-6}–10^{-4} risk range; used RESRAD Version 5.82
Lawrence Livermore	Resident	2.5		EPA Region 9 PRG

Mound Facility	Recreational Industrial/construction	75 55		Pu-238 in canal sediments; 25 pCi/g if reasonably achievable (ALARA level)
Rocky Flats: • Cleanup Agreement	Office worker Open space Resident	1088 1429 252	1996	DOE/EPA Reg. 8/CDPHE; 15 mrem/year; used RESRAD Version 5.61
• Oversight Panel	Resident rancher Industrial worker	41 626	2000	Developed by RAC; 15 mrem/year; used RESRAD Version 5.82; 90% of probability distribution
• PRGs	Resident Office worker Open space	2.5 10 17.5	1995 2000	DOE/EPA/CDPHE; 10^{-6} risk; used HEAST (1994) slope factors for residential PRGs in 1995; used *Federal Guidance Report 13* slope factors for open space and office worker PRGs in 2000
Tonapah Test Range	Resident rancher	200	2000	DOE; initial cleanup level used at Double Tracks and Clean Slate Sites

[a] CDPHE – Colorado Department of Public Health and Environment, DOD – U.S. Department of Defense, DOE – U.S. Department of Energy, EPA – U.S. Environmental Protection Agency, DNA – Defense Nuclear Agency, DTRA – Defense Threat Reduction Agency, OEPA – Ohio Environmental Protection Agency, RAC – Risk Assessment Corporation, USAF – U.S. Air Force, WDOH – Washington Department of Health

Table 26. Derived Soil Concentrations for Uranium

Site	Exposure Scenario	Soil Concentrations (pCi/g)	Date	Comments (Regulatory Standards, Dose Assumptions, and Models Used)
Fernald	Park user (on site): Total U (K_1=325 L/kg) Total U (K_1=15 L/kg) Resident farmer (off site) Total U (K_1=325 L/kg)	 82 ppm 20 ppm 50 ppm	1995	EPA/DOE/OEPA[a]; 10^{-6} risk; dependent on leachability (K_1)
New Jersey	Unrestricted use: U-234 U-235 U-238 Limited restricted use: U-234 U-235 U-238 Restricted use: U-234 U-235 U-238	 62 29 54 69 37 64 81 62 82	2000	New Jersey Commission of Radiation Protection; represents 15-mrem/year TEDE in a 1-foot thickness of soil at the surface with no cover; spreadsheet calculations
Hanford	Rural resident: U-234 U-235 U-238 Commercial/industrial: U-234 U-235 U-238	 160 26 85 1200 100 420	1997	WDOH; 15 mrem/year; used RESRAD Version 5.61

Site	Exposure Scenario	Soil Concen-trations (pCi/g)	Date	Comments (Regulatory Standards, Dose Assumptions, and Models Used)
Linde Site	Industrial/commercial (total uranium) Subsurface (total uranium)	600 3,021	2000	USACE; 10^{-5} risk; 8.8 mrem/year for surface cleanups and 4.1 mrem/year for subsurface cleanups; FUSRAP site
Oak Ridge – Melton Valley	Industrial worker: U- 233 U-234 U-235 U-238	 5100 6000 81 310	2000	DOE; 10^{-4} risk, except for U-235 (25-mrem/year dose); used RESRAD
Rocky Flats: • Cleanup agreement	Industrial Use: U-234 U-235 U-238 Open Space: U-234 U-235 U-238 Resident: U-234 U-235 U-238	 1627 113 506 1738 135 586 307 24 103	1996	DOE/EPA Reg. VIII/CDPHE; 15 mrem/year; used RESRAD Version 5.61
• Oversight panel	Resident rancher, w/ GW: U-234 U-235 U-238 Resident rancher w/o GW: U-234 U-235 U-238	 21 22 23 494 28 134	2000	Developed by Risk Assessment Corp.; 15 mrem/year; used RESRAD Version 5.82; 90% of probability distribution
• PRGs	Resident: U-233 + D U-234 U-235 + D U-238 + D Office worker: U-233 + D U-234 U-235 + D U-238 + D Open space: U-233 + D U-234 U-235 + D U-238 + D	 44.7 17.5 0.2 0.7 68 69 0.8 3.8 122 123 4.2 17.8	1995 2000	DOE/EPA Reg. 8/CDPHE; 10^{-6} risk; used HEAST (1994) slope factors for residential PRGs in 1995; used *Federal Guidance Report 13* slope factors for office worker and open space PRGs in 2000

[a] CDPHE – Colorado Department of Public Health and Environment, EPA – U.S. Environmental Protection Agency, DOE – U.S. Department of Energy, OEPA – Ohio Environmental Protection Agency, USASCE – U.S. Army Corps of Engineers, WDOH – Washington Department of Health.

- **Observation 6—Final cleanup numbers at some sites may differ from calculated soil concentrations due to modifying factors.**

Modifying factors, such as the CERCLA evaluation criteria and the ALARA concept, may be applied to soil concentrations derived from a risk assessment. EPA Region 9 chose a cleanup level of 13.5 pCi/g of plutonium for Johnston Atoll, almost half of the value proposed by the risk assessment, since that lower level had been achieved in previous cleanups. The 8-pCi/g plutonium cleanup level established in a 1992 ROD for Ft. Dix is acceptable to the state of New Jersey because the state later calculated a 15-mrem dose to be about 25 pCi/g. At Rocky Flats, as well as elsewhere, remedial actions may go beyond the derived cleanup values by applying the ALARA concept and stewardship considerations in the field. That is, additional soil that is convenient to areas being remediated may be included, or isolated areas with lower levels of contamination may be remediated to avoid imposing land use controls or long-term management.

- **Observation 7—Input parameters used in deriving soil concentrations have significant influence on the output.**

Generally, a few input parameters used in computer codes or risk equations have significant influence on the result. These may include inhalation rate, dose conversion factors, soil ingestion rate, mass loading for inhalation, assumed chemical form of a radionuclide, and others. In some cases, especially for sensitive parameters, distributions may be available and used in place of discrete values. Using distributions allows the entire range of possible values to be considered for a parameter. Differences in physical settings from site to site or between site-specific and default values account for some of the variations in calculated risk levels. Table 5 demonstrates the wide variations in key input parameters selected at different sites.

- **Observation 8—Improvements to biokinetic/dosimetry models have also led to considerable changes in dose contributions from various exposure pathways.**

Improvements made to the air model in the RESRAD code, beginning with Version 5.82, have led to attributing a greater percentage of risk through soil and plant ingestion in more recent risk assessments as compared to the older ones, which attributed up to 93% of risk to the inhalation pathway (see Table 27).

Table 27. Comparison of Residential Pathway Dose Contributions from RESRAD-Calculated Cleanup Levels for Plutonium, in percent

Pathway	Rocky Flats Cleanup Agreement (1996)	Hanford Site (WDOH, 1997)	Clean Slate Sites, Nevada (1997)	Rocky Flats Oversight Panel[a] (2000)	Johnston Atoll (2000)	Rocky Flats Revised Soil Action Levels (draft) (2001)
Inhalation	93	30	30	65	5	7
Soil ingestion	6	23	31	20	87	73
Water ingestion	0	0	0	0	0	0
Plant ingestion	1	45	29	15	0	20
Other	0	1	10	0	8	0

[a] Estimates at 35-pCi/g level.

Table 27 shows that over time, the dose or risk contribution attributed to the inhalation pathway has generally decreased, while the contributions from the soil and plant ingestion pathways have generally increased. These trends are mainly due to the following reasons:

- The formerly used respiratory tract model from ICRP 1979 has been revised in ICRP 1994 to accommodate greater physiological detail, add more realism, and include three new absorption types—fast, medium, and slow. In essence, the model accounts for mechanical clearance of particles from the lungs in addition to dissolution and absorption to blood.
- The ingestion model has also been refined to account for actinide absorption and deposition on bone tissue. Thus, the impact of new ICRP biokinetic and dosimetric modeling increases the predicted quantities for ingestion but decreases the predicted quantities for inhalation.

- **Observation 9—Some important elements in each site's cleanup level development process are specific to that site.**

Besides all the quantitative differences in calculation methodologies, physical, sociological, and political settings differ and contribute to differences among final cleanup levels. Soil chemistry, chemical form of radionuclides, and potential impacts to groundwater or surface water are important physical elements that are site specific. Various implementing agencies sometimes interpret regulations and guidance somewhat differently. Some sites (e.g., Hanford) strive to include Native American and other local habits, beliefs, and values in the cleanup level development process. Local stakeholder involvement is required.

- **Observation 10—Long-term stewardship is now an integral part of cleanup decisions at many sites. Decision makers at these sites are grappling with balancing the cost of stewardship for restricted land use areas with the cost of cleaning up to unrestricted levels.**

Many of the sites identified in this document have developed cleanup levels that, because of the associated hazards, will require land use restrictions. The effectiveness of institutional controls has historically been poor. Current cost-estimating methods may not sufficiently account for multigenerational care and stewardship of contaminated lands. States and other local entities have generally favored remedies that are as protective as possible to reduce the requirements for stewardship later. In the absence of much guidance, sites that have closed or are approaching closure, such as Weldon Spring, Rocky Flats, and Fernald, have had to find ways to incorporate stewardship into cleanup decisions and to develop stewardship plans.

6.0 CONCLUSIONS

Differences in cleanup levels from site to site are due to variations in one or more of the elements in the cleanup level development process. These elements include regulatory authority, future land use assumptions, site conceptual models, computer models or risk equations, selected input parameters, site-specific physical parameters, and modifying factors, such as the ALARA concept. Variations in the elements of this process have led each site to establish different cleanup levels. The differences in cleanup levels can be understood only by understanding the context in which the decisions in each cleanup level development process were made. The following conclusions have been drawn from the case study observations:

- Because of differing bases and differing assumptions, cleanup numbers used at one site should not be used to justify similar cleanup numbers at other sites.
- Land use assumptions have major consequences for cleanup levels, cleanup costs, and long-term stewardship.
- The decision to leave waste in place that will reduce the land use and create a stewardship obligation for many generations, given the long half-lives of some of the radionuclides, must be carefully analyzed and incorporated in cleanup/closure decisions for these sites.
- Variation in health assessment approaches (risk and dose) leads to variation in assessed site risk.
- Consistency within a given risk assessment approach is a worthwhile and achievable goal for agencies charged with conducting risk assessments of radioactively contaminated sites. Tools such as EPA's new radionuclide PRG calculator should greatly help with this effort.
- Models and input parameters make a difference in assessed risks, and they need to be carefully examined for assumptions made. Sensitive input parameters must be carefully chosen and justified, using distributions of data where appropriate and available.
- The risk assessment and risk management processes should be distinct and separate. During the risk management process, modifying factors such as feasibility, cost, stakeholder values, stewardship considerations, and the ALARA concept can and should be applied to calculated soil concentrations to produce final cleanup levels.
- Risk managers need additional guidance for converting calculated concentrations to actual cleanup levels at the sites.
- The selection and application of cleanup goals have a direct impact on selection and use of remedial technologies. Consistency in decision making for developing cleanup goals will enhance selection and deployment of appropriate environmental remediation and characterization technologies.
- Workshops and training would help lend consistency to the risk assessment process and would greatly assist in application of updated guidance by state, tribal, and federal agencies involved with those risk assessments.

The determination of cleanup levels can involve complex and emotional issues (actual cost, social costs, net benefit to stakeholders, land values, environmental detriment, etc.). At each site, special circumstances exist, and each cleanup action should be evaluated on its own merits.

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APPENDIX A

Acronyms

ACRONYMS

AEA	Atomic Energy Act
AEC	Atomic Energy Commission
AF	Air Force
ALARA	as low as reasonably achievable
ALF	Action Levels and Standards Framework
AM	action memorandum
ARAR	applicable or relevant and appropriate requirement
BNL	Brookhaven National Laboratory
BOMARC	Boeing Michigan Aeronautical Research Center
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CLARC	cleanup levels and risk calculation
COC	contaminant of concern
CRCPD	Conference of Radiation Control Program Directors
DCF	dose conversion factor
DCGL	derived concentration guideline level
DNFSB	Defense Nuclear Facilities Safety Board
DOD	Department of Defense
DOE	Department of Energy
DTRA	Defense Threat Reduction Agency
EDE	effective dose equivalent
EE/CA	engineering evaluation/cost analysis
EIS	environmental impact statement
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Administration
FRL	final remediation levels
FUSRAP	Formerly Utilized Sites Remedial Action Program
GAO	General Accounting Office
HEAST	Health Effects Assessment Summary Tables
HSRAM	Hanford Site Risk Assessment Methodology
ICRP	International Commission on Radiologic Protection
ILCR	incremental lifetime cancer risk
INEEL	Idaho National Engineering and Environmental Laboratory
IRA	interim remedial action
LET	linear energy transfer
LDR	land disposal restrictions
LLW	low-level waste
MARSSIM	*Multi-Agency Radiation Survey and Site Investigation Manual*
MCL	maximum contaminant level
MTCA	Model Toxics Control Act (Washington Administrative Code 173-340)
NAFR	Nellis Air Force Range
NARM	Naturally Occurring or Accelerator-Produced Radioactive Material
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NCRP	National Council on Radiation Protection and Measurements

NDEP	Nevada Division of Environmental Protection
NEPA	National Environmental Policy Act
NESHAPs	National Emissions Standards for Hazardous Air Pollutants
NNSA/NV	National Nuclear Security Administration Nevada Operations Office
NORM	Naturally Occurring Radioactive Material
NPL	National Priorities List
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
NYDEC	New York State Department of Environmental Conservation
OSDF	On-Site Disposal Facility
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
OU	operable unit
ppm	part per million
PQL	practical quantitation limit
PRG	preliminary remediation goal
PTSM	principal threat source material
Pu	plutonium
RAC	Risk Assessment Corporation
RAGS	Risk Assessment Guidance for Superfund
RAO	remedial action objective
RBE	relative biological effectiveness
RCRA	Resource Conservation and Recovery Act
RESRAD	RESidual RADioactive materials (computer code)
RFCA	Rocky Flats Cleanup Agreement
RG	remedial goal
RGO	remedial goal option
RI/FS	remedial investigation/feasibility study
RME	reasonable maximum exposure
ROD	record of decision
SARA	Superfund Amendments and Reauthorization Act
SCDHEC	South Carolina Department of Health and Environmental Control
SRL	Savannah River Laboratory
SRS	Savannah River Site
TBC	to be considered
TEDE	total effective dose equivalent
TMR	total media risk
TPA	Tri-Party Agreement
TRU	transuranic
UMTRCA	Uranium Mill Tailings Radiation Control Act (of 1978)
WSSRAP	Weldon Spring Site Remedial Action Project

APPENDIX B

Radionuclides Reference Information

Summary of U.S. and Standard International (SI) Radiological Units

Quantity	U.S. Units (Symbol)	SI Units (Symbol)
Activity	curie (Ci)	becquerel (Bq)
Absorbed dose	rad (rad)	gray (Gy)
Dose equivalent	rem (rem)	sievert (Sv)
Exposure	roentgen (R)	coulomb per kilogram (C/kg)

Common Conversions

Multiple	By	To Obtain
becquerel	27.03	picocurie
curie	3.70E+10	disintegration per sec (dps)
curie	2.22E+12	disintegration per minute (dpm)
curie	3.70E+10	becquerel
gray	100	rad
rem	0.01	sievert
rad	2.39E+09	ion pair/cm^3 of air (STP)
sievert	100	rem

SI Prefixes

Factor	Name	Symbol	Factor	Name	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Information on Common Radionuclides

Nuclide	Name	Emissions	Half-life
H-3	Tritium	Beta	12.3 years
C-14	Carbon 14	Beta	5730 years
P-32	Phosphorus 32	Beta	14.3 days
S-35	Sulfur 35	Beta	87 days
K-40	Potassium 40	Beta/gamma	1.27E+9 years
Co-60	Cobalt 60	Gamma	5.26 years
Sr-90	Strontium 90	Beta	28.1 years
Mo-99	Molybdenum 99	Beta/gamma	66.7 hours
Tc-99	Technetium 99	Beta	2.1E+5 years
I-129	Iodine 129	Beta/gamma	1.57E+7 years
Cs-137	Cesium 137	Beta/gamma	30.0 years
Ra-226	Radium 226	Alpha/gamma + D	1602 years
U-235	Uranium 235	Alpha/gamma + D	7.04E+8 years
U-238	Uranium 238	Alpha + D	4.5E+9 years
Pu-238	Plutonium 238	Alpha	87.75 years
Pu-239	Plutonium 239	Alpha	2.4E+4 years
Am-241	Americium 241	Alpha/gamma	433 years

Additional useful radiological information (glossary of regulatory terms and information tables) can be found in another ITRC publication, *Radiation Reference Guide: Relevant Organizations and Regulatory Terms* (December 1999).

APPENDIX C

ITRC Contacts, ITRC Fact Sheet, ITRC Product List, and User Survey

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