Radionuclide Transport in the Environment

Draft Research Program Plan

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1. Introduction

A portion of the Office of Nuclear Regulatory Research's (RES's) overall research is devoted to radionuclide transport in the environment (RTE). The RTE research program addresses the effect on public health and safety and the environment from nuclear materials that enter the environment from NRC-licensed activities. The technical issues examined include:

- source-term characterization,
- the effectiveness of engineered and natural containment systems surrounding the radioactive material,
- multi-phase flow of water, including episodic infiltration, into and through contaminated systems
- the transport of radioactive material through the geosphere
- the transport of radioactive material through the biosphere, and
- exposures of members of the public to radiation from these materials.

The primary customer for RTE research is the NRC's Office of Nuclear Material Safety and Safeguards (NMSS). Potential customers include the Office of Nuclear Reactor Regulation, NRC Regional Offices, Agreement State Regulatory programs, licensees, and public interest groups. Results from the RTE research program are intended to be generically applicable to NRC licensing activities including the decommissioning of facilities, disposal of uranium mill tailings, low-level radioactive waste (LLW) disposal, and high-level radioactive waste disposal, as shown in **Figure 1**.

This plan establishes the basis for the RTE research program, describes the key elements of the program, describes how research priorities are set, and presents a plan for carrying out specifics of the research.

1.1 Vision Statement

The NRC and RES Vision Statements are as follows:

NRC: *In implementation of its mission, NRC's actions enable the Nation to safely (sic) use nuclear materials. NRC's actions should be such that the public, those it regulates, and other stakeholders in the national and international nuclear community have the utmost respect for and confidence in the NRC.*

RES: *The Office of Nuclear Regulatory Research furthers the regulatory mission of the NRC by providing technical advice, technical tools and information for identifying and resolving safety issues, making regulatory decisions, and promulgating regulations and guidance. RES conducts independent experiments and analyses, develops technical bases for supporting realistic safety decisions by the agency, and prepares the agency for the future by evaluating safety issues involving current and new designs and technologies. RES develops its program with consideration of Commission direction and input from the program offices and other stakeholders.*

The RTE research program is structured to support the NRC and RES vision statements. The RTE research program's Vision Statement is:

RTE: The Radionuclide Transport in the Environment research program includes the conduct of independent confirmatory and anticipatory research and analyses to provide data and models and other technical information that will support credible, realistic, and defensible estimates of risk to the public from alternative courses of action at decommissioning and nuclear waste disposal facilities and will support agency decisions concerning decommissioning and waste disposal. This research will be planned and executed in response to Commission direction, input from the other NRC offices and other stakeholders, industry and other federal agency initiatives, and the best scientific information on uncertainties and risk.

The NRC makes decisions on a daily basis that deal with the decommissioning of licensed facilities and on a less frequent basis with disposal facilities. These decisions generally deal with very low levels of radioactivity.

However, they are levels that are or will be found in the environment and the best information and scientific tools must be applied to these decisions in order to accomplish the agency's primary mission: "to protect public health and safety and the environment." The plan that is contained in the following sections provides the rationale for research to support these goals and identifies the areas in which research is needed. The last section provides details on current and proposed future program content.

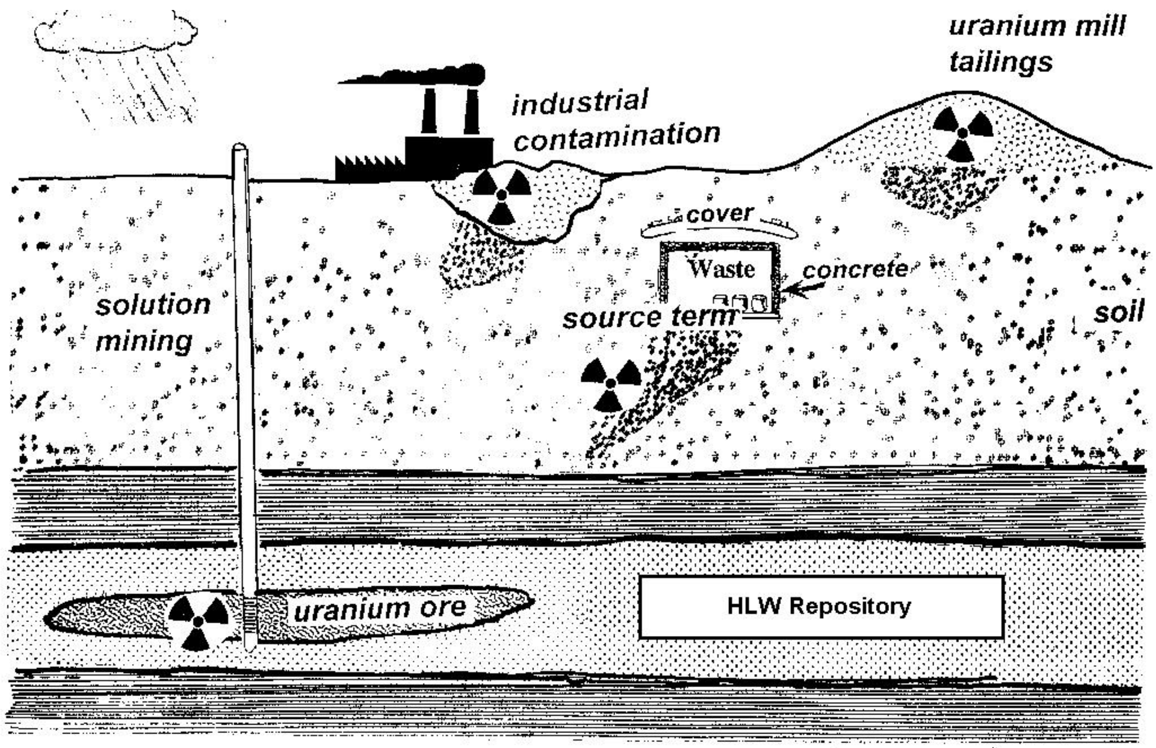

Figure 1: Areas of applicability of RTE research

2. Basis for Research

2.1 Conditions for Doing Research

In the Nuclear Waste Safety Strategic Arena, there is an interlocking set of performance goals, strategies, and measures, summarized in this plan's Appendix A, that define the decisions that must be made and the actions that must be taken to support these decisions. The RTE research program supports decisions relating to limits on long-term doses from releases of radioactive materials to the environment.

Given the NRC's strategic goals and the regulatory framework, there is a need for research to accomplish the Nuclear Waste Safety Strategic Arena's strategies where there are limitations in knowledge and uncertainties in data and models supporting regulatory decisions or the regulatory framework. Where models are known to be oversimplifications of complex systems, uncertainties are known to be large, or calculations are known to be inconsistent with data, dose calculations can significantly underestimate or overestimate individual exposures. Underestimations could support decisions that realistic estimates would show to be inconsistent with regulatory limits. In this case, opportunity and obligation exist to improve the NRC's assessment capabilities. Overestimates could cause unnecessary regulatory burden on stakeholders. In this case, opportunity and obligation exist to improve the efficiency, effectiveness, and realism of agency analyses.

2.2 Research Objective

The ultimate objective of research on radionuclide transport is more realistic and defensible estimates of exposure of the public to radiation from radionuclides released from contaminated sites or waste disposal facilities.

Bounding estimates of the consequences of radionuclide transport from radioactive waste to humans may be hard to defend. The fundamental issue for estimates of the consequences from radionuclide releases to the environment is credibility. Parameter and model uncertainty and unanticipated sensitivities to parameters or processes assumed to be unimportant can invalidate the results of overly simplified analyses. More confidence in safety evaluations is attainable if they are based on realistic estimates of radionuclide transport.

Current estimates of risk from releases of radioactive materials use computational tools that attempt to compensate for uncertainty and lack of knowledge with parameter and model selections intended to overestimate potential exposure. Such "conservative" estimates lead to decisions that may be more restrictive than necessary and may actually incorrectly predict the locations and arrival times of radionuclides, and underestimate the greatest magnitude of potential exposure. In each case where conservative assumptions are employed, great care must be taken to assure that those assumptions are justified and will have the intended result. When they are not justified or when the regulatory response associated with such an approach is extreme, more realistic tools are needed to support an appropriate regulatory position, i.e. one that is consistent with a realistic estimate of the risk from public and environmental exposures.

2.3 Applicability of the Research

The NRC makes use of data and models developed by RES to provide technical support to the development or modifications of regulations and guidance, and in reviews of licensing submittals and licensing actions. The review actions focus on issues being addressed by the RTE research program, namely those associated with the decommissioning of sites and facilities contaminated with residual radioactivity. However, because of the generic nature of the RTE research, it also is applicable to the disposal of uranium mill tailings, LLW, and high-level radioactive waste (HLW). The common technical needs of regulating these diverse activities must be a primary factor in identifying and prioritizing research. As part of the development of this plan and to assure the applicability of its results, user office review has been sought both to assess current and planned content of this program and to identify additional issues or questions to be addressed.

All projects developed under this plan will be coordinated with NMSS and other affected user offices.

2.4 Establishing the Content of the Research

While responses to user needs must form the core of this program, an important component will be research that addresses future needs anticipated by RES and NMSS. One function of research is to maintain awareness of the latest scientific or technological developments that may challenge accepted understanding or offer opportunities for more robust analyses that were precluded by older technology. In soliciting ideas from NRC staff and other peers we will develop a reservoir of topics to be addressed.

2.5 Anticipatory Research on High-Level Radioactive Waste Regulatory Issues

Prior to Fiscal Year 1996, RES conducted an HLW research program that was primarily confirmatory. Following budget cuts in Fiscal Year 1996, the confirmatory research was severely curtailed and its management was transferred to NMSS. In a recent letter to NRC Chairman Richard Meserve[1], the NRC's Advisory Committee on Nuclear Waste (ACNW) recommended that the NRC expand its HLW program "to have a modest, long-term 'anticipatory' research component." The NRC's Executive Director for Operations, William D. Travers, subsequently agreed with this recommendation[2].

Because the decision on anticipatory HLW research is so recent, there has been no coordination between RES and NMSS to establish the content of such a program and no resources have been identified to apply to such issues. Once the content and resources for anticipatory HLW research are established, this plan will be modified to include discussions on this topic.

3. Key Elements of the RTE Research Program

The RTE research program will contribute to improvements in the NRC's performance assessment capabilities. The program has four key elements that support performance assessment.

The NRC and its licensees often use performance assessment (PA) to estimate the hazard of radioactive materials that are available or may become available for transport to and through the biosphere and to humans. A typical PA uses data and mathematical models to estimate the inventory and possible means of transporting the radioactive material from its original location to the biosphere and to humans. The data and mathematical models used in a PA estimate the effects of any process considered significant for the specific situation and provide an estimate of doses to humans as a function of time and location. The steps taken in a typical PA, shown in **Figure 2**, consist of estimations of water infiltration at a decommissioned or disposal facility; the performance of any engineered barriers meant to confine radionuclides; the rates and amounts of release of radionuclides when the engineered barriers fail to confine them; the transport of radionuclides by ground water, surface water, air, and biota; and doses to humans. PA is generally an iterative process because uncertainty is inherent in all PA's. The uncertainties are attributable to conceptual errors or simplifications used to obtain PA's mathematical models and to a lack of precise values of parameters used in the mathematical models. The RTE research program focuses on the most important of these uncertainties. The key research elements are described in more detail in Chapter 5.

Table 1: Performance Assessment Components and Key RTE Research Elements

PA Component	Key Research Element
Infiltration	Transport (ground-water flow)
Engineered-barrier performance	Engineered barriers to radionuclide transport
Rates and amounts of release of radioactive materials	Release of radioactive materials
Transport by ground water	Transport
Transport by surface water	Transport
Transport by air	Transport
Transport by biota	Transport
Dose	Performance assessment
Integration of the above	Performance assessment

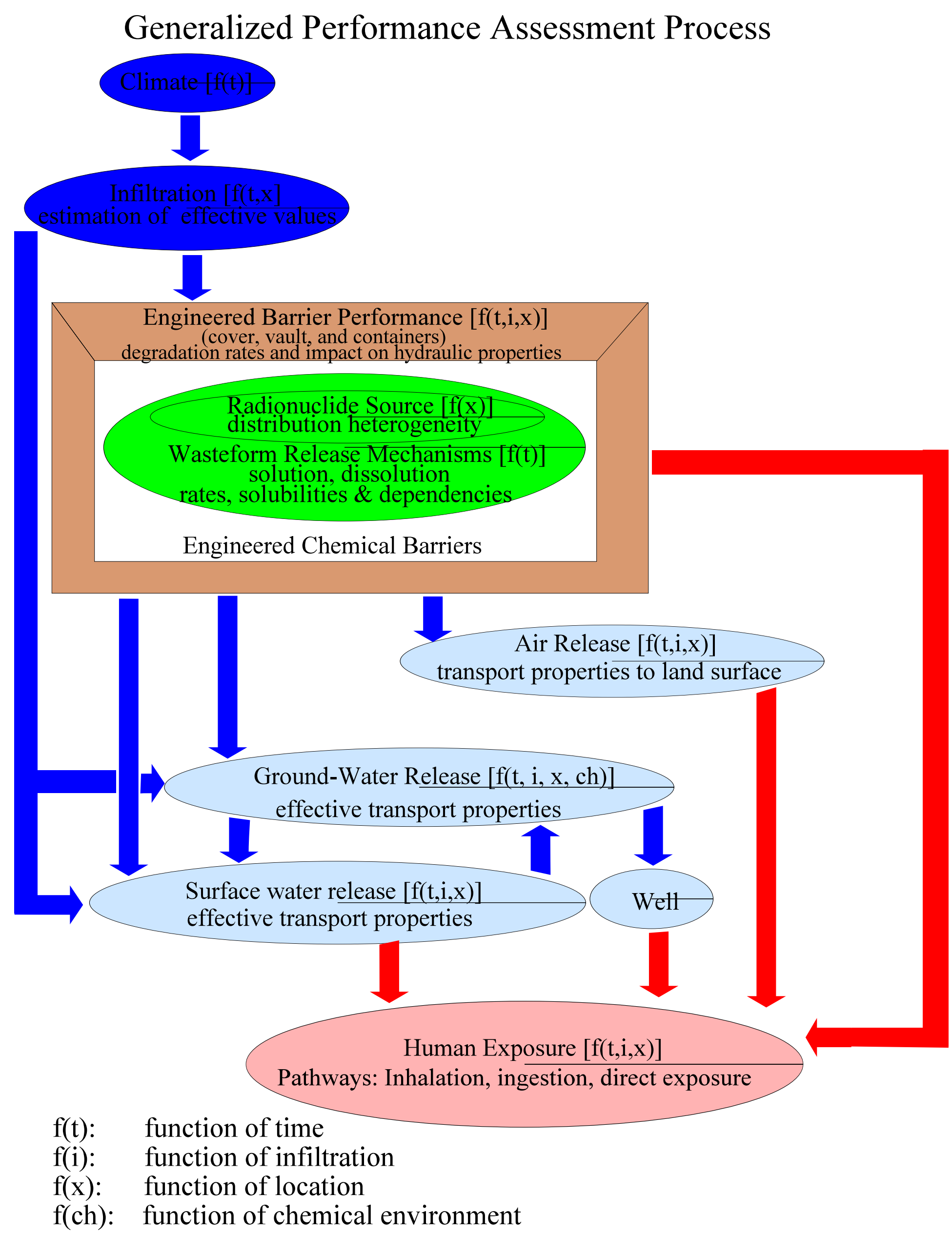

Figure 2: Generalized Performance Assessment Process

4. Setting Research Priorities

In order for the RTE research program to be effective, it is essential to define areas where knowledge is needed, define the issues that need to be investigated in order to obtain the knowledge, and rank the issues by their importance to safety and other NRC performance goals. Several methods of prioritization, described in Section 4.1, are currently available to the RTE research program.

4.1 Current RES Research Prioritization Systems

RES has organized its projects into groups called “activities.” RES currently has a prioritization system that ranks all of the Office’s activities, including those of the RTE research program, according to the factors given in the “Current System” part of Table 2. Each RES activity is rated according to the criteria listed in Table 2 and all RES activities are ranked according to scores obtained from Table 2. Funding is then allocated to these activities based on this ranking.

4.2 Proposed Prioritization System for RTE Research

The RES prioritization system uses rating factors derived from an analytical hierarchy process. The basic assumption of such an approach is that the goals, criteria and measures are selected to form an independent and complete set of decision factors. The basis for the goal and criteria structure of the prioritization system is the structure of the NRC’s Strategic Plan.

Table 2 contains a second column of rating factors which parallels those of the existing prioritization system but has been modified to address the goals, strategies and measures more appropriate to RTE research. Many of the factors are unchanged because they deal with such things as credibility of the issue (cf. Table 2's left column). A detailed comparison of each set of factors follows.

4.2.1 Issue Credibility / Agency Support

There is little variation suggested here. The first two criteria are Commission Staff Requirements Memoranda (the work is being conducted at the request of the Commission) and User Need (the work is in response to a specific written request from the User Office). These remain important determinants in work that is funded in the Nuclear Waste Safety Arena. The third rating factor, Operating Experience /technology /ACRS has been modified because there is no systematic assessment of extensive operating experience for many of these concerns nor is the industry necessarily expert in many of the issues. The federal agencies with significant regulatory and clean-up responsibilities have a significant body of experience and expertise that can be tapped to assist in the identification and evaluation of issues. The National Academies, international agencies dealing with nuclear waste problems, and the regulatory and developmental bodies of other countries are another source of expertise. The other significant change would be the substitution of the ACNW for the Advisory Committee on Reactor Safeguards (ACRS). The thrust of these changes is not significant, it is merely the identification of an alternative set of appropriate sources and authorities.

4.2.2 Safety Contributors

4.2.2.1 Safety Significance

Addresses significant new safety challenges

The primary measure under the Performance Goal, “Maintain safety, protection of the environment, and the common defense and security” that is addressed by the RTE research program is “No events resulting in radiation over-exposures from radioactive waste that exceed applicable regulatory limits.” This program deals not with large preventable doses and deterministic effects of direct exposure but with low level exposures from potential releases to the environment. It is bounded by stochastic effects due to lifetime exposures to low levels of radiation. The challenge of this program is credibly and realistically to address the level and location of potential exposures of individuals in the public. It is suggested that the appropriate rating factor here be whether the process proposed for study have a potential to cause an order of magnitude effect on dose estimates. A new title for this factor could be "Addresses Significant Environmental Challenges."

Maintains/assures current level of safety

In this case the description of the factor is heavily weighted with reactor accident concerns. A comparable factor description for environmental transport issues would be development of technologies to control, mitigate or prevent degraded isolation system performance or to reduce the uncertainty in performance estimates. Engineered systems designed to enhance waste isolation or flexible PA tools that allow more realistic combinations of subsystem models would be such technologies. The title of this factor would be changed to "Addresses Technologies to Control, Mitigate or Prevent Degraded Isolation Performance"

Monitors safety performance

This factor looks at assessing performance with real time data from operating systems. The perspective is establishing a data base of like systems and equipment performance so that failure trends can be identified and corrective action taken on an agency wide basis. For the RTE research program, there is a corollary that deals with the long time frames for which regulatory decisions are made. The corollary is development of technologies for long-term monitoring that would permit remediation of early failure and development of institutional controls that will assure the efficacy of long-term monitoring systems. This issue has become a major concern of the DOE for its legacy sites and may become of equal concern for the NRC in dealing with those sites that will not qualify for unrestricted release. The title of this factor would be changed to "Addresses Monitoring and Long-Term Institutional Control."

4.2.2.2 Scope of licensees

The only change for this factor would be to establish scope based on classes of waste activities. The same percentages could be used.

4.2.3 Effectiveness, Efficiency, and Realism Contributors

4.2.3.1 Realistic decision making

These factors can be adapted to the review of RTE research.

4.2.3.2 Industry participation / Leverage

A large, well financed waste disposal and decommissioning industry with its own technical resources and research institutes does not exist for decommissioning and waste licensees. However, there are potential partners in the US government and in other countries. The suggested change here would be to generalize from "industry" to the term "external." The structure would be similar but the highest rating suggested would be for "Sharing with multiple partners or where NRC contributes significantly less than half." The second level would be for "Approximately equal sharing with one partner." The last level would be for "Sharing where NRC contributes significantly more than half."

4.2.4 Contributors to Reduction of Unnecessary Regulatory Burden

For this factor a significant difference between reactor licensees and decommissioning and waste licensees must be recognized. Decommissioning and other waste activities are one time savings opportunities. For the RTE research program, the suggestion is that only cumulative savings be considered, not annual savings. It may also be necessary to adjust the level of the savings but that is not possible to determine at this time.

4.3 Effect of Proposed Improvements: Summary

The improvements above would leave the RTE research program's activities with a comparable system to that currently used for the entire RES program but would place them on much more even footing. It would also create a situation amenable to treating them separately as a group while retaining the same structure as that already used for the budget process.

4.4 Program Implementation

This program plan has described the regulatory context for RTE research at the NRC. In order for this plan to become a program it requires support from its stakeholders.

The first step is taken in Section 5. There are listed all current research projects currently funded in this program. Also listed are ideas for future work developed by the staff based on their own professional judgment and interactions with their peers on the NRC decommissioning and waste licensing staff and in the general scientific community.

The second step will be distribution of this plan for review by internal stakeholders. In addition to general comments on the context for the program, the stakeholders will be requested to provide topics that they believe should be studied to improve the NRC's assessment capabilities in the Nuclear Waste Safety Arena. Licensing staff experience and expertise applied to this request will be an invaluable tool for defining the set of topics that will be considered for prioritization.

The third step in this process will be solicitation of comments and ideas for future research from external stakeholders including other federal and state regulatory agencies and organizations such as the ACNW and the National Academies which the NRC supports in order to secure high caliber professional reviews for agency activities.

The fourth step in the process will be the compilation of a master list of activities from the internal and external stakeholder input for prioritization within the framework described earlier in this section.

Table 2: Prioritization Rating Factors

Current System: Reactor Safety Based				Proposed: Waste Safety Based	
Issue Credibility/Agency Support (Projects must meet at least one of these criteria)					
1	Commission STAFF REQUIREMENTS MEMORANDA			1	No change
2	Formal User Need			2	No change
3	Operating experience/technology/ACRS			3	Regulators/research org./ACNW
Safety Contributors		Maximum Score	Multiplier		
Safety Significance		3			
1	Addresses significant new safety challenges		1	1	Addresses significant environmental challenges
2	Maintains or assures current level of safety		0.6	2	Addresses technologies to control, mitigate or prevent degraded isolation performance
3	Monitors safety performance		0.4	3	Addresses monitoring or long-term institutional control
Scope of licensees		2			
1	>50% of all licensees		1	1	No change (Apply to any class of licensees)
2	>10% of all licensees		0.6	2	No change (Apply to any class of licensees)
3	<10% of all licensees		0.4	3	No change (Apply to any class of licensees)

	Efficiency and Effectiveness Contributors	Maximum Score	Multiplier		Efficiency, Effectiveness and Realism Contributors
	Realistic Decision Making	2			
1	Realistic tools or data to confirm safety		1	1	No change
2	Realistic tools or data to reduce margins, burden		0.6	2	No change
3	Maintain capabilities for independent verification and identification of issues		0.4	3	No change
	Industry Participation / Leverage	1			External Participation / Leverage
1	Major external participation/NRC < 25% support		1	1	Multiple partners or NRC << 50%
2	NRC and ext. part. / NRC ~ 50% support		0.6	2	Equal sharing with one partner
3	Minor external support / NRC > 75% support		0.4	3	Sharing where NRC >> 50%
	Unnecessary Burden Reduction Contributors	Maximum Score	Multiplier		
		1			
1	Cumulative savings > $10M / year		1	1	Cumulative savings > $10M
2	Cumulative savings > $1M / year		0.6	2	Cumulative savings > $1M
3	Cumulative savings > $0.1M / year		0.4	3	Cumulative savings > $0.1M
	Public Confidence Contributors - not included in system				
	Composite score = Sum {multiplier x maximum score}				

5. Proposed Research

5.1 Release of Radioactive Material (Source Term)

5.1.1 Technical and Regulatory Background

Releases of radionuclides to the environment from waste disposal facilities and decommissioned sites must be understood to predict the transport of radionuclides in soil, rock fractures, ground water, surface water, and atmospheric systems to the public and to ensure compliance with NRC regulations.

Determining radionuclide releases from decommissioning and waste materials under varying chemical and physical conditions is one of the most difficult but important aspects in assessing the performance of decommissioning and radioactive waste facilities. Within the context of a risk informed and performance based assessment, this “source term” modeling uses input from the infiltration analysis (i.e., the calculated flux of water through engineered barriers into the disposal facility) to estimate radionuclide releases that are then used in environmental ground-water or atmospheric transport models. Additionally, one needs to consider various features of the decommissioning and waste disposal facilities that affect radionuclide releases when developing a source term model.

In order to estimate radionuclide releases, one needs to consider radionuclide inventories, radionuclide solubilities and release rates, waste behavior and dissolution, waste types and forms, waste containers and cladding, backfill, and chemical conditions impacting these materials are needed to estimate radionuclide releases.

Specific data and information on long-lived fission products, activated materials, and transuranic radionuclides are used as input to computer codes used to assess the performance of decommissioning and waste disposal facilities to meet applicable NRC design objectives and regulatory requirements, including dose commitments. Much of the radionuclide data and information needed for use in establishing inventories, determining source terms and understanding the chemical behavior of radionuclides in PA applications are not available, or if available, the data are generally of either poor quality or have been obtained under differing conditions from those that could be expected to be present in decommissioning and waste disposal facilities.

Further research is needed to develop confidence source-term models used in PAs by updating existing mathematical models where deficient, identifying analysis required for PAs, and validating models with experimental and field data derived from waste stream spills to the environment, doint research investigations such as spent fuel and waste stream leaching experiments, and doing field studies.

5.1.2 Technical and Regulatory Objectives

The primary objective of the release element of the RTE research program is to provide experimental data and information to be used to determine realistic radionuclide inventories and to calculate realistic radionuclide releases from radioactive waste disposal facilities and decommissioned sites using source term computer codes.

Both laboratory and field research studies of actual decommissioning and waste disposal materials are needed to provide an understanding of radionuclide release, to understand and quantify, where possible, conceptual, parameter, and data uncertainties associated with radionuclide source term models used in PA computer codes, and test the validity of the source-term models.

5.1.3 Research to be Performed and Products

RES is currently conducting research on (1) SDMP slags and soils[3], (2) characterization and leaching of decontamination waste obtained from nuclear power stations[4], and (3) evaluating radionuclide-chelating complexes in soils and groundwaters from decontamination waste[5]. The research results are expected to be used to revise and update PA codes, provide data and information for decommissioning SDMP sites and to provide information for use in determining radiological criteria for license termination of NRC-licensed nuclear facilities.

The research on the SDMP slags and soils involves: (1) characterizing slag and soils for radionuclides (mainly U and Th and their progeny) and chemical content, (2) assessing the importance of parent and daughters in slags and soils, (3) determining the solubilities of radionuclides SDMP sites, and (4) determining radionuclide releases and estimating radionuclide colloids from SDMP site samples.

Decontamination waste from a full-core decontamination from Indian Point 2 is being characterized for long-lived fission products, activated metals and transuranic nuclides and chelating agents. The decontamination waste is undergoing leaching tests to estimate the release rates for radionuclides and chelating agents.

Radionuclide-chelating agents research studies are looking into reactions of radionuclides with chelating agents found in decontamination wastes that form radionuclide-chelate complexes that may enhance migration of radionuclides through groundwater to people.

Recently completed research has shown that: (1) field lysimeters can be used to study waste form behavior, radionuclide release rates and transport in soils under field conditions, and the data and information can also be used in studies to validate source term models[6]; (2) microbial organisms can influence waste degradation and have the potential to release radionuclides from solidified waste forms containing radioactive waste[7]; (3) activated metals contain radionuclides, many of them hard-to-measure, that are not listed in 10 CFR Part 61 or considered in PA calculations[8]; and (4) adsorption and desorption of radionuclides from ion-exchange resins vary depending on the chemical composition of waters used in the experiments[9].

Proposed new projects in this element of the RTE research program are listed below.

1. *Characterization of radioactive waste and decommissioning sites for radionuclide and chemical content.* Estimates of radionuclide inventories are used in NRC PAs to calculate radionuclide releases from waste forms and decommissioning slags and soils. There are many uncertainties associated with the radiological and chemical characterization of fission products, transuranics and activated metals to determine accurate inventories and information needed as input to the PAs. The overall goal of characterizing radioactive waste forms and decommissioning soils and slags is to evaluate the uncertainties associated with determining radionuclide inventories and provide the necessary data and information for determining source terms for NRC PAs.

This work will address activated metals and issues involving secular equilibrium of daughter products , or progeny, for particular radionuclides. Samples of actual radioactive waste (e.g., activated metals, decontamination waste, hardened concrete) will be collected from nuclear power stations, waste disposal facilities, and other generators. The phases present, activity levels, and parent/daughter equilibria will be determined for each radionuclide present in the radioactive waste. Radionuclides that will be determined include long-lived radionuclides, fission products, transuranic radionuclides, and activated corrosion products and materials.

Both organic and inorganic chemical compounds will be determined in the radioactive waste and decommissioning sites. For decontamination waste, both the radionuclide and chelating agent content will be determined. This research will support the NRC staff's need to characterize properly radionuclides available for transport.

2. *Determination of Solubilities of Radionuclides.* NRC PA models use radionuclide solubilities to estimate the concentrations of radionuclides released to ground waters and to estimate the migrations of radionuclides in both the near and far fields. Many of these radionuclide solubility limits measurements have uncertainties associated with them that could cause PAs to estimate inaccurate radionuclide releases to the environment thereby increasing the uncertainty in estimating the dose to people. The proposed research will address the main uncertainties associated with determining radionuclide solubilities used in PAs and will soncider the effects of pH, redox conditions, and variations in near field and groundwater chemistry composition.

Experimental radionuclide solubility data will be obtained for important long-lived radionuclides present in radioactive waste and at decommissioning sites under varying pH levels (6 to 13), temperature conditions (15 to 40^{o}C) and chemical factors (e.g. carbonate/bicarbonate concentrations and ionic strength concentrations (0.01 and 0.10$\underline{M}$)). Solubility data should be obtained for the following long-lived radionuclides: ^{129}I, ^{99}Tc, ^{36}Cl, ^{14}C, ^{59}Ni, ^{94}Nb, ^{239}Pu, ^{241}Am, ^{237}Np, ^{238}U, ^{232}Th, ^{226}Ra and other radionuclides including daughter products, and will be used to obtain probabilistic distributions to support realistic assessments of performance.

3. *Determination of radionuclide chemical speciation data and information.* To test models of speciation, chemical speciation of radionuclides in ground water environments needs to be experimentally determined. Radionuclide chemical species distribution diagrams will be experimentally determined and calculated as a function of pH and different chemical conditions covering both oxidized and reduced conditions for aqueous systems both within a disposal facility and in ground water systems. Eh-pH chemical species diagrams will be determined for long-lived radionuclides from available chemical thermodynamic data. Existing chemical thermodynamic data used in calculating chemical species diagrams will be reviewed and assessed. Recommendations will be provided for improving the thermodynamic chemical data base to calculate the radionuclide chemical species.

4. *Radionuclide leaching studies.* Radionuclide release rates from radioactive waste are used by NRC to determine whether applicants and licensees are in compliance with NRC standards. Difficulties in determining release rates from waste forms and applying radionuclide release rates for some long-lived fission products, transuranics and activated metals have limited their applications in PAs. This research task will focus on determining radionuclide release rates from a variety of waste forms and evaluate the uncertainties associated with determining radionuclide release rates.

Laboratory studies of actual radioactive waste, decommissioning materials, concrete and activated metals will be used for short-term and long-term leaching studies. Both flow-through and batch leaching will be employed to determine the important radionuclides released and this will be related to the phases present. The leaching studies will be performed using leaching waters of varying pH level, ionic strength, carbonate/bicarbonate concentration, and water chemistry. Leachates will be analyzed for all major long-lived radionuclides. From these data, release rates will be determined for all major radionuclides in the leachates. Dissolution information and rates for the radioactive waste forms will also be determined during the leaching experiments.

Release rates will be used in source term computer codes to determine release rates for overall PA, and probability distributions will be calculated. The leaching studies will lead to more realistic modeling of source terms releases and behavior of radionuclide releases.

5. *Determination of releases and assessment of transport of radionuclides in waste streams that are not listed in Part 61 and not considered in current PAs.*

Recent research studies have shown that radioactive metals disposed in waste disposal facilities contain long-lived activated metals. Data and information on activated metal and hardened concrete radionuclide solubilities, release rates and sorption coefficients are needed to estimate radionuclide releases and migration in soils.

The release and transport of long-lived radionuclides present in activated metals (e.g, ^{10}Be, ^{36}Cl, ^{93}Mo, ^{93m}Nb, ^{108m}Ag, ^{113m}Cd, and ^{121m}Sn) and concrete will be assessed. Radionuclide solubility and leaching studies on activated metals and concrete will be performed. Radionuclide release mechanisms will be proposed and PA computer codes will be modified to account for radionuclide release from activated materials and hardened concrete.

6. *Chemical thermodynamic data.* For NRC PAs, many factors are evaluated to ensure the calculated dose is in compliance with applicable NRC regulations. Many calculations involve chemical forms of the radionuclides in which the parameters (e.g., solubility, sorption, species) may be calculated over a range of varying physical and chemical conditions using available chemical thermodynamic data. However, chemical thermodynamic data for many long-lived fission products and transuranics are either not available or of poor quality for the range of temperatures, ionic strength and water quality chemical composition conditions in which PA analyses are applied. Reliable chemical thermodynamic data are needed to reduce the uncertainties in these calculations.

Important thermodynamic data will be determined for long-lived radionuclides in aqueous and solid media under varying chemical and physical conditions for use in computer codes that calculate radionuclide chemical species, radionuclide solubility, and solid phases as a function of pH as well as for determining radionuclide species in Eh vs pH diagrams. The calculations are needed to provide an understanding of the behavior and migration of radionuclides under varying chemical conditions and will provide support for licensing decisions. This work also has ramifications for transport because thermodynamic data are needed to support mechanistic sorption modeling.

7. *Performance Assessment for Sites Containing ^{232}Th*

Some sites contain ^{232}Th and its progeny at low activity levels. Research results indicate that Th in these soils and slags has extremely low solubility limits. Therefore, it may be possible for NRC to perform a generic PA in house for ^{232}Th in these soils and slags to show that the doses from the sites to people may be below NRC regulatory limits. Such a determination may be cost effective in determining that ^{232}Th is not a problem at these sites.

Doses at decommissioning sites containing ^{232}Th and daughter products as the major radionuclides will be assessed generically using the experimental thorium solubility data obtained in ongoing research. This approach may allow for a generic assessment to be made for all thorium related decommissioning sites and provide support for decisions regarding decommissioning of these sites thus reducing unnecessary burden.

8. *Assessment of new waste disposal and storage technologies (e.g., assured isolation).* New technologies are being proposed to store

and dispose of radioactive waste in waste disposal facilities. Radioactive waste is planned to be incorporated in waste forms that have not been tested to ensure that they meet NRC's branch technical position on waste form criteria (e.g., leaching, compression). Independent research results using actual radioactive waste would provide a basis for evaluating whether the waste forms conform to the NRC's guidance.

New LLW waste form disposal technologies will be evaluated to determine if they meet the BTP's guidance. These new disposal technologies will include, but not be limited to assured isolation storage, waste compaction, incineration, glassification, and molten metal. Testing procedures will be developed where necessary to ensure the waste forms meet NRC requirements for disposal. The initial research effort is expected to focus on assessing the performance of a proposed polymer waste solidification method for use in assured waste storage. The waste will be characterized for radionuclide and chemical content and leaching experiments will be performed to determine radionuclide releases.

9. *In-situ and real-time monitoring of radionuclides at waste disposal facilities over long times.* Disposal facilities are required to monitor water and soils for radionuclides to ensure compliance with NRC regulations. Many of these radionuclide measurements are difficult, costly, and require considerable time to compile and collect the data for interpretation and analysis. Recently advances in radiological and chemical instrumentation and in on-line radionuclide monitoring methods suggest the possibility that in-situ and real-time isotopic and chemical measurements can be made for radionuclides in soils and groundwater at waste disposal and decommissioned sites.

This work will assess the feasibility of determining radionuclides in soils and rocks (matrices and fractures) *in-situ* and in real time over long times using radionuclide/chemical measurements and fiber optics systems. The fiber optics and sensitive probes will be buried in soils and rock fractures below waste disposal facilities and along expected radionuclide transport plumes to measure actual concentrations of radionuclides released from the disposal facilities using chemical spectrophotometer or other chemical measuring systems outfitted with conventional and laser light sources. The system will also measure water using standard adsorption bands eliminating the need for monitoring wells. The data will be collected in computer systems, transported by satellite, and be available for review in real time by NRC staff.

10. *Radionuclide releases by microbial organisms.* Microorganisms present in disposal facility environments could influence the release of radionuclides from waste disposal facilities. Microorganisms present in the subsurface environment could interact with fission products and transuranics to alter the behavior of radionuclides in groundwaters, soil and rock fractures and either retard or enhance their mobility in groundwater systems. Such behavior could either increase or decrease the estimated dose to people from exposure to radionuclides in PAs. The models in PAs that simulate radionuclide transport do not include effects due to microorganism interactions with radionuclides. These microorganism exist in the soils at low-level waste disposal sites and in nuclear waste repositories, including the proposed HLW repository at Yucca Mountain, NV[10]. The wide diversity and widespread occurrence of microorganisms, particularly bacteria, suggest that these microorganisms may effect the long-term stability and mobility of radionuclides in waste disposal facilities. These microorganisms appear also to create chelates and other organic compounds in the environment that could react with radionuclides to increase their mobility in the transport process. Because the size of microorganisms falls within the colloidal size range of 1 nm to 1 μm, they may attach themselves to radionuclides in ground water and soils and be transported as biocolloids. Results from a

recent NRC LLW research program on microbial organism effects on cement-solidified LLW containing ion-exchange resins provided results which strongly suggest that microbial organism could release radionuclides from the resins in leaching experiments[11]. More recent research has shown that: (1) the biosorption of uranium and plutonium occurs in microorganisms found in groundwaters at the WIPP site and the Grimsel Test Site in Switzerland [12]; (2) Plutonium and uranium can react with chelates and extracellular polymers produced by aerobic soil microorganisms[13]; (3) sorption and desorption of plutonium and uranium occur with soil bacteria and aerobic soil bacteria react with Pu(VI) to form Pu(VI) complexes, reduction of Pu(VI) to Pu(V) and the formation of Pu (IV)[14]; (4) sulfate reducing bacteria may reduce and precipitate Np(V) thereby reducing its solubility in aqueous solutions[15], and (5) actinides can interact with microbial cells and exopolymers[16].

Research is needed to determine the effects of microorganisms found in soils and groundwaters at waste disposal and decommissioning sites on the release and migration of radionuclides that contribute to the dose to people. The data and information will be used to modify existing PA models and computer codes to account for microorganism affects on the retardation of radionuclides, confirm research results on microbial interactions with radionuclides, and provide information to the NRC staff to review independently applicants' and licensees' data, information, analyses and computer codes.

5.2 Engineered Barriers to Radionuclide Transport

5.2.1 Technical and Regulatory Background

Engineered barrier systems may be used (1) to limit the contact of infiltrating surface and/or ground-water with the radioactive materials and/or (2) to mitigate the leaching and migration of radionuclides to the surrounding environment. Typical engineered barriers used to limit water infiltration are "caps" composed of soil materials, geomembranes, clay liners, etc., placed over waste deposits. Other barriers used to mitigate the release of radionuclides include reinforced and plain concrete structures and boxes, high integrity containers that isolate the radioactive materials, hot mix asphalt, and various backfills and infill materials that can mitigate radionuclide transport by sorption and retardation. Subsurface barriers to contaminant migration and transport include cement and bentonite slurry walls and grout curtains, geotextiles and sheet pile impermeable walls, and permeable reactive barriers designed to intercept contaminant plumes that transform contaminants into environmentally acceptable forms at the discharge end of the barrier. Another class of engineered barriers arises from stabilization approaches often used to immobilize radionuclides and hazardous chemicals and thereby preclude their leaching and migration. The material is either combined with chemical additives such as lime, Portland cement, etc., or transformed into solid or glass forms from which the radionuclides will not leach or migrate easily. In the case of hydraulic barriers, ground water collection and extraction with subsequent pump-and-treat methodologies may provide an effective but temporary barrier to transport.

The key technical issue that needs to be addressed for the use of engineered barriers for isolation of radioactive material is the effective performance lifetimes of these barriers, for both natural and synthetic materials, as a function of climate, hydrology, geology, and time. Convincing scientific and engineering evidence that barriers retain their effectiveness and isolation capabilities for periods of hundreds of years is needed. There is a critical need for examining the credit that can be taken for engineered barriers in the PAs of decommissioning and waste disposal facilities. Of concern to regulators is the lack of available supporting technical bases and scientific proof of isolation. For example, in the development of the NRC's PA methodology for LLW facilities[17], it became clear that only by assuming that the engineered barriers (cover soil and other materials in conjunction with the concrete vaults containing the wastes and/or separately) precluded contact with and leaching of the wastes for a period of 300 to 500 years, would it be possible to assure that no dose from the mobile short-term radionulides would be possible. Such assumptions have no basis in the scientific and technical literature and experience. Similar results have been evidenced from PA to ascertain releases from engineered barriers from HLW and degraded engineered soil "caps" placed over mill tailings and other radioactive wastes including some decommissioned sites. For instance, in the latter case, the results of dose assessments are predicated on the assignment of service life estimates on the performance of engineered caps placed over contaminated fills including slags.

Implicit in the assessment of the effective lifetimes of engineered barriers for radioactive materials is the realization that it is very difficult to predict long-term environmental events and the attendant physical, chemical and biological factors that can cause degradation of engineered barriers. Development and refinement of invasive and non-invasive techniques may be useful in ensuring that engineered barriers are functioning as designed as well as for detection of defects in the barriers. There is little understanding of the long-term performance of some engineered containment systems which may be used in the near future and there is an absence of effective methods to verify that such systems are properly installed or that they can provide effective long-term performance. The National Academy of Sciences (NAS) recommends that research will be needed in the development of methods for assessing the long term durability of containment barrier systems[18]. The NAS also has considered contamination isolation measures and stated that, due to the lack of experience with engineered barriers, there is a need to confirm and ensure the effectiveness of barrier structures and durability over time by the use of management measures such as sampling and/or monitoring to determine if the barriers are in fact functioning as designed[19].

5.2.2 Technical and Regulatory Objectives

It is imperative to have a technical basis for assessing the long-term performance of engineered barriers, particularly in critical areas of uncertainty such as the performance effectiveness of engineered barrier systems to prevent releases of radionuclides over long periods of time. As a result, research projects are needed to support the development of guidance on engineered barrier performance. Research needed includes the development of mathematical models of engineered barrier degradation behavior, testing of the mathematical models with data from the published literature and controlled laboratory and field testing, mathematical modeling to determine compliance with regulations, and the analysis of monitoring data for confirmation of the effectiveness of both successful and unsuccessful barrier installations.

The regulatory objectives outlined above cover a whole range of licensing areas such as: (1) entombment of nuclear reactor facilities, (2) rubblization of buildings and materials as applied to the decontamination and decommissioning of NRC licensed facilities, (3) LLW disposal facilities that include assured isolation facilities and earth mounded/above ground/below ground reinforced concrete facilities, (5) sites with engineered soil "caps' and other composite materials placed over waste materials and/or subsurface barriers to intercept contaminant plumes, and (6) engineered barriers for the containment of waste in the Independent Spent Fuel Storage Installations (ISFSI) and other Monitored Retrievable Storage (MRS) programs.

The NRC staff has developed a rulemaking plan and an Advance Notice of Proposed

Rulemaking for Commission approval in anticipation of the development of a rule to allow entombment as a decommissioning option for nuclear power plants. As part of this development, the NRC staff has identified research needs for evaluating performance criteria for entombed structures. They include two topics pertaining to the effectiveness and performance of the entombment structure and the surveillance and monitoring of its performance over the period of entombment. They include evaluation strategies for the entombment structure to determine the physical condition of the structure, and obtain the necessary data for inputs to concrete performance codes in the PAs of these facilities and evaluating surveillance and monitoring strategies to obtain data to confirm the performance modeling of the entombed structures.

5.2.3 Research to be Performed and Products

Engineered barrier systems are widely used to isolate waste and mitigate leaching and migration of radionuclides. Key technical issues associated with their use that need to be addressed are the effectiveness of these systems and their ability to function for hundreds of years. RES has concluded research projects[20] to predict the durability and service life of reinforced concrete engineered barriers primarily for concrete structures for LLW, proposed assured-isolation-facilities, and entombment structures. The computer program 4SIGHT developed under the program can be used to evaluate the degradation and fluid transport properties of entombed waste structures, rubbilized concrete disposed in concrete structures, subsurface grout curtains and slurry walls that use cement materials. Major conclusions from the concrete engineered barriers research program was that although the modified 4SIGHT code developed under the program represents the-state-of-knowledge of sound scientific and engineering principles, the absence of data from the in-service performance of concrete makes it necessary to obtain and analyze surveillance and monitoring data from these barriers to confirm code predictions. A description of these projects follows.

1. *Methods for evaluating existing concrete structures prior to entombment.* Investigations will include non-destructive testing, mapping of imperfections in the concrete that may be preferential pathways, e.g., corroded steel, segregation of aggregates, etc. Development of such methods will help in the characterization of reactor structures planned to be entombed.

2. *Inspection, maintenance and monitoring strategies to evaluate the effectiveness of concrete performance as repair strategies to fix defects and preferential pathways.* Development of these strategies will help in obtaining the data necessary to test concrete service life and durability predicted by the 4SIGHT code.

3. *Addition of radionuclide transport and sorption to the 4SIGHT code.* The code as presently available considers the transport of only non- radioactive ions such as H, Ca, Na, K, OH etc. This work will incorporate the radionuclides of prime importance to decommissioning and waste disposal. Results from this work will allow determination of the rate of radionuclide transport through concrete.

4. *Investigation of the effects of various admixtures in concrete e.g., silica fume, fly ash, blast furnace slags, fiber reinforcement on the durability of concrete barriers.* LLW sites in France, England, Spain have used some of these admixtures in their constructed facilities. Experimental research results and monitoring data from these facilities would be obtained and considered for incorporation in the 4SIGHT code.

5. *Rubblization.* Research on leaching of radionuclides from rubblized concrete will be

conducted using laboratory methods such as ion chromotography and x-ray diffraction.

In addition to concrete-based physical barriers, non-concrete based barriers, e.g., soil caps, geomembranes, permeable and impermeable barriers with wide applications in containing radionuclide migration from decommissioned facilities, uranium tailings piles and subsurface contaminated sites will likely be employed. The NAS surveyed the current knowledge on the performance of several non-concrete based barriers and concluded that there is need for knowledge concerning effective lifetimes of selected barrier materials; noted the importance of inspection, maintenance, and monitoring of the containment barriers; and stressed the importance of compiling data on both successful and unsuccessful barrier installations[21]. Research needs in these areas are described below.

1. *Long-term soil cap performance.* Data on the performance of both successful and unsuccessful soil caps, in different climatic, geologic and hydrologic regions will be collected and analyzed so that reliable estimates of effective lifetimes of these barriers can be developed. The information from this work can be complemented by controlled, accelerated tests in the laboratory, e.g., centrifuge testing to test mathematical models of "cap" performance.

2. *Development and testing of mathematical models of the degradation of geomembranes.* Geomembranes are being widely used as barriers in waste facilities. Some of the degradation mechanisms include those due to ultraviolet light, radioactivity, biological and chemical processes, thermal effects and oxidation. By developing and testing mathematical models to evaluate these mechanisms, the RTE research program can develop reliable performance estimates.

3. *Long-term performance of asphaltic concretes.* Asphaltic concretes are being proposed in some situations over clay soils as a low permeability layer to meet the requirements of engineered barriers designed to have a 1000-year design life. Mechanisms for the aging of asphalt and the subsequent physical and chemical changes in the materials need to be investigated as well because premature age hardening of the materials may lead to a breakdown in the performance of asphaltic materials.

4. *Following EPA and DOE work on reactive permeable barriers.* The technology of reactive permeable barriers involves the passive removal of contaminants, e.g., uranium, technetium, chlorinated organic compounds etc., in ground-water, through redox driven precipitation and sorption to iron and other materials. Information on the monitoring and performance evaluation that is underway should be obtained to better understand these processes and develop predictive methods on the flow through iron and other media, the potential for clogging, and the design and long-term effectiveness of the reactive permeable barriers and their ability to sequester various radionuclides.

5. *Following EPA and DOE work on impermeable subsurface barriers.* These barriers include viscous-liquid barrier walls, *in-situ* vitrification, and cement-based grout curtains. Results from these programs are expected to improve prediction and understanding of these barriers' long-term behavior.

5.3 Transport

5.3.1 Ground-Water Flow and Transport

5.3.1.1 Technical and Regulatory Background

Ground water is the principal pathway for radionuclide migration through the subsurface environment. Ground-water conditions such as infiltration affect radionuclide leaching, mobilization, transport rates and concentrations. Many of the important exposure pathways involve ground-water sources for drinking and irrigation water. Information on location of ground-water wells, pumping and irrigation application rates, as well as water use, are needed to characterize scenarios and quantify potential doses to an individual.

Analyses of ground-water flow and radionuclide transport involve an evaluation of hydrogeologic features, events, and processes, and their attendant uncertainties. This realization of uncertainties in both the conceptual ground-water flow and transport models, and the parameter estimates, is based in part on research insights learned from real-site contaminant studies, and from NRC Staff participation in international cooperative ground-water studies (e.g., INTRACOIN, HYDROCOIN and INTRAVAL). Significant insights were derived from ground-water monitoring and modeling studies at DOE's uranium remediation sites, DOE's Nevada Test Site and West Valley Site, DOE national laboratories (e.g., Hanford Reservation tank evaluations, Oak Ridge National Laboratory's White Oak watershed, and Savannah River wetland studies), and foreign nuclear facilities (e.g., Atomic Energy Canada, Ltd's Chalk River Facility, and Russia's Chernobyl and Mayak sites). These studies have greatly improved NRC staff understanding of ground-water features, processes, and events that influence radionuclide transport. In recent years the NRC has funded field studies (e.g., Las Cruces Trench, Apache Leap Research site, and the Maricopa Environmental Monitoring site) to develop further the technical bases for reviewing ground-water models and monitoring programs, and to collect detailed datasets for testing new ground-water flow and transport models (e.g., MIT stochastic model, PNNL water budget model).

Ground-water analyses have evolved to the point that analysts now recognize the need to examine realistic site features, events, and processes. Previously, ground-water analyses involved simplistic, "worst-case" scenario analyses based on the analysts' assumption of steady-state vertical migration through fully saturated homogeneous media. The ground-water portion of the RTE research program focuses on the technical and regulatory objectives which require more detailed and realistic analyses in order to assess uncertainties.

An additional long-standing area of concern in subsurface transport modeling is the representation of complex chemical sorption processes with computationally efficient distribution coefficients that compare, by laboratory experiment, the amount of radionuclide held by at least one of several mechanisms in the geologic media to that remaining in the liquid ground water. With increases in readily accessible high-speed computing capacity, practical alternatives to simple linear distribution-coefficient-based mathematical models of radionuclide retardation may be within reach. The NRC needs to assess these new models to determine if they should be incorporated into its PA methodologies.

Surface complexation models have been developed for use in the prediction of radionuclide transport in the environment. Much theoretical and laboratory work has been done to date. There has been some application of surface complexation modeling to the Alligator Rivers natural analog site in Australia. More recently, RES has been working cooperatively with the U.S. Geological Survey at the Naturita, Colorado, uranium waste site to assess the application of surface complexation modeling for prediction of uranium migration at an actual field site. Characterization of the soil particles indicates that there are particle coatings and the coatings may play an important role in the sorption and desorption of uranium. Unknown are the phases present in the coatings, their composition, and more importantly, the role played by the particle coating in sorption/desorption of uranium. The applicability of this uranium-specific work to other radionuclides needs to examined and exploited to the extent possible.

5.3.1.2 Technical and Regulatory Objectives:

The regulatory objective of groundwater flow and transport research is to develop technical bases in the form of ground-water information, databases, models, and monitoring strategies to support staff reviews of licensees' submittals. Although these regulatory objectives cover a wide range of licensing areas such as nuclear power plant siting and operations, LLW site characterization, modeling and monitoring, HLW site characterization and analyses, uranium mill tailings and *in-situ* leach uranium recovery monitoring, and decommissioning reviews, there are common technical objectives. The common technical objectives involve characterizing the hydrogeologic system and ground-water use scenarios in order to calculate potential exposures to an individual. The research objective is to develop tools and technical bases to support each licensing area by focusing on the appropriate hydrogeologic features, events, and processes associated with the applicable performance measure.

Early radionuclide analyses in PA were limited to conservative, bounding analyses. For simple hydrogeologic sites with a well-defined source term at or near the surface, these analyses are still used. NUREG-1549[22] addresses the needed complexity of generic screening and site-specific models. However, for more complex sites with either an established ground-water contaminant plume, or for evaluating the potential of long-term consequences of radionuclide releases, a realistic, risk-informed analysis that takes into account conceptual model and parameter uncertainty is being used in PA. Current outstanding issues in ground-water flow and transport focus on these conceptual model and parameter uncertainties as well as retardation mechanisms.

Conceptual model uncertainty arises from the fact that several alternative conceptual models of subsurface flow and transport can be derived from a single set of site characterization data which are often sparse. Since site characterization data generally cover only a few years or decades, regulatory authorities need to have confidence that alternative conceptual models of the systems characterized are consistent with all available data and that they will not diverge significantly over time with regard to estimates of system performance. The NRC needs to be able to evaluate the conceptual models used in licensee submittals to determine if a licensee's choice of one or more conceptual models is sufficient to support claims of regulatory compliance made in the submittal.

Among the unresolved questions in ground-water transport is the degree to which colloidal transport enhances the movement of radionuclides. There have been cases where ground water contains colloidal-sized material that incorporate radionuclide species. In fact, colloid-based transport has been proposed by numerous researchers to account for the unexpectedly rapid transport of some radionuclides (e.g. Pu and Cs). However, there is also a lingering question related to the influence of sampling methods, particularly that of ground water extraction in partially saturated media. In saturated media, pumping associated with ground-water sampling may disturb sediments and mobilize colloidal sized material that would otherwise be inert.

For site stewardship, protection of ground-water is a key technical issue and research needs to focus on monitoring and model confirmation. An important technical objective is the development and testing of integrated unsaturated-saturated zone monitoring strategies to understand the selection, placement and calibration of field instruments and methods.

5.3.1.3 Research to be Performed and Products

The current hydrologic research program involves studies on: (1) development of a methodology to assess hydrogeologic conceptual model uncertainty [23]; (2) a related effort to develop a methodology on hydrologic parameter uncertainty[24]; (3) field studies at the Beltsville Agricultural Research Center to confirm uncertainty estimates of ground-water recharge[25]; and (4) partial funding of a workshop on conceptual models of flow and transport in the fractured vadose zone[26]. The parameter uncertainty research, which was done in response to an NMSS-user need, provided databases for probabilistic dose models (those implemented in DandD and RESRAD). The conceptual model uncertainty research, which is anticipatory, has provided insights on alternative conceptual models, particularly for reviews involving fracture flow and transport in unsaturated media. The ARS field studies on ground-water recharge have demonstrated the importance of real-time, nearly temporally continuous datasets for estimating transient infiltration and recharge. The ARS studies also provided detailed site-specific databases to compare steady-state and transient approaches for estimating ground-water recharge[27], a major factor in leaching, mobilizing and transporting radionuclides in the subsurface. The NAS study provided an overview of the process through which hydrogeologic conceptual models are developed, tested, refined and reviewed, as well as a peer-review of conceptual models involving flow and transport in the fractured, unsaturated zone at Yucca Mountain[28].

Current RTE research also is addressing sorption, a major chemical effect on subsurface radionuclide transport, to determine a more realistic methodology for estimating radionuclide retardation in soil[29]. A complementary effort involves the NRC's participation, along with organizations from other OECD/NEA member countries, in an effort to test and compare various models of sorption[30].

Additional research and anticipated products to address questions that are common to many waste facilities and decommissioning sites are listed below:

1. *Selection of ground-water conceptual and mathematical models.* Establish and test a methodology with supporting technical bases and guidance for selecting and evaluating appropriate ground-water flow and transport conceptual/mathematical models, and for assessing uncertainties with regard to related licensing performance measures. Within the methodology, identify tools for quantifying conceptual model uncertainty in the mathematical models of ground-water flow and transport. Conduct field tests to provide datasets for testing the conceptual model uncertainty methodology. The methodology will examine uncertainties introduced by model abstraction and simplification, and will identify methods and criteria for discriminating among alternative models. This research builds on the accomplishments of the two developed methodologies, one on conceptual model uncertainty and the other on parameter uncertainty, and their limited testing[31]. This research follows from an NMSS user need related to model development and confirmation for decommissioning site reviews. The research strongly supports NRV reviews of decommissioning, LLW, and HLW sites, and in-situ leach uranium recovery facilities.

2. *Hydrologic parameter estimation.* Develop and test a methodology for estimating hydrologic parameters and their attendant uncertainties for decommissioning site reviews. Within the methodology, identify information such as national databases from USDA, USGS and NOAA for estimating parameters and appropriate statistical methods for characterizing uncertainties for a specific site. The methodology will identify hydrologic data sources including distributions from national and regional databases. Licensing staff will be able to examine sensitivity and uncertainty analyses in a systematic manner based on well-documented technical bases. This research builds on the generic databases developed in the earlier PNNL study on parameter uncertainty[32] and the ARS field studies[33]. This research follows directly from an NMSS user

need related to model development and confirmation for decommissioning site reviews. The research will support decommissioning reviews and the new model parameter activity (MARPAR) of the Interagency Steering Committee on Radiation Standards (ISCORS).

3. *Monitoring ground-water flow near the capillary fringe and in shallow water-table systems.* Extend the ground-water monitoring strategy documented in NUREG/CR-5698[34] to the capillary fringe and shallow water-table system. Develop an integrated monitoring strategy and test the methodology at a field demonstration site. Document the integrated monitoring strategy and technical bases developed with emphasis on relevancy to decommissioning sites such as entombment facilities and remediated sites. This research builds on the accomplishments of the development and testing of an unsaturated zone monitoring strategy[35]. This research follows from an NMSS user need related to monitoring at LLW sites and was revised to include decommissioning sites with residual radionuclides. The research also follows from National Academy of Sciences recommendations on monitoring and model confirmation[36]. The research strongly supports NRV reviews of decommissioning, LLW, and HLW sites, and in-situ leach uranium recovery facilities.

4. *Colloid transport.* Radionuclides present as colloids could cause radionuclides to be more mobile and travel faster than expected during the transport process and lead to higher doses than expected to people. Recently completed RES research programs have focused on determining ^{90}Sr and ^{137}Cs radiocolloids from waste forms containing ion-exchange resins solidified in cement and vinyl-ester styrene[37] and effects of organic materials on plutonium migration[38]. Current research is assessing uranium and thorium colloid formation from leaching experiments using slags and soils obtained from SDMP sites. Research is needed to determine the extent to which colloids contribute to transport and behavior of radionuclides in groundwater systems. The research studies will feature both laboratory experiments and field tests in soils and fractured systems and will be designed to obtain data for existing computer codes. Efforts will be directed toward plutonium and other transuranics and will attempt to determine if radiocolloids are released from waste forms and the nature of the attachments of these radionuclides with waste form colloids, corrosion-product colloids, and groundwater containing natural colloids including organic materials, microorganisms and inorganic materials such as clays, iron, and manganese oxides. Aqueous radiocolloid sorption coefficients will be determined. Experiments will be performed to determine radiocolloid mobility in saturated and unsaturated soils and through fully and partially saturated porous media and rock fractures all as a function of water quality chemistry. Chemical reaction mechanisms will be proposed and modifications to existing models on colloid transport will be suggested.

5. *Estimating infiltration and recharge using real-time data.* Conduct cooperative research with the Agricultural Research Service using "real-time," nearly continuous field datasets collected at the Beltsville Agricultural Research Center over different temporal and spatial scales to estimate episodic infiltration and ground-water recharge. The RES and Agricultural Research Service staffs will jointly identify methods useful for estimating infiltration (both steady-state and transient) and test them using Beltsville Agricultural Research Center datasets. Licensing reviews of infiltration and ground-water recharge data and analyses will benefit from the ARS-NRC evaluation of methods and instrumentation for estimating infiltration and ground-water recharge over temporal and spatial scales. This research builds on the accomplishments of the earlier field studies at the Beltsville Agricultural Research Center[39]. This research supports NMSS licensing staff and Agreement State regulators review of ground-water infiltration and

flow modeling and performance confirmation of decommissioning, HLW, and LLW sites, and uranium mill tailings facility assessments.

6. *Historical case analysis of plumes.* Historical case analyses of actual contaminant plumes to see what has moved, how far it moved and the factors controlling migration will provide a data base useful for NRC licensing decisions regarding site clean-up and closure. This work will build on similar work done for uranium plumes[40]. The data from the uranium work indicate that with rare exceptions, uranium plumes migrate less than 2 km. There is a need to extend historical case analysis to other key radionuclides to identify dominant transport processes that may be common to all plumes. Future research will be directed toward examining plume migration in both the unsaturated and saturated zones for evaluating ground-water flow and transport models. Under a USGS-NRC MOU, the research will examine multi-phase vapor transport in heterogeneous, partially saturated media at the Amargosa Desert Research site to determine controlling radionuclide migration processes.

7. *Testing the validity of ^{14}C transport models.* The NRC studied ^{14}C transport from the point of release at a radioactive waste disposal area to uptake in vegetation at Chalk River Nuclear Laboratories over a two year period in 1995-1996[41]. There is need to update that work by examining the temporal changes that have happened to the ^{14}C plume and to relate that to transport models to rest the validity of their predictions. Some field measurements will need to be taken to determine environmental changes in the C-14 plume at Chalk River with time. The Chalk River ^{14}C research will be useful for predictions of ^{14}C transport in the environment. Preliminary results indicate that wetlands are highly effective in sequestering ^{14}C and that the gaseous pathway plays a prominent role in uptake and releases. These data need to be quantified, linked to seasonal changes, and then input into transport models.

8. *Reactive chemical transport models.* Continue to develop reactive chemical transport models to simulate radionuclide transport in both saturated and partially saturated media at waste disposal facilities. The reactive chemical transport computer codes will incorporate chemical process such as aqueous complexation, adsorption-desorption, ion-exchange, precipitation-dissolution, redox, acid-base reactions, equilibrium and kinetic considerations and biodegradation to calculate the transport, behavior and fate of radionuclides in the environment realistically.

9. *Characterization of soil-particle coatings.* Characterize the chemical composition and phases present in coatings of soil particles at the Naturita, CO, site to support surface complexation modeling work done for the NRC by the USGS and Sandia National Laboratories. Following characterization (including synchrotron-based methods), the role of coatings in the retardation of radionuclide movement is to be assessed by laboratory measurements and molecular modeling. The Naturita soil characterization research will assist in demonstrating the effectiveness of surface complexation models for prediction of radionuclide movement through soil. In addition, it will address the role played by soil coatings in retardation and those data will be factored into geochemical codes which can be used for regulatory decisions affecting SDMP sites, uranium mill tailings sites, and waste disposal sites.

10. *Collection of retardation data on radioncuclides other than uranium.* Despite the numerous studies that have been performed to obtain data and information for the sorption of radionuclides in soils and other materials for use in PAs, there are several new areas that require investigations to determine radionuclide sorption behavior. These areas include; (1) activated metal radionuclides, (2) arid and dry environments, (3) rock fractures and porous materials, (4) alluvium materials, (5) radiocolloids, (6) unsaturated groundwater

conditions, (7) irrigation mechanism of the food-chain pathway, (8) the effects of water quality chemistry on radionuclide sorption, and (9) the impacts of soil particle size fractions of sorption of radionuclides. Research is needed to determine absorption and desorption distribution coefficients for the radionuclides ^{10}Be, ^{94}Nb, ^{99}Mo, ^{108m}Ag, $^{63/59}$Ni, ^{239}Pu, ^{241}Am, ^{237}Np, ^{244}Cm and ^{36}Cl; evaluate the radionuclide sorption processes associated with the irrigation pathway for determining doses to people; determine radionuclide sorption behavior in alluvium through a combinations of both laboratory and field experiments as a function of the water quality chemistry; investigate sorption process for radionuclides in rock fractures and rock matrixes as function of water quality chemistry; investigate the sorption of radionuclides in the unsaturated zone under conditions of varying moisture saturation; and determine both integrated and separate effects of sorption, colloids, and microorganisms on the retardation of radionuclides. Concurrently, the extension of mechanistic sorption modeling developed for the subsurface transport of uranium to these other radionuclides and situations will be pursued.

5.3.2 Soil Biotic Effects on Radionuclide Transport

5.3.2.1 Technical and Regulatory Background

Vegetation plays a role in enhancing transport through biotic processes operating in the rhizosphere (root zone) of plants. Biotic processes produce organic ligands which can mobilize radionuclides and other metals. This was demonstrated in a scoping study of the effect of rhizosphere processes on radionuclide mobilization[42] that showed that hickory trees were capable of mobilizing Co-60 to a far greater degree than other types of deciduous trees.

To support regulatory decisions, further work is needed on soil biotic processes that affect transport. The preliminary scoping study of the effect of rhizosphere processes on radionuclide mobilization was on a limited number of radionuclides and on a limited suite of trees typical of eastern deciduous forest. This work needs to be expanded to a wider range of radionuclides and metals and on a wider range of vegetation. Because water is more prevalent as a transport vehicle in the eastern U.S., emphasis should be given to vegetation typical of eastern humid region sites, especially those likely to be found in proximity to decommissioning sites.

5.3.2.2 Technical and Regulatory Objectives

The regulatory objective is to assess the magnitude of the impact of soil-biotic factors affecting radionuclide transport with particular emphasis on processes operating in the rhizosphere of vegetation and to estimate its contribution to doses to people.

5.3.2.3 Research to be Performed and Products

Perform focused laboratory studies of the effect of vegetation on the mobilization of key radionuclides. The vegetation studied will be representative of types likely to be employed in site closure of decommissioning, uranium mill tailings, and waste disposal sites. Research results are to be in the form of reports useable by the NMSS staff in PA.

5.3.3 Bioaccumulation of Radionuclides

5.3.3.1 Technical and Regulatory Background

Bioaccumulation of radionuclides can be an early-warning monitoring system at sites contaminated with long-lived radionuclides. Vegetation promises to be a cost effective and highly effective monitoring tool for early detection of radionuclide transport from contaminated sites. Conventional monitoring methods rely heavily on sampling wells. These wells sample only a small portion of the subsurface. However, vegetation acts as an integrator and concentrator of subsurface radionuclides. Tritium in the plant transpiration stream was used successfully in this manner at the Maxey Flats, KY, LLW disposal facility. This is a site in which fracture flow plays a prominent role and monitoring wells were typically dry unless they encountered a fracture. Tritium in trees located several plumes that could not be located by monitoring wells. Because vegetation plays a role as an integrator of contaminants it offers promise in allowing for early detection of radionuclide releases from contaminated sites.

5.3.3.2 Technical and Regulatory Objectives

The regulatory objective will be to demonstrate the effectiveness of vegetative uptake (bioaccumulation) of radionuclides as an early-warning monitoring method for detecting environmental releases from contaminated sites.

5.3.3.3 Research to be Performed and Products

The research is to be conducted at contaminated sites (e.g. Chalk River and/or DOE sites). Field measurements will be taken to characterize the transport rates and transfer coefficients for long-lived radionuclides moving from waste to the surface to determine bioaccumulation rates in vegetation. Monitoring strategies and sampling protocols will be developed for use in assessing bioaccumulation of radionuclides.

The transport rates and transfer coefficients for long-lived radionuclides will be useful for PAs of contaminated sites in that they will provide real data from actual sites. The monitoring strategies and protocols will be of use to regulators and site managers for ensuring protection of public health and safety.

5.4 Performance Assessment

5.4.1 Technical and Regulatory Background

There are many extant computer programs that implement mathematical models of radionuclide transport in the biosphere (collectively called environmental pathways models) and doses to humans exposed to the radionuclides. The NRC has generally accepted these models and used them in its regulatory decision-making. However, most of the existing models use a conservative approach and are not useful for complex sites.

Current PA tools are often criticized for constraints alleged to require oversimplification of complex systems, and are not adaptable for extended applicability beyond the originally-designed problem type without extensive software modification.

5.4.2 Technical and Regulatory Objectives

One objective of the RTE research program's PA element is to examine environmental pathways models and parameters currently used by the NRC in decommissioning and waste decisions.

The other objective is to establish an adaptive PA framework that will integrate tools for:

1. conceptualization of the problem and supporting data;
2. sampling (Monte Carlo) of complex features, events, and process;
3. flexible database access;
4. importing, exporting or reporting of data or results;
5. incorporating additional models into the framework;
6. analysis of data and intermediate or final results; and
7. visualization of intermediate and final results.

The framework will allow the NRC to develop more risk-informed approaches for identifying the most important parameters and models for demonstrating compliance with license-termination requirements and criteria. The framework also would be adaptable to LLW and uranium recovery applications.

5.4.3 Research to be Performed and Products

The RTE research program is currently conducting PA projects to

- benchmark the RESRAD and RESRAD-BUILD codes to ensure the quality and technical defensibility of dose analysis performed for complicated decommissioning cases; and
- identify and prioritize data gaps in RESRAD's and RESRAD-BUILD's parameters to be filled by future research.

Proposed future PA research in the RTE research program is described below.

1. *Assessment of parameters used in environmental pathways models.* Perform confirmatory analyses to identify possible deficiencies in parameters used in dose-assessment models. Obtain experimental field data and information for resuspension factors, food consumption values, soil-plant concentrations factors, feed-animal product transfer coefficients, plant weathering loses, translocation fractions, food preparation losses for crops and other parameters for estimating the radionuclide pathways component of food-chain pathways analysis. The product of this work will be a report of revisions to parameter distributions used in dose assessment models.

2. *FRAMES (Framework for Risk Analysis in Multimedia Environmental Systems).* Join the ongoing cooperative effort to enhance the FRAMES tool initially developed by EPA and DOE. Joining this effort offers a significant opportunity for NRC to leverage complementary work of other federal agencies to establish an adaptive PA framework that will support PAs at complex sites.

3. *Testing the validity of performance assessment computer codes.* Research is needed to assess available DOE data and information on radionuclide migration in the environment for use in testing the validity of models implemented in PA computer codes. An evaluation of the available data and information on radionuclide migration in the environment (e.g., soils and plumes) from releases at DOE facilities will be performed to determine the suitability of the data and information for use in evaluating PA computer codes to predict radionuclide source term releases and migration in soils. If the data and information are of sufficient quality, a study will be performed to compare the field data with results calculated by the PA computer codes in an effort to improve the PA codes' ability to predict radionuclide migration in soils and ground-water systems.

5.5 Cooperation with Other Organizations

The RTE research program leverages its resources through cooperative interactions and special research agreements (e.g., Memoranda of Understanding (MOU) and Interagency Agreements (IAA)) with other national and international research organizations that are pursuing similar work. The technical objective is to gain access to technologies, databases, computer software, and methodologies useful to the NRC's regulatory activities. The RTE program cooperates with other Federal Agencies (e.g., the USDA's Agricultural Research Service, U.S. Geological Survey, NIST, EPA, U.S. Army Corps of Engineers), DOE national laboratories, universities (e.g., Johns Hopkins University), National Academy of Sciences (NAS), National Academy of Engineers (NAE), and international organizations (e.g., OECD/Nuclear Energy Agency (NEA), Swedish Nuclear Power Inspectorate, IAEA and AECL). These cooperative ventures help to identify important research findings, datasets (e.g., Chernobyl and Mayak site data through the American Institute of Hydrology and Lawrence Berkeley National Laboratory), and lessons learned for use in evaluating and testing multi-media environmental models.

5.5.1 Participation in Phase 2 of the NEA Sorption Project

RES, NMSS, the Center for Nuclear Waste Regulatory Analyses, and the US Geological Survey have formed teams to participate in Phase 2 of the NEA Sorption Project, an international cooperative effort on sorption modeling. In Phase 1 of the NEA Sorption Project, the participating organizations concluded that practical alternatives to modeling sorption with linear isotherms are within reach[43]. Phase 2, which started in 2000, will test that conclusion. Phase 2's Technical Direction Team has defined several test cases that the participating teams will use to test their sorption models. The Technical Direction Team will evaluate the results of the teams' modeling exercises and issue a report on which models are the best for estimating sorption.

5.5.2 Interagency Cooperation on Integrated Environmental Transport Modeling

NRC has entered into an agreement with the Environmental Protection Agency, the Department of Energy, and the Army Corps of Engineers on issues integrated environmental transport modeling methods and software that all of the involved agencies have to deal with. An MOU has been developed that will establish policies and administrative practices to facilitate cooperation and coordination among the involved agencies, and possibly other federal agencies, in research and development of multimedia environmental models, software, and related databases. The intent of this MOU is to provide a mechanism for the cooperating federal agencies to pursue a common technology in multimedia environmental modeling with a shared scientific basis. The work cited in Section 5.4 on FRAMES is part of this cooperation.

5.6 Stakeholder Involvement

The RTE research program has pursued several avenues of stakeholder involvement. The technical objective of these "outreach" activities is to transfer timely research results to stakeholders, and in return obtain periodic reviews of ongoing research studies. This public outreach takes many forms: publication of research results as NUREG's and NUREG/CR's; convening public meetings and site visits, research symposia held at NRC Headquarters or at cooperating Federal Agency locations (e.g., USGS and ARS), and special sessions at professional meetings (e.g., American Geophysical Union meetings). In the area of hydrology research, RES has held annual research reviews attended by federal agencies (EPA, DOE, USGS, ARS, NWTRB), universities (University of Arizona, Pennsylvania State University, University of Southern Illinois), DOE national laboratories (PNNL, SNL and ANL), the Center for Nuclear Waste Regulatory Analyses, and Agreement States regulators and consultants. Input received from these "outreach" activities has benefitted both the individual research projects reviewed, and research users (i.e., the NRC licensing staff and Agreement State regulators).

RES will continue ongoing discussions with the National Academy of Sciences (NAS) on the role of Engineered Barrier Systems in waste disposal. The NAS has scheduled a Workshop, to be held in mid-July 2001, on the performance of and credit to be taken for engineered barriers in waste disposal PAs. Recommendations from the workshop proceedings as applicable to NRC will be included in a revision to this RTE research plan.

5.6.1 Archival and Conference Publications and NUREG Reports

All work published under the auspices of the RTE research program is publicly available. The staff and contractors publish their results in archival and conference publications and NUREGs and NUREG/CRs. Journals such as *Water Resources Research*; conferences such as those of the American Geophysical Union, American Chemical Society, and the Geological Society of America; and more specialized conferences such as the annual *Waste Management* conference in Tucson, AZ, and the international *Migration* conferences have published work from the RTE research program.

5.6.2 Advisory Committee on Nuclear Waste

The RTE research program regularly briefs the ACNW on its ongoing activities and on the details of specific projects and solicits feedback the committee's feedback.

Appendix A: Strategic Plan Context

The NRC's Strategic Plan provides direction for the staff to embrace in accomplishing the agency's mission.

A.1 Strategic Arenas Supported by RTE Research

The "U.S. Nuclear Regulatory Commission Strategic Plan" (NUREG-1614, September 2000) organizes its mission-specific goals and strategies into four strategic arenas: Nuclear Reactor Safety, Nuclear Materials Safety, Nuclear Waste Safety, and International Nuclear Safety Support. For each strategic arena, NUREG-1614 defines a strategic goal and performance goals, strategies, and measures to be employed in achieving and assessing accomplishment of the performance goals. In the sections that follow, those goals and strategies that the RTE research program is addressing will be listed and discussed briefly.

The RTE research program mainly supports the Nuclear Waste Safety strategic arena, which includes the regulation of decommissioning and low- and high-level radioactive waste facilities. The RTE research program also supports the regulation of aspects of the Nuclear Materials Safety arena that deal with uranium recovery and the disposal of uranium mill tailings. The goals, strategies, and measures applicable to the regulation of nuclear waste also are applicable to the regulation of uranium mill tailings. The RTE research program also supports the International Nuclear Safety arena through its participation "in international safety cooperation, information exchange, and cooperative safety research."[1] Aspects of this participation are described below in the context of Nuclear Waste Safety.

A.2 *Strategic Goal for Nuclear Waste Safety: Prevent significant adverse impacts from radioactive waste to the current and future public health and safety and the environment, and promote the common defense and security*

To support this goal, the NRC "... will use domestic and international research, technical studies, and risk information to ensure that the regulatory framework is based on technically sound and realistic information." The NRC will conduct and support domestic research, follow the results of relevant domestic and international research, and leverage its resources through cooperative projects with other federal agencies and other countries. The specific Performance Goals and related *strategies* are discussed below.

A.2.1 *Performance Goal: Maintain safety, protection of the environment, and the common defense and security*

The RTE research program supports this performance goal by providing a technical basis to support regulatory decisions. This technical basis is expressed through existing regulatory guidance and review procedures that are supported by "the body of technical information, obtained from research performed by the NRC or by others and from evaluation of operational experience." The RTE research program supports the following strategies for meeting this performance goal.

> "We will continue developing a regulatory framework to increase our focus on safety, including the incremental use of risk-informed and, where appropriate, less prescriptive performance-based regulatory approaches to maintain safety."

> "We will evaluate potential new information from research, new safety issues, changing external factors,

[1]Quoted and italicized text in this appendix is from NUREG-1614.

international programs, and licensee operational experience so that improvements can be made to maintain an adequate regulatory framework."

A.2.2 *Performance Goal: Make NRC activities and decisions more effective, efficient, and realistic*

The RTE research program supports this performance goal by providing a technical basis for more realistic regulatory assessments. The conventional regulatory response to uncertainty is to attempt to over-predict consequences from regulatory decisions so that the final choice is always protective of safety. However, for complex natural systems, the bounding assumptions and simplified models used in regulatory decision-making have been shown in some cases to under-predict consequences. The uncertainties that cause such anomalies can be dealt with only by employing data and models that yield more realistic assessments of performance. The RTE research program will support the following strategy to meet this performance goal.

> "We will continue to improve the regulatory framework to increase our effectiveness, efficiency and realism."

NUREG-1614 states that, in meeting the goal of more realistic activities and decisions, "The NRC will ensure that its decisions are scientifically-based; risk-informed; and shaped by operational experience, new information, and research, including cooperative international activities. As a result, the NRC's decisions will be realistic, will be systematic, and will appropriately treat areas of uncertainty." The RTE research program will provide new data and models from NRC-supported research and information derived from cooperative national and international activities. "We will pursue international cooperative research in order to leverage our resources, share research facilities wherever possible, and maintain an environment in international committees and working groups which can best further our interests and minimize unnecessary duplication of effort... NRC [will make its] decisions more realistic by eliminating excessive conservatism. Realism is supported by risk information, research results, and operational experience."

A.2.3 *Performance Goal: Reduce unnecessary regulatory burden on stakeholders*

Unnecessary regulatory burden can increase costs with no significant reduction in risk or result in no significant improvement in the protection of the public health and safety. The NRC strategy to address unnecessary burden as outlined in NUREG-1614 is to "... use domestic and international research and technical studies to evaluate new information in order to identify areas in our regulatory programs where unnecessary burden and duplication can be reduced." The RTE research program will provide much of the domestic research, and through international cooperation, provide the NRC with access to research in other countries that it can use to reduce unnecessary regulatory burden. The RTE research program supports the NRC's strategy to "continue to improve [its] regulatory framework in order to reduce unnecessary regulatory burden" by reducing uncertainty in regulatory judgments so that they are more realistic.

A.2.4 *Performance Goal: Increase public confidence.*

The RTE research program supports this goal in two ways. Its primary contribution comes from providing a sound technical basis for NRC decisions and a clear articulation of how its results affect the existing regulatory framework. In order to assure the proper incorporation of research results into the regulatory program, RES will provide summaries of all significant products or results and the implications and potential uses for these products in regulatory analyses. These summaries also will become available to the public through the NRC's electronic systems, thereby improving public awareness of new information and its significance.

The second way the RTE research program supports this goal is by proactively seeking to provide increased access to both the planning and implementation aspects of its research activities. By seeking stakeholder input on this plan, RES will ask stakeholders for comment on those topics already suggested for further study and to suggest areas that they think should be examined. By opening program reviews of ongoing research to public attendance and providing opportunities for public participation at these program reviews the NRC is increasing the opportunity for concerned parties to have an impact on the ongoing execution and focus of funded research. As a result of these interactions, RTE research products should more fully address the full range of stakeholder concerns and improve confidence in the results and their application to the regulatory process.

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