Used Fuel Disposition Campaign Disposal Research and Development Roadmap

Fuel Cycle Research & Development

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*Note: In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity along with the Document Cover Sheet is sufficient to demonstrate achieving the milestone. QRL for such milestones may be also be marked N/A in the work package provided the work package clearly specifies the requirement to use the Document Cover Sheet and provide supporting documentation.

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CONTENTS

USED FUEL DISPOSITION CAMPAIGN DISPOSAL RESEARCH AND DEVELOPMENT ROADMAP

1. INTRODUCTION

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology (OFCT) has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development (R&D) activities related to storage, transportation and disposal of used nuclear fuel (UNF) and high level nuclear waste (HLW). The Mission of the UFDC is

> *To identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles*.

The U.S. has, for the past twenty-plus years, focused efforts on disposing of spent nuclear fuel[1] (SNF) and HLW in a geologic repository at Yucca Mountain, Nevada. The recent decision by DOE to no longer pursue the development of that repository has necessitated investigating other geologic media and concepts for the disposal of SNF and HLW that exists today and that could be generated under future fuel cycles. The disposal of SNF and HLW in a range of geologic media has been investigated internationally. Considerable progress has been made in the U.S and other nations, but gaps in knowledge still exist.

The U.S. national laboratories have participated in these programs and have conducted research and development related to these issues to a limited extent. However, a comprehensive R&D program investigating a variety of geologic media has not been a part of the U.S. waste management program since the mid 1980s. Such a comprehensive R&D program is being developed in the UFDC.

An aspect of the UFDC's considerations associated with implementing a geologic repository in different geologic media is the marked differences between the U.S. and other nations, in the regulatory bases for assessing suitability and safety of a repository. Because the probability based – risk informed nature of U.S. regulations is sufficiently different from other regulations, information gained in previous studies, while useful, likely needs to be supplemented to enable more convincing communication with the public, better defense of the scientific basis, and stronger safety cases.

Revision 0 of the UFDC Disposal R&D Roadmap was an initial evaluation and prioritization of R&D opportunities that could be pursued by the campaign. It is a "living" roadmap and will be revised to update the status and prioritization of R&D needs as progress is made in the R&D program or as necessary to reflect changing understanding of these needs.

[1] Nuclear fuel discharged from a transmutation system (i.e., reactor or accelerator-driven system) is termed as "used nuclear fuel" until it is determined that the fuel has no subsequent value and will be disposed of in a geologic repository. At this point the fuel is termed as "spent nuclear fuel." The UFDC is investigating the direct disposal of discharged nuclear fuel should such a decision be made and as such the terminology "spent nuclear fuel" or SNF is used throughout this roadmap.

Revision 1 is a second evaluation and prioritization of R&D opportunities that could be pursued by the campaign. R&D completed by the UFDC through the middle of 2012 (calendar year) and progress made by programs in other countries was used to re-evaluate each of the R&D opportunities presented in Revision 1 of the UFDC Disposal R&D Roadmap.

1.1 Goals of the UFDC R&D Program

The U.S. has a strong commitment to nuclear power. As President Obama noted in an announcement awarding federal loan guarantees for two nuclear reactors to be built in Georgia: "Nuclear energy remains our largest source of fuel that produces no carbon emissions. To meet our growing energy needs and prevent the worst consequences of climate change, we'll need to increase our supply of nuclear power. It's that simple." In his 2011 State of the Union address, he said that the country should try to generate 80% of its electricity from clean sources, including nuclear power, by 2035.

At the direction of the President, the Secretary established the Blue Ribbon Commission on America's Nuclear Future to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste, and materials derived from nuclear activities. The Commission is to provide advice, evaluate alternatives, and make recommendations for a new plan to address issues, including several of particular importance to the Used Fuel Disposition Campaign Disposal Research and Development Roadmap:

- Evaluation of existing fuel cycle technologies and R&D programs;
- Options for permanent disposal of used fuel and/or high-level nuclear waste, including deep geological disposal; and
- Options to ensure that decisions on management of used nuclear fuel and nuclear waste are open and transparent, with broad participation.

The Used Fuel Disposition Campaign Disposal R&D Roadmap is an evolving document that will ensure that the technical information needed to implement new national policy for managing the back end of the nuclear fuel cycle is available when decisions are made to move forward. Initially, it focuses on generic research and development work undertaken today that will support future site-specific work. The research and development is focused on finding solutions to difficult issues related to nuclear waste repository siting. The Used Fuel Disposition Campaign will conduct its Research and Development in collaboration with university, industrial, and international collaborators.

As discussed further in the subsequent sections of the report, the roadmap focuses on identifying knowledge gaps and opportunities where research and development have the greatest potential to contribute to advancing the understanding of technical issues regarding the deep geologic disposal of nuclear waste. The research that will be conducted also will help to maintain U.S. expertise in repository sciences, both within the U.S. national laboratories and university system (through the Nuclear Energy University Program). The UFDC will also collaborate, where appropriate, with other countries that are pursing the geologic disposal of spent nuclear fuel and high level radioactive waste (UFDC 2010).The research proposed is of value in communicating information about repository sciences. A principal use of research and development on technical issues related to nuclear waste repository siting is in the area of confidence building. Research programs can be selected to support broad confidence building and education efforts with stakeholders and the public. In particular, this research can provide information to address misperceptions about repository science and the siting of nuclear waste repositories. Uncertainty, particularly over the time period involved geologic disposal, plays an important role in public and stakeholder decisions and confidence in moving the nuclear waste repository program forward.

In particular there is a need to quantify the levels of uncertainty, and understand how that uncertainty propagates through the technical analyses supporting the safety case for a nuclear waste repository. The information that would be collected through research and development provides a basis to communicate the safety case for a general repository, or a repository in a specific medium.

It must be recognized that this R&D roadmap is for one aspect of the UFDC R&D portfolio and focuses on the potential R&D needs associated with the permanent geologic disposal of spent nuclear fuel and high level nuclear waste. A similar effort is underway to identify R&D needs related to the very long term dry storage of used nuclear fuel and to identify alternatives for obtaining the needed data to address these needs. In addition, the UFDC will conduct broad R&D related to the entire waste management system to obtain perspectives regarding the implementation of future waste management strategies.

1.2 Disposal Environment Options

The UFDC is currently evaluating the viability of mined repositories in three geologic media (salt, clay, and crystalline rock), and, in addition to mined repository disposal, the use of deep boreholes in crystalline rock (Rechard et.al. 2011). For each of these disposal options, the rock type is identified at a broad level. Thus, salt includes both bedded and domal salt, clay includes a broad range of fine-grained sedimentary rock types including shales, argillites, and claystones as well as soft clays, and crystalline rock includes a range of lithologies[2] including granite, metamorphic gneisses and a variety of igneous rock types.

These disposal options are not presented as a final list of the best possible alternatives, and the DOE recognizes that other options have been identified in the past that also have the potential to provide safe long-term isolation, including, for example, sub-seabed disposal and the mined repository in volcanic tuff at Yucca Mountain. As other disposal concepts are identified that warrant further investigation they will be evaluated. There are multiple reasons for focusing on these four main concepts at this stage of the program.

First, the U.S. went through an extensive review of all available options for disposal and management during the 1970s, culminating in the 1980 *Environmental Impact Statement on Management and Disposal of Commercially Generated Radioactive Wastes* (DOE/EIS-0046). This review considered a full range of alternatives to mined geologic repositories, including deep boreholes, sub-seabed disposal, space disposal, and ice sheet disposal. Mined repositories were the favored option, but sub-seabed disposal and deep boreholes were retained for further consideration. Sub-seabed disposal remained technically a promising option, but was precluded by international treaty in the 1990s. Deep boreholes were considered to require further technological advances, and disposal programs in both the U.S. and other nations focused on mined repositories beginning in early 1970s. The U.S. program evaluated salt, granite, shale, basalt, and volcanic tuff before focusing exclusively on volcanic tuff at Yucca Mountain as a result of the 1987 Nuclear Waste Policy Amendments Act.

Second, conclusions drawn in the U.S. program in the early and mid 1980s about the potential viability of salt, granite, and clay as disposal media have been confirmed by extensive work

[2] Crystalline rock is a general term used here to refer to large bodies of igneous intrusive rock and high-grade metamorphic rock regardless of its protolithic type. Examples are predominantly granitic in composition, but other metamorphic and igneous lithologies may also be suitable.

internationally. Crystalline (granite) repository concepts have been evaluated in detail in Sweden, Finland, Switzerland, and Japan. Clay disposal concepts have been evaluated in detail in France, Belgium, and Switzerland. Salt has been shown to be a viable medium for disposal of non-heat-generating transuranic waste at the Waste Isolation Pilot Plant in the U.S., and research in Germany continues to show promise for the disposal of heat-generating waste in salt. Other geologic media are under consideration for specific purposes (e.g., Canada is investigating the use of a mined repository in carbonate rock to dispose of intermediate level waste, and the U.S. has disposed of low-level and transuranic waste in near-surface alluvium).

Third, deep borehole disposal continues to be the primary viable alternative to mined repositories. DOE investigated the concept in the 1990s for the disposal of surplus plutonium, and studies have continued at Sheffield University in the United Kingdom, in the Swedish high-level waste program, at MIT, and at Sandia National Laboratories in the U.S.

Finally, no new information has been developed since the early 1980s to suggest that options evaluated and screened from further consideration at that time (e.g., space disposal or ice-sheet disposal) should be re-evaluated.

1.3 Interfaces

The UFDC has several interfaces, both internal to the FCT program and external. The interfaces within the FCT program are:

- *FCT Separations/Waste Form Campaign:* This campaign is responsible for conducting R&D related to waste forms that would be generated from separations/ recycling processes (FCT 2010). A wide variety of waste forms are under investigation within that campaign. A research and development roadmap for these investigations has been developed and is being implemented (Peters et al. 2008]. The UFDC is responsible for conducting R&D to enable the direct disposal of used nuclear fuel as a waste form in a geologic environment, should that decision be chosen, and the disposal of any waste forms that would be developed under a future advanced nuclear fuel cycle.
- *FCT Advanced Fuels Campaign:* This campaign is responsible for conducting R&D on advanced fuels that could be used in future nuclear reactors (FCT 2010). Since the UFDC is responsible for SNF as a waste form, knowledge and understanding of the properties and characteristics of the fuels following irradiation is needed. The FCT Advanced Fuels Campaign will conduct the R&D to determine these properties and characteristics.
- *FCT Fuel Cycle Options Campaign:* This campaign is responsible for developing the system analysis tools to evaluate future advanced fuel cycles (FCT 2010). The UFDC R&D will help inform the development of these tools in the area of waste management. In addition, the System Analysis campaign evaluates the merits of different fuel cycle approaches (trade studies and alternative analysis). The UFDC R&D will both inform and support these analyses.

  The FCT program is applying system engineering principals and techniques to prioritize activities (FCT 2010). UFDC R&D will support the development of quantitative and qualitative metrics related to waste management that will be used to rank different fuel cycle alternatives.

The DOE-NE Nuclear Energy Advanced Modeling and Simulation (NEAMS) and the DOE-EM Advanced Simulation Capability for Environmental Management (ASCEM) programs are developing advanced high-fidelity, fully-coupled, multi-physics models for geologic disposal-related processes. While the ASCEM effort supports the DOE-EM environmental remediation mission, the tools under development may have direct applicability to deep geological disposal primarily in the area of radionuclide transport through the natural environment. These tools, when complete, could represent an enhancement of the modeling capabilities used to support the Waste Isolation Pilot Plant (WIPP) certification and the Yucca Mountain license application. UFDC R&D will support the development of these advanced capabilities and when available these tools will be used by the UFDC.

The UFDC recognizes that a considerable amount of work has been completed in other countries regarding the geologic media being considered by the UFDC and for a variety of engineered materials within these media. The UFDC will leverage this information and conduct future R&D through international collaborations as discussed in the *Used Fuel Disposition Campaign International Activities Implementation Plan* [UFDC 2010].

The UFDC is also actively participating in international collaborative activities. In 2012 the DOE and the UFDC began active collaboration on three international programs. Decisions to join these international collaborations and the choice of specific projects to participate on are informed by the prioritization of R&D topics presented in this UFDC Disposal R&D Roadmap.

- The DOE became a partner organization in the ongoing DECOVALEX phase (started in 2012), referred to as DECOVALEX–2015. DECOVALEX is an acronym for "Development of Coupled Models and their Validation against Experiments". Starting in 1992, the project has made important progress and played a key role in the development of numerical modeling of coupled processes in fractured rocks and buffer/backfill materials.
- The DOE became a Mont Terri Project Partner. The Mont Terri Project is an international research project for the hydrogeological, geochemical and geotechnical characterization of a clay/shale formation suitable for geologic disposal of radioactive waste. The project, which was officially initiated in 1996, utilizes an underground rock laboratory, which lies north of the town of St-Ursanne in northwestern Switzerland and is located at a depth of ~300 m below the surface in argillaceous claystone (Opalinus Clay).
- The DOE and UFDC are actively participating on the Colloid Formation and Migration (CFM) Project. The CFM project is an international research project for the investigation of colloid formation/bentonite erosion, colloid migration, and colloid-associated radionuclide transport, relevant to both natural and engineered barriers. This collaborative project is one of several experimental R&D projects associated with the Grimsel Test Site (GTS) in the Swiss Alps.

The UFDC is also collaborating with the Republic of Korea under the ROK-US Joint Fuel Cycle Studies and with Japan under the US-Japan Joint Nuclear Energy Action Plan in the area of nuclear waste disposal. Collaborative activities with the Republic of Korea are being established in 2012 and collaboration with Japan will be resumed in early 2013 following their recovery from the devastating earthquake/tsunami and the accident at the Fukushima Dai-Ichi nuclear power plant that occurred in 2011. The higher priority activities identified in this UFDC Disposal R&D Roadmap were and will be instrumental in establishing the collaborative activities that will be conducted under these bilateral agreements.

The UFDC will also collaborate with industry, as appropriate, to obtain their expertise in areas regarding geosciences and the geologic disposal of radioactive waste. In addition, the UFDC will also collaborate with research and development organizations conducting R&D on geologic systems (i.e., geothermal energy and carbon sequestration).

UFDC geologic disposal R&D is also tightly integrated with the storage/transportation part of the UFDC program. The properties and characteristics of the materials that would be disposed of after long term storage and transportation are input conditions to disposal-related R&D.

2. SYSTEMATIC APPROACH TO UFDC R&D PRIORITIZATION

The UFDC is applying a systematic approach to developing its R&D portfolio, consistent with the system engineering approaches being used across the DOE-NE Fuel Cycle Technology program. The UFDC applies a five step process to establish its R&D portfolio:

1. Identify potential R&D issues (information needs and knowledge gaps)
2. Characterize and evaluate R&D issues to support prioritization
3. Identify overall UFDC issue priorities based on the evaluation
4. Identify R&D projects to address high-priority issues
5. Evaluate R&D projects and select projects for funding.

Issues are, in the context of the UFDC Disposal R&D roadmap, opportunities to conduct R&D to fill information needs and knowledge gaps. The use of the word "issue" does not necessarily imply that information is needed or a knowledge gap is present, but rather presents a topic that needs to be addressed to implement a geologic disposal system. This approach is similar to the "issue resolution strategy" approach that has been utilized in the past U.S. site characterization programs.

This UFDC Disposal R&D Roadmap identifies and prioritizes potential R&D issues (through step 3 above) and specifies higher priority issues to be addressed by the program. The identification of R&D projects and their evaluation and prioritization will be a continual activity. Having the high-priority issues identified will allow researchers to develop R&D projects aimed at key issues. Additionally, the issues themselves will continue to be evaluated as R&D progresses and issues are addressed.

Applying a systematic approach to each issue, and subsequent R&D topic, prioritization allows for objectivity in deciding which issues should be addressed, and when, and provides defensibility to the UFDC R&D portfolio. The systematic approach that will be applied by the UFDC is shown in Figure 1 below. Each of the information categories needed to support issue prioritization is discussed further below.

UFDC management will retain flexibility to redirect activities that are of lower priority or may not be included in this roadmap to respond to evolving circumstances within the FCT program.

2.1 Potential R&D Issues

This section describes the identification of R&D issues. Again, such issues are opportunities to conduct R&D to fill information needs and knowledge gaps. The use of the word "issue" does not necessarily imply that information is needed or a knowledge gap is present, but rather it is a topic that needs to be addressed to implement a geologic disposal system.

2.1.1 Objectives

A "System Engineering" approach to issue identification would first begin with the high-level requirements. However, the existing high-level regulatory framework for a future disposal system in the U.S. (not at Yucca Mountain) may change when considering future disposal sites, as it is inconsistent with current thinking as exemplified in the recommendations of the U.S. National Academy of Sciences (NAS 1995). Accordingly, it would not be appropriate to define specific disposal requirements from the existing regulatory framework. Rather, a set of high-level objectives has been determined from safety guidelines developed by the IAEA (IAEA 2003).

The UFDC will address objectives that are important to the disposal concept at any stage during implementation. For the purposes of this UFDC Disposal R&D Roadmap, objectives for a disposal system are (developed from IAEA 2003):

- Containment: Provide a high probability of substantially complete containment of short lived radionuclides for some hundreds or thousands of years, perhaps largely within the engineered barriers of the repository.
- Limited Releases: Delaying and limiting the rate and the consequent concentrations in which radionuclides will be released from the immediate environment in which the waste was emplaced into the surrounding geological environment and eventually transported to the biosphere. This is achieved by a combination of physical and chemical mechanisms which, among other functions, may limit the access and flux of ground water to the wastes and from the repository to the biosphere, and may limit the solubility of radionuclides, or sorb or precipitate them reversibly or permanently onto surfaces in the host geology and the engineered barrier system (EBS). In addition, the process of radioactive decay progressively reduces the amounts of radionuclides present in the disposal system (although the amounts of some important radionuclides will increase through in-growth).
- Dispersion and Dilution: The flux of long lived radionuclides through the geological barriers involves three-dimensional dispersion, and may take place in widely different groundwater environments. In some concepts and at some specific proposed repository sites, releases would encounter major aquifers at depth or closer to the surface, or similar large bodies of surface water. This would result in an additional, but <u>secondary</u>, function to limiting releases (i.e. an overall dilution of released radionuclides such that concentrations on initial return to the biosphere are lowered).
- Defense in depth ensured by performance of a geological disposal system dependent on multiple barriers having different safety functions.

Other objectives have been described, but are either addressed by the objectives listed above, are inherent to the disposal system itself, or are site- and/or design-specific.

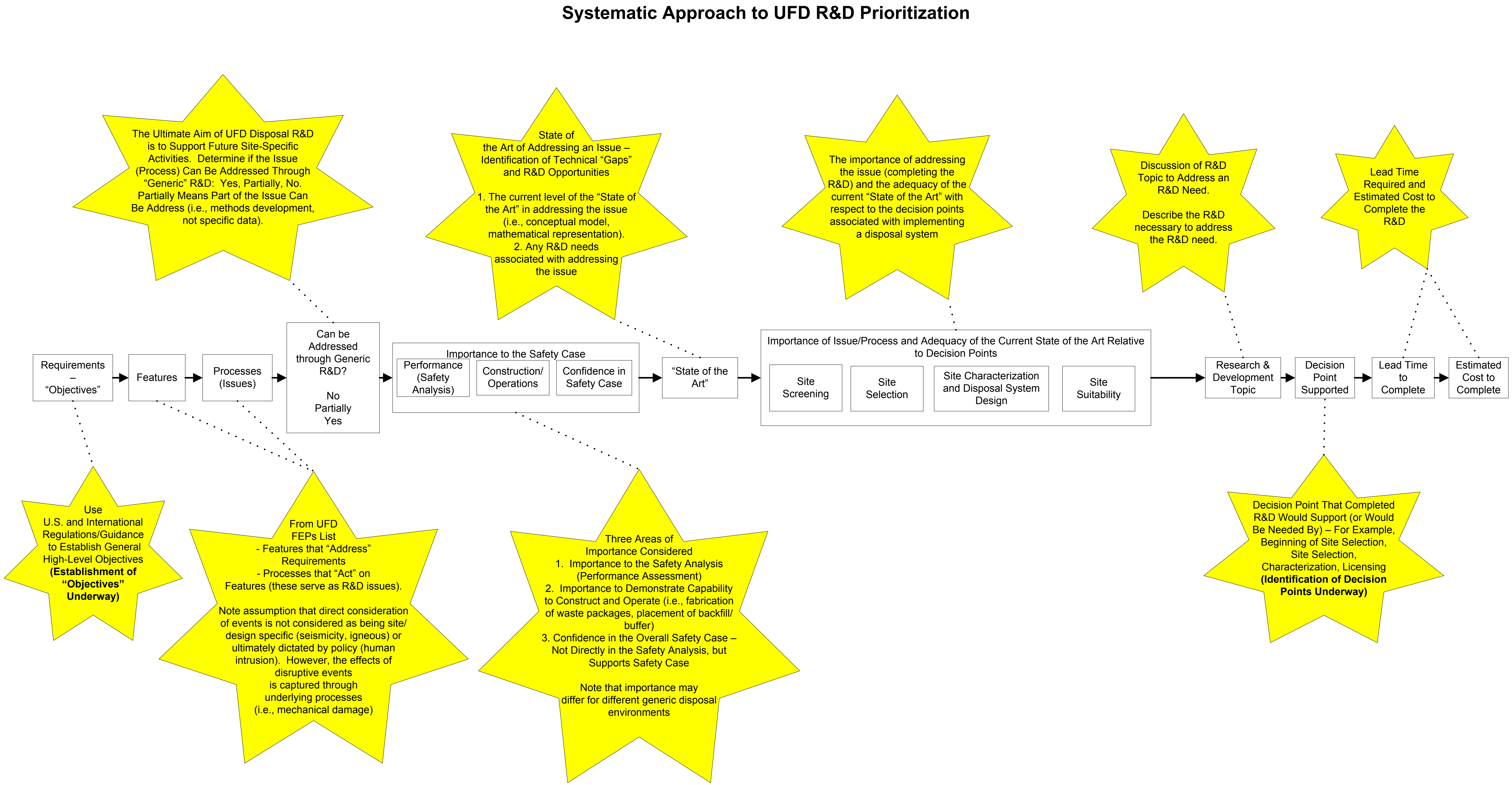


Figure 1. Systematic Approach to UFDC R&D Prioritization

2.1.2 Features

The next step involves identifying the features that would be used to meet the objectives listed above. The features would be well defined for a specific disposal system design in a specific environment. However, the UFDC is investigating generic disposal system concepts and environments, so a broad set of features is defined and mapped to the objectives. The features considered were obtained from the UFDC features, events, and processes list (Freeze et al., 2010, Freeze et al. 2011):

- Waste Form
- Waste Packaging
- Backfill/Buffer
- Seals
- Other Engineered Features (i.e., waste package supports, tunnel liners, etc.)
- Engineered Barriers (the collection of engineered barriers)
- Natural System - Geosphere
- Natural System - Biosphere
- System (the entire disposal system)

While the features have been mapped to the high-level objectives, it must be recognized that the mapping is not necessarily one-to-one (features may support multiple objectives), and not all features are relevant for every disposal system or environment.

It must also be recognized that this is a high-level listing of features and does not explicitly account for lower-level features that would ultimately be considered. As an example, waste packaging may consider multiple materials, each of them being a feature. Additionally, the natural system may involve multiple rock types and features within a given geologic unit (e.g., fractures). However, a high-level categorization of features is appropriate for applying a systematic prioritization of R&D issues.

Moreover, the features, events, and processes categorization scheme examines the system from the perspective of individual components, and does not explicitly call out important interactions among system components. In this report, such interactions are described as "cross-cutting" issues, and are explicitly included.

2.1.3 Issues/Processes

The next step involves the identification of issues associated with each feature. Again, while a specific disposal system design in a specific disposal system environment will have unique issues that must be addressed, the UFDC is considering generic systems at this point, and the issues under consideration are somewhat broad. These issues correspond well with the processes under consideration in the UFDC FEP evaluation process. As such, the features, events, and processes identified in the UFDC FEP list (Freeze et al. 2010, Freeze et al. 2011) are used to develop the comprehensive set of issues under consideration in developing the UFDC Disposal R&D Roadmap.

Disruptive events represent another set of issues that must be considered. However, the issues associated with disruptive events are site-specific (seismicity, volcanism, the potential for human induced disturbance), possibly defined within the regulatory framework, and would depend on the disposal system design. Since the UFDC is considering generic systems, it is not possible to address the specific issues that would be associated with disruptive events. Rather, these issues can be indirectly addressed within the generic issues under consideration (e.g., mechanical damage to waste packaging materials) or methods to support the siting process (experimental and analytic).

2.2 Characteristics of Potential R&D Issues Relevant to Priorities

This section discusses the categories of information that were used to evaluate each of the identified R&D issues.

2.2.1 Applicability of Generic R&D

An objective of UFDC R&D is to develop information that could ultimately be applied to a site-specific application. As such, the first question to ask for each issue is whether it can be addressed through generic R&D. That is, the identification of R&D that can be conducted without requiring site-specific data (data from actual sites that would be considered for implementation of a disposal facility).

- For some issues the answer is no; the issue can only be addressed in site-specific and/or design-specific evaluations. For example, issues related to disruptive events as discussed above are usually site-specific and design-specific.
- In some cases an issue can be fully, or close to fully, addressed through generic R&D both in terms of methodology development and parameter quantification. As an example, corrosion mechanisms for potential waste package materials could be investigated over a range of geochemical conditions to develop both mechanistic models and provide corrosion rate parameters.
- In many cases the issue can be partially addressed through generic R&D. In such cases, the focus of the R&D is expected to be on developing methods (experimental and analytic), rather than quantifying specific parameters. For example, models and methods for improved understanding of thermal processes can be developed without site-specific data, but ultimately site and design characteristics will determine the actual parameters and evolution of those thermal processes.

Only those issues that can be fully or partially addressed through generic R&D would be considered by the UFDC at this point.

Conducting site- and design-specific R&D on other engineered barrier system materials and components would require the selection of a site, the development of the subsurface facility design, and the selection of materials. Most of this information would not be known until much later in the disposal facility development process (i.e., at the conceptual design phase). Thus, it is anticipated that generic R&D could be conducted, focusing primarily on the performance of materials that could be used and their interaction with generic disposal system environments. Methods (experimental and analytic) methods to evaluate the behavior of such materials could be developed and/or improved. However, such methods would be developed or improved focusing on the engineered barriers with principal roles in performance.

2.2.2 Importance to the Safety Case

A critical set of information needed to prioritize the remaining R&D issues is importance to the safety case. The UFDC R&D program uses the following definition of the safety case for geologic disposal, taken from the definition given by the OECD/NEA (NEA 2004):

> *A safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe after closure and beyond the time when active control of the facility can be relied on. The safety case becomes more comprehensive and rigorous as a programme progresses, and is a key input to decision making at several steps in the repository planning and implementation process. A key function of the safety case is to provide a platform for informed discussion whereby interested parties can assess their own levels of confidence in a project, determine any reservations they may have about the project at a given planning and development stage, and identify the issues that may be a cause for concern or on which further work may be required.*

A detailed safety case, presented in the form of a structured set of documents, is typically required at major decision points in repository planning and implementation, including decisions that require the granting of licenses. A license to operate, close, and in most cases even to begin construction of a facility, will be granted only if the developer has produced a safety case that is accepted by the regulator as demonstrating compliance with applicable standards and requirements. Less detailed technical evaluations and safety assessments [see following discussion of safety assessment below] may be adequate to support some levels of internal planning and decision making by the developer. Crucially, the discipline of preparing a safety case, and presenting the case for scientific and technical review, regulatory review or wider non-technical reviews, ensures that post-closure safety is explicitly and visibly considered at each project stage.

Figure 2 provides an overview of the components of a safety case for geologic disposal (NEA 2004). Given the current status of the geologic disposal program in the U.S., the UFDC disposal R&D program is focusing primarily on supporting the development of a future safety assessment basis.

The safety strategy, the high-level approach adopted for achieving safe disposal, will evolve as the U.S. geologic disposal program evolves and will be informed by UFDC R&D. However, other areas in addition to the safety assessment must also be considered: designing and constructing the disposal system, and overall confidence in the safety case.

A fundamental part of the safety case is the system concept: a description of the repository design including the engineered barriers, the geologic setting and its stability, how both engineered and natural barriers are expected to evolve over time, and how they are expected to provide safety (NEA 2004). In order to develop its R&D program, the UFDC will develop one or more safety concepts or aspects of the safety concepts for the generic disposal environments under consideration (at a conceptual level). The issues must also be evaluated for their importance to the design and construction of disposal systems (system concepts).

2.2.2.1 Role of the Safety Assessment in the Safety Case

Safety assessment is an analysis to predict the long-term performance of the overall system and its impact and confidence in the assessment of safety, where the performance measure is radiological impact or some other global measure of impact on safety (NEA 1999, IAEA 2003, and NEA 2004). Within the current U.S. regulatory framework, performance assessment is defined essentially synonymously with this definition of safety assessment.

Safety assessment addresses the ability of the site and the design of the repository facility to meet the applicable technical requirements and provide for the safety functions. Safety assessment includes quantification of the overall level of performance, analysis of the associated uncertainties and comparison with the relevant design requirements and safety standards. As site investigations progress, safety assessments become increasingly refined, and at the end of a site investigation sufficient data will be available for a complete assessment. Safety assessments also identify any significant deficiencies in scientific understanding, data or analysis that might affect the results presented. Depending on the stage of development, safety assessments may be used to aid in focusing research, and their results may be used to assess compliance with the various safety objectives and standards (IAEA, 2006).

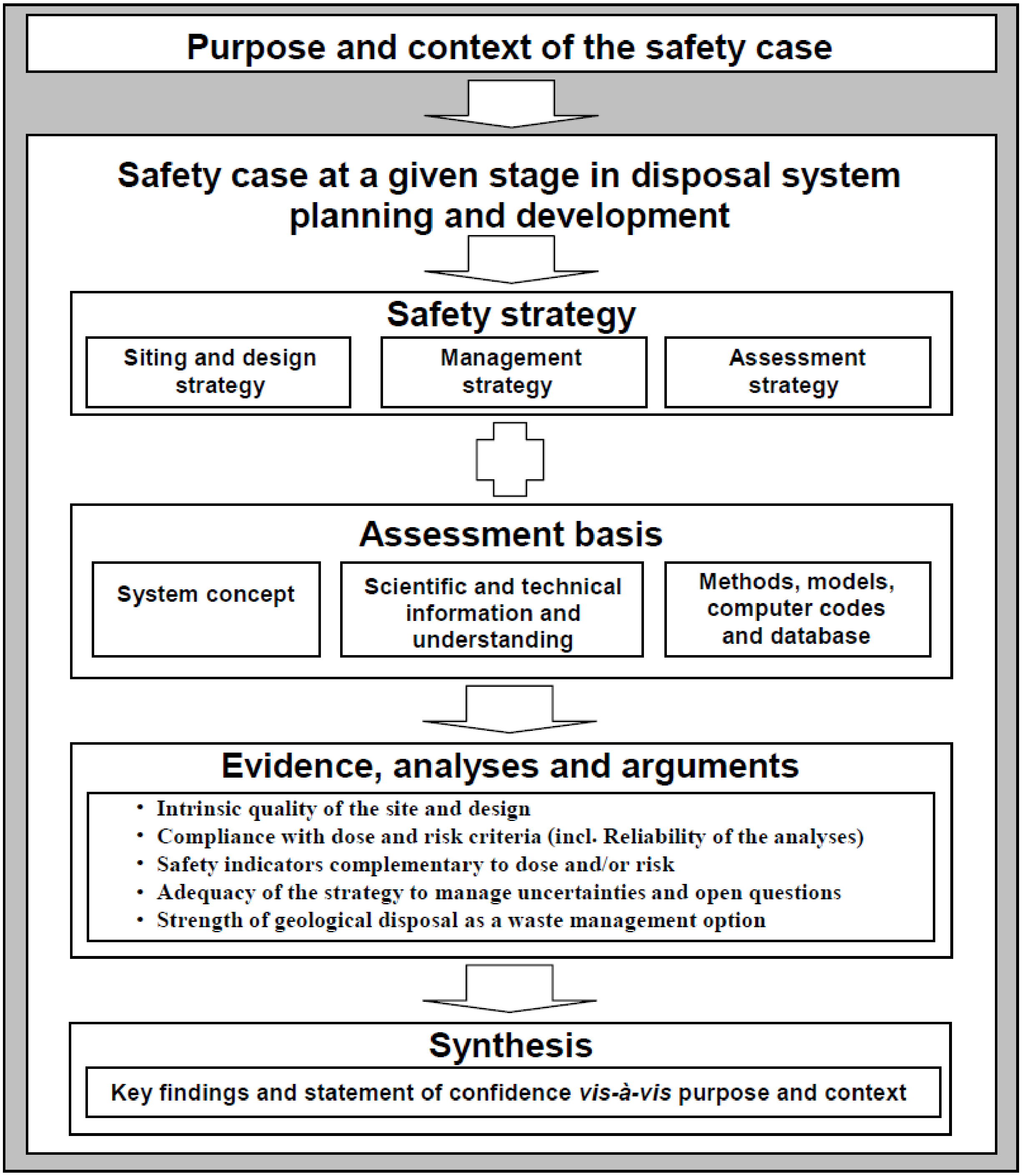


Figure 2. Overview of the Safety Case for Geologic Disposal

While the safety assessment is the principal technical basis for determining the importance of system elements, it is not sufficient. The safety case substantiates the safety, and contributes to confidence in the safety, of the geological disposal facility. The safety case is an essential input to all the important decisions concerning the facility. It includes the output of safety assessments, together with additional information, including supporting evidence and reasoning on the robustness and reliability of the facility, its design, the design logic, and the quality of safety assessments and underlying assumptions. The safety case may also include more general arguments relating to the need for the disposal of radioactive waste, and information to put the results of the safety assessments into perspective. Further, it aids in addressing perceptions of safety that may in fact not have a strong technical basis. Importance to the safety case alone is not sufficient for determining R&D priorities.

Even issues not deemed important to either performance (safety assessment) or the design/construction of the disposal system may be of importance to the safety case. Specifically, some issues may need to be addressed to build confidence in the overall safety case. As an example, issues associated with features that may not be important to performance, but act as part of a multiple-barrier system that demonstrate defense in depth could be of importance with respect to confidence in the overall safety case.

2.2.3 State of the Art

A considerable amount of work has been completed both in the U.S. and in other countries on many, if not all, of the issues under consideration by the UFDC identified above. This body of work can be used to determine the current level of understanding, or the "State of the Art" with respect to each issue across the generic disposal environments, and to identify information gaps. The UFDC intends to leverage the R&D that has been completed to identify those gaps that need to be addressed. If an issue has been adequately addressed, then there is no point in continuing R&D on that issue.

The "State of the Art" of each issue can be categorized as one of the following:

- Well Understood – the representation of an issue (process) is well developed, has a strong technical basis, and is defensible. Additional R&D would add little to the current understanding
- Fundamental Gaps in Method: the representation of an issue (conceptual and/or mathematical, experimental) is lacking
- Fundamental Data Needs: the data or parameters in the representation of an issue (process) is lacking
- Fundamental Gaps in Method, Fundamental Data Needs: Both
- Improved Representation: The representation of an issue may be technically defensible, but improved representation would be beneficial (i.e., lead to more realistic representation).
- Improved Confidence: Methods and data exist, and the representation is technically defensible but there is not widely-agreed upon confidence in the representation (scientific community and other stakeholders).
- Improved Defensibility: Related to confidence, but focuses on improving the technical basis, and defensibility, of how an issue (process) is represented

2.2.4 Importance and Adequacy of Information With Respect to Decision Points

The R&D conducted by the UFDC will support the implementation of a geologic disposal system as it progresses through different decision points. Issues may have different importance or priority for different decisions. For example, it may be very important to understand well the waste inventory when making a site suitability decision, where detailed assessment of the potential for radiation exposure to future populations must be compared with regulatory standards. However, it may be not at all important when making site screening decisions, where geologic and other factors are likely to dominate the decision-making. Given the importance of an issue with respect to a decision point, the adequacy of the current level of knowledge (the "state of the art") can be estimated.

The importance of an issue was evaluated with respect to each decision point: issues were characterized as being high (information about the issue is essential to the decision), medium (information about the issue will support or improve decisions), or low (information about the issue is useful but not necessary) in importance. It is also possible for a particular issue to be irrelevant for a specific decision. In addition to importance, each issue was evaluated in terms of the adequacy of current knowledge to support that decision: completely sufficient, partially sufficient, and insufficient.

The decision points under consideration by the UFDC with respect to developing its R&D portfolio and the type of safety/performance information that would be needed at each decision point are shown in Table 1.

Table 1. Types of Information Needed at Different Decision Points for Implementing a Geologic Disposal System

Decision	**Type of Safety / Performance Information Required**
Site screening [broad siting, site down-select]	- Identification of show-stoppers. - Is there something that makes the site clearly unsuitable in terms of performance, safety, or other screening criteria (e.g., proximity to population centers?)
Site selection [environment feasibility, concept feasibility, site designation]	- *Relative* performance of the sites (for site selection, being able to compare the sites is more important than having a highly accurate model of site performance) - Key contributors to isolation, containment, delay, dispersion, and dilution for each site (preliminary sensitivity analyses) - Potential weaknesses in the safety case for each site
Site characterization and disposal system design [site characterization]	- Sufficient understanding of the site and its strengths and weaknesses in terms of performance to design a complimentary engineered system. - Sufficient understanding of the ability of the system to isolate, contain, delay, disperse, and dilute - Ability to model potential releases and dose to human receptors for the site/design combination
Site suitability [licensing]	- Ability to model releases and doses and compare them to a regulatory standard - Sufficient confidence in models and supporting data to make a convincing case that the site is either suitable or not suitable (i.e., to know with confidence whether or not it will meet the regulatory standard)

2.3 Issue prioritization

Prioritization of issues requires combining technical and management judgments. Technical judgments are the evaluation of each issue in terms of the criteria described above. Management judgments are necessary to determine how the various criteria, and the evaluation of issues against those criteria, combine into a relative priority. Management judgments can be as simple as judgments about whether it is more important to focus on one decision point over another, or as complicated as whether an issue that is of low importance to a particular decision but for which current information is judged inadequate to support that decision is of higher or lower priority than an issue that is of medium importance to that decision point but for which current information is partially sufficient to support the decision.

The characteristics described above are used to establish the relative priorities of identified R&D issues using the following basic principles:

- The overall priority of an issue is a function of the importance of the issue to the safety case, the importance of the issue to each decision point, and the adequacy and state of the art of current information.
- The importance of an issue to the safety case is relevant at all decision points; the relative contribution of the three components to overall importance to the safety case may differ over time and at different decision points. For example the importance of issues that need to be addressed to increase confidence in the safety case may be higher for decisions related to site suitability than for site screening decisions.
- Issues that are important for nearer-term decisions such as site screening are of higher priority than those that are not important for near term decisions but important for later decisions, all other things being equal.
- Issues for which the current state of the art is well understood, and / or where currently available information is fully adequate to support a particular decision point are of low priority, at least with respect to that decision point.
- For issues evaluated differently for different media, media-specific priorities should be considered.

Given the number of issues evaluated and the coarseness of the evaluation criteria, the goal of the prioritization step is to group issues into a few categories, not to produce a full sequential ranking of all of theR&D issues identified.

Section 3.2 describes the specific assumptions and algorithm used to translate the basic principles above into a prioritization.

2.4 Research and Development Topics

The evaluation and prioritization of issues, including the detailed assessment of the importance of each issue and the adequacy of current information to support various decisions allow R&D topics to be developed to appropriately address the issue. Three information items are needed in order to evaluation the benefit of an R&D topic against the issues. These are:

- Primary Decision Point Supported: Identifies which decision point completion of the R&D would support, recognizing that partial completion of the R&D could also support earlier decision points.
- Lead Time to Complete: An estimate of how long it will take to complete the R&D
- Cost: An estimate of the total cost needed to complete the R&D

Again, this R&D roadmap focuses on evaluating and prioritizing the R&D issues. R&D topics will be developed following completion of this R&D roadmap. It is anticipated that R&D topic identification will be continual and not a one-time occurrence that occurs once the R&D roadmap is completed. Each R&D topic will be mapped to the prioritized R&D issues, and will be prioritized using the information items shown above against fiscal year funding levels.

As R&D is completed the issue prioritization within the R&D roadmap will be revisited and perhaps reprioritized. This continual update of issue prioritization and focusing R&D on the higher priority issues allows for structured progress of R&D within the UFDC.

2.5 R&D Project Evaluation and Prioritization

The identification and prioritization of R&D issues presented herein will allow UFDC researchers to identify research topics to address them. Each R&D topic should include the information described immediately above. This will allow the UFDC management team to evaluate R&D topics against the issues and their priority, supporting the development of the annual integrated priority list for the campaign that is combined with those of other campaigns into a comprehensive integrated priority list for the entire Fuel Cycle Technology program.

3. USED FUEL DISPOSITION CAMPAIGN DISPOSAL R&D ROADMAP PRIORITIZATION INFORMATION MATRIX

A matrix has been developed to document the information collected for each of the categories discussed in Section 2 and was used to prioritize the issues and develop the UFDC Disposal R&D Roadmap. The *UFDC Disposal R&D Roadmap Prioritization Information Matrix* is currently captured in Microsoft Excel©. The current version of the matrix including all information collected and categorized to date is provided in Appendix A. As discussed above, the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* will be maintained and revised as:

- Decisions about how the U.S. program will evolve are made, and in particular, the regulatory framework is developed
- The description of features, events, and processes in the UFDC FEP list are revised
- R&D topics are identified and subsequently mapped to issues within the matrix
- R&D is completed necessitating an update to the information and reprioritization of the issues

3.1 Sources of Information for the UFDC Disposal R&D Roadmap Prioritization Information Matrix

The development of the UFDC Disposal R&D roadmap began in Fiscal Year 2010 and included a workshop held at Argonne National Laboratory on June 28th – 30th 2010. Experts in the area of radioactive waste management from across the DOE national laboratory complex participated and provided input regarding potential R&D opportunities that could be considered by the UFDC. The input received at that workshop in addition to efforts within the Natural System and Engineered System UFDC work packages were used to develop "*Used Fuel Disposition Research and Development Roadmap – FY10 Status*," (UFDC 2010). That report listed potential R&D topics that may warrant consideration by the UFDC, but no effort was made at that time to prioritize those topics. This report served as one source of information in the development of the matrix.

Two additional UFDC reports also provided information used to develop the matrix:

- *Disposal Systems Evaluations and Tool Development - Engineered Barrier System (EBS) Evaluation* (Jove-Colon, et al., 2010)

- *Natural System Evaluation and Tool Development – FY10 Progress Report* (Wang 2010)

These reports were developed by UFDC researchers and provided an initial assessment of R&D opportunities pertaining to the disposal of radioactive waste in different geologic media.

A second workshop was held at Argonne National Laboratory on December 1st – 2nd, 2010. As with the first workshop, experts in the area of radioactive waste management from across the DOE national laboratory complex participated. The goal of that workshop was to evaluate each issue on the criteria described above: to obtain information that would enable prioritization of the issues. UFDC researchers made an initial effort to populate the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* and provided it to workshop participants and additional UFDC researchers in advance of the workshop. The workshop was a working meeting to review the initial drafting of and further develop the *UFDC Disposal R&D Roadmap Prioritization Information Matrix*.

A core set of UFDC participants reviewed the matrix that was completed during the workshop and revised it where necessary. The matrix was subsequently provided to workshop participants and a broader group of researchers within the UFDC for review. Feedback was incorporated into the final matrix provided in Appendix A.

The UFDC participants used published information regarding the feasibility and performance of geologic disposal facility concepts developed throughout the world. Three reports were published by Sandia National Laboratories that investigated the feasibility of different disposal concepts and media within the U.S. These reports were also used in the initial development of the roadmap.

- *Deep Borehole Disposal of High-Level Radioactive Waste* (Brady et al. 2009)
- *Shale Disposal of U.S. High-Level Radioactive Waste* (Hansen et al. 2010)
- *Salt Disposal of Heat-Generating Nuclear Waste* (Hansen and Leigh 2011)

UFDC Leads in the Natural System, Engineered System, Generic Disposal System Modeling have reviewed the Disposal R&D Roadmap Prioritization Information Matrix considering progress that has been made both within the UFDC and international programs. A number of recently completed reports informed this review, including:

- *Final Draft Deployment Plan - Implementing Geological Disposal of Radioactive Waste Technology Platform* (IGD-TP 2011)
- *The Post-closure Radiological Safety Case for a Spent Fuel Repository in Sweden, An International Peer Review of the SKB License-application Study of March 2011* (NEA 2012)
- *Generic Repository Design Concepts and Thermal Analysis (FY11)* (Hardin et al. 2011)
- *Generic Disposal System Modeling – Fiscal Year 2011 Progress Report* (Clayton et al. 2011)
- *Disposal Systems Evaluations and Tool Development – Engineered Barrier System (EBS) Evaluation* (Jove-Colon et al. 2011)
- *Natural System Evaluation and Tool Development – FY11 Progress Report* (Wang et al. 2011)
- *Integrated Tool Development for Used Fuel Disposition Natural System Evaluation – Phase I Report* (Wang et al. 2012)
- *Evaluation of Generic EBS Design Concepts and Process Models: Implications to EBS Design Optimization* (Jove Colon et al. 2012)

In summary, the information used to prioritize the various R&D issues is subjective, based on a variety of information sources and the expert judgment of people in the field of radioactive waste disposal.

3.2 Evaluation and Prioritization of Issues

The following four steps were followed to calculate an overall priority metric for each issue based on the technical assessments of the importance of the issue to the safety case, the importance of the issue to each decision point, and the adequacy and state of the art of current information, and value measures assessed from participants at a UFDC Disposal R&D Roadmap development team workshop held on March 8, 2011[3]. The scores, weights, and overall algorithm reflect a consensus among the workshop participants, but can be changed to reflect differing priorities.

Step 1: Importance of the issue to the safety case (at each decision point)

- The importance of an issue to the safety case (IS) is a function of its importance to each of the three components of the safety case (I_{SA}= importance to safety assessment, I_D = importance to design, construction & operations, I_C = importance to overall confidence in the safety case)
    - I_{SA}, I_D, and I_C are assigned numerical scores as follows:

Evaluation of importance	"Score"
Low	1
Medium	2
High	3
N/A	0

- An issue can be important to the safety case if it is important to any one of the three components, and the importance to the safety case increases the more components the issue is important for.
    - Implication: a weighted additive function is a reasonable way to combine the three components into an overall score for importance to the safety case. It is the simplest approach that is consistent with these general assumptions.
    - Let w(Ixx) = the weight assigned to the xx component of the safety case, then:

$$IS = w(I_{SA}) * I_{SA} + w(I_D) * I_D + w(I_C) * I_c$$

- *However,* importance to the safety case is relevant at all decision points; and the relative contribution of the three components may differ at different decision points
    - That is, w(Ixx) is decision-point specific.
    - Let d represent the four decision points as follows: d =1=site screening, d=2=site selection, d=3=site characterization, and d=4=site suitability)
    - Now, let wd(Ixx) = the weight assigned to the xx component of the safety case at decision point d. Then

$$IS_d = w_d (I_{SA}) * I_{SA} + w_d (I_D) * I_D + w_d (I_C) * I_c$$

[3] Participants were Mark Nutt (ANL), Carlos Jove-Colon (SNL), Yifeng Wang (SNL), Hua-Hai Liu (LBNL), Robert Howard (ORNL), James Blink (LLNL), Ernie Hardin (SNL), Michael Voegele (Complex Systems Group LLC)., Mark Tynan (DOE NE-53), Prasad Nair (DOE NE-53), Ram Murthy (DOE NE-53), Bill Spezialetti (DOE NE-53)

- Weights were assigned by workshop participants as shown in Table 2 below, reflecting the following logic:
  - At all points, importance to design, construction, and operations is of lesser importance to the overall safety case that the other two components.
  - In nearer-term decisions, importance to the safety case is the most critical component of the overall safety case
  - Later in the process (at site suitability), the importance of overall confidence increases to be about equal to the importance of the safety case

Table 2. Weights Assigned to Safety Case Importance Components

	Safety case component		
Decision point (d)	**Safety assessment**	**Design, construction, operations**	**Confidence**
Site Screening	0.5	0.2	0.3
Site selection	0.5	0.2	0.3
Site characterization	0.5	0.2	0.3
Site Suitability	0.4	0.2	0.4

Step 2: Importance of an issue to each type of decision

- The importance of an issue at a specific decision point I_d (d =1, 2, 3, or 4) is a function of the importance to the safety case at that point (IS_d, as calculated in Step 1), and the importance of the information to the decision ($DI_{d)}$
  - This value function was assessed by the workshop participants as shown in Table 3 below, reflecting the following philosophy:
    - The importance of the information to the decision is of greater relevance than importance to the safety case, in determining the importance of an issue at each decision point
    - Importance to the safety case has a larger impact on overall importance when the decision importance is high than when the decision importance is low.
  - Because IS_d scores are continuous (see equation in Step 1), it is necessary to interpolate between values shown in the table above for non-integer IS_d scores.

Step 3: Priority of an issue at each decision point

- The priority of an issue at a specific decision point (P_d) depends on the importance of that issue for the decision (I_d, calculated in Step 2) and the adequacy of current information to support that decision (A_d).
  - Workshop participants assessed the overall priority of an issue at a decision point as shown in Table 4 below, reflecting the following basic judgments
    - Issues for which the current state of the art is well understood, and / or where currently available information is fully adequate to support a particular decision point are of low priority with respect to that decision point, because there is no information gap.

- Any issue for which current information is insufficient is of higher priority than any issue for which current information is partially sufficient.

- Because I_d scores are continuous (see step 2), it is necessary to interpolate between values shown in the table above for non-integer I_d scores.

Table 3. Value Function for Importance of an Issue to Decision Points

	Importance to the Decision at decision point d (DI_d)			
Importance to the safety case at decision point d (IS_d)	**Low: information is useful to not necessary**	**Medium: information supports or improves decision**	**High: information is essential to the decision**	**N/A**
1 (e.g., of "low" importance to all three components of the safety case)	1	4	13	0
2 (e.g., of "medium" importance to all three components of the safety case)	2	8	22	0
3 (e.g., of "high" importance to all three components of the safety case	3	12	31	0
NA (not relevant to any aspect of the safety case	0	0	0	0

Table 4. Value Function for Priority of an Issue at Decision Points

	Adequacy of current information to support the decision (A_d)			
Importance to Decision Points (I_d)	**Completely sufficient (no additional info needed)**	**Partially sufficient (issue can be represented but needs improvement)**	**Insufficient (cannot adequately represent issue)**	**N/A**
Low importance to safety case and low importance to the decision point (e.g., I_d = 1)	0	2	7	0
Medium importance to all elements of the safety case and medium importance to the decision (e.g., I_d = 8)	0	4	10	0
High importance to all elements of the safety case and to the decision (e.g., I_d = 31)	0	6	13	0
NA	0	0	0	0

Step 4: The overall priority of an issue

- Overall issue priority is the weighted sum of the priority of the issue at each decision point.
  - Weights were assigned by workshop participants as shown in Table 5 below, reflecting the following logic:
    - Site screening could be done with information currently available, At all points, importance to design, construction, and operations is of lesser importance to the overall safety case that the other two components.
    - In nearer-term decisions, importance to the safety case is the most critical component of the overall safety case
    - Later in the process (at site suitability), the importance of overall confidence increases to be about equal to the importance of the safety case

Table 5. Weight of Decision Points

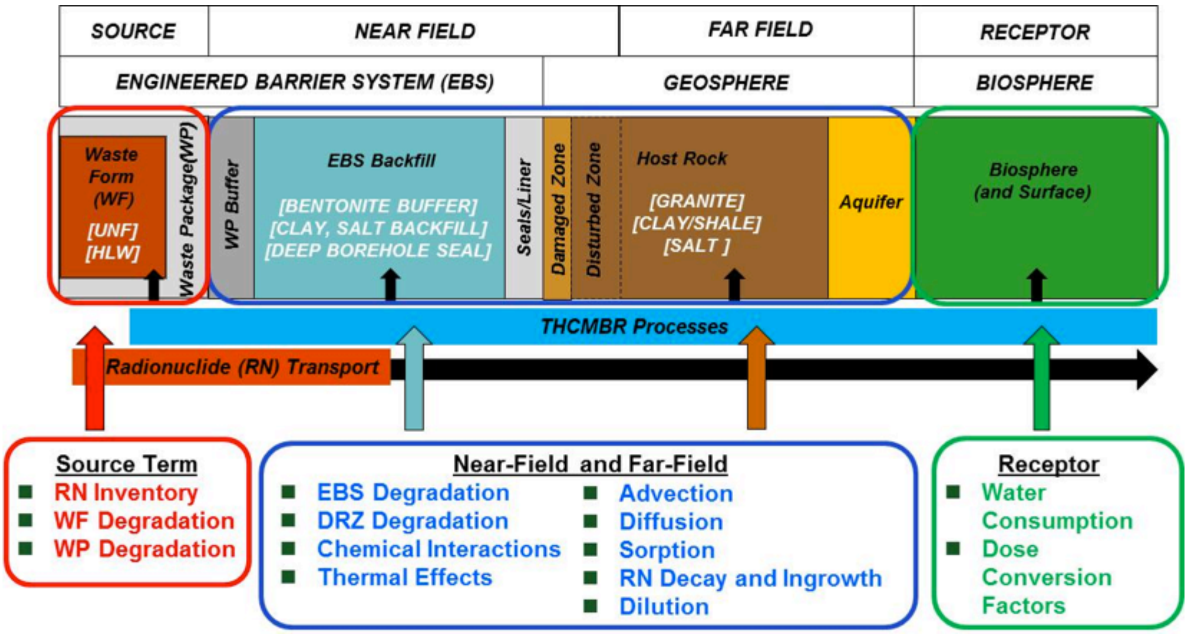
Decision point (d)	Weight
Site Screening	0.20
Site selection	0.45
Site characterization	0.30
Site Suitability	0.05

4. USED FUEL DISPOSITION CAMPAIGN DISPOSAL R&D ROADMAP SUMMARY

This section summarizes the information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* and the prioritization of broad R&D topical areas. The structure of this section and the R&D issues is based on the structure of the UFDC features, events and processes set (Freeze et al. 2010, Freeze et al. 2011). The *UFDC Disposal R&D Roadmap Prioritization Information Matrix* has 210 individual potential R&D issues, developed from the FEPs potentially important to the long-term performance of a geologic disposal facility. The information collected and categorized for each of these 210 individual R&D issues is provided in Appendix A. The scoring and weighting of each individual R&D issue, using the methodology shown in Section 3.2, was used to develop an overall priority ranking of each R&D issue. These were then sorted for the different media types because the priority ranking of some R&D issues is media-specific. A single issue thus may have multiple rankings where media-specific scores were assigned.

The sorted priority rankings are provided in Appendix B. The sorted priority rankings serve to identify the relative priority of the R&D issues by which specific R&D topics can be identified and evaluated against the prioritization of the issue. While sorted numerical scores are provided in Appendix B, they should not be construed as being an issue-by-issue ranked priority list. Rather, the scores were used to identify priorities at a much higher level, essentially by broad topic.

The detailed information provided in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* (Appendix A) also follows this structure. As can be seen in Figure 3, there is a straightforward breakdown of the system into engineered barrier system, geosphere, and biosphere; the features, events and processes are assigned to these categories. However, coupled processes, in particular the thermal-hydrologic-chemical-mechanical-biological-radiological processes (THCMBR) transcend this categorization. These processes apply to most of the features and are thus included in both the engineered and natural barrier portions of this section and the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* (Appendix A). It is recognized that the R&D focusing on these coupled processes won't be separated into natural- and engineered-specific R&D, but rather will be treated as R&D focusing on the processes themselves and how they affect the various engineered and natural features.



Source: Freeze and Vaughn (2012, Figure 2-4)

Figure 3. Components of a Generic Disposal System

This revision to the UFDC Disposal R&D Roadmap resulted in changes to a few of the 210 individual issues provided in Appendix A. Additional discussion for some of the issues was provided and in some instances the importance to the safety case or importance and adequacy of information relative to the decision point scores were modified. These changes are identified in red in Appendix A. Some of these changes resulted in changes to the overall priority ranking of some of the R&D issues shown in Appendix B. These are highlighted in yellow.

Overall, the high-level importance of each of the topical areas, discussed in this section, is un-changed. This, and the relatively minor changes made to the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* (Appendix A) indicates that the initial development of the UFDC Disposal R&D Roadmap was thorough and comprehensive.

4.1 Synopsis of UFDC R&D Issues/Opportunities

A synopsis of the results of the rankings for R&D issues, opportunities for cross-cutting, and engineered system, and natural system R&D issues. The *UFDC Disposal R&D Roadmap Prioritization Information Matrix*, has four levels and includes information for each issue under higher-level topical areas. The priority scoring of individual issues, shown in Appendix B, was used to determine an overall ranking of each broad topical area – low, medium, and high. In some areas, specific issues are identified that are different (higher or lower) than the overall ranking for some topical areas. These exceptions are identified. It must be recognized that the discussion and ranking herein are subjective, but are informed by the issue priority rankings shown in Appendix B that were developed based on the information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix*. While a quantitative score is provided, the underlying foundation is primarily expert judgment, both the information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* and the evaluation of the resultant quantitative priority ranking scores.

The development of this R&D roadmap identified a number of cross cutting issues. While not explicitly included in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix*, they are broad R&D issues. A synopsis of these issues is shown in Table 6 with additional detail provided in Section 4.2.

Table 6. Synopsis of the Results of Cross-Cutting R&D Issues

DESIGN CONCEPT DEVELOPMENT	High
DISPOSAL SYSTEM MODELING	High
OPERATIONS-RELATED RESEARCH AND TECHNOLOGY DEVELOPMENT	Low
KNOWLEDGE MANAGEMENT	Medium
SITE SCREENING AND SELECTION TOOLS	Medium
EXPERIMENTAL AND ANALYTICAL TECHNIQUES FOR SITE CHARACTERIZATION	Medium
UNDERGROUND RESEARCH LABORATORIES	Medium
RESEARCH AND DEVELOPMENT CAPABILITIES EVALUATION	Medium

A synopsis of the results of the prioritization ranking for the natural system is presented in Table 7. The ranking of the issues are illustrated for repositories in crystalline, salt, and shale or clay media. Also illustrated is the ranking for borehole disposal. While it is likely that borehole disposal would be in crystalline media, the issues are enough different from a crystalline media repository to warrant separate treatment. The highest ranked issues are flow and transport pathways in crystalline media repositories, the excavation disturbed zone for borehole disposal and shale media repositories, hydrologic processes for salt media repositories, chemical processes for shale media repositories, and thermal processes for shale media repositories. Stippling for an entry indicates that research in that area has been undertaken in other repository programs.

A synopsis of the results of the priority rankings for the engineered system is presented in Table 8. It should be noted that the rank scoring was not based according to specific engineered barrier materials but rather through the main components of the engineered barrier system and key potential processes to performance. Therefore, the presentation is broken down by the primary engineered component and the likely set of materials that could be considered for used in the engineered barrier system is also shown. The main reason for this approach is that specific engineered barrier system materials are highly dependent on repository design concepts and these still need to be developed to the point where the engineered components important to waste isolation can be identified and thus evaluated. Moreover, engineered barrier system materials can be considered, to a large extent, independent of the host media, but their performance is inherently important to the safety case. Waste form issues ranked higher than those for inventory. Waste container issues and chemical processes generally ranked higher than those for specific processes such as hydrologic and biologic. Buffer and backfill materials and issues related to chemical processes generally ranked higher than others. For seal and liner materials, issues related to chemical, mechanical, and thermal processes generally ranked higher than those for radiation or nuclear criticality effects. For other engineered barrier materials, issues related to chemical processes and radionuclide speciation / solubility ranked slightly higher than issues related to thermal, mechanical, and hydrological processes. Overall, chemical processes in the considered engineered barrier system components ranked higher than others but these are strongly coupled to thermal, hydrological, and even mechanical processes within the engineered barrier system. The ability to address coupled thermal-hydrologic-mechanical-chemical processes is stressed in subsequent sections of this report.

Recall from Section 2.7 that one of the information categories is the importance and adequacy of information with respect to decision points (site screening, site selection, site characterization, and site suitability). With respect to the site screening decision point, the development of the UFDC Disposal R&D Roadmap indicates that sufficient information currently exists to support a site screening process in the U.S., should a decision made to begin one. In particular, it was concluded that:

- There is limited need to complete additional R&D pertaining to engineered components for the generic site screening process at this time, because until design concepts are developed to the point where the engineered components potentially important to waste isolation can be identified, existing information will suffice. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support generic site screening.
- There is limited need to complete additional R&D for the natural system components to support generic site screening because sufficient information exists in available materials to support conclusions about the general character of the natural system. State, regional, and national geologic maps and information are available for the United States.
- This should not be inferred as meaning that no additional R&D is required until site screening is complete. Rather, it means that no additional R&D is required to initiate and complete a site screening process. R&D could be completed to improve that process and to provide needed information to support future decision points (site selection, characterization, and suitability).

Table 7. Synopsis of the Results of the Priority Ranking for the Natural System

GEOSPHERE →	Crystalline	Borehole	Salt	Shale
1.2.01. LONG-TERM PROCESSES (tectonic activity)	Low	Low	Low	Low
1.2.03. SEISMIC ACTIVITY				
- Effects on EBS	High	High	High	High
- Effects on NS	Low	Low	Low	Low
1.3.01. CLIMATIC PROCESSES AND EFFECTS	Low	Low	Low	Low
2.2.01. EXCAVATION DISTURBED ZONE (EDZ)	Medium	High	Medium	High
2.2.02 HOST ROCK (properties)	High	High	High	High
2.2.03 OTHER GEOLOGIC UNITS (properties)	Medium	Medium	Medium	Medium
2.2.05. FLOW AND TRANSPORT PATHWAYS	Medium	Medium	Medium	Medium
2.2.07. MECHANICAL PROCESSES	Low	Low	Medium	Medium
2.2.08. HYDROLOGIC PROCESSES	Low	Medium	High	Medium
2.2.09. CHEMICAL PROCESSES - CHEMISTRY	Low	Medium - High	Low - Medium	Medium - High
2.2.09. CHEMICAL PROCESSES - TRANSPORT	Medium	Medium - High	Medium - High	Medium
2.2.10. BIOLOGICAL PROCESSES	Low	Low	Low	Low
2.2.11. THERMAL PROCESSES	Low	Medium	Low	Medium
2.2.12. GAS SOURCES AND EFFECTS	Low	Low	Low	Low
2.2.14. NUCLEAR CRITICALITY	Low	Low	Low	Low

Notes:
1. Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs
2. FEP number lists includes all FEPs beneath the third level
3. Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs

Table 8. Synopsis of the Results of the Priority Ranking for the Engineered System: Waste Form and Waste Package

WASTE MATERIALS → SNF, Glass, Ceramic, Metal	
2.1.01.01, .03, .04: INVENTORY	Low
2.1.02.01, .06, .03, .05: WASTE FORM	High
WASTE PACKAGE MATERIALS → Steel, Copper, Other Alloys, Novel[4] Materials	**Steel**
2.1.03.01, .02, .03, .04, .05, .08: WASTE CONTAINER	High
2.1.07.03, .05, .06, .09: MECHANICAL PROCESSES	Medium
2.1.08.02, .07, .08: HYDROLOGIC PROCESSES	Low
2.1.09.01, .02, .09, .13: CHEMICAL PROCESSES - CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59: CHEMICAL PROCESSES - TRANSPORT	Low
- Advection, diffusion, and sorption	Medium
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.01, .02, .04: THERMAL PROCESSES	Medium
2.1.12.01: GAS SOURCES AND EFFECTS	Low
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.01: NUCLEAR CRITICALITY	Low
BUFFER / BACKFILL MATERIALS → Cementitious, bituminous, mixed materials: clay, salt, crystalline environments	
2.1.04.01: BUFFER/BACKFILL	High
2.1.07.02, .03, .04, 09: MECHANICAL PROCESSES	Medium
2.1.08.03, .07, .08: HYDROLOGIC PROCESSES	Medium
2.1.09.01, .03, .07, .09, .13: CHEMICAL PROCESSES - CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59, .61: CHEMICAL PROCESSES – TRANSPORT	Medium
- Colloid facilitated transport	Low
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.04: THERMAL PROCESSES	Medium
2.1.12.01, .02, .03: GAS SOURCES AND EFFECTS	Medium
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.02: NUCLEAR CRITICALITY	Low

[4] In this report, a novel engineered barrier system material refers either to a new material designed for improved performance within a geologic disposal system or an existing material that has not been extensively studied and used in the design of a geologic disposal system that could lead to improved performance.

Table 8. Synopsis of the Results of the Priority Ranking for the Engineered System: Waste Form and Waste Package (continued)

SEAL / LINER MATERIALS → Cementitious, Asphalt, Metal, Polymers	
2.1.05.01: SEALS	Medium
2.1.06.01: OTHER EBS MATERIALS	Medium
2.1.07.02, .08, .09: MECHANICAL PROCESSES	Medium
2.1.08.04, .05, .07, .08, .09: HYDROLOGIC PROCESSES	Low
- Flow through seals	Medium
2.1.09.01, .04, .07, .09, .13: CHEMICAL PROCESSES – CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59: CHEMICAL PROCESSES - TRANSPORT	Low
- Advection, diffusion, and sorption	Medium
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.04: THERMAL PROCESSES	Medium
2.1.12.02, .03: GAS SOURCES AND EFFECTS	Low
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.02: NUCLEAR CRITICALITY	Low
OTHER MATERIALS → Low pH Cements, Salt-Saturated Cements, Geo-polymers, Barrier Additives	
2.1.06.01: OTHER EBS MATERIALS	Medium
2.1.07.08, .09: MECHANICAL PROCESSES	Medium
2.1.08.04, .05: HYDROLOGIC PROCESSES	Medium
2.1.09.04, .07, .09, .13: CHEMICAL PROCESSES - CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
2.1.09.51, .52, .53, .54, .55, .56, .57, .58, .59: CHEMICAL PROCESSES – TRANSPORT	Low
- Advection, diffusion, and sorption	Medium
2.1.10.x: BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
2.1.11.04 THERMAL PROCESSES	Medium
2.1.12.02, .03: GAS SOURCES AND EFFECTS	Low
2.1.13.02: RADIATION EFFECTS	Low
2.1.14.02: NUCLEAR CRITICALITY	Low

Notes:
1. Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs
2. FEP number lists delimited by commas show only the change in the fourth field of the FEP

4.2 Cross-Cutting Issues / R&D Opportunities

Several cross-cutting issues / R&D opportunities have been identified that do not correspond directly to individual issues listed in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix*. However, they either cross or integrate several of the specific issues and are considered as part of the UFDC R&D portfolio.

4.2.1 Design Concept Development

A clear conclusion that arose from developing the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* is the need to develop a range of generic disposal system design concepts (herein called disposal concepts). Many of the issues at the process-level within the matrix are coupled and require the development of generic disposal concepts in order to conduct R&D on the specific issues. As an example, R&D focused on improving the understanding of the processes at material interfaces within the engineered systems requires that disposal concepts be defined. Selection of disposal concepts, the engineered barrier, and the engineered barrier materials also depends on the geologic setting.

In addition, fuel cycle scenarios under consideration by the FCT program would generate waste streams and waste forms having different characteristics, such as radionuclide inventory, decay heat, volume, and total quantity. Different disposal concepts should be considered for the disposal of these wastes in order to quantify and evaluate disposal-related metrics, using the disposal system models described in this report, for fuel cycle system analysis and system engineering activities.

The UFDC will develop a catalog of subsurface design concepts for the disposal of a range of generic waste forms that could potentially be generated in advanced nuclear fuel cycles. A preliminary set of disposal concepts using enclosed emplacement, whereby waste packages are in direct contact with a surrounding solid medium such as buffer material, backfill, or host geology, has been developed (Hardin et al. 2011). This work identified six heat-generating waste types representing what could be produced by advanced fuel cycles in the foreseeable future. It also recognized the need for additional, open emplacement modes that maintain air-filled spaces around the waste packages for ventilation to remove heat. Ventilation for a few years or decades after emplacement allows larger, hotter waste packages to be emplaced in a geologic repository. Development of reference concepts that incorporate open emplacement modes for disposal of the six waste types is ongoing. One motivation for developing concepts that can accept larger packages is to dispose of existing, large dual-purpose (transportation and dry storage) canisters directly without removing and repackaging the spent fuel. Investigation of this alternative to repackaging all of the spent fuel currently in dry storage (approximately 20,000 MTHM) and additional fuel that will be stored the same way (2,000 MTHM per year), is also ongoing.

Mature subsurface disposal system designs have been developed in other countries for the disposal of spent light water reactor fuel and HLW generated from PUREX reprocessing. These have been examined as a starting point for developing the catalog of disposal concepts. Additional emplacement modes (i.e., single level, multi-level, in-drift, horizontal borehole, vertical borehole, deep borehole from the surface, etc.) and engineered barrier concepts (capillary barrier, clay barrier, etc.) will be considered.

These disposal concepts will support the development of the UFDC R&D program to address specific issues, provide frameworks for evaluation using the generic disposal system models described in this report, and allow for integration between the UFDC and the systems analysis/system engineering efforts within the FCT program.

The UFDC has been developing, during the past two years, a tool to facilitate thermal, cost, and performance analysis of the full range of potential subsurface design concepts for a wide range of waste forms. This tool, called the Disposal Systems Evaluation Framework (DSEF) uses a spreadsheet architecture based on results from more detailed thermal, cost, and performance models. As of the end of FY12, the thermal model is mature and has been used in several design studies, and the cost model has been abstracted from a detailed model developed for a comparative design study. Abstraction of the performance model from the more detailed disposal system models (described in Section 4.2.2) is scheduled in FY13. Finally, DSEF includes a catalog of results (currently about 200) that allow users to sort, filter, and compare prior calculations.

4.2.2 Disposal System Modeling

An important use of the generic disposal system environment models and advanced high-fidelity, fully-coupled, multi-physics models for geologic disposal-related processes is to support development of the regulatory basis of future siting efforts, including site screening and selection. The Environmental Protection Agency and Nuclear Regulatory Commission regulations governing disposal of high-level radioactive waste and spent nuclear fuel are largely performance based. Compliance with these regulations is to be demonstrated through the use of total system performance assessment; the rigorous process is defined in the regulations. Historically, in the U.S., two Department of Energy regulations for developing repositories were promulgated; both link the site screening and selection processes to performance assessment results. The original siting guidelines, 10 CFR Part 960, were developed pursuant to the Nuclear Waste Policy Act (NWPA § 112), and are still in force for screening. They were amended, however, to limit their use in suitability evaluations. The older of the two NRC repository regulations, 10 CFR Part 60, while still in force for repositories other than Yucca Mountain, is built on subsystem performance objectives, which were not considered appropriate for a risk-informed, probability based regulation when Congress directed the NRC to promulgate site-specific standards for Yucca Mountain. 10 CFR Part 960 is linked to 10 CFR Part 60 which then makes it based on the outdated approach of subsystem performance objectives. DOE's other regulation for developing a repository, 10 CFR Part 963, is specific to Yucca Mountain. It is linked to Yucca Mountain specific EPA and NRC regulations. It too is performance based, being closely linked to the risk-informed, probability based structure of 10 CFR Part 63.

The structure and sophistication of the U.S. repository regulations evolved as performance assessment capabilities evolved. There is little reason to believe that future U.S. regulatory structure will not build upon the existing regulations, and the UFDC therefore assumes, for the purposes of this report, that future regulations will be risk-informed and will require performance assessment modeling of the full disposal system (i.e., what the DOE has called Total System Performance Assessment, or TSPA). The development of new performance assessment capabilities by the Used Fuel Disposition Campaign is of importance to the development of generic regulatory structure for at least two reasons. First, as noted, as performance assessment capabilities advanced, this was recognized by the regulatory agencies, which then promulgated more sophisticated regulations to take advantage of increased computational capabilities. Continued development of modeling capabilities, particularly as advanced high-fidelity, fully-coupled, multi-physics models are developed, can result in continued increasing sophistication in the treatment of uncertainties, which likely could be recognized in the regulations. Also, the development of regulations will be very sensitive to the then current states of model development and results. The regulators likely will undertake their own performance assessments, which will be informed by the state of DOE models, as they develop their regulations. These reasons argue for DOE to proceed expeditiously in the development of its new models to be ready to support efforts of the regulators to develop the next versions of repository regulations.

Disposal system modeling will be conducted at two levels within the UFDC. The UFDC is developing generic disposal system models (GDSMs) to support its activities over the short-intermediate timeframes. These models will provide a capability for evaluating disposal system performance so as to inform and guide future UFDC R&D activity prioritization and to evaluate disposal-related metrics for fuel cycle system analysis and system engineering activities. These models include generic performance models of long-term repository performance (i.e., performance assessment) and simplified thermal models to evaluate the thermal impacts of different fuel cycle strategies (i.e., thermal limits, repository layout, needed decay storage).

Extending the work conducted to date and efforts to implement the four generic numerical disposal models for salt, clay, granite, and deep borehole into a common GDSM framework have revealed limitations (lack of flexibility and inefficiencies that require significant programming labor associated with the tool being used; GoldSim). To eliminate these limitations a more efficient and flexible disposal system performance assessment (PA) model framework tool will be used to implement a Generic Performance Assessment Model (GPAM) and its scientific component models. Efforts have been initiated to identify and begin development of an advanced PA model framework capable of supporting both simple and complex integrated generic disposal system models in accordance with the requirements identified in FY12 (Vaughn and Freeze 2012). The PA model framework, which includes both a thermal-hydrologic-chemical-mechanical-biological-radiological (THCMBR) computational model capability framework should (Freeze and Vaughn 2012):

- provide the flexibility to examine multiple generic and site-specific geologic disposal options at levels of complexity that are expected to increase as the UFD program matures,
- enable the evaluation of system- and subsystem-level performance,
- enable uncertainty and sensitivity analyses to isolate key subsystem process and components,
- facilitate the modular integration of representations of subsystem processes and couplings, where the level of complexity of the representation may vary with intended use or relative importance to the total system,
- provide the capability to accommodate new or alternative subsystem process representations, including the use of legacy codes,
- provide data and configuration management functions,
- be developed and distributed in an open source environment,
- leverage existing utilities (e.g., meshing, visualization, matrix solvers, etc.), and
- facilitate implementation across a range of computing environments from laptops to high-performance computing (HPC) networks, including distributed code execution.

Existing computational frameworks with the potential to provide some of these advanced PA modeling capabilities have been identified (Freeze and Vaughn 2012). Albany is an existing framework used at Sandia National Laboratory and is based on the Sierra framework. Albany is “open source” and UFDC gains a powerful tool that has been previously developed. It will be further modified to meet specific UFDC needs and requirements.

The DOE-NE Nuclear Energy Advanced Modeling and Simulation (NEAMS) was developing an advanced Waste Form Integrated Performance and Safety Code (WF IPSC). However, that effort has been terminated, although some of the work is being leveraged in the advanced disposal system model development occurring in the UFDC. The DOE-EM Advanced Simulation Capability for Environmental Management (ASCEM) program is developing advanced high-fidelity, coupled, multi-physics models for geologic disposal-related processes. TheASCEM effort involves the development of high-fidelity multi-physics models into a system-level framework, which may ultimately support future safety analysis and licensing efforts. While the ASCEM effort supports the DOE-EM environmental remediation mission, the tools under development may also have direct applicability to deep geological disposal primarily in the area of radionuclide transport through the natural environment. The integration of various capabilities of these tools (Albany, WF IPSC, ASCEM) could represent an enhancement of the modeling capabilities used to support WIPP certification and the Yucca Mountain license application. The UFDC will follow

ASCEM development and collaborate with the ASCEM developers where it is beneficial to both ASCEM and advanced GPAM development.

Ongoing UFDC R&D will support the development and improvement of the simplified GDSMs for clay, granite, salt and deep borehole systems, and the identification and development of an advanced PA model framework for implementing the next generation disposal system model. For a period of time, the UFDC GDSMs will be improved. Ultimately the mature advanced GPAM tool will be developed by leveraging select tools from the most promising sources, including ASCEM, as appropriate. It is anticipated that some further refinement of these select tools will be needed to focus on UFD needs. Experimental investigations, sub-system model development, and treatment of parameters and their uncertainties completed as part of the UFDC program will support the UFDC GDSM, and advanced GPAM The timelines for GDSM and Advanced GPAM development and use is shown in Figure 4.

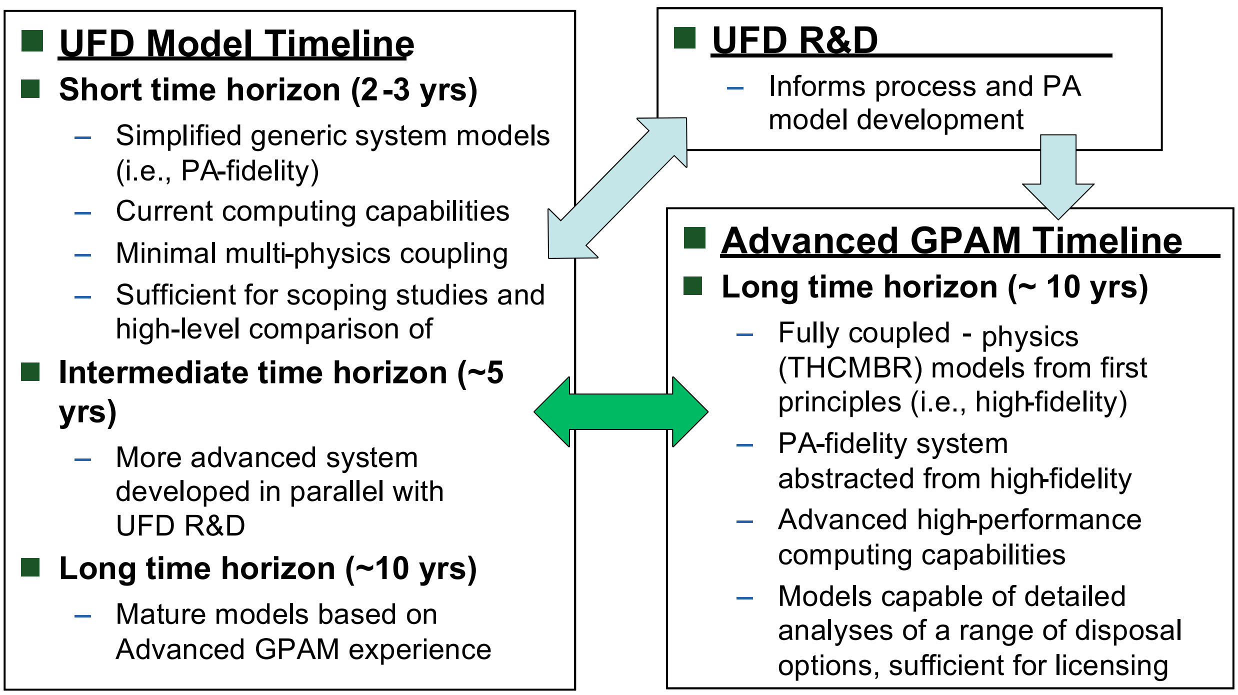


Figure 4. UFDC GDSM and Advanced GPAM Disposal System Model Development

As discussed in Section 2.5.1, safety assessment is an integrated and iterative process applied to all steps in the implementation of a geologic disposal system, from site screening through site suitability. Again, depending on the stage of development, safety assessments may be used to aid in focusing research, and their results may be used to assess compliance with the various safety objectives and standards (IAEA, 2006). The development and continued refining of the UFDC GDSMs along with the development of the Advanced GPAM tool will provide the neededcapabilities to conduct such safety assessments and as investigations progress they will become increasingly refined. Near-term capability would support future site screening activities, should a decision be made to initiate such activities.

The UFDC has developed and used four generic disposal system models over the past two years to evaluate the performance of disposal facilities located in salt granite, clay, and in a deep borehole (Clayton et.al. 2011). While these representations of the disposal system are simplified they do capture at a high level many features and processes for undisturbed conditions. The models have been used to estimate potential releases and dose, to evaluate uncertainties, to conduct sensitivity analyses for identifying important features, processes, and components, and for supporting the Generic Safety Case for geologic disposal (Vaughn et.al. 2012).

These models are currently being maintained for use as needed while further disposal system model development occurs. The development of the UFDC generic disposal system modeling capability proceeds along two primary fronts: 1) the obtaining, modification, and development of the multi-physics component models that make up the disposal system and 2) the obtaining, modification, and development of a computational framework for implementation of the integrated disposal system model. The technical components are numerical representations of the multi-physics that occurs in different regions throughout a disposal system. The computational framework is a tool that is used for constructing a system model made up of a number of linked technical components of varying degrees of complexity. The framework manages execution of simulations and the flow of information from a centralized computational database to the component models as well as among the component models in a way that that automates transparency and traceability.

Figure 3 above shows the current high-level conceptualization of the disposal system model and it components. The Engineered Barrier System (EBS) includes the Source and part of the Near Field. The Source includes the Waste Form and Waste Package. The EBS portion of the Near Field is includes Waste Package Buffer, EBS Backfill, and Seals/Liner. The Geosphere (also called the Natural Barrier System) includes a portion of the near field not included in the EBS, the Host Rock, and other formations including potentially an Aquifer. The Geosphere portion of the Near Field consists of an excavation disturbed zone (EDZ), which contains a damaged zone and a disturbed zone. The damaged zone is a region immediately surrounding the excavation that is influenced both mechanically and thermally by the excavation and disposal of wastes. The disturbed zone may extend further into the host rock and is influenced only thermally. The remainder of the host rock is relatively intact and not significantly influenced by the excavation or its emplaced waste. The Biosphere completes the system model.

4.2.3 Operations-Related Research and Technology Development

Understanding long-term disposal system performance is not the only challenge facing the U.S. waste management program. Whatever the path forward for management of spent fuel and high-level waste in the U.S., implementation of a national system will require routine and reliable handling of those materials at unprecedented amounts and rates, substantially higher than those facing other countries.

In March 1993, a DOE Office of Civilian Radioactive Waste Management task force issued *A Proposed Alternative Strategy for the DOE Civilian Radioactive Waste Management Program*. The report's recommendations included early development of an offsite waste packaging R&D facility to resolve issues concerning package fabrication, closure, and handling, and produce confirmatory data for the repository licensing proceeding. The report further concluded that such a facility could also serve as a center for an ongoing R&D program during the operational life of the repository to improve on the initial waste package design or to develop special packages (if needed) for the many different types of spent fuel from defense activities that might ultimately require direct disposal.

DOE-NE and the UFDC will consider the merits of deploying a similar R&D type facility as progress towards the development of a national disposal facility is made. Such a facility could be used to evaluate the design concepts for packaging, handling, and emplacement of high level radioactive waste and spent nuclear fuel at design rates, and to establish operating capability without exposing workers to excessive radiation. Generically applicable tests regarding packaging, handling, and emplacement technology for high level radioactive waste forms and spent nuclear could be performed.

This facility could be coupled with other R&D facilities that may be developed by DOE-NE for developing technologies for other aspects of used fuel disposition (such as very long term storage and subsequent transportation) and advanced fuel cycles, or it could be coupled to an underground research laboratory (URL, discussed below).

4.2.4 Knowledge Management

The collection, categorization, and dissemination of information regarding disposal system performance is essential as the U.S. embarks on the investigation of a variety of potential geologic media and repository concepts for the disposal of SNF and HLW that could be generated under advanced fuel cycles. As pointed out by the Japan Atomic Energy Agency (Umeki et al., 2009):

> *The exponential growth in the knowledge base (and associated documentation) for radioactive waste management is increasingly seen as a cause for concern in most national programmes.*

This applies to the U.S. program in that both a range of geologic environments and also a range of potential future nuclear fuel cycles and associated waste streams are being investigated. The development of a comprehensive and user-friendly knowledge management system is needed to organize the large quantities of data and information expected to result from UFDC investigations.

The UFDC has developed an integration plan for UFDC data management (Wang, 2011). Execution of this plan will ensure that UFDC data will be managed effectively and coherently across all work packages, in a timely manner to support various UFDC programmatic decisions including an eventual license application of a disposal or storage facility. Execution will also ensure that all relevant legacy data will be appropriately captured and the data to be collected from the UFDC R&D activities will be traceable and recoverable for future uses. It is envisioned that a data management system to be developed under this plan will comprise two major databases and one document repository: the performance assessment database (PADB), the supporting technical database (TDB), and the project document repository (DOCR). The PADB contains input parameter data for PA calculations and the results of the calculations. The TDB stores all technical data, both primary and derived, that support PA parameter development. The primary technical data (PTD) are either experimental data or those obtained from experimental data with minimum model manipulations. The derived technical data are the outputs of interpretive modeling. For example, the solubility measurements of a radionuclide are primary technical data, which are then used to parameterize a chemical equilibrium model. The solubility calculated with the model as a function of solution chemistry is referred as derived technical data. Both primary and derived data will be used to support PA parameter data development. The DOCR archives UFD project documents or other references that are cited for data collection and synthesis.

The UFDC is also developing a Disposal Systems Evaluation Framework (DSEF), also discussed above, that is intended to be a flexible systematic analysis and knowledge-management framework for evaluation of disposal system options for a wide range of potential future nuclear fuel cycles and used fuel disposition alternatives. This knowledge-management framework will also serve as a valuable communication tool for the community of producers and users of knowledge. Part of the DSEF is a systematic catalog of thermal and transport properties taken from the literature, enabling the user to consider the effects of property uncertainties of repository thermal performance, cost, and total system performance.

The DSEF is being developed as a tool to formalize the development and documentation of repository conceptual design options for each waste form and environment combination, and to provide a high-level thermal analysis of disposal concepts. The DSEF will: (1) facilitate integration of UFDC process and system models and data, (2) enhance the UFDC interface with other OFCT elements, and (3) provide rapid response capability to address information requests from DOE or other organizations. The DSEF will establish a UFDC knowledge management system to organize high-level information, data, and assumptions, thereby facilitating consistency in high-level system simulation and economic analyses. The DSEF architecture is being developed as a tool with interfaces to various inputs to conduct concise comparisons between fuel cycles, disposal environments, repository designs, and engineered barrier system materials.

International programs are developing knowledge management systems for their programs. Collaboration with these organizations will be sought. As an example, JAEA is performing non-site specific R&D activities that will ultimately support a site-specific safety/licensing case and is developing a knowledge management system. This is similar to the current situation in the U.S. and their experience in developing their knowledge management system could be beneficial in the development of the DSEF.

4.2.5 Site Screening and Selection Tools

The U.S. will consider several alternative rock types to host future geologic repositories, and could site future repositories in more than one host medium. Such rock types occur across large regions of the U.S.; however, geologic media considered for site selection could be limited depending on future criteria and guidelines adapted for site screening and selection. Guidelines for siting a repository have been adapted by many countries over the years and include specification of a number of factors that could potentially adversely affect the long-term safety of a repository. Host media being considered for disposal of high-level radioactive waste by the UFCD have not been considered in the context of repository siting within the U.S. since passage of the Nuclear Waste Policy Amendments Act of 1987. Results of the crystalline and sedimentary rock programs conducted prior to 1987 were not preserved in modern geospatial databases. There is a need to develop a unified spatial database and visualization tool (i.e., a geographic information system) that will capture host rock potential and support site screening for different regions of the U.S. Potential availability will be tested for sensitivity to alternative future siting criteria that have been formalized in the U.S. and other countries. For example, several countries have in the past few years implemented exclusion criteria, such as the presence of mineral resources, tectonic hazards, and proximity to areas of high population density, as factors that limit site selection; the NWPA currently specifies such criteria if a crystalline rock is proposed for the second repository (NWPA §161). It is not clear how the availability of particular host media would be impacted in the U.S. if different (and currently uncertain) site screening and selection criteria were applied in the future.

Siting of a geologic repository (or a centralized storage facility) ultimately involves a geospatial decision: where will the facility be located. Geospatial analysis tools at the national and regional scales would allow exploration of the implication of various siting guidelines to understand where potential host media are present and how potential host rock distribution would spatially overlap with features and events specified in future siting criteria or guidelines. Some countries have used exclusion criteria to help determine when a potential site is clearly unsuitable for a geologic repository. Development of these tools should also provide a capability for initial and rapid site screening of any potential repository sites nominated by a future U.S. siting process, including possible volunteer sites.

Development of site screening and selection tools began in FY 2011. By the end of FY 2012, significant progress will be made in populating a GIS database with the geometry of salt, shale and crystalline rock formations in the conterminous United States. Several key siting factors have also been included in the database, including seismic hazard, topographic slope, the distribution of oil and gas production, and population distribution. Representative tests have been completed to determine how potential siting criteria would impact the availability of alternative host rocks in different regions of the U.S. Work will begin in FY13 to document the characteristics of deep basement rocks in the U.S. and to formally document the impacts of potential siting factors on host rock availability and site screening.

4.2.6 Experimental and Analytical Techniques for Site Characterization

Experimental and analytical techniques pertaining to site characterization have evolved and improved both in the U.S. and other nations as geologic repository programs have matured. However, future advances both in disposal science and other geotechnical fields may lead to improved site characterization techniques that could be applied to site characterization efforts. Further exploration, research, and development are needed to identify potential experimental and analytical techniques that may prove useful.

The U.S. has extensive history in characterizing the WIPP and Yucca Mountain sites. The U.S. developed site characterization plans for other media during the early stages of the NWPA repository siting effort. These previous site characterization plans, coupled with information from site selection and characterization efforts in other nations can provide insight into the type of information required and the techniques that could be applied. In addition, guidelines from the International Atomic Energy Agency may provide insight regarding techniques and criteria for consideration, especially given the uncertainty pertaining to U.S. guidelines. However, much of this information is dated, and more advanced techniques should be explored.

Research and development in other areas may have developed experimental and analytical site characterization techniques that could be applicable to future geologic repository characterization efforts. These include the oil and gas industry, mineral mining, geothermal energy exploration, and geologic carbon dioxide sequestration. Advances in these areas should be investigated and the potential for collaborative research and development should be explored. Both non-invasive and invasive techniques, as well as applicability of specific techniques to specific media, should be explored.

The use of cost effective and non-invasive geophysical techniques for determining the existence and characteristics of subsurface features will be needed at the site screening, site selection, and site characterization stages of repository implementation. Site screening and selection will entail comparison of alternative sites using available data and potential new data that can be obtained considering cost, potential site disturbance and possible regulatory policy. Geophysical methods have been used by many countries in the early stages of site screening and selection because they are relatively cost-effective, non-invasive, and can provide useful information on the subsurface characteristics of large areas.

Geophysical surveys, including gravity, magnetism and heat flow, can complement existing geologic data by providing information on regional structural features, potential host-rock continuity and homogeneity with depth, as well as detailed information about formation structure, faults and fluid migration paths. In particular, gravity and aeromagnetic surveys are appropriate to identify regional subsurface structures that may impact site-screening and selection decisions. These would include the presence volcanic intrusions, large-scale fault and fracture zones, and regional fluid saturation or anomalous mineralogy.

Existing non-invasive geophysical techniques are adequate for characterizing large-scale subsurface features and physical properties, but continued advances could help achieve high-resolution images of time-varying properties and structural changes that may be important during the site selection or characterization stages. Many of these “technology gaps” are the subject of ongoing R&D efforts, but in general this type of R&D is focused on other application areas, such as oil and gas exploration, carbon sequestration, nondestructive evaluation and medical diagnostics. For example, high-resolution seismic imaging of subsurface faults under development for oil and gas exploration purposes could advance to the point where sub-meter sized features can be more easily resolved and high-angle (near vertical) reflectors can be directly imaged. Similarly, advances in seismic imaging could allow the direct detection of fluids and their migration through fractures. Laboratory experiments and waveform modeling approaches could be pursued to develop and test new seismic methods for fluid monitoring. Additional research could also help better understand the effects of strong thermal gradients on the mechanical properties of materials used in the construction of the repository, and in the repository host rock. Strategies may be needed to integrate multiple geophysical techniques to optimize information gathering in alternative host-rock and geologic environments.

International collaboration could also prove beneficial in developing advanced site characterization experimental and analytical techniques. Several international programs are underway or are planned, such as DECOVALEX and the FORGE project, where U.S. involvement may prove beneficial. Advanced experimental and analytical techniques could also be explored and tested in underground research laboratories, such as the KAERI Underground Research Tunnel (KURT).

In Fiscal Year 2012, the UFDC started to systematically examine the existing geophysical, geochemical and hydrological techniques that can potentially be used for repository site characterization, especially for in-situ characterization in subsurface systems. On a field scale, the UFDC is examining geophysical techniques for fault/fracture identification and characterization in host rock. Geophysical techniques considered were elastic-wave reverse-time migration with wavefield separation, full-waveform inversion, seismic illumination analysis, stonely waves from vertical seismic profiling data, in-situ state of stress, effective stiffness tensor, and resistivity tomography. The pros and cons of using each method for site characterization were also assessed as well as discussion of how techniques could be integrated to augment each other.

New parameter estimation and uncertainty quantification methods have been explored for field well testing. On a borehole/drift scale, the UFDC is evaluating techniques for characterizing the development and evolution of excavation disturbed zones around boreholes or underground tunnels. Laboratory scale experiments have been developed to quantify radionuclide interaction and transport in representative geologic media. The UFDC is currently developing various column-scale experiment techniques, including those for compacted clay materials, which will allow the measurements of radionuclide sorption/desorption under relevant repository conditions. The laboratory-scale measurements will be further integrated with micro-structural analysis data to obtain mechanistic understanding of radionuclide interaction and transport in geologic media.

4.2.7 Underground Research Laboratories

Underground research laboratories (URLs) could be used to conduct experiments designed to address non-site specific issues. While it can be difficult to translate information gained in URL studies to other, specific sites, there are aspects that would make such URL investigations more generally beneficial. A URL could be used to:

- Supplement and focus a site characterization process
- Demonstrate a repository-like system
- Provide a means of identifying and resolving potential repository licensing issues
- Validate scientific models under actual conditions
- Provide analog information for specific sites having similar geology
- Refine design and engineering of repository components and systems
- Supplement siting data
- Evaluate design concepts for waste packaging, handling, and emplacement

In addition, if the U.S. foregoes repository siting for an extended period of time, studies in a domestic URL could help maintain repository development expertise. However, there may be reasons (e.g., cost) not to develop URLs in the U.S. unless they are in geologic media where one does not currently exist elsewhere. Domestic needs for fundamental R&D could potentially be met by gaining access to URLs in other countries working in relevant geologic media through collaborative studies and experiments.

A number of other countries have developed, or are developing URLs as important parts of their repository development process (see Table 9 below). In some, but not all, cases the URLs are at sites that are not expected to develop into repositories. The Department of Energy cooperated in some of these activities before work on crystalline rock was terminated following the 1987 amendments to the Nuclear Waste Policy Act. These activities could be restarted.

Experimental activities conducted in URLs (and operations-related surface facilities) could potentially help improve public confidence through demonstrating fundamental understanding of disposal and operational concepts.

The UFD is beginning to collaborate internationally to gain access to URLs and data obtained from URL investigations. As discussed above, the DOE became a partner on the Mont Terri Project, which utilizes an URL in in argillaceous claystone (Opalinus Clay). The DOE and UFDC are also actively participating on the Colloid Formation and Migration Project, which is one of several experimental R&D projects associated with the Grimsel Test Site in the Swiss Alps. Access to data obtained from URLs will also be available through DOE and UFDC involvement on the DECOVALEX project. The UFDC is also exploring collaborative research with the Republic of Korea that could include collaborative R&D projects in the KAIRI Underground Research Tunnel.

4.2.8 R&D Capabilities Evaluation

The U.S. national laboratories have tremendous capabilities, both experimental and computational, to conduct the R&D needed by the UFDC. However, there may be gaps in these capabilities. The UFDC will conduct a systematic evaluation of these capabilities to address the UFDC R&D needs as identified in this R&D roadmap. This assessment will help identify the resources best capable of performing UFDC R&D and any critical capability needs, supporting the prioritization and allocation of future R&D expenditures. Similar assessments of R&D capabilities across the national laboratory complex have been completed in other portions of the FCT program, in particular an evaluation of facility capabilities in support of addressing very long-term storage R&D needs. This assessment has yet to be completed.

4.2.9 Relationship Between the Engineered and Natural Systems

Important cross-cutting issues arise in understanding the relationships between the engineered and natural components of a repository. Nuclear Regulatory Commission regulations for repository development emphasize the relationships and interdependencies of the barriers and the underground facility. 10 CFR Part 60, the existing regulation governing spent nuclear fuel and high-level radioactive waste repositories other than Yucca Mountain, identifies numerous design criteria for the underground facility that illustrate these relationships. Underground facility means the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals. The underground facility must be designed with sufficient flexibility to allow adjustments where necessary to accommodate specific site conditions. Openings in the underground facility must be designed to reduce the potential for deleterious rock movement or fracturing of overlying or surrounding rock. The design of the underground facility must incorporate excavation methods that will limit the potential for creating a preferential pathway for groundwater to contact the waste packages or radionuclide migration to the accessible environment. The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. And perhaps most importantly, the engineered barriers must be designed to assist the geologic setting in meeting the performance objectives for the period following permanent closure. What these criteria have in common is that they all relate to postclosure performance, and thus are key to development of the total system performance assessment.

Table 9. Summary of National Waste Management Programs

Country	Material to be Disposed	Centralized Storage	Geologic Environments	URL	Site-Selection	Anticipated Start of Repository Operations
Finland	SNF		Granite, Gneiss, Granodiorite, Migmatite	ONKALO (Granite)	Site at Olkiluoto Selected	2020
Sweden	SNF	CLAB - Oskarshamn	Granite	Aspo (Granite)	Site at Osthammar Selected	2023
France	HLW and ILW		Argillite and Granite	Bure (Argillite)	Site near Bure Selected	2025
Belgium	HLW		Clay/Shale	Mol (clay)	Not Initiated	~2040
China	HLW		Granite		Preliminary Investigations Underway - Beishan in Gobi Desert	~2050
Switzerland	HLW	Wulenlingen (ZWILAG)	Clay and Granite	Mont Terri (Clay) Grimsel (Granite)	Initiated	No sooner than 2040
Japan	HLW		Granite and Sedimentary	Mizunami (Granite) Hornonobe (Sedimentary)	Initiated	No Decision Made
Canada	SNF		Granite and Sedimentary	Pinawa (Granite) - being decommissioned	Initiated	No Decision Made
United Kingdom	HLW and ILW		Undecided		Initiated	No Decision Made
Germany	HLW, SNF, heat generating ILW	Gorleben and Ahaus	Salt	Gorleben (Salt)	On Hold	No Decision Made
Republic of Korea	SNF	Envisioned	Granite	Korea Underground Research Tunnel (Granite, Shallow)	Not Initiated	No Decision Made
Spain	No Decision Made	Siting Process Initiated	Granite, Clay, Salt		Not Initiated	No Decision Made

Source: Nuclear Waste Technical Review Board, 2009. Survey of National Programs for Managing High-Level Radioactive Waste and Spent Nuclear Fuel

While 10 CFR Part 60 remains in force for repositories other than Yucca Mountain, it is likely that the NRC would promulgate a new rule for future repositories. That is because the subsystem performance objectives and specificity of the design criteria make the rule less than satisfactory in light of developments of total system performance assessment. An idea of how the NRC might approach a new repository regulation can be seen in the Yucca Mountain regulation, 10 CFR Part 63. There, the NRC required that the geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system, and that the engineered barrier system must be designed so that, working in combination with natural barriers, radiological exposures to the reasonably maximally exposed individual are within the specified exposure limits. Compliance must be demonstrated through a performance assessment, again linking the applicant's design to its interrelationships with the natural system. The applicant must also provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers. Degradation, deterioration, or alteration processes of engineered barriers must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, for 10,000 years after disposal, would be significantly changed by their omission. The only way this can be assessed is through a performance assessment that captures the relationships and interdependencies of the barriers and the underground facility. Practically, this means that a number of features, events and processes to be considered in the repository development cannot be considered as either simply related to the natural system or engineered system. The cross-cutting nature of these requires their combined consideration for both categories of barriers.

Because the geologic repository must use a multiple barrier system, consisting of both natural barriers and an engineered barrier system, opportunities exist to develop redundancies in the barriers relied on for performance. While it is likely that the regulations will require that the engineered barrier system be designed to work in combination with natural barriers to ensure radiological safety, care must be taken to not place so much reliance on one barrier that potential contributions to safety from other barriers are not realized in the safety assessment. In particular, it is possible to place high reliance on the engineered barriers and not perform the detailed research needed to exploit the credit that can be taken for the natural barriers. Research planning should ensure that the capabilities of the natural barrier system are utilized.

A good example of the interrelationship between the engineering and the natural barrier systems is the repository thermal loading limits. The repository thermal limits are of concern for thermal-mechanical effects on the host rocks and the engineered materials, because such effects will directly impact waste package design. Thermal expansion, tensile and compressive stresses, and altered properties of fractures, faults, and the rock matrix in a host rock are possible. There can also be thermal-chemical alteration of the host rocks and the other geologic units, including, mineral precipitation, dissolution, alteration of minerals with attendant volume changes, and altered properties of fractures, faults, the rock matrix, and the formation of near-field chemically altered zones (rind). Similar processes can also occur in engineered buffer/backfill materials. The UFDC is planning a set of experiments to study material properties beyond the currently assumed thermal limits, with an objective to raise or eliminate the existing thermal limits.

4.3 Assessment Basis

The ability to address issues associated with establishing a safety assessment, using generic R&D, is limited. However, R&D for all of the issues discussed in this roadmap must consider certain generic aspects including:

- Timescales of Concern: The overall timescales of concern are expected to be established by future policy and/or regulations. However, generic R&D could be used to address timescale issues, for example, generic R&D to identify the time at which some wastes become much less hazardous (e.g., Cs/Sr separated in an advanced cycle). Timescale considerations will be included in generic R&D as discussed in the following sections.

- Spatial Domain of Concern: This depends on specific site conditions and facility design. Generic R&D could be conducted to develop high-level relationships between possible repository geometries, thermal output, and expected waste volumes.
- Model and Data Issues: These are important to both specific R&D issues and to the overall integration and structure of the safety analysis. Generic R&D would apply primarily in the area of method development and the treatment of model and data issues. Most generic R&D will be captured in R&D to address specific issues discussed below. At a broader level, generic R&D could investigate uncertainty quantification and propagation within both detailed process-level and system-level models (both conceptual and mathematical model uncertainty) and the development of systematic methodologies and tools to support the evaluation of model adequacy, uncertainty propagation, data, etc.

4.4 External Factors

A variety of external factors can affect the safety case. These include repository related design/construction/operations issues, long-term geologic processes, seismic and igneous activity, climatic processes and effects, and future human activity. Discussion of these factors in this section is presented at a high level, informed by *UFDC Disposal R&D Roadmap Prioritization Information Matrix* (Appendix A).

R&D to address a few issues associated with external factors is beyond the scope of the UFDC generic R&D program. Examples of these types of issues include:

- Future human actions including human influence on the climate, deliberate/inadvertent human intrusion, and human-induced explosions/crashes
- Other external factors such as meteoric impact, extraterrestrial events, and earth planetary changes.

4.4.1 Repository Issues

Three external factors related to repository implementation cannot be addressed, even partially, through generic R&D. These are: open boreholes (site-specific), deviations from design/inadequate quality control (design- or operations-specific), and control of the repository site (policy/regulatory).

The remaining repository-related external factors pertain to chemical and mechanical effects resulting from preclosure operations of the disposal facility. These issues are design- or operations-specific, and to some extent site-specific. Specific R&D to address these issues cannot be undertaken until a site is identified and a design concept developed. Generic R&D could be conducted to evaluate what may be allowable with respect to preclosure construction and operations, because of impacts on the engineered and natural barriers, for the different types of geologic media under consideration (for example, construction techniques, emplaced materials, etc). For generic R&D the most important of these potential impacts are effects on the EDZ, and accordingly, preclosure operations effects will be considered in R&D pertaining to the EDZ (see Section 4.6.1).

4.4.2 Geological Processes

A range of long-term geologic processes (tectonic activity, subsidence, metamorphism, diagenesis, diapirism, and large-scale dissolution), seismic activity, and igneous activity are discussed in this section. Igneous activity cannot be addressed, even partially, through generic R&D that could be conducted by the UFDC, because it is completely site-specific.

4.4.2.1 Long-Term Geologic Processes

Long-term geologic processes can define the characteristics of a specific site and, although long term processes may have low likelihood, they can potentially affect the long-term performance of a disposal facility. These include large-scale tectonic activity, subsidence, metamorphism, diagenesis, diapirism, and large-scale dissolution.

<u>Ability to Address through Generic R&D</u>

Subsidence, metamorphism, and large-scale dissolution cannot be addressed, even partially, through generic R&D that would be conducted by the UFDC, because those issues are completely site-specific. The ability to address issues associated with large-scale tectonic activity, diagenesis, and diapirism through generic R&D is considered partial and site-specific. Generic R&D could focus on better understanding of the potential for these processes within potential sites and regions.

<u>Importance to Safety Case</u>

Large-scale tectonic processes are very slow. Diagenesis and diapirism are not expected to be "credible" processes or events that would be explicitly included in the safety analysis. Sites would be chosen to preclude such long-term processes and the associated FEPs would be screened out of the safety analysis. They also are not expected to affect design, construction, and operations. These processes are ascribed low importance for supporting overall confidence in the safety case, requiring only a demonstration that they would not occur and affect long-term performance.

<u>State of the Art</u>

These long-term geologic processes are well understood. Additional R&D would improve confidence in understanding these processes as they relate to potential sites, primarily supporting site screening and site selection activities.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:	The importance of Long-Term Geologic Processes is deemed to be **high** at the site screening decision point. These processes would have to be understood and quantified with respect to the specific locations under consideration to support site screening. The current information base is **sufficient** to support site screening because sufficient information exists in available materials to support conclusions about the general effects and nature of these processes on repository systems.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of Long-Term Geologic Processes is deemed to be **low** at the site selection decision point. It is expected that regions having a potential for these processes affecting the performance of repository systems will have been eliminated from consideration during the site screening process. The current information base is **sufficient** to support site selection because sufficient information exists in available materials to support conclusions about the general effects and nature of these processes on repository systems.
Site characterization and disposal system design [site characterization]:	The importance of Long-Term Geologic Processes is deemed to be **low** at the site characterization decision point. It is expected that regions having a potential for these processes affecting the performance of repository systems will have been eliminated from consideration during the site screening process. The current information base is **sufficient** to support site characterization because sufficient information exists in available materials to support conclusions about the general effects and nature of these

processes on repository systems.

Site suitability [licensing]:	The importance of Long-Term Geologic Processes is deemed to be **low** at the site suitability decision point. It is expected that regions having a potential for these processes affecting the performance of repository systems will have been eliminated from consideration during the site screening process. The current information base is **sufficient** to support site suitability because sufficient information exists in available materials to support conclusions about the general effects and nature of these processes on repository systems.

Overall Importance

Overall, the importance of conducting R&D on issues associated with Long Term Geologic Processes is projected to be **low** for all three repository media and borehole disposal.

4.4.2.2 Seismic Processes

Seismic processes includes seismic activity impacting both the EBS and the geosphere. Potentially significant impacts are mainly limited to mechanical damage to the EBS and altered flow paths and altered stress regimes in the geosphere.

Ability to Address through Generic R&D

The effects of seismic activity on the engineered and natural barriers, primarily the seismic response, would depend on the media, the specific site, and the design of the disposal facility. Limited generic R&D could focus on improved seismic ground motion response method development and improved understanding of impacts in generic media, both of which could be useful in site selection and site characterization. R&D on material response to mechanical impact as a result of seismic activity would be addressed in the R&D to address specific mechanical damage processes discussed below.

Importance to Safety Case

Seismic processes are credible processes or events that would be considered in the safety analysis. Sites could likely be chosen to preclude or limit deleterious effects of such processes. They could affect design, construction, and operations. These processes are ascribed medium importance for supporting overall confidence in the safety case. Medium for the EBS for the safety analysis and low for the geosphere for the safety analysis.

State of the Art

Seismic ground motion and response models exist and are well understood; they are site-specific rather than media-specific. Additional R&D would improve confidence in understanding these processes as they relate to potential sites, primarily supporting site screening and site selection activities.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	The importance of Seismic Processes is deemed to be **medium** for the geosphere and **N/A** for the EBS at the site screening decision point. These processes would have to be understood and quantified with respect to the specific locations under consideration to support site screening. The current information base is **sufficient** to support site screening because sufficient information exists in available materials to support conclusions about the

	general effects and nature of these processes on repository systems.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of Seismic Processes is deemed to be **medium** for the site selection decision point for the geosphere and **low** for the EBS. The current information base is **sufficient** to support site selection for the geosphere because sufficient information exists in available materials to support conclusions about the general effects and nature of these processes on repository systems. It is **insufficient** for the EBS because it depends on the design. Techniques exist for evaluating impacts on EBS components.
Site characterization and disposal system design [site characterization]:	The importance of Seismic Processes is deemed to be **medium** for the site characterization decision point. Site-specific seismic process data will be needed to develop the design and the response of the natural system. The current information base is **insufficient** to support site characterization because it is a site-specific need.
Site suitability [licensing]:	The importance of Seismic Processes is deemed to be **medium** for the site suitability decision point. Site-specific seismic process data will be needed to develop the design and the response of the natural system. The current information base is **insufficient** to support site characterization because it is a site-specific need.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with Seismic Activity is projected to be **medium** for all three repository media and borehole disposal.

4.4.3 Climate Processes and Effects

The local climate at a geologic disposal site can affect processes that influence long term performance. However, the local climate is affected by the regional and global climate and its evolution, both over the short and long terms. Specific processes and effects include:

- Variations in precipitation and temperature
- Seasonal events (i.e., flooding, storms, freeze/thaw, etc.)
- Permafrost
- Glaciation
- Isostatic depression and rebound
- Melt water

<u>Ability to Address through Generic R&D</u>

The ability to address climate change and effects through generic R&D is considered **partial** and site-specific. Specific parameters and processes needed to address climatic processes and effects would depend on the location and conditions of a specific site (i.e., arid/humid, north/south, topography, etc.). Global climate evolution is being investigated world-wide and is outside the scope of the UFDC R&D program. Generic R&D could focus on improved understanding of climate processes and effects as they pertain to the deep geologic environments under consideration by the UFDC.

<u>Importance to Safety Case</u>

The long term performance of a robust and well sited geologic disposal system is not expected to be affected by climate change. Climatic features, processes, and parameters could be of importance in site selection and effects would have to be represented in a safety analysis. The importance of climate processes and effects to the safety case was judged to be **low** for performance (safety analysis), not applicable for design, construction and operations, and **medium** for overall confidence. Overall, climate processes and effects are of **low** importance to the safety case.

State of the Art

Global climate change and associated effects are being investigated extensively throughout the world. Mature geologic repository safety assessments have considered climate evolution specific to the sites under investigation. Periglacial, glacial, and ice sheet effects are well known. Generic R&D could lead to an improved representation of climate processes and effects on geologic disposal systems.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	The importance of Climate Change and Effects is deemed to be **low** at the site screening decision point. The long term performance of a robust and well sited geologic disposal system is not expected to be significantly affected by climate change. Other site features will be more important in identifying potentially robust sites. The current information base is **sufficient** to support site screening because sufficient information exists in available materials to support conclusions about the general effects and nature of climate change and their effects on repository systems.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of Climate Change and Effects to the site selection decision point varies by site location and rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For the site selection decision point, focus will be on the geologic characteristics, so the specifics of Climate Change and Effects can be treated generically. The importance of Climate Change and Effects is deemed to be **low** at the site selection decision point. The long term performance of a robust and well sited geologic disposal system is not expected to be significantly affected by climate change. Other site features will be more important in selecting robust sites. The current information base is **partially sufficient** to support site screening because information beyond that available from general sources is needed.
Site characterization and disposal system design [site characterization]:	The importance of Climate Change and Effects to the site Selection decision point varies by site location and rock type. For the Site Characterization and Disposal System Design decision point, improved representation of the Climate Change and Effects, particularly in the area of reduced uncertainty associated with potential long-term impacts associated with climate change would need to be demonstrated. The importance of Climate Change and Effects is deemed to be **medium** for the at this decision point because potential impacts would have to be addressed during characterization. Site-specific information will be required to augment that available from more general sources and as such the available information is **partially sufficient**.

Site suitability [licensing]: The importance of Climate Change and Effects to the site suitability and licensing decision point varies by rock type. For the site suitability and licensing decision point, further improved representation of the Climate Change and Effects, particularly in the areas of reduced uncertainty associated with potential long-term impacts associated with climate change would need to be demonstrated.

The importance of Climate Change and Effects is deemed to be **medium** at this decision point because potential impacts would have to be addressed during characterization. Site-specific information will be required to augment that available from more general sources, so the available information is **partially sufficient**.

Overall Importance

Overall, the importance of conducting R&D on issues associated with Climatic Processes and Effects is projected to be **medium** for crystalline, and **low** for the other two repository media and borehole disposal.

4.5 Waste and Engineered Features Issues / R&D Opportunities

This section presents a summary of the information that informed the prioritization of R&D issues/opportunities associated with the waste and engineered features of a geologic disposal facility. Discussion in this section is presented at a high level, informed by the information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* (Appendix A).

4.5.1 Inventory

Information regarding waste inventory (waste form types, waste form radionuclide/non-radionuclide inventory, the number of waste packages of each type, or waste form volume such that the number of waste packages can be estimated) is a necessary input in the evaluation of geologic disposal concepts and systems. A variety of nuclear fuel cycle scenarios are under consideration by the DOE-NE FCT program that would generate different waste forms having different radionuclide inventories and different volumes. While R&D is not needed to develop or improve methods for estimating inventories, existing tools will be used to develop inventory estimates for the fuel cycle scenarios under consideration. This will require interfacing and integration with the FCT Separations/Waste Form and Systems Analysis campaigns and the FCT System Engineering effort.

Ability to Address through Generic R&D

Estimating radionuclide inventories for different fuel cycle scenarios can be done generically for the different fuel cycle scenarios under consideration by the FCT program. Some specific aspects related to inventory, including the heterogeneity of waste packages within a geologic disposal facility and the interaction between wastes of a different type, depend on the design of the disposal facility and the types and amounts of waste that would be disposed (which depends on fuel cycle scenario).

Importance to Safety Case

The importance of radionuclide inventory issues to the safety analysis is **high** because it defines a fundamental initial condition needed to assess the performance of the disposal system. The inventory also has a significant effect on the design of a facility, and its importance to design/operations/construction is **high**. Since the overall purpose of a geologic disposal facility is to isolate radionuclides from the environment, the overall importance to the safety case is **medium**. Overall, radionuclide inventory issues are of **high** importance to the safety case.

State of the Art

The radionuclide inventory has been estimated for a variety of fuel cycle scenarios both in the U.S. and in other countries. Much of the associated effort has been spent on estimating inventory for used LWR uranium-dioxide fuel and for HLW that would be created from one-pass PUREX reprocessing. Initial estimates have been made for some waste forms that would be generated in advanced nuclear fuel cycles (Carter and Luptak, 2010). However, additional effort is needed to estimate radionuclide inventories for other fuel cycle scenarios. The estimation of radionuclide inventory for advanced fuel cycles will be continual as the fuel cycle scenarios under consideration by the FCT program evolve and mature.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to potential SNF and HLW inventories for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items that are important to waste isolation (ITWI[5]) can be identified, existing information is expected to suffice. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of inventory-related issues to this stage of the decision process is **low** because the site selection process and ultimate decisions depend primarily on geologic attributes. Limited analyses would be required to evaluate key factors contributing to isolation, which would require estimates of the inventory of waste that would be disposed. However high-level representations and estimates would suffice. The current information is deemed **partially sufficient** to support this decision. No additional methods would need to be developed. Rather, inventory estimates would need to be developed for the fuel cycle scenarios that would be under consideration at this decision point.
Site characterization and disposal system design [site characterization]:	The importance of inventory-related issues to this process and decision point is **medium** because an understanding of the quantity of radionuclides and the different types of wastes that would be disposed is needed both for site characterization and facility design efforts. The current information is deemed **partially sufficient** to support this decision. Again, no additional methods would need to be developed. Rather, inventory estimates would need to be further developed and better represent the wastes that would be disposed of in the facility for the fuel cycle scenarios under consideration.
Site suitability [licensing]:	The importance of inventory-related issues to this process and decision point is **high** because having defensible estimates of inventory is required to finalize the facility design for the wastes that would be disposed and to provide input to other aspects of the safety analysis (e.g., thermal and source term models). Again, inventory estimates would need to be further developed to better represent the wastes that would be disposed of in the

[5] The term Important to Waste Isolation (ITWI) and Important to Safety (ITS) are specifically defined in current U.S. regulations at 10 CFR 60 and 10 CFR 63. The use of these terms in this report is intended to capture the sentiment of those definitions, does not imply a specific regulatory interpretation.

facility for the fuel cycle scenarios under consideration. The current information is therefore deemed **partially sufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with Inventory is projected to be **medium** to **high**.

4.5.2 Waste Form

The waste form is the most "interior" part of the engineered barrier system and is a fundamental part of a multiple barrier system for isolating radionuclides. Two campaigns within the Fuel Cycle Technology program are investigating waste form durability and behavior. The Separations / Waste Form campaign is responsible for conducting R&D related to waste forms that would be generated from separations/ recycling processes. A wide variety of waste forms are under investigation within that campaign. A research and development roadmap for these investigations has been developed and is being implemented (Peters et al. 2008). The UFDC is responsible for conducting R&D to enable the direct disposal of used nuclear fuel as a waste form in a geologic environment, should that alternative be chosen, and the disposal of any waste forms that would be developed under future advanced nuclear fuel cycles.

There are clear interfaces between UFDC and Separations/Waste Form campaign R&D activities due to the overall importance of the waste form. The conditions within the engineered system, both thermal and geochemical, affect the performance of the waste form. These conditions depend on the other engineered barriers that could be used in the design of a repository. The manner that the waste forms degrade, the rate, the degradation products that form, and the resultant geochemistry, affect the radionuclide source term and releases to the remainder of the engineered system. Additionally, waste form volumes will affect disposal design concepts. Thus, strong collaboration between the UFDC and Separations/Waste Form campaigns is essential.

Integration with the FCT System Engineering team and the DOE-NE Office for Nuclear Reactor Technologies is also required to identify the types of spent fuels that could be disposed of in a geologic repository and their characteristics/properties. Integration with the storage and transportation components of the UFDC is also required to understand the characteristics and properties of the SNF after storage and subsequent transport to a geologic disposal facility.

Ability to Address through Generic R&D

Issues associated with the SNF degradation can be addressed through generic R&D to develop data both for degradation rates and degradation products, and methods for representing SNF degradation. The data generated and methods developed by the UFDC could be applied to future site-specific evaluations.

Importance to Safety Case

The importance of SNF degradation, including cladding or any other outer protective barrier, to the safety analysis depends on both the geologic environment and the amount of "credit" that would be taken in the safety analysis for SNF degradation. The rate of SNF degradation has been shown to be a minor contributor to overall disposal system performance in some environments, and in some cases conservative/bounding approaches have been used. However, because the SNF itself (again including cladding or any other outer protective barrier) would be part of a multiple-barrier waste isolation system and would have to be represented in a safety analysis, its importance to the safety analysis is **high**. Similarly, its importance to the overall confidence in the safety case is **high**.

A disposal system that would dispose of SNF would be designed, constructed, and operated specifically for this purpose. As such, the characteristics/properties of the UNF and the ability to preserve, and not degrade these properties during operation of the facility are important. Accordingly, the importance of SNF to design/operations/and construction is **medium**.

The importance of HLW degradation to the safety case would be identical to SNF.

Overall, issues associated with waste form performance are of **high** importance to the safety case.

State of the Art

The behavior of uranium dioxide light water reactor fuel in oxidizing and reducing environments is well understood. However, there is less information available regarding mixed oxide fuels and essentially no information available regarding advanced reactor fuels. Thus, there are fundamental gaps in methods and fundamental data needs for evaluating the degradation of mixed oxide and advanced reactor fuels.

Accurate knowledge of radionuclide inventories at gap and grain boundaries of UNF is needed to estimate radionuclide release rates and to constrain associated uncertainties. Preferential radionuclide accumulation (fraction) and eventual releases from grain boundaries of UNF could render certain radionuclides readily available for dissolution during fuel degradation. The distribution of radionuclides in uranium dioxide light water reactor fuels (gap and grain-boundary regions) is well understood. Little is known regarding radionuclide heterogeneity in mixed oxide and advanced reactor fuels.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to SNF and HLW waste forms for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising Items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of SNF to this process and decision point is **low** because the site selection process and ultimate decisions depend primarily on geologic attributes. Limited analyses would be required to evaluate key contributors to isolation, which would include the SNF. However, high-level models of SNF degradation would be needed, which do not currently exist for mixed oxide and advanced reactor fuels. Thus, the current information is deemed **partially sufficient** to support this decision.
Site characterization and disposal system design [site characterization]:	The importance of SNF to this process and decision point is **medium** because understanding of SNF performance in the specific environment needs to be developed and demonstrated, and the geologic disposal facility design depends on the SNF being disposed. Existing U.S. regulations require characterization of waste form(s) as part of the site characterization phase of repository development. Improved representation of the SNF degradation processes would need to be demonstrated. Since models of SNF degradation do not currently exist for mixed oxide and advanced reactor fuels, the current information is deemed **insufficient** to support this decision.
Site suitability [licensing]:	The importance of SNF to this process and decision point is **high** because having defensible models to represent SNF degradation processes is required. Since models of SNF degradation do not currently exist for mixed oxide and advanced reactor fuels the current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the Waste Form is projected to be **high**.

4.5.3 Waste Container

The waste container, or waste package, can be one of the primary engineered barriers in the design of geologic disposal systems. The relative contribution of the waste container to overall waste isolation differs depending on the design of the facility and the geologic environment. Given the importance of the waste container, the degradation of potential waste container materials has been investigated extensively both by the U.S. and other nations. A variety of waste container design concepts and materials have been investigated and proposed for use in geologic disposal systems. To-date, metallic materials have received the most serious consideration. Other types of materials, such as ceramics or coatings, have received some limited attention.

Different degradation modes can affect waste container performance, depending on the materials selected and the geochemical environment. These include:

- General corrosion
- Localized corrosion (pitting and crevice corrosion)
- Stress corrosion cracking
- Microbially influenced corrosion
- Galvanic corrosion
- Hydrogen embrittlement
- Phase stability

An understanding of waste container behavior involves more than understanding degradation rates for the different modes. While such information allows for the determination of the conditions under which a waste package may fail (here defined as breach of containment integrity) and the ability to forecast when such failures may occur, information related to the size and distribution of penetrations is necessary to develop models of radionuclide transport within the engineered barrier system.

Ability to Address through Generic R&D

Issues associated with waste container behavior and performance can be partially addressed through generic R&D to develop data regarding both degradation rates and degradation products, and methods for representing material degradation. However, specific design concepts and site environments are ultimately needed to evaluate waste container performance within the context of a fully coupled engineered barrier system. The data generated and methods developed by the UFDC through generic R&D could be applied to future design- and site-specific evaluations.

Importance to Safety Case

The importance of the waste container to safety analysis depends on both the geologic environment and the design of the engineered barrier system. However, because the waste container may be used to meet two of the objectives presented above (containment and limited release) and because it would be part of a multiple-barrier waste isolation system and would have to be represented in a safety analysis, its importance to the safety analysis is **high**. Similarly, its importance to the overall confidence in the safety case is **high**.

The design of the waste package is an integral part of the overall design of a geologic disposal system and it will perform its functions during both the preclosure and postclosure time periods. Thus, its importance to design/operations/and construction is **medium**.

Overall, issues associated with waste container performance are of **high** importance to the safety case.

State of the Art

The performance of waste packaging material has been investigated extensively both by the U.S. and other countries. The level of knowledge varies by material type and disposal environments, with some materials well understood and others lacking understanding. For example, nickel-chrome and titanium alloys have been investigated under oxidizing environments at Yucca Mountain, and copper and steel materials have been investigated in the European and Japanese programs. Degradation mode surveys have also been developed (e.g. Farmer 1988a,b; Gdowski 1988a,b; and Bullen 1988) for candidate waste package materials for potential use in the oxidizing environment at the Yucca Mountain, Nevada site. These surveys included carbon steels, three austenitic alloys (304L, 316L and Alloy 825), three copper alloys (CDA 102, CDA 613 and CDA 715), Ni-Cr-Mo alloys, and titanium alloys used in the nuclear industry and marine environments. The work contains information on phase stability, repository environment effects, general corrosion, localized corrosion, stress corrosion cracking, hydride cracking, microbially-influenced corrosion, and internal corrosion of candidate waste container materials. The COBECOMA report (Kursten, et. al. 2004) summarizes various corrosion activities by European countries and provides corrosion rates for various metallic phases.

While there may be opportunity to further improve the knowledge base for the more "traditional" waste container materials, generic R&D could also be conducted on new and novel materials (e.g., high performance alloys, protective coatings, ceramics) that could further improve waste container performance.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	The importance of the waste container to this process and decision point is **low** because it is anticipated that sites having geochemical conditions that would result in low degradation rates, or limited allocation of performance to the waste package, would be preferred. However, there is little or no need to complete additional R&D pertaining to SNF and HLW waste containers for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information will suffice. The waste container is likely to be ITWI; generic metal container designs are available for different media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of the waste container to this process and decision point is **low** because the site selection process and ultimate decisions depend primarily on geologic attributes. Limited analyses would be required to evaluate key contributors to isolation, which would include the waste container. However, high-level models of waste container performance would be needed, which exist for many different materials. Thus, the current information is deemed **partially sufficient** to support this decision since information is available for the "traditional" waste container materials, but not for any new/novel materials.

Site characterization and disposal system design [site characterization]:	The importance of the waste container at this decision point is **high** because understanding of waste container performance in the specific environment needs to be developed and demonstrated and the waste container is an integral part of the design of a geologic disposal facility. Improved representation of the waste container degradation processes would need to be demonstrated for those materials selected for use. Since waste container designs and material selection, and the associated understanding of waste package performance in specific environments are not known, the current information is deemed **insufficient** to support this decision. This includes both "traditional" and new/novel waste container materials.
Site suitability [licensing]:	The importance of the waste container at this decision point is **high** because having defensible models to represent waste container degradation processes is required. The current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the Waste Package is projected to be **high**.

4.5.4 Buffer / Backfill

Most geologic disposal facility design concepts typically involve the use of backfill and/or buffer materials. Buffers are typically installed to completely encapsulate waste containers, to buffer the water chemistry and other conditions at the container surface. Buffers can serve to limit the rate of container degradation, and can also serve as both physical and chemical barriers to radionuclide transport, should the waste container fail. In some disposal concepts the buffer is an important engineered barrier, limiting release of radionuclides from the engineered barrier system. Bentonite and cementitious buffer materials have typically been considered in disposal facility designs in other countries.

Backfill can be used to fill the void space in emplacement boreholes (e.g., where no buffer is used) and emplacement tunnels. Depending on the design of the facility and the materials chosen, backfill can serve as a barrier to hydraulic flow and/or radionuclide transport, and physical ingress. While backfill can be important to performance, it is not typically as heavily relied upon as buffers. Typically the backfill contains crushed host rock that would be mined during excavation of the subsurface disposal facility.

There has been limited investigation into adding specific materials to buffers and backfills to reduce the mobility of key radionuclides during transport within the engineered barrier system. These materials are typically called "getters." Other additives and materials can be added to tailor or improve the performance of the buffer/and backfill with respect to other properties (i.e., redox chemistry), hydraulic flow, and there is little information available regarding such materials in long-term geologic disposal environments.

Ability to Address through Generic R&D

Issues associated with buffer/backfill behavior and performance can be addressed through generic R&D to develop data regarding both material properties (chemical, thermal, mechanical, and hydrologic) and to improve the understanding of how the materials may degrade under conditions relevant to disposal system environments. However, specific design concepts and site environments are ultimately needed to evaluate performance within the context of a fully coupled engineered barrier system. The data generated and methods developed by the UFDC through generic R&D could be applied to future design- and site-specific evaluations.

Importance to Safety Case

The importance of the buffer/backfill to the safety analysis depends on the geologic environment, the design of the engineered barrier system (inclusion of buffer/backfill), and the performance function that would be assigned to it (buffer vs. backfill). However, because the buffer/backfill may be used to meet two of the objectives presented above (containment and limited release) and because it could be part of a multiple-barrier waste isolation system and would have to be represented in a safety analysis, its importance to the safety analysis is **high**. Similarly, its importance to the overall confidence in the safety case is **high** as a potentially important isolation barrier.

For design concepts that include backfill/buffer, the type selected and the manner that it would be emplaced would have an impact on the design, construction, and operation of a disposal facility, so its importance to this factor is deemed to be **high**. The thermal properties of the buffer/backfill and any thermal limits on the materials could have a significant influence on design/construction/operations (i.e., size of canisters, spacing, etc).

Overall, issues associated with buffer/backfill performance are of **high** importance to the safety case for those design concepts and media that assign important performance attributes to the buffer/backfill and of **low** importance to the safety case for those design concepts and media that do not.

State of the Art

The performance of buffer materials has been investigated extensively in other countries. These efforts have focused primarily on bentonite, metallic, and cementitious materials. While much information is available regarding these materials, there are fundamental gaps in data relevant to these materials and fundamental needs in the representation of processes. Specific knowledge gaps include:

- Improved understanding of the long-term ”healing” properties of backfill/buffer materials
- Backfill/buffer stability:
  - The thermal behavior of smectites and clay dehydration:
    - Reversible collapse/expansion of the smectite layers due to loss/gain of interlayer water
    - Irreversible collapse of the smectite layers due to loss of interlayer water and migration of interlayer cations into the layers;
    - Inhomogeneous transformation of smectites into interstratified illites/smectites at elevated temperatures
    - Identification and characterization of new mineral phases (i.e., Fe-chlorite, Fe oxy-hydroxides, green rust) and their impact on backfill/buffer stability
    - Coupled THMC process modeling in clay:
      - Dual structure porous aggregate model
      - TOUGHREACT reactive transport coupling
      - Diffusive reactive transport aqueous species
      - Sorption modeling approaches and database development
      - Benchmarking efforts and international collaborations
  - Thermodynamic methods for description of stability and dehydration of clay and cementitious phases
  - Sulfate stability in the Ca-SO_4-H_2O system, potential redox buffering, and interaction with other phases
- Crushed salt backfill (Hansen and Leigh, 2011):
  - Self-healing properties

    - Consolidation/creep behavior and compaction of crushed salt at elevated temperatures
    - Coupled THMC process modeling issues at elevated pressures and temperatures:
        - Brine migration and wetting phenomena
        - Vapor phase and moisture transport
        - Buoyancy effects
        - Drift stability as a result of HLW heat generation
        - Radiolysis and gas generation
        - Radionuclide transport and solubility in concentrated brines
        - Benchmarking efforts and international collaborations
        - Brine interactions with cementitious materials

- Data to assess chemical and structural evolution in clay materials:
    - X-ray diffraction (XRD) measurements to investigate variations of the basal spacings as a function of vapor pressure for various smectites as well as other clay minerals
    - Degradation of clay minerals as a function of temperature and water/clay ratio
    - Rehydration hysteresis effects for clay phases of interest
    - Experiments at high pressures and temperatures to resolve inconsistencies between models and the scarcity of experimental data
    - Environmental scanning electron microscopy (SEM) observations of clay phases
    - Thermodynamic data retrieval for clay phases of interest to allow for modeling of clay/solution interactions

While there may be opportunity to further improve the knowledge base for the more "traditional" buffer/ backfill materials, generic R&D could also be conducted on new and novel materials used as buffer additives that could further improve barrier performance.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to buffer and backfill materials for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, it is expected that existing information would suffice. For certain media, buffer and backfill materials could be ITWI; generic design concepts are available for different media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of buffers/backfills to this process and decision point is **low** because the site selection process and ultimate decisions depend primarily on geologic attributes. Limited analyses would be required to evaluate key features contributing to isolation, which could include buffers/backfill. High-level models of performance would be needed, which exist for many different materials. Thus, the current information is deemed **sufficient** to support this decision for the "traditional" buffer/backfill materials, but **insufficient** for any new/novel materials that would be considered as part of the site selection process.

Site characterization and disposal system design [site characterization]:	The importance of the buffer/backfill at this decision point is **high**. An understanding of buffer/backfill performance in the specific environment needs to be developed and demonstrated, if the buffer/backfill is an integral part of the design of a geologic disposal facility. Improved representation of material degradation processes and radionuclide transport through the materials would need to be demonstrated for those materials selected for use. Since buffer/backfill designs and material selection, and the understanding of material performance in specific environment are not known, the current information is deemed **insufficient** to support this decision. This includes both "traditional" and new/novel buffer/backfill materials.
Site suitability [licensing]:	The importance of the buffer/backfill at this decision point is **high** because having defensible models to represent degradation and radionuclide transport processes is required. The current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the buffers/backfill is projected to be **medium** to **high**, depending on the buffer/backfill material and media.

4.5.5 Seals

Seals are an important part of the engineered barrier system, serving to isolate emplaced wastes, galleries, tunnels, and shafts/ramps. Seals are more important in saturated environments where they would serve to prevent or limit preferential pathways for water movement to and from the disposal facility. A range of seal materials can be used depending on the geologic environment and design of the disposal facility. This includes cementitious, clay, and bituminous materials. For cementitious phases, for example, this includes novel and/or supplementary cementitious materials that upon contact with groundwater could produce leachates that are less deleterious to the engineered backfill/buffer.

Ability to Address through Generic R&D

Issues associated with seal material behavior and performance can be addressed through generic R&D to develop data for material properties (chemical, thermal, mechanical, and hydrologic) and to understand how the materials may degrade under disposal system relevant environmental conditions. However, specific design concepts and site environments are ultimately needed to evaluate performance within the context of a fully coupled engineered barrier system. The data generated and methods developed by the UFDC through generic R&D could be applied to future design- and site-specific evaluations.

Importance to Safety Case

The importance of seals to the safety analysis depends on both the geologic environment and the design of the engineered barrier system, in that their degradation could provide preferential pathways for radionuclide release from the disposal facility. Seal degradation, depending on the materials selected, could influence the local geochemical environment. Thus, seals can be used to meet two of the objectives presented above (containment and limited release) and would be part of a multiple-barrier waste isolation system for which they would be represented in a safety analysis, so their importance to the safety analysis is **high**. Similarly, the importance of seals to the overall confidence in the safety case is **high**, because they would be a key isolation barrier for various geologic settings and disposal concepts.

Since the seals are a key part of the waste isolation system, their design and construction is important. However, the design/construction/operation of the overall facility does not depend on the seals themselves. As such, the importance of the seals to design/construction/and operation is deemed to be **medium**.

Overall, issues associated with buffer/backfill performance are of **high** importance to the safety case for those design concepts and media that assign important performance attributes to the seals and of **low** importance to the safety case for those design concepts and media that do not.

State of the Art

Repository R&D programs in the U.S. and other countries have conducted investigations on the stability and degradation of concretes and other sealing materials. As an example, the Waste Isolation Pilot Plant has a seal design for sealing mined openings in salt. The U.S. Salt Disposal Project (Deaf Smith) and Basalt Waste Isolation Project (Hanford) also both had seals programs. Mature seal design concepts have also been developed in granitic environments (Swedish and Finnish programs).

However, there some gaps in methods, and data needs for demonstrating and developing improved representations of seal behavior and performance. Several international programs are investigating the behavior and performance of seals in generic environments within underground research laboratories. Also, the European project on Engineering Studies and Demonstration of Repository Designs (ESDRED 2005) has focused their research on low-pH cementitious phases as sealing materials.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to seals and seal materials for the site screening process at this time, because until specific sites are identified and design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information will suffice (for certain media, seals and seal materials could be ITWI). Generic seals design concepts are available for different media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of seals to this process and decision point is **low** because the site selection process and ultimate decisions depend primarily on geologic attributes. Limited analyses would be required to evaluate key contributors to isolation, which could include seals. High-level models of performance would be needed, which exist for many different materials. Thus, the current information is deemed **sufficient** to support this decision.
Site characterization and disposal system design [site characterization]:	The importance of the seals at this decision point is **medium**. An understanding of seal performance in the specific environment needs to be developed and demonstrated. Sealing is an integral part of the design of a geologic disposal facility. Improved representation of any degradation processes and the potential for radionuclide transport through the seals would need to be demonstrated for those materials selected for use. Since seal designs and material selection, and an understanding of material performance in a range of particular environments are not known, the current information is deemed **insufficient** to support this decision.
Site suitability [licensing]:	The importance of the seals at this decision point is **high** because having defensible models to represent degradation and radionuclide transport processes is required. The current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the Seals is projected to be **medium**.

4.5.6 Other Engineered Barrier System Materials

A variety of additional features may be included as part of the engineered barrier system design. These include rock bolts, tunnel/gallery liners, and waste emplacement supports/structures. A variety of different materials can be used and would be introduced into the engineered barrier system. These features might be included to facilitate emplacement of the waste and to protect both the emplaced waste and workers during the operations phase. They are not typically assigned any credit for isolating the wastes, but their performance can affect the long-term behavior of other engineered barriers (physically and chemically) and they would be considered in a safety analysis.

Ability to Address through Generic R&D

Conducting specific R&D on other engineered barrier system materials would require selection of a site, development of the subsurface facility design, and selection of materials. Most of this information would not be known until much later in the disposal facility development process (i.e., at the conceptual design phase). Thus, it is anticipated that only limited generic R&D will be conducted, focusing primarily on the performance of materials, their interaction with generic disposal system environments, and any potentially deleterious effects that these other materials could have on the engineered barrier system environment (for example, certain materials could be limited or precluded from use in geologic settings). Experimental and analytical methods to evaluate the behavior of such materials could be developed and/or improved, focusing on the more "primary" engineered barriers.

Importance to Safety Case

The importance of other engineered materials to the safety analysis is deemed to be **medium**, at the greatest, due to the potential for affecting the performance of other engineered barriers (a secondary affect on isolation). The other engineered features would be an integral part of the design of a disposal facility and the importance of these materials to design/construction/operation is deemed to be **high**. The repository would need to remain open and operational during the operations phase and as such the importance to the overall confidence in the safety case is deemed to be **medium**.

Overall, issues associated with other engineered barrier system material performance are of **medium** importance to the safety case.

State of the Art

The behavior and performance of other engineered barrier system materials have been investigated in the U.S. and in other countries, both generically and for site-specific applications, for a variety of disposal system concepts. An improved understanding of the degradation of other engineered barrier system materials and assessment of the potential impacts on other system elements (e.g., chemical impacts) are needed. For example, additional information regarding degradation modes and impacts at the cement / rock and cement / metal barrier interfaces would improve understanding.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to other engineered materials for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information will suffice. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient

	information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	There is little or no need to complete additional R&D pertaining to other engineered materials for the site selection process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information will suffice. While limited analyses would be required to evaluate key contributors to isolation, it is not necessary to consider and represent such secondary features and processes when evaluating key contributors to isolation and early containment.
Site characterization and disposal system design [site characterization]:	The importance of the other engineered barrier materials at this decision point is **medium**. An understanding of material performance in the specific environment needs to be developed and demonstrated and these features are an integral part of the design of a geologic disposal facility. Improved representation of any degradation processes and the potential for radionuclide transport through the other engineered barrier system materials would need to be demonstrated for those materials selected for use. Since the designs of the other engineered barrier system features, the selection of materials, and the understanding of material performance in specific environments are not known, the current information is deemed **insufficient** to support this decision.
Site suitability [licensing]:	The importance of the other engineered barrier system materials at this decision point is **high** because having defensible models to represent their degradation, impacts on other processes within the engineered barrier system, and impacts on radionuclide transport is required. The current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the Other Engineered Barrier Materials is projected to be **medium**.

4.5.7 Mechanical Processes

Mechanical processes can affect the long-term performance of all of the features of the engineered barrier system. These processes and their impacts are strongly dependent on the design of the disposal facility and the site-specific environment. Mechanical processes include seismic effects on the engineered components of the repository. Mechanical processes are also coupled with thermal, hydrologic, and chemical processes and the potential impacts from such coupling on system performance would be assessed.

Ability to Address through Generic R&D

Specific R&D would require development of subsurface design, selection of materials, and operational techniques that are compatible with the selected site/media. Limited generic R&D could be conducted on the mechanical behavior /performance of materials and the potential impacts of mechanical processes on these materials independent of design and site/media. Generic R&D could also be conducted to improve coupled thermal-mechanical modeling tools.

Importance to Safety Case

The importance of engineered barrier system mechanical processes to the safety analysis is deemed to be **medium**. In that they could directly affect the isolation capabilities of the engineered barriers.

Based on previous experiences in geologic repository design and analysis, mechanical processes are of **high** importance to design/construction/operation as they could affect the design of the engineered barrier system (e.g., rock support), how the facility would be constructed (e.g., excavation method), and how it would be operated (e.g., waste emplacement strategies, thermal limits, ventilation).

Understanding and being able to represent mechanical processes that could affect the features of the engineered barrier system through both the preclosure and postclosure periods is deemed to be of **high** importance to overall confidence in the safety case. Issues and questions raised on other geologic repository programs indicate a higher level of importance. As an example, this issue can impact the preclosure "important-to-safety" classification of ground support systems, waste package transporters, ventilation systems etc.

However, the importance of mechanical processes on the different barriers differs, primarily due to the different contributions to system performance. In addition, the importance of some of the features of the engineered barrier system may be low, or not applicable, depending on the site/media and design of the facility. As an example, mechanical processes that affect backfill/buffers would not be at all important for design concepts that do not include them.

Overall, issues associated with engineered system mechanical processes are of **medium** importance to the safety case.

State of the Art

Mechanical effects in emplacement tunnels, rooms, etc. and on engineered barrier system components have been extensively investigated in other geologic disposal programs. Much of this has focused on coupled thermal-mechanical processes/effects, investigating the mechanical behavior of the surrounding host media and their potential for mechanical interactions with the engineered barriers. Additional information needs and potential knowledge gaps include:

- Understanding of the mechanical properties of candidate engineered barrier system materials, both "traditional" materials to fill knowledge gaps and for new/novel materials, and effects on corrosion and other degradation properties.
- Improved understanding and representation of coupled thermal-hydrologic-mechanical processes to evaluate the potential to enhance the excavated damage zone influencing the hydraulic properties of the EBS backfill/buffer materials.
- Improved understanding of the mechanical effects potentially associated with waste form, waste package, and backfill degradation (volume change impacts).

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to mechanical processes for the site screening process at this time, because until specific sites are identified and design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. The effects of mechanical processes, particularly thermal loading or seismicity could result in the use of components that are ITWI; generic analyses of such effects are available for different designs and media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site

	screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of engineered barrier system mechanical processes to this decision point is **low** because the site selection process and ultimate decisions depend primarily on geologic attributes. Limited analyses would be required to evaluate key contributors to isolation, which could include mechanical damage to engineered barrier system features. However high-level models of performance would be needed, which exist for many different materials. Thus, the current information is deemed **sufficient** to support this decision.
Site characterization and disposal system design [site characterization]:	The importance of engineered barrier system mechanical processes at this decision point is **medium** to **high,** depending on the engineered barrier. An understanding of engineered barrier system mechanical processes in the specific disposal environment needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility. Improved representation of any mechanical degradation processes and their subsequent impact on other processes in the engineered barrier system would need to be demonstrated for those materials selected for use. Since engineered barrier system design/material selection and understanding of material performance in specific environments are not known, the current information is deemed **insufficient** to support this decision.
Site suitability [licensing]:	The importance of engineered barrier system mechanical processes at this decision point is **high** because having defensible models to represent degradation processes is required. The current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with engineered barrier system mechanical processes is projected to be **medium** to **high** when considering effects on the waste container, **medium** to **high** when considering effects on the buffer/backfill, **medium** to **high** when considering effects on the seals and liners, and **medium** when considering effects on other engineered barrier system components.

4.5.8 Hydrologic Processes

Understanding hydrologic processes within the engineered barrier system is necessary to quantify the amount of water that may be available to contact the waste forms, and to develop models for representing radionuclide transport through the engineered barriers. These processes involve the flow of water through the different engineered barriers, which depends on the design of the subsurface disposal facility and the hydrologic properties of the geologic environment.

Ability to Address through Generic R&D

Specific R&D to address hydrologic processes within the engineered barrier system would require development of the subsurface design and selection of materials that would be used. Generic R&D could be conducted on the hydrologic properties of engineered barrier system materials, both in their intact or as-built condition as well as in potentially degraded states (e.g., hydrologic properties of waste package corrosion products). These materials could be both "traditional" and new/novel materials identified by the UFD campaign as having potential to improve waste isolation capabilities. Hydrologic flow within the engineered barrier system, and between the engineered barrier system and the host rock, can be addressed by generic R&D for different configurations.

Importance to Safety Case

The importance of engineered barrier system hydrologic processes to the safety analysis is deemed to be **high** for the ”primary” waste isolation barriers, the waste package and buffer, and **low** for the other features of the engineered barrier system. While it is necessary to understand hydrologic processes for all features of the engineered barrier system, the “primary” barriers are likely to be most important to waste isolation and the safety analysis.

The importance of hydrologic processes is deemed to be of **medium to high** importance to design/construction/operation for the features of the engineered barrier system. Hydrologic properties of engineered barrier materials could influence material selection, and system design, construction, and operation. Understanding and being able to represent hydrologic processes within the engineered barrier system are key aspects of the safety case and are thus deemed to be of **medium** importance to the overall confidence in the safety case.

The importance of some of the features of the engineered barrier system may be low, or not applicable, depending on the site/media and design of the facility. As an example, hydrologic processes that affect backfill/buffers would not be at all important for design concepts that do not include them.

Overall, issues associated with engineered system hydrologic processes are of **medium** importance to the safety case.

State of the Art

Hydrologic processes in the engineered barrier system have been considered in all geologic repository development programs as it is necessary to represent them in safety analyses. The treatment, and R&D to address hydrologic issues, has varied for the different engineered barriers. As an example, considerable effort has been undertaken in other countries to understand hydrologic properties in bentonite buffers, while little has been done to understand the properties of breached waste packages (they are conservatively assumed to provide no contribution to isolation once breached). The U.S. program considered and evaluated hydrologic properties and processes as they affected each of the engineered barriers included in the design of the Yucca Mountain repository. Limited investigations have been performed considering broad hydrologic effects in the engineered barrier system (e.g., the hydraulic cage concept considered in Japan and Sweden). Capillary pressure theory warrants improvement, especially in conditions where dry-out of backfill/buffer materials would be allowed.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to hydrologic processes in the engineered barrier system for the site screening process at this time, because until specific sites are identified and design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. For certain designs and media, hydrologic processes in the engineered barrier system could be ITWI, but generic concepts are understood for different media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information currently exists for available materials to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:	There is little or no need to complete additional R&D pertaining to other engineered barrier system hydrologic processes for the site selection process at this time, because until design concepts are developed to the point where the engineered components comprising items ITWI can be identified, existing information will suffice. While limited analyses would be required to evaluate key contributors to isolation, it is not expected to require explicit representation of hydrologic processes within the engineered barrier system features. High-level models of performance would be needed and could be developed using existing information.
Site characterization and disposal system design [site characterization]:	The importance of engineered barrier system hydrologic processes at this decision point is **medium**. An understanding of engineered barrier system hydrologic processes in the specific environment needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility. Improved representation of any hydrologic degradation processes in the engineered barrier system would need to be demonstrated for those materials selected for use. Since engineered barrier system design/material selection and an understanding of hydrologic performance in specific environments are not known, the current information is deemed **insufficient** to support this decision.
Site suitability [licensing]:	The importance of engineered barrier system hydrologic processes at this decision point is **high** because having defensible models to represent processes is required. The current information is deemed **insufficient** to support this decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with engineered barrier system hydrologic processes is projected to be **low** to **medium** when considering effects on the waste container, **medium** when considering effects on the buffer/backfill, **medium** when considering effects on the seals, and **medium** when considering effects on other engineered barrier system components.

4.5.9 Engineered Barrier System Chemical Environment and Processes

The geochemical environment within the engineered barrier system affects barrier degradation rates, waste form degradation rates, and radionuclide transport characteristics. Understanding of the geochemical evolution in the engineered barrier systems, which is strongly coupled to the thermal and hydrologic processes, is necessary to be able to understand how the engineered barrier system will evolve and contribute to isolating the emplaced waste and limiting radionuclide transport.

<u>Ability to Address through Generic R&D</u>

Specific R&D to address processes within the engineered barrier system that affect the chemical environment would require the identification of a specific site, development of the subsurface design, and selection of materials that would be used. However, generic R&D could be conducted on the chemical evolution of engineered barrier system materials, focusing on methods to quantify and represent the chemical evolution and on obtaining material-specific parameters where it can be shown that they would be independent of a specific site and facility design. The R&D could consider the chemical properties of engineered barrier system materials, both in their intact or as-built condition as well as in potentially degraded states (e.g., chemical properties of waste package corrosion products). These materials could be "traditional" or new/novel materials identified by the UFD campaign as having potential to improve waste isolation. Chemical coupling between different engineered barrier configurations could also be explored.

Importance to Safety Case

The importance of engineered barrier system chemical processes to the safety analysis is deemed to be **high** due to their affect on the performance of engineered barrier system materials with respect to the waste isolation and limiting radionuclide release objectives.

The importance of engineered barrier system chemical processes is deemed to be of **medium** to **high** importance to design/construction/operation for most of the features of the engineered barrier system, as their chemical properties could influence material selection, design of the engineered barrier system, and how it is constructed and operated.

Understanding and being able to represent engineered barrier system chemical processes within the engineered barrier system are key aspects of the safety case and are thus deemed to be of **medium** to **high** importance to the overall confidence in the safety case.

The importance of some of the features of the engineered barrier system may be low, or not applicable, depending on the site/media and design of the facility. As an example, chemical processes that affect backfill/buffers would not be at all important for design concepts that do not include them.

Overall, issues associated with engineered system chemical processes are of **high** importance to the safety case.

State of the Art

Chemical processes in the engineered barrier system have been considered in all geologic repository development programs, in particular to represent the effects on the engineered barriers, in safety analyses. The treatment, and R&D to address chemical issues, has varied for the different engineered barrier system materials. As an example, considerable effort has been undertaken in other countries to understand chemical properties in bentonite buffers, while less work has been performed to understand the evolution of cementitious materials in deep geologic environments. Methods for quantifying chemical processes and forecasting the evolution of the chemical environment in the engineered barrier system exist and have been applied, but can be improved.

No information is available regarding chemical processes and properties of advanced fuels that could be directly disposed and advanced waste forms. Strong interfaces with the FCT program Fuels and Separations/Waste Form Campaigns are needed to quantify properties and understand chemical processes for such materials that the FCT program would consider for ultimate disposal.

Considerable work has been done in the U.S. and in other countries regarding radionuclide speciation and dissolved concentration limits. Improved understanding of solubility controls and dissolved concentration limits would lead to improved radionuclide transport models and better understanding of disposal system performance. There are large knowledge gaps on radionuclide solubilities at elevated temperatures and in concentrated electrolyte solutions. Accurate redox speciation chemistry of important radionuclides such as Pu and Np are still worthy of investigation.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	Except for radionuclide speciation and solubility, there is little or no need to complete additional R&D pertaining to chemical environments and processes in the engineered barrier system for the site screening process at this time, because until specific sites are identified and design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. For certain designs and media, chemical environments and processes in the engineered barrier system could be ITWI, but generic concepts are understood for different media and are well enough

	developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening. Radionuclide speciation and solubility is deemed to be of **medium** importance for the site screening decision point as sites with geochemical conditions that favor low solubility limits for key radionuclides would be preferred. Currently available information is deemed **sufficient**.
Site selection [environment feasibility, concept feasibility, site designation]:	Except for radionuclide speciation and solubility, there is little or no need to complete additional R&D pertaining to other engineered barrier system chemical processes for the site selection process at this time, because until design concepts are developed to the point where the engineered components comprising items ITWI can be identified, existing information will suffice. While limited analyses would be required to evaluate key contributors to isolation, it is not expected to require explicit representation of chemical processes within the engineered barrier system features. High-level models of performance would be needed and could be developed using existing information. Radionuclide speciation and solubility is deemed to be of **medium** importance at the site selection decision point, as sites with geochemical conditions that favor low solubility limits for key radionuclides would be preferred. Current information is deemed **partially sufficient**.
Site characterization and disposal system design [site characterization]:	The importance of engineered barrier system chemical processes at this decision point is **medium**. An understanding of engineered barrier system chemical processes in the specific environment needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility. Improved representation of any chemical processes and the evolution of the chemical environment in the engineered barrier system would need to be demonstrated for those materials selected for use. Since engineered barrier system design/material selection and an understanding of chemical performance in specific environments are not known, the current information is deemed **insufficient** to support this decision.
Site suitability [licensing]:	The importance of engineered barrier system chemical processes at this decision point is **high** because having defensible models to represent processes is required. The current information is deemed **insufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the Engineered Barrier System Chemical Environment and Processes is projected to be **medium** to **high** when considering effects on the waste container, **medium** to **high** when considering effects on the buffer/backfill, **medium** to **high** when considering effects on the seals, and **medium** to **high** when considering effects on other engineered barrier system components.

4.5.10 Engineered Barrier System Radionuclide Transport

The transport of radionuclides through and out of the engineered barrier system is strongly coupled to the properties of the engineered barrier system materials, the manner in which they degrade (and their degraded properties) and the thermal, mechanical, hydrologic, and chemical conditions within the engineered barrier system.

Ability to Address through Generic R&D

Specific R&D to address processes associated with engineered barrier system radionuclide transport would require the identification of a specific site, development of the subsurface design, and selection of materials. However, generic R&D could be conducted on these processes, investigating transport processes in materials for individual barriers and components of the engineered barrier system. The focus would be on the development of improved methods to represent transport processes and the identification of controlling processes in the materials under consideration. Radionuclide transport specific parameters for engineered barrier system materials could be determined from generic R&D if it can be shown that they are independent from site-specific or design-specific considerations.

Importance to Safety Case

The importance of engineered barrier system transport processes to the safety analysis is **high** when considering dissolved radionuclides, as they are directly related to the objective of limiting radionuclide release and determine the rate that radionuclides are released into the natural system. The importance of engineered barrier system transport processes to the safety analysis is **low** when considering colloid-facilitated transport, as has been shown by safety analyses conducted by several geologic repository development programs.

The importance of mechanical processes is of **medium** importance to design/construction/operation for most of the features of the engineered barrier system as their radionuclide transport properties could influence material selection, the design of the engineered barrier system, and how it is constructed and operated.

Understanding and being able to represent radionuclide transport processes within the engineered barrier system are key aspects of the safety case and are thus deemed to be of **medium** importance to overall confidence in the safety case when considering dissolved radionuclides, and of **low** importance when considering colloid-facilitated transport of radionuclides.

The importance of some of the features of the engineered barrier system may be low, or not applicable, depending on the site/media and design of the facility. As an example, radionuclide transport processes within backfill/buffers would not be at all important for design concepts that do not include them.

Overall, issues associated with engineered system radionuclide transport processes are of **medium** importance to the safety case.

State of the Art

Radionuclide transport through and out of the engineered barrier system has been considered in all geologic repository development programs. The treatment, and R&D to address engineered barrier system radionuclide transport issues, has varied for the different disposal concepts and engineered barrier system materials. As an example, considerable effort has been undertaken in other countries to understand radionuclide transport properties in bentonite buffers, while less work has been performed to understand the effects of cementitious materials in deep geologic environments. Methods for representing radionuclide transport in the engineered barrier system exist and have been applied, but can be improved leading to a better understanding of disposal system performance.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to radionuclide transport processes in the engineered barrier system for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to

Waste Isolation (ITWI) can be identified, existing information is expected to suffice. For certain designs and media, radionuclide transport processes in the engineered barrier system could be ITWI, but generic concepts are understood for different designs and media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:	The importance of engineered barrier system radionuclide transport processes at this decision point is **medium** for the transport of dissolved radionuclides and **low** for colloid-facility transport processes. Limited analyses would be required to evaluate key contributors to isolation. High-level models to represent radionuclide transport would be needed and already exist. Information is available to represent radionuclide transport processes, but would have to be applied to specific environments, media, and design concepts. R&D would lead to improved methods and approaches. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.
Site characterization and disposal system design [site characterization]:	The importance of engineered barrier system radionuclide transport processes at this decision point is **high** for the transport of dissolved radionuclides and **medium** for colloid-facilitated transport processes. An understanding of engineered barrier system radionuclide transport processes in the specific environment needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility. Improved representation of any radionuclide transport processes in the engineered barrier system would need to be demonstrated for those materials selected for use. Information is available to represent radionuclide transport processes, but would have to be applied to specific environments, media, and design concepts. R&D would lead to improved methods and approaches. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.
Site suitability [licensing]:	The importance of engineered barrier system radionuclide transport processes at this decision point is **high** for the transport of dissolved radionuclides and **medium** for colloid-facilitated transport processes. Defensible models to represent radionuclide transport processes are required. Information is available to represent radionuclide transport processes, but would have to be applied to specific environments, media, and design concepts. R&D would lead to improved methods and approaches. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with the engineered barrier system radionuclide transport processes is projected to be **medium** when considering effects on the waste container, **medium** to **high** when considering effects on the buffer/backfill, **low** to **medium** when considering effects on the seals, and **low** to **medium** when considering effects on other engineered barrier system components.

4.5.11 Biological Processes

Microbial activity in the engineered barrier system, either natural or anthropogenic, can have an effect on engineered barrier system materials and components. These processes are dependent on the engineered barrier system design concept (disposal facility geometry and materials) and the specific site and geologic medium. Generic R&D would investigate these issues for individual barrier materials as part of material degradation and radionuclide transport R&D. The effect of biological processes should be included with R&D on engineered barrier system degradation and radionuclide transport processes/issues discussed above.

4.5.12 Thermal Processes

Thermal processes in the engineered barrier system affect both the engineered and natural components of the disposal system. Within the engineered barrier system, thermally driven coupled processes can affect the degradation of engineered barriers and their associated properties, the rates that radionuclides are released from the waste forms, and radionuclide transport characteristics.

<u>Ability to Address through Generic R&D</u>

Specific R&D to address thermal processes in the engineered barrier system would require the identification of a specific site, development of the subsurface design, and the selection of materials that would be used. However, generic R&D could be conducted to investigate improved methods for simulating thermally driven processes in different geologic settings and for different design concepts. Simple modeling approaches and methods to investigate the thermal performance of various design concepts (e.g., different buffer/backfill concepts and materials) and to support system-level analyses could also be developed.

Generic R&D could be performed to investigate the thermal properties and behavior of engineered barrier system materials (Sections 4.5.2 through 4.5.6), and modeling of thermally driven processes in these materials (Section 4.5.7). Generic R&D on hydrologic (Section 4.5.8), chemical (Section 4.5.9), and radionuclide transport (Section 4.5.10) processes in the engineered barrier system could also consider thermal processes and coupling.

<u>Importance to Safety Case</u>

The importance of thermal processes in engineered barrier system to the safety analysis is **high** due to the strong thermal-hydrologic-chemical (and perhaps mechanical) coupling.

The importance of thermal processes is of **high** importance to the design/construction/operation of the engineered barrier system because thermal properties and response could influence material selection, the design of the engineered barrier system, and how it is constructed and operated.

Understanding of thermally driven coupled processes within the engineered barrier system is needed to support the overall approach to modeling system performance and is thus deemed to be of **high** importance to the overall confidence in the safety case.

Overall, issues associated with engineered system thermal processes are of **high** importance to the safety case.

<u>State of the Art</u>

Thermal processes (coupled thermal-hydrologic-chemical-mechanical) have been investigated extensively in the U.S. and in other countries. Thermal management criteria have been strongly tied to different engineered barrier system concepts and material performance (e.g., bentonite buffers). While coupled process modeling methods and tools exist, improvements can be made, leading to better understanding of disposal system performance. There is little or no information available regarding the thermal properties and performance of new/novel engineered barrier system materials.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to thermal processes and their effects on the engineered barrier system for the site screening process at this time, because until specific sites are identified and design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. The effects of thermal loading and thermal processes could result in the use of components that are ITWI, but generic analyses of such effects are available for different designs and media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of engineered barrier system radionuclide thermal processes at this decision point is **low**. Limited analyses would be required to evaluate key contributors to isolation and high-level models to represent thermal processes, and the tools to do so exist. For example, high-level representation for evaluating performance and the determining potential "footprint" of a disposal facility would be needed. Information is available to represent thermal processes, but would have to be applied to specific environments/media/designs. R&D would lead to improved methods and approaches. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.
Site characterization and disposal system design [site characterization]:	The importance of engineered barrier system thermal processes at this decision point is **high**. An understanding of engineered barrier system thermal processes in the specific environment needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility. This would directly affect the design of the engineered barrier system and initial assessments of disposal system performance (safety analysis). Information is available to represent these processes, but would have to be applied to specific environments, media, and design concepts. R&D would lead to improved methods and approaches. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.
Site suitability [licensing]:	The importance of engineered barrier system thermal processes at this decision point is **high**. Defensible models to represent coupled thermal-hydrologic-chemical processes are required. Information is available to represent these processes, but would have to be applied to specific environments/media/designs. R&D would lead to improved methods and approaches. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the Engineered Barrier System Thermal Processes is projected to be **medium** when considering effects on the waste container, buffer/backfill, seals, and other engineered barrier system components.

4.5.13 Gas Sources and Effects

Gas sources within the engineered barrier system could potentially affect the performance of the engineered barriers (pressurization and mechanical damage), the flow of water, and the transport of radionuclides within and from the engineered barriers. Potential sources of gas include He generation in the waste forms from alpha-decay, H_2 generation from material corrosion, and CO_2, CH_4, and H_2S from microbial processes.

Ability to Address through Generic R&D

Specific R&D to address processes associated with gases would require the identification of a specific site, development of the subsurface design, and the selection of materials that would be used. However, generic R&D could be conducted to assess the potential for gas generation for different engineered barrier system materials (including emplaced wastes) and design concepts.

Importance to Safety Case

The importance of gases in the engineered barrier system to the safety analysis is **high** because gas transport could potentially be important in controlling the engineered barrier system chemical environment in backfilled repository design concepts.

The importance of gases is of **low** importance to the design/construction/operation of the engineered barrier system because it is not expected that issues associated with gases would significantly influence material selection, the design of the engineered barrier system, or how it is constructed and operated (except that materials that generate significant quantities of gas would likely be precluded).

Understanding and being able to represent processes associated with gases within the engineered barrier are deemed to be of **low** importance to the overall confidence in the safety case.

Overall, issues associated with engineered system gas sources and effects are of **medium** importance to the safety case.

State of the Art

The effects of gases in the engineered barrier system have been investigated to a limited extent and there are needs for modeling approaches and experimental data to assess the importance of gas generation and transport through engineered barrier system.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to gas sources and their effects on the engineered barrier system for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. Generic analyses of such effects are available for different designs and media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:	There is no need to complete R&D pertaining to gases in the engineered barrier system and associated processes to support this decision point. Limited analyses would be required to evaluate key contributors to isolation and the effects of gases are expected to be of secondary importance at this stage.
Site characterization and disposal system design [site characterization]:	The importance of gases in the engineered barrier system at this decision point is **medium**. An understanding of the potential for gas generation and associated effects within the engineered barrier system needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility. This could directly affect the design of the engineered barrier system and initial assessments of disposal system performance, if necessary. Information is available to represent processes associated with gases in the engineered barrier system, but would have to be applied to specific environments, media, and design concepts. R&D would lead to improved understanding of the importance of gases and associated effects. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.
Site suitability [licensing]:	The importance of gases in the engineered barrier system at this decision point is **medium**. Defensible models to represent gas generation and associated effects would be needed, if shown to be important. Information is available to represent these processes, but would have to be applied to specific environments/media/designs. R&D would lead to improved understanding of the importance of gases and associated effects. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with the Engineered Barrier System Gas Sources and Effects is projected to be **low** when considering effects on the waste container, **low to medium** when considering effects on the buffer/backfill, **low** when considering effects on the seals, and **low** when considering effects on other engineered barrier system components.

4.5.14 Radiation Effects

The effects of radiolysis and radiation damage are expected to be minimal and would be most important nearer to the emplaced wastes (e.g., inside the waste packages). Generic R&D related to chemical processes and the evolution of the geochemical environment within the engineered barrier system, in particular within the waste form (Section 4.5.9) would consider the effects of radiolysis. R&D regarding the performance of directly disposed fuels would consider the effects of radiation damage (Section 4.5.2).

Potential R&D could consider radiolysis of complex brines and waters on the surface of a waste package, within or on the backfill, within rock at the tunnel walls, and at each of those interfaces. This relates in particular to gamma or neutron radiolysis in the presence of moisture (and the radiolysis of chloride, nitrate, sulfate, fluoride etc). These are highly complicated reactions and kinetics that may require high-performance computing to resolve (interaction with NEAMS).

4.5.15 Nuclear Criticality

The disposal of fissile material results in the potential for nuclear criticality that must be evaluated and either shown to be not important, or the potential effects represented in the safety analysis. To-date, criticality was screened from consideration in the Yucca Mountain Total System Performance

Assessment in accordance with the probability criterion in proposed 10 CFR 63.342(a), which states: "DOE's performance assessments conducted to show compliance with 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal." The probability of criticality was based on a combination of low probability events and disposal environment conditions that were Yucca Mountain site-specific, and a fixed disposal inventory. Any change in environmental or packaging parameters necessitates a review of the impacts on the design basis configurations used for determining the probability of criticality. Additionally, fuels from advanced fuel cycles that would be directly disposed and/or advanced waste forms may have different concentrations of fissile isotopes and poisons, necessitating the need to assess the potential for nuclear criticality.

Ability to Address through Generic R&D

Specific R&D to address processes associated with the formation of a critical configuration would require the identification of a specific site, determination of the types and configuration of waste that would be disposed, development of the subsurface design, and the selection of materials that would be used. However, generic R&D could be conducted to develop and improve methods for evaluating nuclear criticality in geologic disposal systems and to assess potential effects for different wastes and design concepts. Generic R&D could focus on the identification of potential plausible configurations and the availability of applicable critical benchmarks for validation.

Importance to Safety Case

The importance of a critical event in the engineered barrier system to the safety analysis is **low** because it is anticipated that criticality in the engineered barrier system is unlikely, and the consequences (i.e., heat generation and increase in radionuclide inventory) would be minor with respect to the overall disposal system. However, a defensible basis for this conclusion would have to be developed.

The importance of criticality in the engineered barrier system is of **medium** importance to the design/construction/operation of the engineered barrier system because it could influence the design of the engineered barrier system, in particular waste package configuration and loading, and the use of neutron absorber inserts.

The importance of criticality in the engineered barrier system is of **high** importance to the overall confidence in the safety case due to the perception associated with nuclear criticality in geologic disposal systems.

Overall, issues associated with engineered system criticality issues are of **low** importance to the safety case.

State of the Art

The potential for nuclear criticality has been assessed in all geologic disposal programs and, as discussed above, to-date it has been shown that nuclear criticality is not expected to occur either inside a failed waste package or within the engineered barrier system for disposed light water reactor spent fuel or for the current forms of HLW. Additional data are needed for burn-up credit assessment in light water reactor spent nuclear fuel. Fuels from advanced fuel cycles that would be directly disposed and/or advanced waste forms may have different concentrations of fissile isotopes and poisons, presenting the need to assess the potential for nuclear criticality.

Interfaces with the FCT Fuels and Separations/Waste Form campaigns and the UFD - Storage / Transportation program are needed to determine isotopic and configuration information and to develop improved methods of analysis.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to nuclear criticality and its effects on the engineered barrier system for the site screening process at this time, because until design concepts are developed to the point where the engineered components comprising items Important to Waste Isolation (ITWI) can be identified, existing information is expected to suffice. The effects of nuclear criticality are not considered likely to result in the use of components that are ITWI, but generic analyses of such effects are available for different designs and media, and are well enough developed to support site screening. The site screening process and ultimate decisions depend heavily on the geologic attributes of the site; sufficient information exists in available materials to support site screening.
Site selection [environment feasibility, concept feasibility, site designation]:	There is no need to complete R&D pertaining to nuclear criticality in the engineered barrier system and associated processes to support this decision point. Limited analyses would be required to evaluate key contributors to isolation and the effects of nuclear criticality are expected to be of secondary importance at this stage.
Site characterization and disposal system design [site characterization]:	The importance of nuclear criticality in the engineered barrier system at this decision point is **medium**. An understanding of the potential for nuclear criticality and associated effects within the engineered barrier system needs to be developed and demonstrated for those features that would be included as part of the design of a geologic disposal facility (in particular, the emplaced wastes). This could directly affect the design of the engineered barrier system and initial assessments of disposal system performance, if necessary. Information is available to represent processes associated with nuclear criticality in the engineered barrier system, but would have to be applied to specific environments/media/designs. R&D would lead to improved understanding of the importance of nuclear criticality and associated effects. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.
Site suitability [licensing]:	The importance of nuclear criticality in the engineered barrier system at this decision point is **medium**. Defensible models to identify potentially critical configurations and associated effects would be required, if important. Information is available to represent these processes, but would have to be applied to specific environments/media/designs. R&D would lead to improved understanding of the importance of nuclear criticality and associated effects. Thus, the adequacy of information is deemed **partially sufficient** to support this decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with the Engineered Barrier System Nuclear Criticality is projected to be low when considering effects on the waste container, buffer/backfill, seals, and other engineered barrier system components.

4.6 Geologic Environment Issues / R&D Opportunities

This section presents a summary of the information that informed the prioritization of R&D issues/opportunities associated with the natural system features of a geologic disposal facility. The information in this section is presented at the higher-level topics, informed by the information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* (Appendix A).

4.6.1 Excavation Disturbed Zone

One of the most widely discussed aspects of repository host rock performance, regardless of lithology, is the damage caused by excavation and subsequent emplacement of radioactive waste. The excavation damage zone (EDZ) is the most direct consequence of disturbance from excavation, and represents the region of permanent effects. The EDZ is typically created by changes to the preexisting stress state and is a function of the material properties in relation to the stress conditions. Fractures have an appreciable effect on the permeability of most potential host media, and therefore the characteristics of fractures associated with the EDZ should be investigated. For clay/shale media, the EDZ is also influenced by near-field desaturation and desiccation that may lead to local changes in the rock fabric and properties. A repository rock (such as shale or salt) that has the capacity to re-seal or heal fractures in the EDZ could be highly desirable for isolation purposes. The impact of tunnel convergence and self-sealing on the long-term hydraulic properties of the EDZ has not yet been fully examined at representative scale. While part of the natural system, the EDZ is strongly influence by the engineered system (design of the subsurface disposal facility, construction techniques, quantity and characteristics of the emplaced waste, etc.).

<u>Ability to Address through Generic R&D</u>

Issues associated with the EDZ can be addressed through generic R&D and, as discussed below, such generic R&D has been and is being conducted by other countries. Generic R&D would focus on improved understanding and representation of the processes associated with EDZ formation/evolution, impacts to disposal system design, and effects on long-term performance. Site-specific information would ultimately be needed to evaluate the EDZ. The understanding of processes and their representation developed through generic R&D would support such site-specific evaluations.

<u>Importance to the Safety Case</u>

The importance of the EDZ to the safety analysis, design/construction/operations, and the overall confidence in the safety case is **high**. Radionuclide mobility and transport pathways within the EDZ can potentially directly impact long-term repository performance. The importance to the safety analysis and the overall confidence in the safety case is based on possible enhanced inflow and connection/bypass/fast path through the engineering system and perhaps around repository seals. Short term room closure could directly impact repository design, construction, and operations for salt or clay disposal environments. However, this could potentially be mitigated by design.

<u>State of the Art</u>

There are fundamental gaps in knowledge and data that could be addressed through generic R&D. There is a need for improved understanding and representation of the evolution of EDZ characteristics as a result of thermal-mechanical and wetting changes in salt and clay environments, including the coupled evolution of near-field host rock and any backfill/buffer materials that would be used in the design of the repository. There has been considerable work completed regarding EDZ performance, for example at the Waste Isolation Pilot Plant (WIPP) and in European programs, and information from these sources will be used by the UFDC. Additional activities are underway and are being planned, and the UFDC will consider collaborating on these programs to leverage on the efforts being conducted. Specific examples pertaining to the EDZ in a clay/shale environment include:

- The on-going international DECOVALEX collaboration (<u>DE</u>velopment of <u>CO</u>upled models and their <u>VAL</u>idation against <u>EX</u>periments), with the objective of more complete understanding and improved modeling of the effects of coupled thermal-hydrologic-mechanical-chemical processes. The new phase of DECOVALEX started in 2012 and will end in 2015. DOE and the UFDC are active members of DECOVALEX.
- A long-term, full-scale heater test in Opalinus clay at the Mont Terri URL in Switzerland, the FE test, is being started. The objective of this test is to investigate repository effects in indurated

clay and will investigate many of the specific issues listed above. DOE and the UFDC are active members of the Mont Terri project.

- The PRACLAY test, a long-term full-scale heater test in Boom Clay (plastic clay) is being initiated at the HADES URL in Belgium. The objective of this test is to simulate, at a realistic level, a disposal gallery through all operation phases (construction, backfilling, sealing, re-saturation, and heating for 10 years). This test will also investigate many of the specific issues listed above.

Modeling of the excavation process, and the formation and evolution of the EDZ, is challenging. This is an intrinsically three-dimensional problem involving tunnel orientation, direction of bedding planes, and the anisotropic stress field present at the site. To date, no single set of consistent modeling approaches has been able to reproduce all the URL observations. Thermal and geochemical effects on long-term EDZ evolution may also need to be considered. Potential occurrence of a geochemical damage zone has not been ruled out, and its long-term effects may need to be evaluated. Modeling of excavation procedure and emplacement of waste and buffer need to be considered as well. A time-dependent pore pressure response to excavation occurs in clay rock types because these media have very low permeability and high initial water saturation. Local changes in normal stress caused by excavation produce changes in pore pressure. The locally increased pore pressure decreases the effective stress acting through the solid framework, and causes dilation in directions transverse to loading. Porewater may drain in response to increased pressure, increasing the deviatoric stress. These changes, combined with stress redistribution near excavated openings, locally reduce the rock strength and produce additional deformation. A coupled hydro-mechanical model for excavation response of indurated clay/shale media would enhance understanding of these processes.

Evolution of the EDZ in salt is very sensitive to the stress state and exhibits steep transient deformation behavior that evolves into steady-state deformation. This behavior can be understood in terms of plastic dislocation mechanisms in salt crystals. Hence, creep closure of underground openings in salt at ambient temperature can be understood at a mechanistic level. Based on studies at WIPP, the nature of the EDZ can be adequately described for engineering and analysis purposes in terms of stress invariants, which is conducive to finite element calculations. Long-term behavior including healing can be assessed by tracking the stress state within the structural calculation. For the long-term disposal of high level wastes, a better understanding of rock salt creeping and fracture sealing around the EDZ at elevated temperatures and in the presence of moisture is required.

Modeling of EDZ extent depends on the constitutive law used with its choice of the elastic limit and fracturing criteria. A strain softening model may help reproduce the progressive change in material strength during excavation, in order to properly reproduce strain localization and shear band occurrences. It is important to ensure that modeling results are not mesh dependent and indeed represent the physics of the processes involved. Outstanding research issues include scale effects in adopting laboratory-measured rock properties to the study of site behavior, methods to limit damage to samples, and changes in sample hydraulic conditions from in situ to laboratory environments.

Gas production from metal corrosion and radiolysis in a clay or salt repository is a potentially important process for increasing permeability in the EDZ. Discrete pathways that may arise from gas overpressure form from slow “creep” deformation rather than brittle fracture processes. Once a pathway forms, the pressure is relieved by gas flow, and resealing occurs, until the pressure rises again (depending on gas supply). A fully coupled thermal-hydrologic-mechanical and chemical model may help evaluate the effect of gas generation on disposal room closure.

In situ testing could prove quite valuable for proof-of-principle testing. A field test provides an opportunity to observe anticipated phenomenology, validate modeling capabilities, and fine tune design options. Focused full-scale field testing could be undertaken after the knowledge gaps that can be addressed in the laboratory are evaluated and preliminary modeling studies are complete. In situ testing confirms the predictive ability of repository models and provides a range of expected parameters and rock mass response. Full-scale heater tests can determine: 1) the extent and properties of the disturbed zone, 2) fracture healing characteristics, 3) changes in permeability and porosity, 4) thermomechanical response of compacted backfill, 5) brine migration and influx rates (where applicable), 6) moisture behavior (e.g., partial vapor pressure), and 7) compositional changes; all for heated conditions representative of repository conditions.

Specific issues associated with the EDZ that could be addressed through generic R&D are:

- Improved methods for representing the complex coupling of processes (physical, chemical, mechanical), including the coupling of the engineered and natural systems
- Improved methods for representing near- and far-field interface chemistry (perturbation and transient phenomena, repository operation, thermal effect)
- Quantifying gas generation and representing potential impacts (gas displacement and leakage)
- Evaluating the effects of excavation and ventilation-induced fracturing in clay/shale environments
- Better understanding of fracture initiation and healing (re-compaction)
- Improved understanding of heterogeneity and anisotropic properties in the EDZ and their impacts
- Evaluating the potential for the development of fast transport pathways that could bypass the natural or engineered system and associated impacts
- Better understanding of the coupling between rock mechanics and hydrology; improved method development
- Evaluation of the technical basis for thermal limits with respect to the EDZ
- Improved understanding of and development of methods to quantify the rate of EDZ growth and healing/compaction in different geologic media (i.e., fracture initiation and healing).
- Quantification and representation of the geochemical environment in the disturbed rock zone.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to the zones of excavation disturbance or damage to support site screening because sufficient information exists to support conclusions about the general character of the excavation damage zone for different rock types relative to the conceptual design information available to support this decision point.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of excavation disturbance or damage to the site selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For the Site Selection decision point, focus is on the geologic character and the design related aspects are initially treated generically.

- For repository systems developed in crystalline rock, the understanding of the EDZ is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of the EDZ is of **medium** importance and the available information is **insufficient** with respect to the decision.

- For repository systems developed in salt, the understanding of the EDZ is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of the EDZ is of **medium** importance and the available information is **insufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of excavation disturbance or damage to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of excavation disturbance and damage, particularly reduced uncertainty, and how these processes impact and are affected by the developing design would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of the EDZ is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of the EDZ is of **medium** importance and the available information is **insufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of the EDZ is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of the EDZ is of **high** importance and the available information is **insufficient** with respect to the decision.

Site suitability [licensing]:

The importance of excavation disturbance or damage to the Site Suitability and Licensing decision point varies by rock type. For this decision point, improved representation of excavation disturbance and damage, particularly reduced uncertainty, and how these processes impact and are affected by the developing design would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of the EDZ is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of the EDZ is of **medium** importance and the available information is **insufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of the EDZ is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of the EDZ is of **high** importance and the available information is **insufficient** with respect to the decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with excavation disturbance, and especially the EDZ, is projected to be **medium** for crystalline media**, medium** for salt media, **high** for shale media, and **high** for borehole disposal in crystalline rock.

4.6.2 Host Rock

The host rock is of importance to the performance of a repository as it is the component of the repository system that provides the principal natural barriers, establishes the boundary conditions on performance of the repository and the engineered barriers (e.g., chemical composition of the water in and around the repository excavation). The physical features/characteristics of the host rock play an important role in defining its ability to limit the transport of radionuclides away from the engineered barriers to other geologic units. Of interest are the characteristics of the rock units, in particular, the thickness, lateral extent, heterogeneities, discontinuities, and contacts. The physical properties are important for hydrologic calculations and the determination of flow pathways; they dictate construction and design approaches, and have a bearing on thermal response of the repository system.

<u>Ability to Address through Generic R&D</u>

The ability to address host rock features, events and processes through generic R&D is considered partial, and site-specific. The parameters needed to address host rock features, events, and processes are site-specific. Research and development of characterization methods could be done generically, and would focus on improved methods for characterizing host rock features, events and processes, and their effects on long-term performance. Site-specific information would ultimately be needed. Improved characterization methods developed through generic R&D would support such site-specific evaluations.

<u>Importance to Safety Case</u>

The importance of host rock features, events and processes to the safety case was judged to be **high** for performance (safety analysis), **medium** for design, construction and operations, and **high** for overall confidence.

<u>State of the Art</u>

Many site characterization methods have been developed and implemented for geologic repository development in the U.S. and in other countries. Similar and applicable characterization techniques have been developed in the private sector (oil exploration, mining) and other related Federal programs (e.g., Environmental Management, carbon sequestration). More refined methods can be developed to identify and characterize flow paths, including discontinuities, heterogeneities, and fracture connections. There is a fundamental need to better characterize and quantify the uncertainty in host rock properties. Characterization data can be unified in a geospatial database to support site screening decisions and understand how screening criteria would impact the regional availability of particular host rock types (see Section 4.2.5).

Data compiled from outcrops, cuttings and drill cores, and geophysical explorations, suggest that about 90% of the conterminous United States is underlain by crystalline basement rock with large areas covered by less than 1 km of sedimentary and volcanic rock and about 10% exposed at the surface. However, field and laboratory studies of crystalline basement rock indicate that these rock types have long and complex histories. Because of age, compositional differences, and structural variations, simple reconnaissance petrologic and geochemical investigations may not suffice to characterize the evolution of granitic rock. Multidisciplinary, integrated, field and laboratory studies will be used to identify favorable geological settings containing appropriate crystalline basement rock on the surface or at shallow depths.

The preferred disposal sites in crystalline basement rock are likely to be in homogeneous formations, such as the central parts of intrusive bodies or plutons. Accurately determining the spatial extent of crystalline basement rock formations is important for site selection. Geophysical surveys using seismic, gravity, aeromagnetic, and remote sensing methods are important for characterizing geology at the early stages, and for site location during the site characterization stage. At the local scale, fabric and textural features provide information about the flowage and crystallization history of the intrusive body and its interaction with the intruded host rock. At the sample level, detailed petrological, geochemical, and geochronological investigations can be used to characterize the imprint of changes in geologic history, alteration related to water-rock interaction, the state of uplift and erosion, sorption properties, etc.

For site screening and selection in salt host rock, a major potential R&D need is improved remote detection and prediction of gas outbursts (e.g., Ehgartner et al. 1998). Outbursts are sudden, usually unexpected expulsions of gas and salt from a mining face, and can release over one million cubic feet of methane and fractured salt. Outbursts have occurred in both salt domes and bedded salt deposits.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to the host rock to support site screening because sufficient information exists in available materials to support conclusions about the general character of the geology of the host rock. State, regional, and national geologic maps and information are available for the United States. These data can be unified in a geospatial database to support site screening decisions and understand how screening criteria would impact the regional availability of particular host rock types (Section 4.2.5).

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of the host rock and its properties to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point, focus is on the geologic character and the design related aspects are initially treated generically.

- For repository systems developed in crystalline rock, the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt**,** the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale**,** the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of the host rock and its properties to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of the host rock properties, particularly reduced uncertainty, and how the properties impact and are affected by the developing design would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt**,** the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale**,** the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of the host rock and its properties to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of the host Rock properties particularly reduced uncertainty, the details of how the properties impact and are affected by the design, and validated models would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt**,** the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of host rock properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with the host rock and its properties is projected to be **high** for all three repository media and borehole disposal.

4.6.3 Other Geologic Units

Other geologic units are important to the performance of a repository as they are the components of the repository system that provide natural barriers, either secondary or perhaps principal, and generally are the media through which water must flow to reach the accessible environment. Of interest are the characteristics of the rock units, in particular, the thickness, lateral extent, heterogeneities, discontinuities, and contacts. Physical properties are important for hydrologic characterization and the determination of flow pathways, and have a bearing on thermal response of the repository system. The R&D conducted on potential host rock media could be applicable to other geologic units as well.

<u>Ability to Address through Generic R&D</u>

The ability to address features, events, and processes important to the other geologic units through generic R&D is considered partial, and site-specific. The parameters needed to address host rock features, events and processes are site-specific. Research and development of characterization methods could be done generically, and would focus on improved understanding and representation of the features, events and processes, important to the other geologic units and their effects on long-term performance. Site-specific information would ultimately be needed. Improved characterization methods developed through generic R&D would support such site-specific evaluations.

Importance to the Safety Case

The importance of features, events and processes important to the other geologic units to the safety case was judged to be **high** for performance (safety analysis), **low** for design, construction and operations, (Information about other geologic units above the repository horizon is necessary for the development of ramps, shafts, and seals) and **high** for overall confidence.

State of the Art

The state of the art related to other geologic units is identical to that of the host rock discussed above.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to other geologic units to support site screening because sufficient information exists in available materials to support conclusions about the general character of the geology of the host rock. State, regional, and national geologic maps and information are available for the United States.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of the other geologic units and their properties to the Site Selection decision point varies by rock type. Because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt**,** the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of other geologic unit rock properties is of **medium** importance and the available information is partially sufficient with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of the other geologic units and their properties to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of other geologic units and their properties, particularly reduced uncertainty, and how the properties impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of the other geologic units and their properties to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of the properties of other geologic units, particularly reduced uncertainty, validated models, and details of how the properties impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of other geologic unit rock properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.

<u>Overall Importance</u>

Overall, the importance of conducting R&D on issues associated with other geologic units and their properties is projected to be **medium** for all three repository media and borehole disposal.

4.6.4 Flow and Transport Pathways

This section discusses the identification, quantification, and understanding of features within the natural system pertaining to groundwater flow and potential radionuclide transport pathways. These features include fractures and faults. The R&D that would address these topics would be an integral part of characterizing the properties of EDZ (Section 4.6.1), the host rock (Section 4.6.2), and other geologic units (Section 4.6.3). In addition, information pertaining to the understanding of flow and transport pathways is necessary to develop an understanding of hydrology (Section 4.6.6) and radionuclide transport within the natural system (Section 4.6.8).

Flow and transport pathways determine how groundwater would move and interact with the emplaced waste and how radionuclides might move from the waste package, through the engineered barriers, and through the host rock and other geologic units to the accessible environment. Much of the information on flow and transport pathways would be site-specific, but there are opportunities for generic R&D to improve representation of heterogeneity, and the influence of discontinuities such as fractures and faults. For example, generic work on faults in clay or shale formations could be used to better understand their influence on the hydrologic system.

The presence of the repository and its effects on the host rock and other geologic units may cause alteration and evolution of the geosphere flow and transport pathways. For example, thermal or chemical effects from the repository, may cause changes in rock properties, characteristics of fractures and faults, changes in flow pathways, and changes in hydrologic conditions such as water saturation.

<u>Ability to Address through Generic R&D</u>

The ability to address flow and transport pathways through generic R&D is considered partial, and site-specific. The parameters needed to address flow and transport pathways are site-specific. Research and development of characterization methods, and methods for modeling the evolution of flow and transport pathways over time, could be done generically. Generic R&D would focus on aspects important to the transport of radionuclides. Site-specific information would ultimately be needed to evaluate specific flow and transport pathways. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

<u>Importance to the Safety Case</u>

The importance of flow and transport pathways to the safety case was judged to be **high** for performance (safety analysis); **low** for design, construction and operations; and **high** for overall confidence.

<u>State of the Art</u>

There are fundamental gaps in the methods of characterizing fracture/fault systems, and modeling sparsely fractured media. There is a need for improved modeling tools to represent fractures as discrete features. Information is needed to characterize connectivity and channelization, which could be obtained through tracer tests. There is a need for improved understanding of uncertainty in flow through fractured systems, and for model validation approaches. There is also a need to develop capability to predict the nature of repository-induced alteration and evolution of the geosphere flow pathways, and for modeling the associated uncertainty. Some gaps may exist in modeling the interaction of chemical (e.g., alkaline) plumes with the surrounding rock.

Better understanding of flow processes involving multiphase fluids in fractured rock would support improved evaluations of repository performance in those media. Understanding for flow in unfractured media or for saturated flow in fractured or unfractured media may be adequate to make meaningful predictions given sufficient site characterization. Research and development to improve site characterization efficacy is discussed in Section 4.2.5.

With regard to modeling tools, it is important to make the distinction between continuum models and discrete feature/fracture models. Continuum models (including dual porosity and dual permeability models) are appropriate for unfractured porous media or for highly fractured media. Software tools implementing continuum-type models are generally more mature and capable of addressing multiple coupled processes of interest. Experience in Sweden and Finland suggests that discrete fracture network (DFN) models offer advantages over continuum models for sparsely fractured media such as fractured crystalline basement rock, especially when fracture networks or network statistics are well characterized. DFN modeling capability would provide an alternative to continuum codes and would also be invaluable for numerically determining effective parameters for use in existing continuum codes. At present there are limited DFN tools available for modeling large-scale, three-dimensional fracture networks.

Regardless of whether DFN or continuum representations are used, repositories situated in the saturated zone present the challenge of representing repository tunnels, shafts, and other openings. Flow models with sufficient detail to represent all tunnels, emplacement boreholes, and access shafts have been demonstrated. However, these are computationally intensive, and flow codes that take advantage of multi-core architectures and/or parallel computing resources would be advantageous for simulating repositories in the saturated zone.

Flow localization, caused either by large-scale flow through discrete conductive features or by small scale heterogeneity, is a potentially important site characteristic affecting natural system performance. As already discussed, large-scale flow focusing can occur through intensely fractured zones, along faults, or within repository tunnels and adjacent excavation damage zones. Small-scale flow localization, whether by pervasive fracturing or geologic heterogeneity in geologic media, reduces net travel time of radionuclides (through a reduction in transport porosity). The increased rate of downstream transport is partially mitigated by increased retention of radionuclides due to diffusion into relatively immobile water zones. The degree of flow localization and associated diffusion into immobile water are difficult to characterize and typically require field-scale tracer tests.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to flow and transport pathways to support site screening because sufficient information exists in available materials to support conclusions about the general character of the hydrology and likely flow pathways. State, regional, and national geologic maps, hydrologic maps, and other sources are available, as well as more detailed hydrologic models at state and regional scales throughout the United States. Hydrologic investigations in support of water resource management and from underground research laboratories in various media throughout the world provide an extensive data base of information sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of the flow and transport pathways to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically. For repository systems developed in crystalline rock, there is a strong need for R&D activities, and the resulting information would likely be essential to support the decision.

- For repository systems developed in crystalline rock, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of flow and transport pathways and properties is of **high** importance and the

available information is **partially sufficient** with respect to the decision.

- For repository systems developed in clay or shale, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of the flow and transport pathways to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of the flow and transport pathways, particularly reduced uncertainty, and how the pathways impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]:

The importance of the flow and transport pathways to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of the flow and transport pathways, particularly reduced uncertainty, validated models, and the details of how the pathways impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding flow and transport **path**ways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of flow and transport pathways and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of flow and transport pathways and properties is of **high** importance and

the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with flow and transport pathways is projected to be **medium** for crystalline media**, low** for s**alt** media, **medium** for shale media, and **medium** for borehole disposal in crystalline rock.

4.6.5 Mechanical Processes

There are two general classes of mechanical impacts or damages of concern to repository performance: mechanical processes related to the excavation damage zone, discussed in section 4.6.1, and mechanical processes that affect the geosphere, which are the subject of this section. This division is somewhat subject to regulatory definition. For example, the existing U.S. high-level radioactive waste and spent nuclear fuel regulation, 10 CFR Part 60, includes the underground facility in the definition of the engineered barrier system. In that regulation, the underground facility means the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals. In this report, both types of mechanical impacts are included in the geosphere components.

Mechanical effects on the host rock may arise from rock mass deformation, for example, tunnel collapse or rock fall into openings. These responses are characteristic of hard, competent rock such as granite or shale if well indurated. Mechanical effects can also result from plastic deformations, for example creep deformation in salt or clay. Depending on the magnitude of deformation, mechanical effects could be propagated toward the ground surface, where they could be manifested as subsidence. Chemical precipitation or dissolution (e.g., carbonate dissolution along focus flow pathways) can also lead to mechanical effects in the geosphere.

There are a number of natural geologic characteristics or processes that could contribute to mechanical damage in low-permeability media such as salt or clay/shale host rock. These include burial and compaction, mineral diagenesis, tectonic uplift and erosion, glaciation, siliciclastic intrusions and mud volcanism, seismic activity, salt or mud diapirism, hydrothermal activity, volcanic intrusions, changes in recharge, large-scale dissolution, and buoyant geofluids. Such factors operating either individually or in some combination could already have caused host rock damage, or may produce such damage during the future performance of a repository. One result can be development of preferred pathways through otherwise low-permeability rock.

As the effects of mechanical damage and stress change propagate outward from the repository, through the host rock, there is a potential for mechanical effects in the other geologic units. While similar to those experienced by the host rock, the effects are likely to be of lesser magnitude in the other geologic units, as they tend to decrease with distance from the causative event or process.

Thermal effects on the geosphere are discussed in Section 4.6.10; chemical effects that can lead to mechanical effects are discussed in Section 4.6.7.

Mechanical processes in a low-permeability environment such as in a clay or salt repository are closely coupled to thermal, hydrologic, and chemical processes. To account for these couplings and their impact on repository performance, requires knowledge of constitutive relationships for the host rock, especially relationships between hydraulic and mechanical properties. These relationships control the degree of coupling among the relevant processes.

Ability to Address through Generic R&D

The ability to address mechanical processes through generic R&D is considered partial, site-specific, and design-specific. The parameters needed to address mechanical processes are somewhat site-specific, but can be addressed generically for different rock types. Research and development of methods for modeling the evolution of mechanical processes over time can be done generically, and would focus on improved understanding of mechanical effects in rock types or circumstances important to the transport of radionuclides. Site-specific information would ultimately be needed to evaluate specific mechanical processes. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

Importance to the Safety Case

The importance of mechanical processes to the safety case was judged to be **high** for performance (safety analysis); **high** for design, construction and operations; **high** for overall confidence for the host rock; **medium** for performance (safety analysis); not applicable for design, construction and operations; and **high** for overall confidence for the other geologic units.

State of the Art

There are fundamental gaps in the methods of characterizing mechanical effects on the host rock and for other geologic units, and fundamental gaps in data availability. There are several European programs, including URLs starting 10-year projects investigating thermal-mechanical and moisture effects. The UFDC should get involved in these and then initiate independent activities. There are also international collaborations being coordinated by DOE-EM that could be leveraged.

Development of understanding of mechanical processes and their effects needs to be done in collaboration with engineered barrier development, with particular emphasis on areal power density and host rock and other geologic unit mechanical response to excavation and thermally induced stresses.

There is a need for studying of the impact of rock-property heterogeneity as well as in situ stress fields on repository systems in clay or shale. The permeability of indurated clays can vary over two orders of magnitude, while mechanical properties can vary by a factor of five or more. Spatial variability may have some characteristic length or may have a fractal character. Understanding clay variability could be key to predicting strain localization and fracturing processes. The stress field may also be spatially varying, depending on local structures and temporal changes in clay properties.

There is also a need for the development of constitutive relationships for clays and other media, especially relationships between hydraulic and mechanical properties. These relationships control the degree of coupling among the relevant processes. Although considerable progress has been made in developing constitutive relationships, the following important issues, associated with clay rock, warrant continued R&D:

- Multiphase flow conditions with rock property changes (including self-sealing of fractures)
- Constitutive relationships for fractures in clay rock
- How the deformation is related to hydraulic property changes for fractured clay rock associated with swelling and shrinkage

In addition, there is a need for improved understanding of rock stress and fracture issues in deep crystalline rock, especially as they pertain to borehole stability for very deep borehole disposal.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to mechanical processes to support site screening because sufficient information exists in available materials to support conclusions about the general types and nature of mechanical process effects on underground excavations. Mining and rock mechanics studies, in support of mine development and from underground research laboratories in various media throughout the world provide an extensive data base of likely effects sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of mechanical processes to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of mechanical processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of mechanical processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of mechanical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of mechanical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of mechanical processes to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of mechanical processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of mechanical processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of mechanical processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of mechanical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of

mechanical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of mechanical processes to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of mechanical processes, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of mechanical processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of mechanical processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of mechanical processes and properties is of **high** importance and the available information is **partially sufficient w**ith respect to the decision.
- For repository systems developed in clay or shale, the understanding of mechanical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the mechanical processes is projected to be **low** for **crystalline** media**, medium** for **salt** media, **medium** for **shale** media, and **medium** for **borehole** disposal in crystalline rock.

4.6.6 Hydrologic Processes

This section discusses the quantification and understanding of hydrologic processes within the natural system. The R&D that would address hydrologic process topics would be integrated with activities to characterize the EDZ (Section 4.6.1), the host rock (Section 4.6.2), other geologic units (Section 4.6.3), and flow pathways within them (Section 4.6.4). In addition, information pertaining to the understanding of hydrologic pathways is necessary to develop and understanding of radionuclide transport within the natural system (Section 4.6.8).

An understanding of hydrologic processes is fundamental to modeling the transport of radionuclides from the repository to the accessible environment and then to the receptor. Such modeling involves understanding flow mechanisms in the host rock, typically at saturated flow conditions. It also involves defining and understanding preferential flow pathways, and the effects from fluid density on flow (e.g., in the deep basement). Porosity, permeability, and other important properties of the host rock dictate how fluid flows through the rock. If the flow occurs through the matrix, its calculation is relatively straightforward. Fracture flow and matrix imbibition can be important aspects of determining flow, particularly if there is multiphase or unsaturated flow. If flow occurs under unsaturated conditions, fingering, capillary effects, and imbibition are important hydrologic processes. The flow pathways typically involve not only the host rock, but the other geologic units as well. Other geologic units may possess confining properties; or they may be regional aquifers.

The excavation and operation of the repository itself affect flow through the host rock. Under saturated flow conditions, repository openings might act to channel flow. Under unsaturated flow conditions the excavations can introduce capillary phenomena such as capillary diversion, perching, film flow, and seepage. All natural flow systems may exhibit episodicity. Of particular importance is flow through the excavation damage zone, which typically would be dominated by fracture flow for harder rock. For clay rock types there is the potential for dehydration, leading to slaking, in the immediate vicinity of excavations while rock is exposed during preclosure operations. Dehydration of clay-rich media leads to volume changes and attendant mechanical effects, while rehydration leads to complementary volumetric changes and mechanical effects.

Ability to Address through Generic R&D

The ability to address hydrologic processes through generic R&D is considered partial, and site-specific; for hydrologic processes related to the host rock and the excavation damage zone, it is design-specific as well. The parameters needed to address hydrologic processes are site-specific. Generic R&D would focus on improved characterization and modeling methods of the hydrologic processes important to the transport of radionuclides. A better understanding of the effects of mineral dehydration on hydrologic processes is important for clay host media. Site-specific information would ultimately be needed to evaluate specific hydrologic processes. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

Importance to the Safety Case

The importance of hydrologic processes to the safety case is generally judged to be **high** for performance (safety analysis), **low** for design, construction and operations, and generally **high** for overall confidence. The importance of mineralogical dehydration on hydrologic processes for clay repositories was judged to be **low** for performance (safety analysis), **medium** for design, construction and operations, and **low** for overall confidence.

State of the Art

There are fundamental gaps in the methods of characterizing flow through the host rock and how it interacts with the repository system, and fundamental gaps in available data. There is a need to develop improved modeling tools to represent fractures and fracture sets as discrete features in granites and other indurated rock types. Information is needed to characterize and model connectivity and channelization, which could be obtained through tracer tests. There is a need to characterize the uncertainty in flow through fractured systems, and validate the models.

There is a need to understand the development of fracturing and subsequent healing in clay and salt media; acquisition of data and development of modeling methods are needed. Water migration in salt is a unique process that needs to be better understood; there is a need to better understand the effects from thermal and pressure gradients on gas generation and brine migration. These R&D needs carry with them the need to model the associated uncertainty and validate the models.

There are fundamental gaps in the methods of characterizing flow through the other geologic units and how it interacts with the host rock and other components of the repository system (e.g., leakage, overpressure, and flow channelization).

There are fundamental gaps in the methods for characterizing the effects of repository excavation on flow through the host rock. There is a need to develop improved modeling tools to represent fractures and fracture sets as discrete features in granites and other crystalline rock types. Information is needed to characterize and model connectivity and channelization, which could be obtained through tracer tests.

There are fundamental gaps in the methods for characterizing flow through the EDZ and at the interface with the host rock, and similar gaps in available data. Flow in the EDZ is closely tied to the other aspects of excavation disturbance (Section 4.6.1).

There are fundamental gaps in the methods for characterizing mineralogical degradation as the flow system interacts with the host rock and other components of the repository system; there are also fundamental gaps in available data. Significant work has been done, but significant gaps exist in modeling the coupled THMC processes; this is most important to the EDZ in clay media (Section 4.6.1).

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to hydrology to support site screening because sufficient information exists in available materials to support conclusions about the general character of the hydrology system and response of regions. State, regional, and national geologic maps hydrologic maps and information are available, as well as detailed hydrologic models at state and regional scales throughout the United States. Hydrologic investigations in support of water resource management and from underground research laboratories in various media throughout the world provide an extensive data base sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of hydrologic processes to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of hydrologic processes and properties is of **high** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of hydrologic processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of hydrologic processes and properties is of **high** importance and the available information is **insufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of hydrologic processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of hydrologic processes to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of the hydrologic processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of hydrologic processes and properties is of **high** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of hydrologic processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of

hydrologic processes and properties is of **high** importance and the available information is **insufficient** with respect to the decision.

- For repository systems developed in clay or shale, the understanding of hydrologic processes and properties is of **high** importance and the available information is partially sufficient with respect to the decision.

Site suitability [licensing]: The importance of hydrologic processes to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of the hydrologic processes, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of hydrologic processes and properties is of **high** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of hydrologic processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of hydrologic processes and properties is of **high** importance and the available information is insufficient with respect to the decision.
- For repository systems developed in clay or shale, the understanding of hydrologic processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with hydrologic processes is projected to be **low** for crystalline media**, high** for salt media, **medium** for sh**ale** media, and **medium** for borehole disposal in crystalline rock.

4.6.7 Chemical Processes/Chemistry

An understanding of the repository far-field geochemical system is important for understanding repository performance. Geochemical conditions and the characteristics and composition of groundwater in the repository far field govern the mobility and solubility of radionuclides. In addition, the chemistry of water flowing from the far field into the near-field environment may affect the near-field chemical environment, which, in turn, affects engineered barrier degradation rates. Important chemical properties affecting the dissolved species include temperature, pH, Eh, ionic strength,, the reduction-oxidation potential, and reaction kinetics. The geochemical transport performance of a repository is strongly related to the compositions of the host rock and groundwater, which influence radionuclide solubility, radionuclide mobility, and the capacity to chemically buffer water that originates in the near field (e.g., carrier plumes). Interaction with the engineered barrier system components, particularly as they degrade, further affects the system chemistry. Host rock and groundwater compositions also determine the chemical compatibility of waste forms, containers, engineered barrier, and backfill material.

Groundwater geochemical conditions in the far-field environment are governed by the origin and mixing of source waters and by rock-water interactions in the flow system. Mineral dissolution and precipitation are affected by temperature and chemical changes; the chemistry of recharge waters also affects evolving geochemical conditions. Groundwater pH and major ion concentrations are usually dictated by water-rock interactions, with the rule of thumb being that waters that have spent longer residence times in a system have greater total dissolved solids (salinity). This principle can be affected by evaporative processes above the water table, and by temperature gradients, particularly in geothermally active areas. Some rock types, such as sedimentary carbonates, are very effective at buffering pH and major ion concentrations because of their relatively high solubility, while other rock types have weak buffering capacity. In many locations, particularly near oceans, deeper waters tend to have higher salinity than shallow waters. Waters that have moved rapidly from the surface to the deep subsurface also tend to be more oxygenated than waters that have spent long residence times below the water table. However, oxygen can be depleted even in relatively shallow waters in areas that are densely vegetated at the surface because the presence and breakdown of organic matter in the shallow subsurface results in oxygen consumption (oxygen concentration is negatively correlated with organic carbon content in ground waters). Oxygen depletion can also occur as water moves through rock containing reduced metals and metal oxides.

<u>Ability to Address through Generic R&D</u>

The ability to address fundamental chemical processes through generic R&D is considered partial, and site-specific. The parameters needed to address chemical processes are site-specific. Generic R&D would focus on improved characterization and modeling methods of the chemical processes important to the transport of radionuclides. Site-specific information would ultimately be needed to evaluate specific chemical processes. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

<u>Importance to the Safety Case</u>

The importance of chemical processes to the safety case was generally judged to be **high** for performance (safety analysis); **not applicable** for design, construction and operations; and generally **high** for overall confidence. The importance of chemical interactions and evolution of groundwater was judged to be **medium** for performance (safety analysis); **not applicable** for design, construction and operations; and **medium** for overall confidence.

<u>State of the Art</u>

There are fundamental gaps in the methods of characterizing chemical characteristics of groundwater in the host rock and other geologic units, and their relationship to the performance of the repository system, and fundamental gaps in available data. Methods to characterize groundwater composition, particularly spatial and temporal variability, and scale dependence need to be identified and developed.

There is a need to define a generic chemistry for each geologic environment, as well as a need to identify interactions with EBS materials, for example, introduced fluids, and the alkaline plume from the near field). In the definition of generic chemistries for the different geologic environments, there should be emphasis on development an understanding of favorable and unfavorable groundwater chemistries; interactions of various waste forms/waste streams with various chemical environments should also be evaluated. Further, there is a need to characterize effect of microbial activity on water chemistry.

For clay and unsaturated rock in particular, there is a need to identify chemical sampling methods to characterize initial fluid composition. For salt, there is a need to better understand brine chemistry and the interaction of high ionic strength brine with EBS components. A better characterization of deep crystalline water chemistry is needed to support deep borehole disposal development.

There are fundamental gaps in the methods of characterizing chemical interactions and evolution of groundwater in the host rock and other geologic units, and their relationship to the performance of the repository system, and fundamental gaps in available data. Methods for characterizing groundwater chemistry and models to predict water chemistry evolution in the near field need to be further improved.

There are fundamental gaps in the methods of characterizing radionuclide speciation and solubility in the host rock and other geologic units, and their relationship to the performance of the repository system, and fundamental gaps in available data. Accurate prediction of radionuclide speciation in a natural system under various conditions is still challenging.

There is a need for thermodynamic data for modeling speciation and solubility for high ionic strength and high temperature environments, methods are needed to acquire information to fill in thermodynamic data gaps. Some of this can be accomplished by participating in international collaborations, and EM and Office of Science work.

There are fundamental gaps in the methods to measure in situ oxidation-reduction conditions, characterize actinide and radionuclide speciation, and model radionuclide speciation for a range of oxidation-reduction conditions. While significant work has been done on simple systems, better characterization of complexants is needed.

Associated with water flow localization, the spatial heterogeneity in chemical condition, specifically the oxidation-reduction condition, usually exists in the repository far field, which will directly affect radionuclide mobility in the far-field. Field characterization of this heterogeneity is technically challenging. In addition, chemical heterogeneity can also arise in the vicinity of a waste disposal room, where the contaminant plume leached from the disposal room, e.g., alkaline plume from cementitious materials, will interact with the ambient rock. A fully coupled reactive transport code would help capture this heterogeneity.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to chemistry and chemical processes to support site screening because sufficient information exists in available materials to support conclusions about the general character of the chemical processes. Laboratory and field investigations of chemical processes, including that from underground research laboratories in various media throughout the world performed in support of nuclear waste disposal programs, provide a comprehensive data base of information sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of chemical processes/chemistry to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of chemical processes and properties is of **medium** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of chemical processes and properties is of **medium** importance and the available information is **insufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of chemical processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of chemical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:	The importance of chemical processes/chemistry to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of the chemistry related chemical processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of chemical processes and properties is of **medium** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of chemical processes and **p**roperties is of **medium** importance and the available information is **insufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of chemical processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of chemical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]:	The importance of chemical processes/chemistry to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of chemical processes, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of chemical processes and properties is of **medium** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of chemical processes and properties is of **medium** importance and the available information is **insufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of chemical processes and properties is of **medium** importance and th**e** available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of chemical processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with the chemical processes/chemistry is projected to be **low** for crystalline media**, low** for salt media, **medium** for shale media, and **high** for borehole disposal in crystalline rock.

4.6.8 Chemical Processes – Radionuclide Transport

A principal mechanism for transport of dissolved radionuclides in the host rock is through advective flow along flow pathways and velocities determined by the hydrologic character of the system. Important advective properties include porosity, and tortuosity, and advection is affected by dispersion, matrix diffusion, and saturation. Advection is also a principal means of transport of dissolved radionuclides in other geologic units (non-host-rock). Confining units and aquifers also affect the flow pathways and velocity. A second principal mechanism for transport of dissolved radionuclides in the host rock, particularly if it is of low permeability, is diffusion of the dissolved radionuclides. Important properties affecting diffusion include gradients in concentration and chemical potential, diffusive properties (diffusion coefficients) and saturation. Diffusion is also a principal means of transport of dissolved radionuclides in other, low permeability, geologic units (non-host-rock).

Transport of dissolved radionuclides in the host rock and other geologic units is affected by sorption along the flow pathways, particularly, surface complexation properties. Complexation in the host rock and other geologic units is influenced by the presence of organic complexants (for example, humates, fulvates, or carbonates), and enhanced transport of radionuclides associated with organic complexants. Colloidal transport in the flow pathways of the host rock and other geologic units is possible, and is affected by colloid concentration, saturation, advection, dispersion, diffusion, and sorption

Of particular importance to the determination of the source term is radionuclide transport through excavation damage zone. Here, properties including advection, dispersion, diffusion, and sorption play important roles. Once transport of radionuclides from the engineered barrier system begins, there is opportunity for dilution of radionuclides in groundwater of the host rock and other geologic units. To be considered are mixing with uncontaminated groundwater, and mixing at withdrawal well. Opportunities exist for dilution of radionuclides with stable isotopes in the host rock and other geologic units, including mixing with stable and/or naturally occurring isotopes of the same element

Radionuclides released may be in dissolved, colloidal, or gas phases. Spatial and temporal distribution of releases from the engineered barrier system, through the excavation damage zone, into the host rock and then into the to the other geologic units must be considered due to varying flow pathways and velocities, and varying transport properties.

Generally speaking, radionuclide transport tends to be enhanced in oxidizing geochemical environments relative to reducing environments because most radionuclides that can exist in multiple oxidation states are more soluble and less strongly sorbing in their higher oxidation states. Carbonate is usually considered the most important inorganic complexant in groundwater systems, as it can enhance the transport of several radionuclides that form neutral or negatively-charged carbonate complexes in solution (e.g., U, Np, Pu, Am). Higher salinity tends to suppress the sorption of cation exchanging radionuclides (e.g., Cs, Sr) because the higher cation concentrations in the water result in increased competition for cation exchange sites on minerals. Near-neutral pH conditions usually result in lower radionuclide solubilities and stronger sorption than either acidic or alkaline pH conditions, although the effects of pH are radionuclide specific and are often linked to the influence of pH on the abundance of complexing anions (e.g., carbonate) or on the surface properties of sorbing minerals in the system.

Experience with repository performance assessments in this country and abroad suggests that radiological risk is usually driven by very mobile radionuclides such as I-129 and, counter-intuitively, by strongly sorbing radionuclides such as isotopes of plutonium. Strongly sorbing radioelements contribute in performance assessments because radioelements that strongly associate with stationary mineral surfaces also tend to associate with mobile surfaces on colloids. However, colloid facilitated transport (CFT) may have been overestimated in previous performance assessments because many aspects of CFT are not well constrained, thus making pessimistic bounding assumptions necessary. Important uncertain processes and parameters associated with CFT include desorption processes and rates, colloid immobilization processes and associated parameters, the degree to which colloids behave as heterogeneous populations in the subsurface, the role of chemical and flow transients in mobilizing and immobilizing colloids, and colloid generation processes.

Ability to Address through Generic R&D

The ability to address chemical processes related to transport through generic R&D is considered partial, and site-specific. The parameters needed to address chemical processes related to transport are site-specific. Generic R&D would focus on improved characterization and modeling methods of the chemical processes important to the transport of radionuclides. Site-specific information would ultimately be needed to evaluate specific chemical processes related to transport. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

Importance to Safety Case

The importance of chemical processes related to transport to the safety case was generally judged to be **high** for performance (safety analysis); **not applicable** for design, construction and operations; and generally **high** for overall confidence. The importance of colloidal transport, dilution, and microbial effects were judged to be **medium** for performance (safety analysis); not applicable for design, construction and operations; and **high** or **medium** for overall confidence.

State of the Art

The conventional approach for representing sorption in radionuclide transport modeling is through the use of an equilibrium partitioning coefficient Kd, which quantifies the partitioning between sorbed and dissolved states. Partitioning coefficients for far-field transport modeling are typically developed for specific combinations of radionuclide, medium, and groundwater chemistry based on laboratory experiments and expert judgment. The Kd approach does not, however, explicitly account for changes in groundwater chemistry or mineralogy that may occur along the transport pathway. If such changes are considered possible or likely, Kd values must be spatially varied or assigned appropriate uncertainties. Temporal changes in groundwater chemistry may also occur due to changes in groundwater flow in future climate states. Degradation of engineered barriers and subsequent downstream movement of the chemically altered water (carrier plume) may also induce chemical changes affecting sorption. The Kd parameters for different radionuclides must be statistically correlated to account for a shared dependence on groundwater chemistry and mineralogy.

Surface complexation modeling, which represents surface species equilibria using mass action equations corrected for changes in electrostatic energy (e.g. electrical double layer theory) and non-electrostatic forces, provides an alternative to the simple Kd approach. Surface complexation modeling can explicitly account for spatial and temporal changes in groundwater chemistry, including the effect of a carrier plume, albeit with increased computational burden. This modeling approach and the supporting thermodynamic data have reached a level of maturity that makes incorporation into transport models feasible, at least for simple systems.

There are additional approaches for incorporating the effect of sorption into transport models that are of intermediate complexity between a simple Kd model and full multi-species reactive transport simulations with surface complexation. These approaches generally are based on developing correlations between major chemical parameters and Kd using surface complexation modeling without transport. These correlations (response functions) are then be used in transport models. Such correlations can account for changes or uncertainties in groundwater chemistry within the range used to develop the response functions. Groundwater chemistry changes caused by the action of a carrier plume are, however, difficult to incorporate.

Radionuclide transport modeling remains a computationally challenging task. Except for the extreme situation of diffusion-dominated conditions, transport models are more sensitive than flow models to numerical grid effects and small-scale heterogeneity. Relatively fine grids are needed to avoid numerical dispersion when traditional finite-difference or finite-element methods are employed. Multiple radionuclides linked through decay chains need to be considered, and the simulation time steps are thus limited by the most mobile (least retarded) radioelement. In addition, transport modeling to assess geosphere performance typically requires parametric uncertainty to be addressed, which places a premium on fast execution time of modeling codes.

Because of these computational challenges, repository performance assessments often employ representative waste packages with associated representative transport pathways instead of attempting to model transport from all waste packages. For example, all waste packages that occupy a specified region of a repository and have experienced certain conditions are typically lumped into a single representative package. Package-to-package variability and pathway-to-pathway variability within the far field are not represented by such an approach. Moreover, performance studies of repositories situated in fractured crystalline rock suggest that natural system transport may be driven by a small fraction of package/pathway combinations. Because of these considerations, the use of representative waste packages introduces significant uncertainties and potential biases in repository performance studies. Streamline-based transport codes, which neglect transverse dispersion, are efficient enough to represent transport from all failed waste packages. However, obtaining groundwater flow fields with sufficient spatial resolution to represent transport from thousands of waste packages can be challenging. Existing and emerging flow codes that take advantage of multi-core and parallel computer architectures and clustered computer resources will make it possible to avoid the use of the representative waste package concept, thus removing one source of systemic model uncertainty.

Performance assessment models of proposed and existing geologic repositories are commonly limited by the lack of definitive experimental data describing the sorption of radionuclides onto the important mineral surfaces in the natural system. For a given sorption substrate, the formation of surface complexes for actinide elements and other radionuclides of interest is highly dependent on the oxidation state of the radionuclide ions in solution and the presence of complexing agents that compete with sorption sites to bind with radionuclide ions. Thus, sorption is strongly linked to solution chemistry. The most important chemical parameters are solution pH, reducing-oxidizing (oxidation-reduction) conditions, and presence of complexing agents such as carbonate ions. In addition, competition among various radionuclide ions and solution complexes for sorption sites can reduce sorption for specific radionuclide species. Sorption data obtained from laboratory-scale batch and column experiments, and especially field determinations, can be difficult to interpret due to the highly complex nature of flow in mixed-phase porous media and the interactions of fluids with complex mineral surfaces. Sorption data from the scientific literature are generally restricted to specific ranges of temperature, solution composition, pH, and ionic strength, and therefore have limited applicability to conditions expected along transport pathways from a repository.

The last decade has seen the use of computational chemistry methods to improve the understanding of clay minerals and associated phenomena. In particular, molecular dynamics simulations have begun to provide critical adsorption data associated with the binding of various cations onto the surfaces of important clay minerals. Molecular modeling efforts have demonstrated that structures, swelling, adsorption, and related processes of clay minerals can probably be predicted. However, applying such methods to actual systems, even as simple as radionuclide sorption on edge sites of clay minerals, is yet to be demonstrated.

Although simple rock-water systems allow straightforward experimental interpretations, they also place the burden of accounting for the combined effects of reactions and physical transport, and the related issues of scaling and system heterogeneity. This additional work is dependent almost entirely on modeling efforts. As a result, experience with scaling results from simple rock-water experiments to the field scale has been less than satisfactory. Differences between field-scale retention and results of simple rock-water systems are likely caused, at least in part, by limited rates of mass transfer between mobile water and the immobile zones that contain sorption sites. However, the mass transfer process depends on heterogeneity across a broad range of scales and is difficult to quantify without direct experimental results at the appropriate scale. Block scale, 1 m scale or larger experiments could lead to a better understanding and possibly help quantify retention at the scales relevant for making geosphere transport predictions. Both fractured media and heterogeneous porous media are of interest because multiple geologic media are likely to be encountered at any one site. There are opportunities to work with EM and Office of Science and International Programs.

As an alternative to continuum codes, discrete fracture network flow model development coupled with advanced methods of characterizing sparse fracture networks would greatly help in the assessment of mined repositories or borehole disposal systems in crystalline basement rock. In addition, it may be useful to move beyond the use of a representative waste package modeling approach to full representation of repository geometry, especially for repositories sited in the saturated zone. Some refinement and adaptation of existing transport simulation approaches may be needed in support of that improved representation. Studies to better define the degree of detail required in transport models would also be useful to help design efficient and adaptive licensing strategies in an evolving regulatory environment.

Low-porosity geologic media such as clay formations include nanometer scale pores. For example, in a compacted bentonite, the pores are so small that the electrical double layers balancing the charge of the bentonite (typically negative at circumneutral pH) overlap, thus potentially excluding anions altogether, or creating a deficiency of them within the diffuse electrical double layer balancing the surface mineral charge. It is common to observe the effects of anion exclusion, which in a diffusive regime is reflected by a late arrival (or release) of the negatively charged ions relative to neutral species. It has been shown that radionuclides may behave differently in a nanopore confinement than in large pores. The diffusion and sorption of radionuclides in nano-scale pores are particularly interesting. Better characterization and conceptualization of diffusion in small pores (e.g., clays) and membrane effects are needed, together with generic R&D on the EDZ in clay environments (Section 4.6.1) and on engineered materials, buffers/backfills (Section 4.5.4) that could be used as part of the repository system.

Experience with repository performance assessments in this country and abroad suggests that radiological risk is usually driven by very mobile radionuclides such as I-129 and, counter intuitively, by strongly sorbing radionuclides such as isotopes of plutonium. Strongly sorbing radionuclides contribute in performance assessments because radionuclides that strongly associate with stationary mineral surfaces also tend to associate with surfaces on mobile colloids. However, colloid facilitated transport (CFT) may have been overestimated in previous performance assessments because many aspects of CFT are not well constrained, and thus they are often modeled using pessimistic bounding assumptions necessary. On the other hand, evidence suggests that Pu travels further than Kd models would predict. There is a need for improved models that can reproduce this observed behavior. Important uncertain processes and parameters associated with CFT include desorption processes and rates, colloid immobilization processes and associated parameters, the degree to which colloids behave as heterogeneous populations in the subsurface, the role of chemical and flow transients in mobilizing and immobilizing colloids, and colloid generation processes. There is a need for the development of improved techniques for in situ characterization and quantification of colloids. There are opportunities to work with the NAGRA working group on colloids.

Issues include colloid formation and a better understanding of formation from clay materials, sorption and desorption (attachment and detachment), and colloid instability in high ionic strength environments. To better understand colloid transport, there are needs to better understand and reduce uncertainty in colloid formation and stability, a need to better represent heterogeneous behavior of colloids, and a need for better understanding of colloid transport behavior in unsaturated environments to reduce conservatisms in current models. There is a fundamental need to better understand size dependence and multiple rate kinetics and irreversibility of radionuclide sorption onto colloids.

The rate of desorption of radionuclides from colloids is a particularly problematic parameter. Although irreversible sorption can significantly enhance transport relative to the colloid-free case, even slow desorption can mitigate this transport enhancement. As a useful rule of thumb, CFT will be significantly reduced when desorption time scales are comparable to or less than colloid transport time scales over the distance of interest. However, given that transport time scales can be extremely long, experimental measurements of relevant desorption rates may be very difficult or impractical, especially considering the competitive processes that will occur in real systems that will likely have much more immobile surface area available for sorption than colloid surface area (a situation that is not easily replicated in long-duration experiments). Moreover, analyses of radionuclide sorption/desorption experiments onto colloids have revealed more than one governing rate, with initial rates tending to be faster and thus nonconservative relative to rates observed at later experiment times.

To complicate matters further, transport depends non- monotonically on the desorption rate if colloids are filtered (permanently immobilized). This non-monotonic dependence means that if credit is taken for colloid filtration in a repository performance assessment, it will be difficult to identify a desorption rate that is bounding. Another potential complication in assessing colloid-facilitated transport is that the relatively low colloid concentrations may make it possible to saturate sorption sites with radionuclides, especially if radionuclides have a higher affinity for colloids than other system surfaces and if multiple radionuclides are competing for the same sites. Nonlinear sorption models would then be necessary. Invoking a limited number of sorption sites is one strategy for bounding colloid-facilitated transport and may yield a useful pessimistic bound in some circumstances. Saturation of colloid sorption sites is more likely to be an issue in the near field where radionuclide concentrations are highest.

Yet another potential complication in assessing colloid-facilitated transport is that colloid mobility itself is not well understood and colloids in the subsurface will likely not behave as a homogeneous population. A small fraction of natural colloids may move more freely (without retardation or filtration) in the subsurface, for example. If such a subpopulation of highly mobile colloids exists, then it would be important to determine whether this population also has an inherently greater affinity for radionuclides (slower desorption rates) than the bulk colloid population, thus exacerbating CFT.

Additional key uncertainties and information gaps for CFT include (1) poorly constrained generation rates and transport characteristics of colloids that are produced in the near field from engineered barrier degradation and have essentially irreversibly sorbed radionuclides (possibly embedded in the colloid matrix), and (2) the unknown effects of geochemical and hydrological transients on colloid mobilization and transport over the long time scales of repository performance assessments.

To summarize, CFT may be a significant transport mechanism for sparingly soluble and strongly sorbing radionuclides such as plutonium, which would be relatively immobile otherwise; kinetic limitations on radionuclide desorption are necessary to significantly enhance transport; desorption rates are critically important but are poorly constrained and difficult to measure; a key mitigating process, colloid filtration, is also poorly constrained and difficult to verify. Laboratory experiments will provide data to help understand fundamental colloid transport processes and radionuclide sorption/desorption onto colloids, allowing improved understanding and more realistic transport modeling. In addition, field-scale experiments will contribute to understanding scale-up of these processes to the field scale.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to radionuclide transport to support site screening because sufficient information exists in available materials to support conclusions about the general character of the radionuclide transport. Laboratory and field investigations of radionuclide transport, including that from underground research laboratories in various media throughout the world performed in support of nuclear waste disposal programs, provide a comprehensive data base of information sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of chemical processes/transport to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of natural system radionuclide transport processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of natural system radionuclide transport processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of natural system radionuclide transport processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of natural system radionuclide transport processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of chemical processes/transport to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of transport related chemical processes, particularly reduced uncertainty, and how the transport processes impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of natural system radionuclide transport processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of natural system radionuclide transport processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of natural system radionuclide transport processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of natural system radionuclide transport processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of chemical processes/transport to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of the transport related chemical processes, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of natural system radionuclide transport processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of natural system radionuclide transport processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of natural system radionuclide transport processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of natural system radionuclide transport processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with chemical processes/transport is projected to be **medium** for all three repository media and borehole disposal.

4.6.9 Biological Processes

Transport of dissolved radionuclides in the host rock and other geologic units is affected by microbial activity in the host rock and other geologic units (non-host rock). The effects of biological processes are manifested as production of complexants and microbial colloids, as enhanced by biodegradation and bioaccumulation. Similar to purely chemical complexants, there is a potential for enhanced transport of radionuclides associated with organic complexants.

Ability to generic R&D

The ability to address biological processes through generic R&D is considered partial and site-specific. The parameters needed to address biological processes are site-specific. Research and development of characterization methods could be done generically, and would focus on improved models of biological processes affecting radionuclide transport, and the effects on long-term performance. Site-specific information would ultimately be needed to evaluate specific biological processes. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

Importance to Safety Case

The importance of biological processes to the safety case was judged to be **medium** for performance (safety analysis); **not applicable** for design, construction and operations; and **medium** for overall confidence.

State of the Art

There are fundamental gaps in the methods of characterizing biological processes and their effects on the repository system, and fundamental gaps in available data. In particular, emphasis on microbial activity in host media and the other geologic units could prove useful. Better methods to quantify microbial activity in subsurface environments and its impact on water chemistry are needed (Section 4.6.8). It would be worthwhile to build upon other work underway by DOE Environmental Management, the Office of Science, and the WIPP to better understand how microbes may be limited by the repository environment.

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to biological processes to support site screening because sufficient information exists in available materials to support conclusions about the general character of the biological processes. Laboratory and field investigations of biological processes., including that from underground research laboratories in various media throughout the world performed in support of nuclear waste disposal programs, provide a comprehensive data base of information sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of biological processes to the Site Selection decision point is similar for the rock types examined; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of biological processes to the Site Characterization and Disposal System Design decision point is similar for the rock types examined. For this decision point, improved representation of the biological processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would likely be useful.

- For repository systems developed in crystalline rock, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.

- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of biological processes to the Site Suitability and Licensing decision point is similar for the rock types examined. For the Site Suitability and Licensing decision point, further improved representation of the biological processes, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient wi**th respect to the decision.
- For repository systems developed in clay or shale, the understanding of biologic processes and properties is of **low** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with biological processes is projected to be **low** for all three repository media and borehole disposal.

4.6.10 Thermal Processes

Thermal management strategies, while closely related to repository design, have an important role in understanding flow and transport in the geosphere. The repository thermal loading strategy must of course be driven by consideration of heat effects on the engineered barrier system (Section 4.5.12); there is however, the potential for significant thermal impacts to the host rock and other geologic units that must be considered before finalizing a thermal loading strategy.

Repository heat induces thermal effects on flow in the geosphere; effects include the potential for altered saturation and relative humidity, including dry-out and resaturation, altered gradients, density, and/or flow pathways, vapor flow, and condensation. Thermally-driven flow in the geosphere can lead to convection, thermally-driven buoyant flow, heat pipes in the geosphere, and vapor flow. Repository heat also can lead to thermal effects on chemistry, transport, and microbial activity in the geosphere, resulting in mineral precipitation or dissolution, and altered solubility, thermal diffusion (Soret effect), and thermal osmosis.

The repository thermal loading strategy is of particular concern for thermal-mechanical effects on the host rock and the other geologic units of the geosphere. Thermal expansion, tensile and compressive stresses, and altered properties of fractures, faults, and the rock matrix are possible. There can also be thermal-chemical alteration of the host rock and the other geologic units, including, mineral precipitation, dissolution, alteration of minerals with attendant volume changes, and altered properties of fractures, faults, the rock matrix, and the formation of near-field chemically altered zones (rind).

Heat conduction is well understood and has been modeled quite successfully in various repository programs, exploratory facilities, and other tests.

Ability to Address through Generic R&D

The ability to address thermal processes through generic R&D is considered partial and site-specific. The parameters needed to address thermal processes are site-specific. Research and development of characterization methods could be done generically, and would focus on improved models of thermal processes affecting radionuclide transport, and the effects on long-term performance. Site-specific information would ultimately be needed to evaluate specific thermal processes. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

Importance to the Safety Case

The importance of thermal processes to the safety case was judged to be **medium** to **high**, primarily for thermal effects on chemistry, for performance (safety analysis); **medium** for design, construction and operations; and **medium** to **high** (thermal effects on chemistry) for overall confidence.

State of the Art

While there is a need for improved representation of repository-induced thermal effects on flow in geosphere such as thermally-driven flow (convection) and thermally-driven buoyant flow and the formation of heat pipes in unsaturated media, much is known from current geothermal studies. Further, there is a need for improved representation of natural geothermal effects when considered with superposition of the repository effects. Improved representation would be needed for unsaturated sites.

The state of the art for modeling thermal processes is limited by calculational efficiency; high performance computing may provide for more transparent modeling of large-scale, complex systems. There is a need for improved representation of the thermal, thermal-mechanical, and thermal-chemical effects on geosphere environments, although no additional thermal data (i.e., properties) are needed for generic R&D. Development of understanding of thermal processes and their effects needs to be done in collaboration with engineered barrier system R&D, with particular emphasis on thermal loading and host rock and other geologic unit thermal response. There is a large gap in thermodynamic data for elevated temperatures, potentially applicable to both the engineered and natural systems.

Heat and mass transfer behavior at interfaces including between the canister, buffer, tunnel lining, ground support, and host rock, need to be evaluated. The possibility for sustained disequilibrium between the host rock, repository openings, and engineered barrier system components, should be investigated.

For deep borehole disposal, simulation of multi-borehole arrays should be undertaken for a system consisting of 10 to 100 individual boreholes. Such investigations could evaluate the potential for communication between boreholes, thermal or hydrologic interactions, and large-scale responses to borehole arrays. Performance assessments are needed to establish a better sense of the potential performance variability that might be expected in multiple implementations of borehole disposal fields.

Assuming that young, heat-generating wastes must be either stored or disposed directly, there is a need to understand the general thermal considerations for siting and screening. Work is needed to define metrics representing thermal management, e.g., host rock thermal conductivity, solubility vs. temperature, other geologic sensitivities to elevated temperature, etc.

A useful generic study on thermal management could catalog reference thermal loading conditions, using reference design concepts. Thermal limits associated with different waste streams, media, and design concepts could be characterized. For example, for HLW (containing mainly fission products) tabulate the waste packaging, decay storage, and repository areal thermal loading required in clay, salt, crystalline rock, and deep borehole settings. Such a study could be repeated for used fuel and other wastes and waste forms.

Such a generic study could also identify the sources of thermal limits, based on waste isolation performance evaluations by the U.S. and international programs. For example, given the prevalence of below-boiling contraints, specify how and why such constraints would apply to a repository in the U.S. Consider the coupled-process issues that would affect performance in saturated systems under several hundred meters of hydrostatic head, and how these have been evaluated using U.S. and international experience. Include deep borehole disposal, for which even higher temperatures have been predicted. Examine the standard contract, and identify the advantages or cost savings in waste disposal that could result from changes in thermal management, if those contracts were revised. Also, evaluate stakeholder and licensing perspectives on thermal management, to summarize the extent to which predicted elevated temperatures have driven stakeholder or licensing interactions.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:

There is little or no need to complete additional R&D pertaining to thermal processes to support site screening because sufficient information exists in available materials to support conclusions about the general types and nature of thermal process effects on repository systems. Thermal studies, particularly those from underground research laboratories in various media throughout the world provide a comprehensive data base of likely effects sufficient to support site screening.

Site selection [environment feasibility, concept feasibility, site designation]:

The importance of Thermal Processes to the Site Selection decision point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of thermal processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of thermal processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of thermal processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of thermal processes and properties is of **high** importance and the available

information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]: The importance of thermal processes to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of the thermal processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of thermal processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of thermal processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of thermal processes and properties is of **medium** importance and the available information is **partially** sufficient with respect to the decision.
- For repository systems developed in clay or shale, the understanding of thermal processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of thermal processes to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of the thermal processes, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of thermal processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of thermal processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of thermal processes and properties is of **medium** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of thermal processes and properties is of **high** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with thermal processes is projected to be **low** for crystalline media**, low** for salt media, **medium** for shale media, and **medium** for borehole disposal in crystalline rock.

4.6.11 Nuclear Criticality

Transport of dissolved radionuclides from the engineered barrier system, through the excavation damage zone, into the host rock and then through the other geologic units must consider the possibility that certain radionuclides could become concentrated at a particular location. If the concentration becomes sufficiently large, and chemical conditions are appropriate, the formation of a critical configuration cannot be discounted, and a self sustaining nuclear reaction (i.e., criticality) could occur.

Such a criticality reaction is of very low probability, solubility limits of uranium and plutonium are low, and the conditions likely to lead to high enough fissile material concentrations (e.g., a redox front, or some other type of sink that could trap and segregate heavy nuclides) are not characteristic of a hydrologic environment likely to be selected for a repository location.

<u>Ability to Address through Generic R&D</u>

The ability to address external nuclear criticality through generic R&D is considered partial, and site-specific, and design-specific. The parameters needed to address nuclear criticality are site-specific. Research and development of modeling methods could be done generically. Features, events and processes related to external nuclear criticality are likely to be screened out. Generic R&D would focus on improved models of nuclear criticality, the design and development of applicable critical benchmark experiments for computational validation, and the effects on regulatory compliance. Site-specific information would ultimately be needed to evaluate specific nuclear criticality processes and material degradation and accumulation rates. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

<u>Importance to Safety Case</u>

The importance of nuclear criticality in the natural system to the safety case was judged to be **low** for performance (safety analysis); **not applicabl**e for design, construction and operations; and **low** for overall confidence.

<u>State of the Art</u>

Nuclear criticality processes are well understood. Modeling tools need to be in place and validated for screening calculations. Fuels from advanced fuel cycles that would be directly disposed and/or advanced waste forms may have different material characteristics affecting fissile solubility rates, necessitating the need to assess the potential for nuclear criticality. Capability to simulate and defensively evaluate risks and consequences associated with criticality excursions is needed. Critical benchmark experiment design and development for validation of external critical configurations are also necessary.

<u>Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points</u>

Site screening [broad siting, site down-select]:	There is little or no need to undertake R&D pertaining to nuclear criticality to support site screening because the repository system is not well enough known at the time of screening to ascertain the likelihood of a criticality event occurring.
Site selection [environment feasibility, concept feasibility, site designation]:	The importance of nuclear criticality to the Site Selection decision point is similar for the rock types examined; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically. • For repository systems developed in crystalline rock, the understanding

of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.

- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of nuclear criticality in the natural system is o**f low** importance and the available information is **sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]:

The importance of Nuclear Criticality to the Site Characterization and Disposal System Design decision point is similar for the rock types examined. For this decision point, improved representation of nuclear criticality processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would likely be useful.

- For repository systems developed in crystalline rock, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of nuclear criticality in the natural system is of **low** importance**.** The available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of nuclear criticality in the natural system is o**f low** importance and the available information is **sufficient** with respect to the decision.

Site suitability [licensing]:

The importance of nuclear criticality to the Site Suitability and Licensing decision point is similar for the rock types examined. For this decision point, further improved representation of nuclear criticality, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of nuclear criticality in the natural system is of **low** importance and the available

information is **sufficient** with respect to the decision.

- For repository systems developed in clay or shale, the understanding of nuclear criticality in the natural system is of **low** importance and the available information is **sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with nuclear criticality is projected to be **low** for all three repository media and borehole disposal.

4.6.12 Gas Sources and Effects

There is a possibility of gas sources in spent nuclear fuel and gas generation by radiolysis and corrosion of metallic barrier materials. The presence of gasses in the flow system can result in two-phase flow, vapor or air flow, gas bubbles, and altered gradients and/or flow pathways. Gas generation as a result of radiolysis and corrosion of metallic barrier materials can, to a large extent, be addressed during design; if it is present in the flow system, however, it has the potential to modify the flow system, the transport of radionuclides, and local redox chemistry. If the governing regulations require analyses of transport to the receptor by all pathways, then gas phase release and transport in geosphere must be considered.

Ability to Address through Generic R&D

The ability to address gas sources and their effects through generic R&D is considered partial and site-specific. The parameters needed to address gas sources and their effects are site-specific. Research and development of characterization and modeling methods could be done generically. Features, events and processes related to gas sources and effects are likely to be screened out.

Generic R&D would focus on improved characterization techniques and models of gas sources and their effects on transport of radionuclides. Site-specific information would ultimately be needed to evaluate specific gas source processes. The understanding of these processes and their representation developed through generic R&D would support such site-specific evaluations.

Importance to Safety Case

The importance of gas sources and their effects to the safety case was judged to be **medium** to **low** for performance (safety analysis); **low** to **not applicable** for design, construction and operations; and **medium** to **low** for overall confidence.

State of the Art

There are fundamental gaps in the methods of characterizing sources of gas and their effects on the repository system, and fundamental gaps in available data. There is relevant research in European programs (GAST - NAGRA, FORGE - small scale modeling) and in Japan. Gas Transport in the geosphere is well understood

Importance of Issue/Process and Adequacy of the Current State of the Art Relative to Decision Points

Site screening [broad siting, site down-select]:	There is little or no need to complete additional R&D pertaining to gas sources and their effects to support site screening because sufficient information exists in available materials to support conclusions about the general types and nature of gas sources and their effects on repository systems. Laboratory studies provide a comprehensive data base of likely effects sufficient to support site screening.
Site selection	The importance of gas sources and effects to the Site Selection decision

[environment feasibility, concept feasibility, site designation]: point varies by rock type; because the site selection process and ultimate decisions depend primarily on geologic attributes of the site, information beyond that available from general sources is needed. For this decision point the focus will be on the geologic character, and design-related aspects will initially be treated generically.

- For repository systems developed in crystalline rock, the understanding of gas sources and effects is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of gas sources and effects is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of gas sources and effects is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of gas sources and effects is of **low** importance and the available information is **partially sufficient** with respect to the decision.

Site characterization and disposal system design [site characterization]: The importance of gas sources and effects to the Site Characterization and Disposal System Design decision point varies by rock type. For this decision point, improved representation of the gas sources and effects processes, particularly reduced uncertainty, and how the processes impact and are affected by the developing design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of gas sources and effects is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding of gas sources and effects is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of gas sources and effects is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of gas sources and effects is of **low** importance and the available information is **partially sufficient** with respect to the decision.

Site suitability [licensing]: The importance of gas sources and effects to the Site Suitability and Licensing decision point varies by rock type. For this decision point, further improved representation of gas sources and effects, particularly reduced uncertainty, validated models, and the details of how the processes impact and are affected by the design, would need to be demonstrated.

- For repository systems developed in crystalline rock, the understanding of gas sources and effects is of **low** importance and the available information is **sufficient** with respect to the decision.

- For repository systems developed in deep boreholes, assumed to be in crystalline rock, the understanding gas sources and effects is of **low** importance and the available information is **sufficient** with respect to the decision.
- For repository systems developed in salt, the understanding of gas sources and effects is of **low** importance and the available information is **partially sufficient** with respect to the decision.
- For repository systems developed in clay or shale, the understanding of gas sources and effects is of **low** importance and the available information is **partially sufficient** with respect to the decision.

Overall Importance

Overall, the importance of conducting R&D on issues associated with gas sources and effects is projected to be **low** for all three repository media and borehole disposal.

4.7 Surface Environment Issues / R&D Opportunities

Conducting R&D to address issues associated with the surface environment is of generally low priority within the UFDC. Much of the R&D that would be conducted would be specific to a geologic disposal site identified in the future and generic R&D is generally not applicable.

4.7.1 Surface Characteristics

Surface characteristics (topography, surface morphology, surficial soil type, surface water, and biosphere characteristics) are site-specific, and generic R&D by the UFDC to address these issues is not warranted.

4.7.2 Mechanical Processes

Mechanical processes in the surface environment (erosion, deposition) are site-specific, and generic R&D by the UFDC to address these issues is not warranted.

4.7.3 Hydrologic Processes

Hydrologic processes in the surface environment (surface runoff, evapotranspiration, infiltration, and recharge) are site-specific, and generic R&D by the UFDC to address these issues is not warranted.

4.7.4 Chemical Processes

R&D related to radionuclide speciation and solubility in the biosphere could be conducted without the identification of specific sites. However, generic R&D described above to better understand speciation and solubility controls in a variety of media would be applicable to biosphere environments. These processes are expected to be of **low** importance to the safety analysis, and **low** importance to the overall confidence in the safety case due to the low radionuclide concentrations that would ultimately migrate to the biosphere.

4.7.5 Radionuclide Transport Processes

R&D related to radionuclide transport processes in the biosphere could be conducted without the identification of specific sites. However, these processes are well understood and used in many different applications. They are of **low** to **medium** importance to the safety analysis, and low importance to the overall confidence in the safety case.

While there is no near-term need, improved models for representing process could potentially build confidence in the safety case. However, much of the R&D in this area is beyond the scope of the UFDC and falls under the purview of such organizations as the International Commission on Radiological Protection or the National Council on Radiation Protection and Measurement.

4.7.6 Biological Processes

Addressing issues associated with biological processes in the surface environment would be site-specific, and generic R&D by the UFDC to address these issues is not warranted.

4.7.7 Thermal Processes

Addressing issues associated with thermal processes in the surface environment would be site-specific, and generic R&D by the UFDC to address these issues is not warranted.

4.8 Human Behavior Issues / R&D Opportunities

R&D pertaining to human characteristics and lifestyle are beyond the scope of the UFDC. Addressing issues associated with land and water use would be site-specific, and generic R&D by the UFDC to address these issues is not warranted.

4.9 Biosphere Radionuclide and Contaminant Issues / R&D Opportunities

Conducting R&D to address issues associated with fate and transport of radionuclides or other contaminants in the biosphere is of low priority within the UFDC. Much of the R&D that would be conducted would be specific to a geologic disposal site identified in the future and/or is beyond the scope of the UFDC campaign. Generic R&D is generally not applicable.

4.9.1 Radionuclide/ Contaminant Considerations in Surface Environment

Radionuclide concentrations in biosphere media, in food products, and in non-food products depend on site-specific biosphere conditions (characteristics of the local population, type of agriculture, types of dwellings, etc.). Thus, generic R&D to address these issues is not warranted. In addition, R&D related to the migration of radionuclides in the biosphere is beyond the scope of the UFDC.

4.9.2 Exposure Modes

Exposure modes (ingestion, inhalation, and direct exposure) are well understood and used in many different applications. They are of **medium** importance to the safety analysis, and **low** importance to the overall confidence in the safety case.

While there is no near-term need, improved models for representing process could potentially build confidence in the safety case. However, much of the R&D in this area is beyond the scope of the UFDC and falls under the purview of such organizations as the International Commission on Radiological Protection or the National Council on Radiation Protection and Measurement.

4.9.3 Toxicity/Effects

Specific R&D related to this issue is beyond the scope of the UFDC campaign.

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APPENDIX A

UFDC Disposal R&D Roadmap Prioritization Information Matrix

(Separate Adobe Acrobat File)

APPENDIX B

UFDC Disposal R&D Roadmap Prioritization Information Matrix – Issue Scoring/Sorting and Sensitivity Analysis

The information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* was used to develop an overall priority score for each individual issue using the methodology described in Section 3.2. The sorted results are provided in an Adobe Acrobat file.

Figure B-1 summarizes the calculated scores for each individual issue. Using this graph and the sorted list of issues by priority score, the UFD Disposal R&D Roadmap development team selected two cutoffs to identify low, medium, and higher priority issues. These cutoffs were selected to correspond to the two "knees" shown in Figure B-1. These cutoffs also divide the number of issues in the high, medium, and low categories as shown, with a slightly smaller proportion being categorized as high. A large number of individual issues were evaluated to having zero priority. Issues could have a priority score of zero for any of the following reasons:

- The issue could not be addressed through generic R&D
- The issue would be fully addressed by conducting R&D on other issues, or
- The current level of information was judged to be completely sufficient at all decision points.

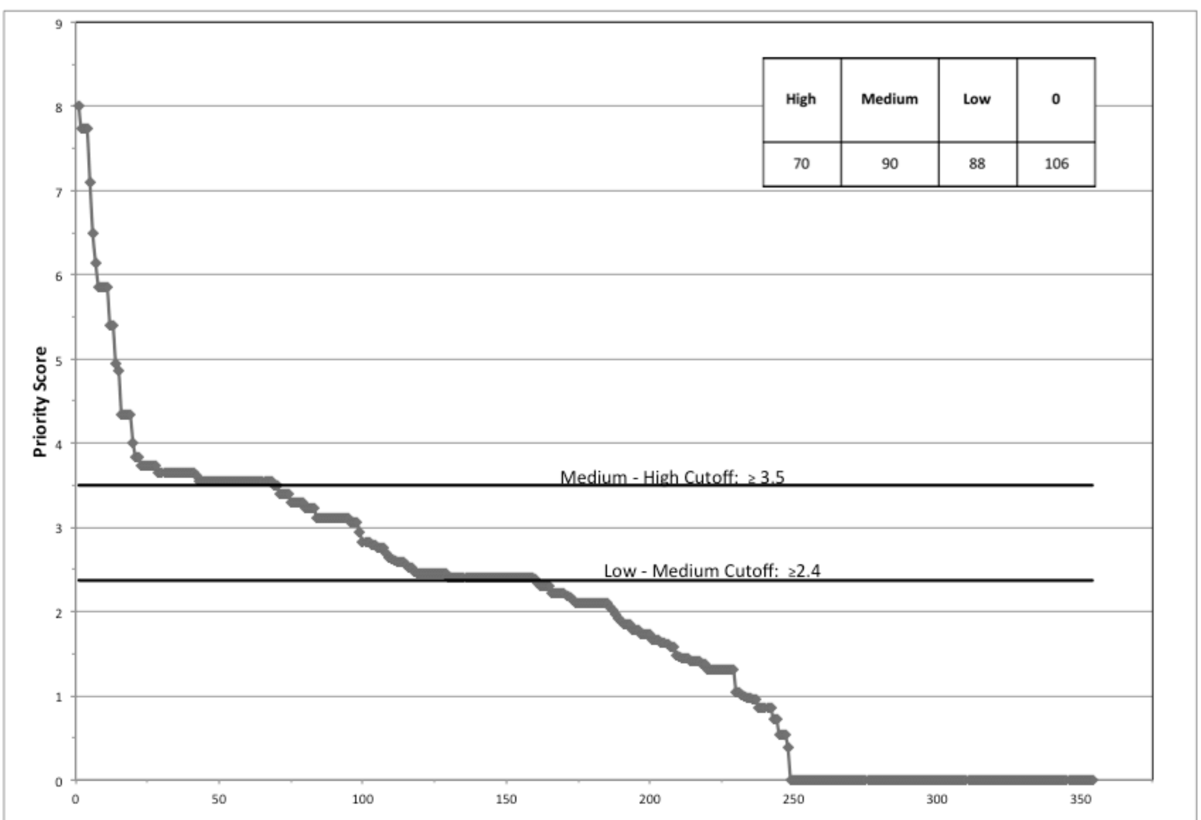

Figure B-1. Priority Ranking of Issues

Sensitivity to evaluation factor and input scores[6]

The UFD Disposal R&D Roadmap development team was interested in exploring the potential overlap between the three major components of the prioritization algorithm: importance to the safety case, importance to the decision points, and adequacy of the current information to support decisions. Understanding the sensitivity to each of these major factors will help (a) understand whether the prioritization matrix could be simplified when updates are required, and (b) indicate where efforts to update or confirm the evaluation results would have the biggest impact.. To examine this issue, three related sensitivity analyses were conducted. In each, the influence of a single factor on the overall priority score was effectively eliminated by setting it equal to a single value for every issue. So, for example, the importance to the safety case was assumed to be equal to a safety case score of "2" for every issue at every decision point (rather than being calculated from the input scores for each activity). Figures B-2, B-3, and B-4 illustrate the results of these analyses.

Each of these three figures shows a cross-plot of the base priority score (on the x-axis) and sensitivity priority score (on the y-axis). Figure B-2 compares the base priority with the priority that would be derived if the importance to the safety case were ignored. Without considering the importance to the safety case, differences in the resulting prioritization would be evident: for example, there are numerous issues that would have a score around 3.4 if the safety case were ignored (circled in Figure B-2), for which the priority score ranges from 0 to 3.8, covering all three priority classes. Figure B-3 shows a similar plot comparing the base priority with the priority that would be derived if importance to the decision point were ignored. And Figure B-4 compares the base priority to the priority that would result if the adequacy of information to support decisions were ignored. Each of these shows the same pattern, where the elimination of the sensitivity factors would lead to major changes in the priority ranking.

Based on these analyses, it appears the ranking is most sensitivity to the information adequacy, second to the importance of the issue to the decision points, and thirdly to the judged importance to the safety case. This is expected based on the values discussed in Section 3 and reflects the overall emphasis on applying higher priority to issues where information is necessary to support the nearer-term decision points (site screening and site selection).

[6] Revision 1 of the *UFDC Disposal R&D Roadmap Prioritization Information Matrix* resulted in changes to the overall priority score for only a few R&D issues. The trends identified in this sensitivity analysis are not affected.

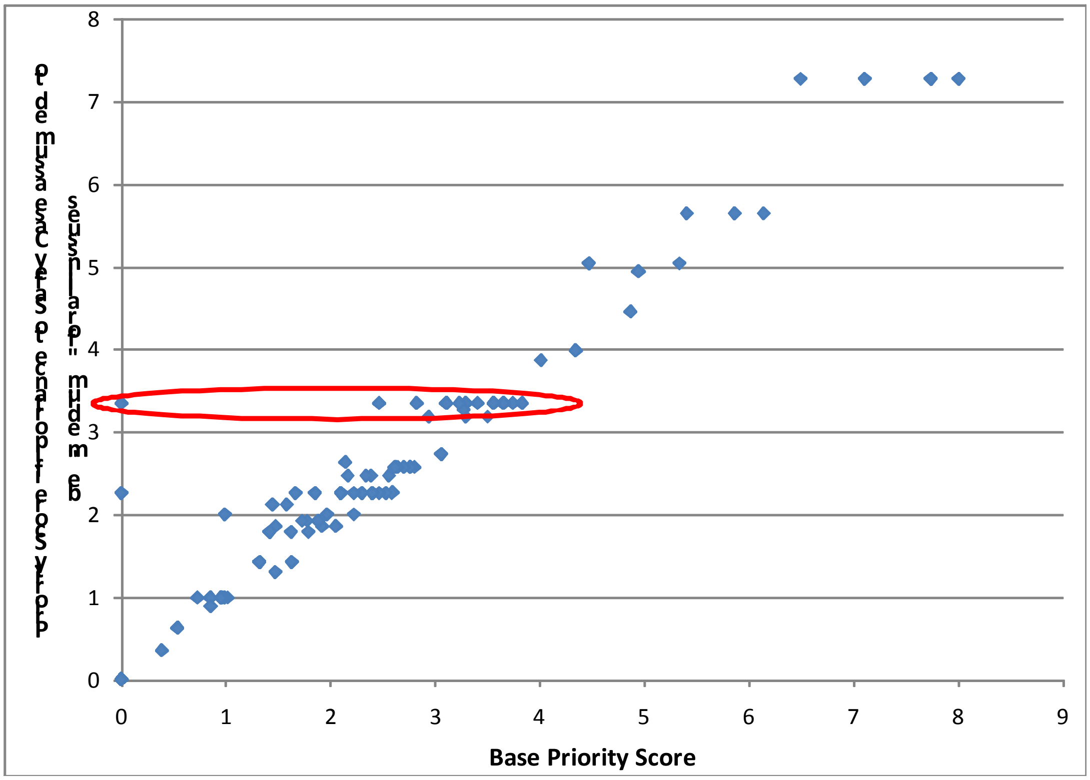

Figure B-2. Sensitivity of Prioritization to the Importance of an Issue to the Safety Case

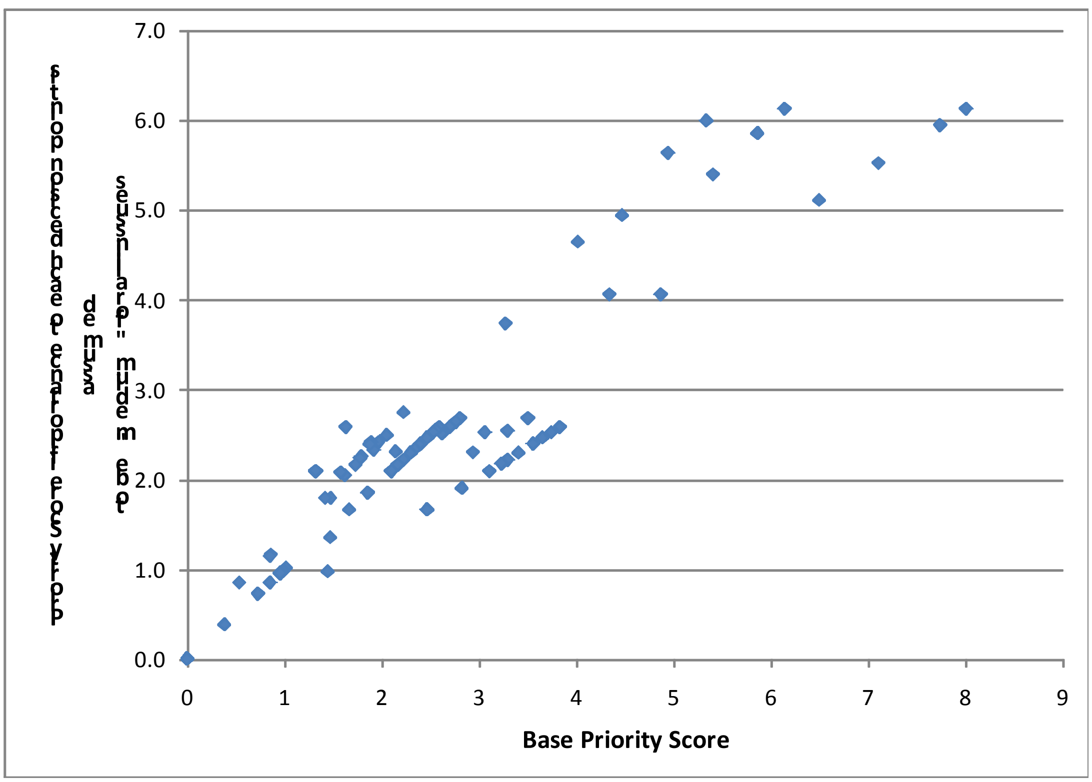

Figure B-3. Sensitivity of Prioritization to the Importance of an Issue to the Decision Points

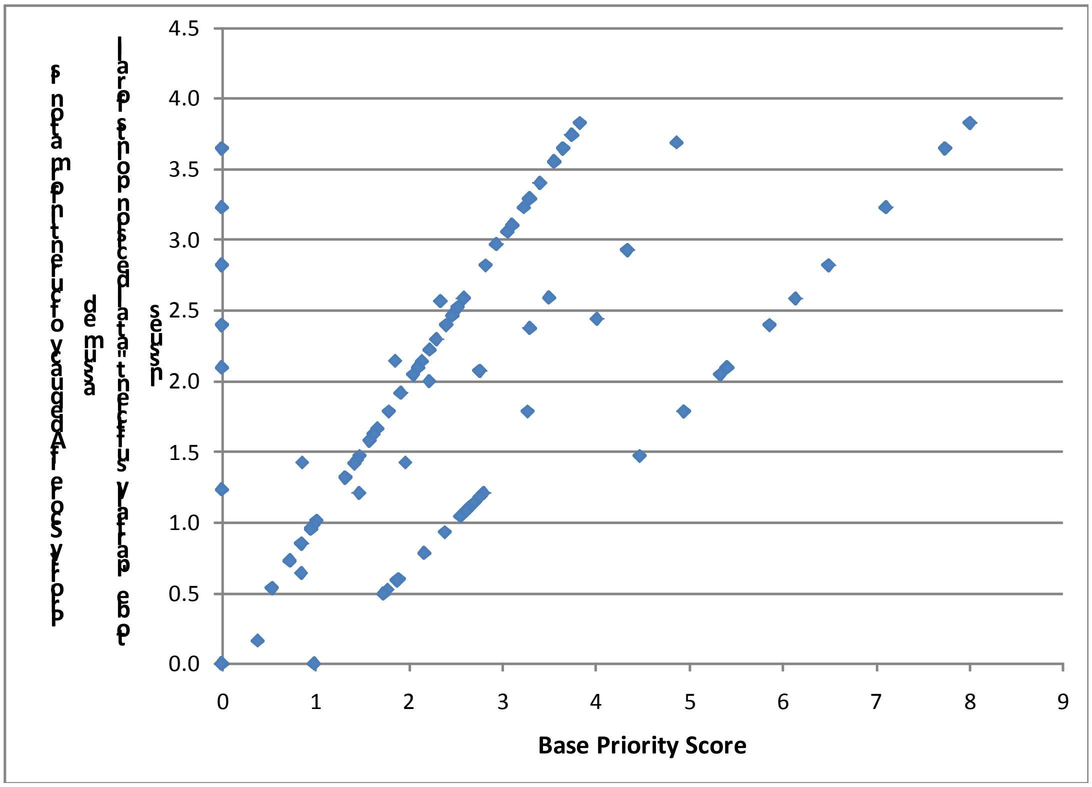

Figure B-4. Sensitivity of Prioritization to the Adequacy of Current Information to Support Decisions

Sensitivity to weighting factors

An additional sensitivity analysis was conducted to investigate alternative weighting of the importance of the different components of the safety case at the different decision points (Section 3.2). During the discussion leading to the development of the scores and weights for the prioritization algorithm, one of the UFD Disposal R&D Roadmap development team, while concurring with the base safety case importance weights that were used, suggested a sensitivity analysis be conducted using different weights as shown in the red font in Table B-1 below.

The results of this sensitivity analysis are shown in Figure B-5 as a cross-plot of the base and alternative priority score for each issue. Little sensitivity is observed.

Table B-1. Alternative Weighting of Importance of the Safety Case Components at Decision Points

	Safety case component		
Decision point (d)	Safety assessment	Design, construction, operations	Confidence
Site Screening	0.5	0.2	0.3
Site selection	0.50	0.20 **0.1**	0.30 **0.4**
Site characterization	0.50 **0.7**	0.2 **0.15**	0.3 **0.15**
Site Suitability	0.4	0.2	0.4

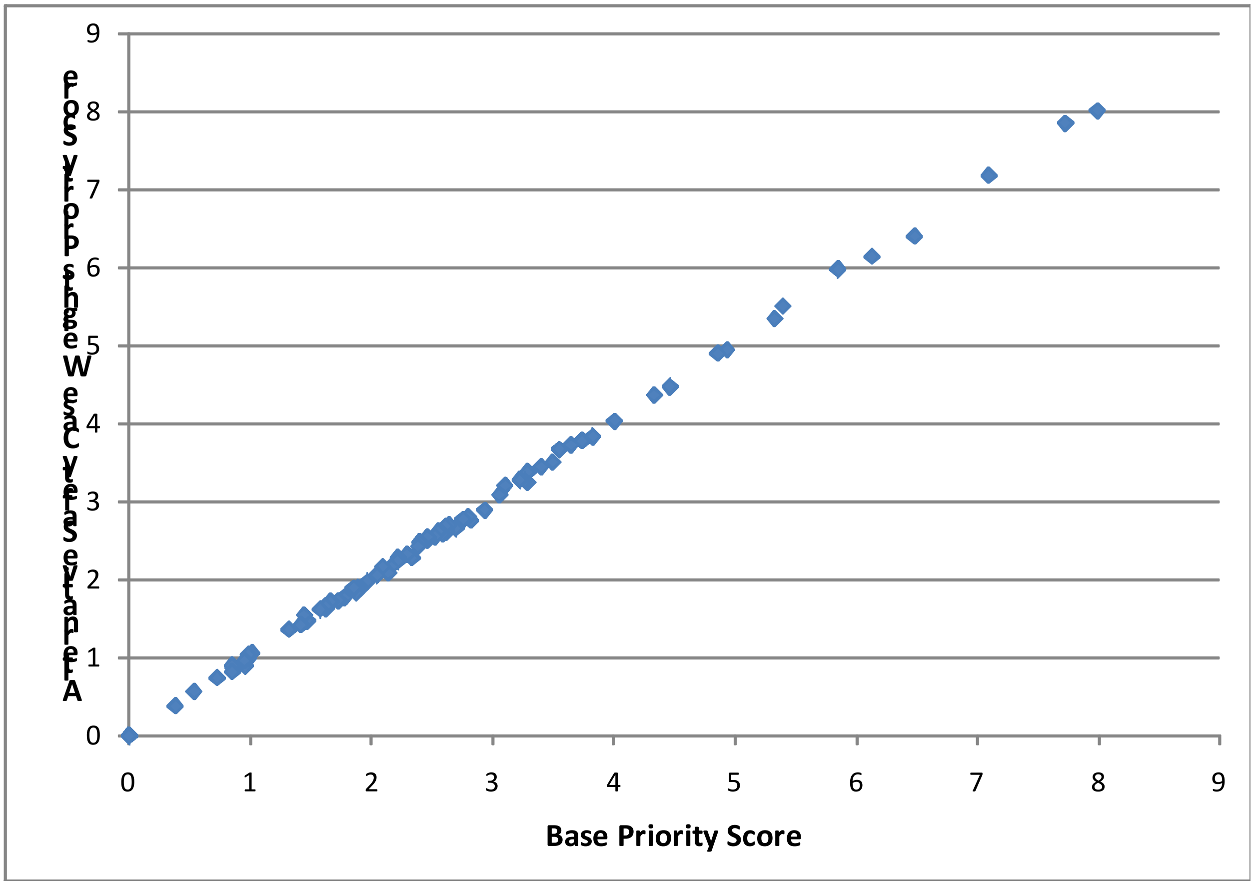

Figure B-5. Sensitivity of Alternative Importance to the Safety Case Weights