ESTABLISHMENT OF RESEARCH AND DEVELOPMENT PRIORITIES REGARDING THE GEOLOGIC DISPOSAL OF NUCLEAR WASTE IN THE UNITED STATES AND STRATEGIES FOR INTERNATIONAL COLLABORATION

Kevin McMahon, *kamcmah@sandia.gov*
Peter Swift, *pnswift@sandia.gov*
Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185 USA

Mark Nutt, *wnutt@anl.gov*
Mark Peters, *mtpeters@anl.gov*
Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439 USA

Jeff Williams, *Jeff.Williams@Hq.Doe.Gov*
US. Department of Energy, Washington, D.C., USA

Michael Voegele, *mvoegele@cox.net*
Complex Systems LLC, Las Vegas, NV

Jens Birkholzer, *JTBirkholzer@lbl.gov*
Lawrence Berkeley National Laboratory,

ABSTRACT

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

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

INTRODUCTION

The United States 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 the state of 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.

The management and disposition of UNF and/or HLW is fundamental to the nuclear fuel cycle. The U.S. currently utilizes a once-through fuel cycle storing UNF on-site in wet or dry storage with ultimate disposal in a geologic repository. The decision not to use the Yucca Mountain Repository may result in longer storage at reactor sites. Additionally, alternatives to the once-through fuel cycle are being considered and options explored under the DOE-NE Fuel Cycle Technology (FCT) program.

These factors lead to the need to develop strategies for managing radioactive wastes from any future nuclear fuel cycle and providing acceptable disposition pathways for all wastes regardless of fuel reprocessing scheme(s) and/or fuel cycle(s). Strategies developed will include the storing, transporting and disposal of radioactive wastes.

To address these needs, the DOE-NE established UFDC as part of the FCT program. The mission of the UFDC is to identify alternatives and conduct scientific research and development to enable storage, transportation and disposal of UNF and wastes from existing and future nuclear fuel cycles.

The UFDC Disposal R&D Roadmap[1] 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 knowledge gaps in issues related to nuclear waste repository disposal yet to be addressed. While this paper focuses on disposal related activities, similar efforts are underway to identify and prioritize research opportunities associated with the very long term storage of UNF. The UFDC is conducting its research and development activities in collaboration with university, industrial, and international collaborators.

U.S. participation in international UNF and HLW exchanges and cooperative/collaborative activities leads to safe management of nuclear materials, increased security through global oversight, and protection of the environment worldwide. Such interactions offer the opportunity to develop consensus on policy, scientific, and technical approaches. Dialogue to address common technical issues helps develop an internationally recognized foundation of sound science, benefiting the U.S. and participating countries.

The manner that the UFDC will cooperate and collaborate in the future is expected to change as R&D is conducted regarding long-term storage and the potential disposal of UNF and HLW in different geologic environments than was being considered by the DOE Office of Civilian Radioactive Waste Management (OCRWM) during the development of the Yucca Mountain geologic repository. While some continuation of on-going or recent cooperative and collaborative activities are expected to continue, the approach taken in these activities may be different than past activities given the changes in the U.S. waste management program. In

addition, new cooperative and collaborative activities with different scope than in the past may be undertaken.

UFDC RESEARCH AND DEVELOPMENT ROADMAP

The UFDC is currently evaluating the viability of mined repositories in three geologic media (salt, clay/argillites/shale, and crystalline rock), and, in addition to mined repository disposal, the use of deep boreholes in crystalline rock[2]. These disposal options selected are representative of reasonable 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. 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[2]. In addition, the UFDC is not performing R&D on unsaturated tuff media because the fact that the submitted a license application for the construction of a repository at Yucca Mountain, Nevada evidences the availability of sufficient knowledge.

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, in the context of the UFDC Disposal R&D Roadmap[1], 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 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[1] 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 by the UFDC and other geologic repository programs.

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. 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.

Identification of 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. A systematic process, centered around features, events, and processes (FEPs) important to the performance of a geologic disposal system, was used to identify R&D issues.

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. may change when considering future disposal sites. Congressionally directed changes to U.S. repository regulations incorporated recommendations of the U.S. National Academy of Sciences[3]; these changes were specific to a repository at Yucca Mountain, and were not applied to the generic regulations. 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[4].

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, high-level objectives for a disposal system are (developed from IAEA 2003)[4]:

- 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 lower-level 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.

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 FE) list[5]:

- Waste Form

- Waste Packaging
- Backfill/Buffer
- Seals
- Other Engineered Features (i.e., waste package supports, tunnel liners, etc.)
- 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 generic R&D issues.

Moreover, the FEPs categorization scheme examines the system from the perspective of individual components, and does not explicitly call out important interactions among system components. Such interactions are described as "cross-cutting" issues, and are explicitly included in the identification of generic R&D issues.

Research and Development Issues

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 processes identified in the UFDC FEP list[5] are used to develop the comprehensive set of issues that were considered in developing the UFDC Disposal R&D Roadmap[1].

Disruptive events represent another set of issues that must be considered. However, the issues associated with disruptive events (for example, seismicity and volcanism) are site-specific and would depend on the disposal system design. Further, the potential for human-induced disturbance is likely to be defined within the regulatory framework. 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).

A total of 206 R&D issues were identified for subsequent characterization.

Characterization of R&D Issues

With the R&D issues identified, the next step was their characterization. Several categories of information were used to evaluate and prioritize each of the identified R&D issues.

Generic Applicability

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 in the U.S.).

- 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 in the host rock can be developed without site-specific data from an actual site considered for disposal in the U.S., but ultimately site and design characteristics will determine the actual parameters and evolution of those thermal processes. However, it is recognized that data from representative geologic environments elsewhere (salt, clay/argillites/shale, and crystalline rock) should be utilized for generic R&D, to ensure that the models and methods work for the desired purpose. As pointed out later, international collaboration may provide access to relevant data and information.

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) 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.

Of the 206 R&D issues evaluated, 52 were evaluated as not being amenable to generic R&D and were not further evaluated. This not meant to imply that these issues are not important, but that they cannot be addressed through generic R&D.

Importance to the Safety Case

A critical piece of information needed to prioritize the remaining R&D issues is their importance to the safety case. The UFDC R&D program uses the safety case definition given by the OECD/NEA[6] to define the components considered (e.g., safety analysis, safety concept) in evaluating the R&D issues.

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. The UFDC

disposal R&D program is focusing primarily on supporting the development of a future safety assessment basis. 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.

The issues must also be evaluated for their importance to the design and construction of disposal systems (system concepts). 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[6]. In order to develop its R&D program, the UFDC is developing one or more safety concepts or aspects of the safety concepts for the generic disposal environments under consideration (at a conceptual level).

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.

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.

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. 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) are lacking

- 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

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 below.

UFDC Disposal R&D Roadmap Prioritization Information Matrix

A matrix was developed to document the information collected for each of the categories discussed above 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©.

Table 1. Information Needs at Decision Points

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?)

Table 1. Information Needs at Decision Points (continued)

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)

UFDC Disposal R&D Roadmap Prioritization Information Matrix

A matrix was developed to document the information collected for each of the categories discussed above 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©.

Focused development of the UFDC Disposal R&D roadmap began with a workshop held 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 and information obtained from additional reviews conducted by the UFDC during 2010 were used to identify potential R&D topics that may warrant consideration by the UFDC, but no effort was made at that time to prioritize those topics.

A second workshop was held 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 using the criteria described above to obtain information that would enable prioritization of the issues. This workshop resulted in the initial iteration of 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, primarily to fill in information gaps and to clarify discussions regarding categorization. The matrix was subsequently provided to workshop participants and a broader group of researchers within the UFDC for review. Their feedback was incorporated into the final *UFDC Disposal R&D Roadmap Prioritization Information Matrix*.

The UFDC participants used published information regarding the feasibility and performance of geologic disposal facility concepts developed throughout the world. Recently, three reports were published by Sandia National Laboratories that investigated the feasibility of different disposal concepts and media within the U.S (deep boreholes[7], shale[8], and salt[9]). These reports, which provide a concise discussion of issues for different geologic disposal media and concepts, were also used in the development of the UFDC Disposal R&D Roadmap:

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.

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

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.

Information categories and scores were developed for each R&D 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. Value measures were assessed from participants at a UFDC Disposal R&D Roadmap development team workshop (UFDC researchers, UFDC management, and DOE-NE staff). The scores, weights, and overall algorithm reflect a consensus among the workshop participants, but can be changed to reflect differing priorities.

Summary of Results

This section presents 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. Further detail can be found in the UFDC Disposal R&D Roadmap[1].

The *UFDC Disposal R&D Roadmap Prioritization Information Matrix*, includes information for each issue that could be addressed with generic R&D (154 total) under higher-level topical areas. The priority scoring of individual issues was used to determine an overall ranking of each broad topical area – low, medium, and high. It must be recognized that the discussion and ranking herein are subjective, but are informed by the individual issue priority rankings that were developed based on the information contained in the *UFDC Disposal R&D Roadmap Prioritization Information Matrix*. While a quantitative score was developed, 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 the UFDC Disposal R&D Roadmap[1] 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 2.

Table 2. 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 priority rankings for the engineered system is presented in Table 3, broken down by the primary engineered component and the likely set of materials that could be considered for use 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 was identified as being a key R&D need.

A synopsis of the results of the prioritization ranking for the natural system is presented in Table 4. 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.

Table 3. Synopsis of the Results of the Priority Ranking for the Engineered System: Waste Form and Waste Package

WASTE MATERIALS → SNF, Glass, Ceramic, Metal	
INVENTORY	Low
WASTE FORM	High
WASTE PACKAGE MATERIALS: Steel, Copper, Other Alloys, Novel Materials	
WASTE CONTAINER	High
MECHANICAL PROCESSES	Medium
HYDROLOGIC PROCESSES	Low
CHEMICAL PROCESSES - CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
CHEMICAL PROCESSES - TRANSPORT	Low
- Advection, diffusion, and sorption	Medium
BIOLOGICAL PROCESSES	Low
THERMAL PROCESSES	Medium
GAS SOURCES AND EFFECTS	Low
RADIATION EFFECTS	Low
NUCLEAR CRITICALITY	Low

Table 3. Synopsis of the Results of the Priority Ranking for the Engineered System: Waste Form and Waste Package (continued)

BUFFER / BACKFILL MATERIALS → Cementitious, bituminous, mixed materials: clay, salt, crystalline environments	
BUFFER/BACKFILL	High
MECHANICAL PROCESSES	Medium
HYDROLOGIC PROCESSES	Medium
CHEMICAL PROCESSES - CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
CHEMICAL PROCESSES – TRANSPORT	Medium
- Colloid facilitated transport	Low
BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
THERMAL PROCESSES	Medium
GAS SOURCES AND EFFECTS	Medium
RADIATION EFFECTS	Low
NUCLEAR CRITICALITY	Low
SEAL / LINER MATERIALS → Cementitious, Asphalt, Metal, Polymers	
SEALS	Medium
OTHER EBS MATERIALS	Medium
MECHANICAL PROCESSES	Medium
HYDROLOGIC PROCESSES	Low
- Flow through seals	Medium
CHEMICAL PROCESSES – CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
CHEMICAL PROCESSES – TRANSPORT	Low
- Advection, diffusion, and sorption	Medium
BIOLOGICAL PROCESSES	Low
THERMAL PROCESSES	Medium
GAS SOURCES AND EFFECTS	Low
RADIATION EFFECTS	Low
NUCLEAR CRITICALITY	Low

Table 3. Synopsis of the Results of the Priority Ranking for the Engineered System: Waste Form and Waste Package (continued)

OTHER MATERIALS → Low pH Cements, Salt-Saturated Cements, Geo-polymers, Barrier Additives	
OTHER EBS MATERIALS	Medium
MECHANICAL PROCESSES	Medium
HYDROLOGIC PROCESSES	Medium
CHEMICAL PROCESSES - CHEMISTRY	Medium
- Radionuclide speciation/solubility	High
CHEMICAL PROCESSES – TRANSPORT	Low
- Advection, diffusion, and sorption	Medium
BIOLOGICAL PROCESSES (no FEPs were scored in this category)	Low
THERMAL PROCESSES	Medium
GAS SOURCES AND EFFECTS	Low
RADIATION EFFECTS	Low
NUCLEAR CRITICALITY	Low

Note: Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs

UFDC INTERNATIONAL COLLABORATION STRATEGY

For the UFDC, international collaboration is a beneficial and cost effective strategy for advancing disposal science in multiple disposal options and different geologic environments. While the United States disposal program had focused solely on unsaturated tuff at Yucca Mountain, Nevada as host rock, several international programs have made significant progress over the past decades in the characterization and performance evaluation of other geologic repository options, most of which very different from the Yucca Mountain site in design and host rock characteristics. Because Yucca Mountain was unique (e.g., no backfill, unsaturated densely fractured tuff), areas of direct collaboration with international disposal programs were quite limited.

The decision by the U.S. Department of Energy to no longer pursue the disposal of UNF at Yucca Mountain has shifted UFDC's interest to disposal options and geologic environments more in line with many international disposal programs; much can be learned in close collaboration with these programs to get access to valuable experience and data gained over decades. UFDC researchers are actively pursuing opportunities for such collaboration. The UFDC has issued the initial *Used Fuel Disposition Campaign International Activities Implementation Plan*[10], continues to mature its international collaboration strategy, and is beginning the execution of international collaborative activities.

International geologic disposal programs are at various different states, ranging from essentially "no progress" to selected sites and pending license applications to regulators. Thus, the opportunity exists to collaborate at different levels ranging from providing expertise to those countries "behind" the U.S. to obtaining access to information and expertise from those countries with more mature program while providing them access to U.S. expertise and capabilities.

Table 4. 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

Note: Shading for an entry indicates that research in that area has been undertaken in other geologic disposal programs

As to the possible types of international involvement, two broad categories can be distinguished. The first category comprises participation in multi-national or bilateral organizations, working groups, or committees. These interactions typically involve high-level information exchanges, expert panels, review functions, training and education, etc.

A few selected examples include multi-national activities such as under IAEA (e.g., review activities, conference participation, training within the International training Center), the OECD/NEA (e.g., participation in annual meetings, Integration Group for the Safety Case membership, R&D on NEA Thermodynamic Database), EDRAM (International Association for Environmentally Safe Disposal of Radioactive Waste), or bilateral agreements such as PUNT (U.S. – China Peaceful Uses of Nuclear Energy) and JNEAP (U.S. – Japan Joint Nuclear Energy Action Plan. The UFDC will continue participation and/or support of many of the international activities discussed above, and may need to expand on certain activities, but will need to be selective in its choices to further those opportunities that are of most benefit to the campaign and the FCT program.

The second category involves *active* R&D collaboration of UFDC researchers within international projects or programs in close collaboration with multi-national scientists. With active R&D, it is meant that UFDC scientists work together closely with international scientists on concrete research projects relevant to both sides. Such active collaboration would provide direct access to information, data, and expertise on various disposal options and geologic environments that has been collected over the past decades. Many international programs have operating Underground Research Laboratories (URLs) in clay/shale, granite, and salt environments, in which relevant field experiments have been and are being conducted.

Depending on the type of collaboration, UFDC researchers may be able to participate in planning, conducting, and interpreting these experiments, and thereby get early access to field studies without having to develop *in situ* research facilities in the U.S. Such active R&D activities would likely be most beneficial to UFDC, to help efficiently achieve its long-term goals of conducting experiments to fill data needs and confirm advanced modeling approaches, and of having a robust modeling and experimental basis for evaluation of multiple disposal system options. U.S. collaboration would bring additional expertise and analytic capabilities to the projects/programs along with the potential for additional funding to support international experimental investigations.

Active collaboration can be achieved under different working models. One first straight-forward option is informal peer-to-peer interaction with international R&D organizations. Several UFDC scientists, most of which are associated with DOE's national laboratories, have close relationships with their international counterparts, resulting from workshops and symposia meetings, or from active R&D collaboration outside of UFDC's scope. Continued UFDC support for participation of UFDC researchers in relevant international meetings will help to foster and expand such relationships.

Other working models for active collaboration may require formal agreement and sometimes long-term (financial) commitment before R&D collaboration can take place. It is advisable that such agreements with international organizations/partners should be exercised by DOE, rather than by the UFDC or individual DOE national laboratories. Collaboration with the Japanese under a bilateral agreement (JNEAP) is already underway, primarily focusing on waste management issues and optimization for advanced nuclear fuel cycles.

Examples of valuable multi-national and multi-partner initiatives that would promote active R&D in nuclear waste disposal science and that require DOE membership are the DECOVALEX Project[11], the Mont Terri Project[12] and the Colloid Formation and Migration Project[13]. Instead of multi-partner initiatives, there may also be direct participation of DOE national laboratories in specific projects run by individual international disposal programs. The latter may or may not require formal bilateral agreements.

The UFDC is developing a concise list of promising international opportunities, which documents their cost and benefits, the mode of participation, and the key research gaps addressed (with tight linkage to the *Used Fuel Disposition Campaign Disposal Research and Development Roadmap*[1]. Based on this, potential activities will be ranked and recommendations will be made to during the annual planning process.

CONCLUSION

The DOE-NE UFDC has developed a first iteration of the UFDC R&D Roadmap[1] using a systematic approach. The prioritized ranking of R&D issues (opportunities) is being used by UFDC researchers and management to develop its R&D portfolio. The UFDC R&D Roadmap[1] is a "living" document and will be updated as R&D progresses, both within the U.S. and internationally. The UFDC is also developing and implementing its international collaboration strategy.

The UFDC welcomes feedback on both the UFDC R&D Roadmap and on opportunities to collaborate with international colleagues performing R&D related to waste management, including both the disposal and long-term storage of UNF and HLW.

ACKNOWLEDGMENTS

The authors acknowledge those who participated in the development of both the UFDC Disposal R&D roadmap and the international collaboration implementation strategy. Their efforts are very much appreciated and all those who participated cannot be listed within the space allotted for this paper.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Argonne National Laboratory is a United States Department of Energy Office of Science laboratory, operated by UChicago Argonne, LLC, under contract DE-AC02-06CH11357.

REFERENCES

1. Nutt, M. (editor), "Used Fuel Disposition Campaign Disposal Research and Development Roadmap," FCR&D-USED-2011-000065 REV0, U.S. DOE Used Fuel Disposition Campaign, 2011.
2. Rechard, R.P., B. Goldstein, L.H. Brush, J.A. Blink, M. Sutton, F.V. Perry, "Basis for Identification of Disposal Options for Research and Development for Spent Nuclear Fuel and High-Level Waste," FCR&D-USED-2011-000071 REV0, U.S. DOE Used Fuel Disposition Campaign, 2011.
3. National Academy of Sciences (NAS), "Technical Bases for Yucca Mountain Standards," 1995.
4. International Atomic Energy Agency, "Scientific and Technical Basis for Geological Disposal of Radioactive Wastes," Technical Reports Series No. 413, 2003.
5. Freeze, G.A., P. Mariner, J.E. Houseworth, J.C. Cunnane, 2010, "Used Fuel Disposition Campaign Features, Events, and Processes (FEPs): FY10 Progress Report," SAND2010-5902, 2010.
6. Nuclear Energy Agency (NEA), "Post-Closure Safety Case for Geological Repositories, Nature and Purpose," OECD Nuclear Energy Agency, 2004.
7. Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein 2009. "Deep Borehole Disposal of High-Level Radioactive Waste," SAND2009-4401, August 2009.
8. Hansen F.D.,, E.L. Hardin, R.P. Rechard, G.A. Freeze, D.C. Sassani, P.V. Brady, C.M. Stone, M.J. Martinez, J.F. Holland, T. Dewers, K.N. Gaither, S.R. Sobolik, and R.T. Cygan, 2010. Shale Disposal of U.S. High-Level Radioactive Waste, SAND2010-2843, May 2010.

9. Hansen, F.D. and C.D. Leigh, Salt Disposal of Heat-Generating Nuclear Waste, SAND2011-0161, January 2011.
10. Nutt, M., "Used Fuel Disposition Campaign Disposal Research and Development Roadmap," FCR&D-USED-2011-000065 REV0, U.S. DOE Used Fuel Disposition Campaign, 2011.
11. Tsang, C.-F., O. Stephansson, L. Jing, L., F. Kautsky, "DECOVALEX Project: from 1992 to 2007," Environmental Geology, 57, 1221–1237, 2009.
12. Zuidema, P., "Advancements in Deep Geological Disposal of Radioactive Waste through International Cooperation: The Role of Underground Laboratories – Mont Terri Project," Proceedings of the 10 Year Anniversary Workshop, pp 69-71, Rep. Swiss Geol. Surv. 2, 2007.
13. Schäfer T., Seher H., Hauser W., Walther C., Geckeis H., Degueldre C., Yamada M., Suzuki M., Missana T., Alonso U., Trick T., Blechschmidt I. (2009): The CFM (Colloid Formation and Migration) project at the Grimsel Test Site (GTS, Switzerland): First field experiments. 12th International Conference on the Chemistry and Migration Behaviour of Actinides and Fission Products in the Geosphere, Kennewick, Washington, September 20 - 25, 2009.