A Decision Methodology for Prioritizing R&D Supporting Geologic Disposal of SNF/HLW in Salt – 14030

S. David Sevougian*, Robert J. MacKinnon*
*Advanced Nuclear Energy Programs Group, sdsevou@sandia.gov
Sandia National Laboratories
P.O. Box 5800, M.S. 0747
Albuquerque, NM 87185

ABSTRACT

Because the future site of a permanent U.S. geologic repository for used nuclear fuel and nuclear waste will not be established for some time, the Used Fuel Disposition (UFD) Campaign in the U.S. Department of Energy (DOE) has pursued research, development, and demonstration (RD&D) activities to support a suite of generic disposal concepts. The work described in the present study focuses in greater detail on the bedded salt disposal concept, and aims to help define a set of key RD&D activities needed to support a generic safety case for disposal of heat-generating SNF/HLW in bedded salt, given the current state of knowledge. Unresolved technical, socio-political, and economic issues at any stage of repository development can be evaluated by using an *objectives hierarchy* that is a standard part of decision analysis. This objectives hierarchy provides a logical structure for choosing between alternatives in a complex decision problem by assigning a *metric* or *performance measure* that can be used to quantify the degree of achievement of each objective. In the present context, the highest objective or goal to be achieved is to choose an appropriate set of RD&D activities that advance the overall safety case by resolving outstanding issues. Individual elements of the safety case, such as postclosure safety, preclosure safety, confidence enhancement, or repository design and construction provide a logical construct for developing a safety-case-based objectives hierarchy. RD&D activities can be evaluated against one or more of the objectives in this hierarchy for their potential value to resolve remaining issues. At the present stage of RD&D planning and prioritization for a generic salt repository the only "quantitative" metric utilized is one associated with the postclosure safety objective of the safety case. Achievement of postclosure safety relies upon a set of safety *functions* provided by the engineered and/or geological components of the repository system. Safety functions identify key attributes of the repository system and/or its physical components and associated processes that are relied upon to achieve long-term safety. The three postclosure safety functions used to rate the importance of remaining salt RD&D issues relative to the overall postclosure safety objective (and, by proxy, the value of RD&D activities to resolve these issues) are isolation/stability, containment, and limited or delayed releases. An evaluation based on the potential "impact" of an RD&D issue on each safety function produces an importance or value rating for each RD&D issue. The resulting issue importance ratings can be combined with additional qualitative judgments to produce a more comprehensive prioritization of future RD&D activities. For example, the current state of knowledge for a particular RD&D issue, and the associated degree of uncertainty, will help determine both the necessity and focus of future RD&D.

INTRODUCTION

Part of the promise and appeal of geologic disposal in a bedded (or domal) salt formation is the robustness of the natural barrier system for the undisturbed, expected-evolution scenario, i.e., for the scenario with no disruptions of the repository by either human-intrusion events, such as borehole drilling, or unlikely natural events, such as volcanism (see 40 CFR 191.12). Under these conditions, the salt host rock by itself ensures the successful operation of the "containment" safety function that is important to all geologic disposal systems. Thus, for the undisturbed scenario, reliance on extensive engineered barriers is not necessary for long-term containment of the waste due to the extremely low fluid permeability of the native salt host rock, which will only allow transport of radionuclides by the very slow process of molecular diffusion (although engineered barriers can provide "defense in depth"—see [1] or [2]). Salt host rock also resists and restores perturbations to its containment function caused by (1) mechanical stresses induced by excavation of the emplacement tunnels (which could potentially cause fast fracture transport pathways) and (2) high levels of waste heat from the disposed radionuclide inventory (which could cause high fluid pressures and mechanical stresses). Excavation stresses are ameliorated by the visco-plastic properties of the salt, causing it to creep and consolidate to a near pristine condition, while heat-induced stresses are dissipated by the rapid dispersal of the waste heat due to the high thermal conductivity of the salt. Thus, a mined repository in salt (referred to herein as a salt repository) could likely achieve complete containment, with no radionuclide releases to the environment for the undisturbed scenario [3].

It should be recognized that knowledge of the expected postclosure evolution of physical-chemical processes in a salt repository does not come from supposition but from an extensive existing knowledge base, much of it from activities associated with the Nation's salt repository for defense-generated transuranic (TRU) waste, the Waste Isolation Pilot Plant (WIPP), sited in the Delaware Basin of Southeast New Mexico in the United States [4]. Lessons learned from siting and operating this facility can be used to support the development of a generic salt repository for heat-generating waste [5]. However, phenomena caused by decay heat from spent nuclear fuel (SNF) or used nuclear fuel (UNF) and high-level waste (HLW) do add some potentially beneficial and/or detrimental features, events, and processes (FEPs) that are not relevant for the ambient thermal TRU waste that is disposed at WIPP. Many of these FEPs, or "issues" as they will be called here, could benefit from additional research and development activities, as well as further *in situ* demonstration and testing, to build confidence for the salt repository concept for heat-generating radioactive waste. However, given the substantial knowledge base, including past *in situ* experiments to investigate disposal of heat-generating waste [6], future research, development, and demonstration (RD&D) activities are mainly intended to fortify and confirm the current technical bases and to reduce remaining uncertainties. They also offer the opportunity to apply more advanced measurement methods and test designs to improve confidence, and to be proactive regarding potential questions that might be posed during a licensing proceeding, if salt were eventually chosen as a disposal medium for commercial and/or defense-related radioactive waste in the U.S.

SAFETY CASE CONTEXT FOR RD&D ACTIVITIES

The formulation of a *safety case* for bedded salt host rock is consistent with the U.S. DOE's current generic approach to repository research and development [7] and to the consent-based repository siting procedure recommended by the Blue Ribbon Commission on America's Nuclear Future [8]. A safety case for bedded salt will provide the structure by which to compare the merits of a bedded salt repository with the merits of generic repositories sited in other media. It also will provide a structured framework to (1) guide the activities of the implementer (e.g., DOE) through the various phases of repository development, including the planning and prioritization of RD&D activities, and (2) transparently communicate the current understanding of repository safety to a broad range of stakeholders, decision makers, and the general public, as well as explain the nature and potential impact of any remaining uncertainties [9].

The development of any geologic repository takes place over a period of years and, as the repository program evolves, the level of completeness and rigor in the associated safety case becomes more robust with additional data from site characterization, repository design, and safety assessment activities. These three key activities combine to form an iterative process wherein the safety assessment from one development phase feeds site characterization and design at the next phase (Fig. 1). Planning for, and transitioning to, each subsequent phase requires some form of decision-making process, as indicated in Fig. 1, to prioritize RD&D activities designed to resolve remaining issues and uncertainties. Public and stakeholder participation are important inputs to the decision-making process, before proceeding to the next phase of development. Phase "A" and Phase "B" in Fig. 1 are "typical" phases in the development of the repository, such as those outlined by the National Research Council [10]: (1) concept or "disposal option" selection, (2) site selection and characterization, (3) licensing, (4) construction, (5) operation, (6) closure, and (7) post-closure.

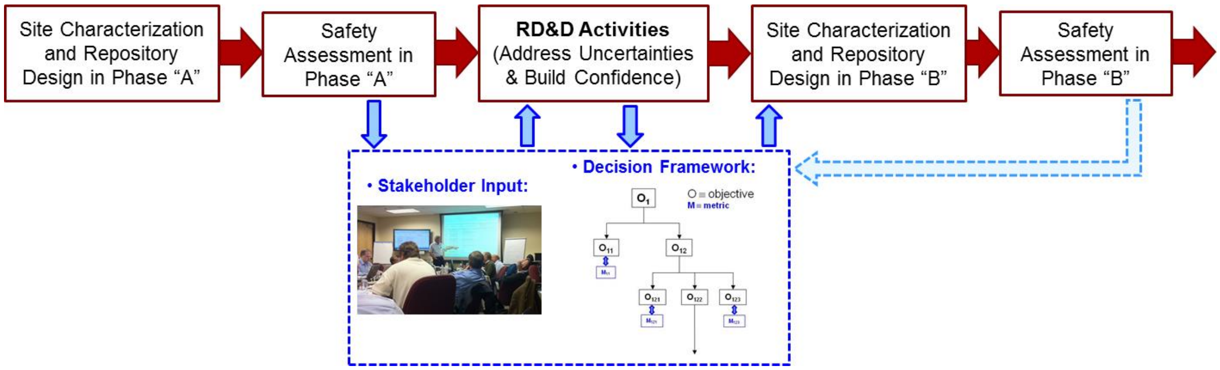

Fig. 1. Iteration of site characterization, repository design, and safety assessment as part of a decision-making process to prioritize RD&D activities. {Note: Phases "A" and "B" are generic phases such as "licensing" or "construction".}

This paper documents the methodology of a decision-making process developed to help guide salt repository investigations at this generic stage. This methodology was used as a basis for an initial prioritization of potential salt RD&D needs (issues)—see TABLE IV, which was further refined during a Salt RD&D Workshop comprised of experts in the field of salt repository science and engineering [11]. This workshop had the goals of formulating an expert consensus on the relative importance of various technical issues and recommending RD&D activities to address them, including modeling studies, laboratory studies, and field testing. Recommendations about which RD&D activities to pursue were based on their expected relevance to the objectives and goals of a safety case for a generic bedded salt repository, as well as their ability to help resolve any remaining uncertainties associated with the technical issues they are designed to address.

Major Elements of the Safety Case

As described below, the major components or elements of a safety case can be used to structure a comprehensive objectives hierarchy that guides and evaluates science and engineering activities that help bolster safety confidence. With these safety case elements as the objectives or goals of RD&D activities, sound decisions can be made as to the relative importance of each activity, based on how well each one supports these goals or objectives. These elements or components of the safety case have been outlined elsewhere [12, 13, 14, 15, 16, 17], but are briefly summarized here, and shown in more detail in Fig. 2:

- *Statement of Purpose*. Describes the current stage or decision point within the repository program against which the current strength of the safety case is to be judged.
- *Safety Strategy*. This is the high-level approach adopted for achieving confirmation of safe disposal, and includes the sub-elements of an overall management strategy, a siting and design strategy, and an assessment strategy.
- *Assessment Basis*. This element describes the technical bases (or knowledge base) for the major components/features/processes of the postclosure repository system [18], including the engineered barrier system, the natural barrier system, and the biosphere. It also describes the

conceptualization of preclosure systems and operations. These technical bases provide confidence in the conceptualization of system performance.

- *Disposal System Safety Evaluation.* This element includes two major sub-elements for assessing repository behavior: a preclosure safety analysis and a postclosure safety (or performance) assessment [16, 19]. It is primarily a *quantitative* assessment of potential radiological consequences associated with a range of possible evolutions of the system over time but also includes *qualitative* confidence-building arguments based on other evidence and activities.
- *Synthesis and Conclusions.* This element includes a summary of the key findings, and one or more statements of confidence regarding the perceived safety of the repository system. It recognizes the existence of any open issues and remaining uncertainties, and includes perspectives about how they can be addressed in the next phase(s) of repository development.

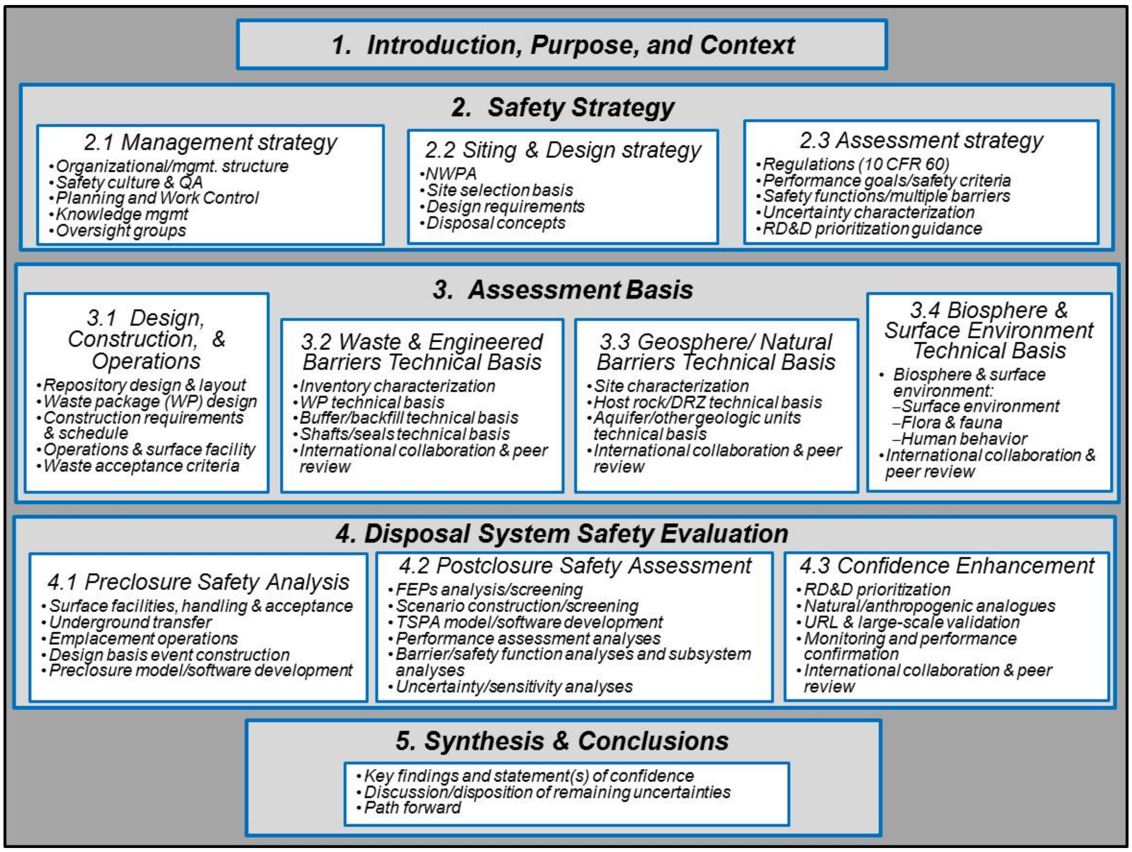

Fig. 2. Major elements of a safety case (see [18] for the FEPs structure underlying the "Assessment Basis.")

Safety Case Objectives Hierarchy

Remaining technical, socio-political, and economic questions at any stage of repository development can be systematically organized and addressed in a comprehensive *objectives hierarchy* that is a standard part of decision analysis [20]. This objectives hierarchy, also called a "value tree" [21, 22], provides a logical structure for choosing between alternatives in a complex decision problem by assigning a *metric* or *performance measure* (called an *attribute* in the decision analysis literature) that quantifies the degree of achievement of each objective by a given alternative [23, 24]. An example of its application to the selection of a nuclear waste repository site may be found in [25]. In the present context the highest objective to be achieved is to choose an appropriate set of RD&D activities that advance the safety case for a generic bedded salt repository. To evaluate the degree of that achievement with a logical and measurable construct, elements and subelements of the safety case structure, described above, can be used to formulate the appropriate objectives hierarchy. RD&D activities can then be measured against one or more of the objectives in this safety-case-based hierarchy for their potential value in supporting the overall safety case.

Fig. 3 shows a high-level objectives hierarchy formulated to evaluate salt RD&D activities based on their importance to the safety case. This particular hierarchy is primarily based on key *sub*elements of safety-case elements 3 ("Assessment Basis") and 4 ("Disposal System Safety Evaluation") from Fig. 2. RD&D work related to these subelements has the most benefit for safety case support at this phase of generic repository investigations. A more detailed objectives hierarchy may also be formulated for classifying and measuring the success of RD&D activities, by specifically including an even lower level of safety case subelements, such as "Support the EBS Technical Basis." This is indicated in Fig. 4.

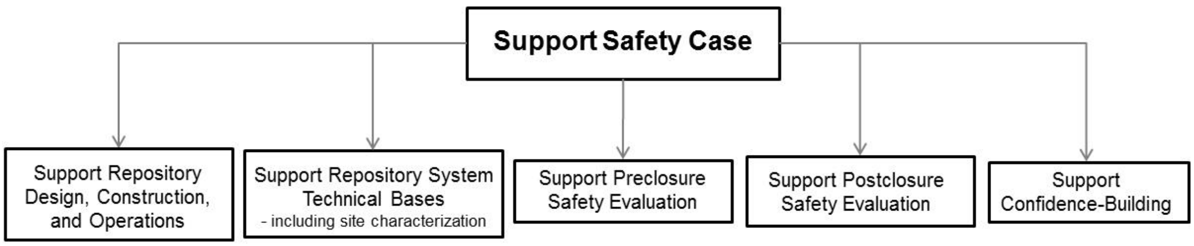

Fig. 3. Safety case objectives hierarchy, similar to that used in the Salt RD&D Workshop [11]. {Note: This hierarchy is applicable to the disposal of either or both DOE-owned and commercial heat-generating waste. Transportation, waste receipt, and surface facilities are not considered at this stage.}

Support Safety Case

- **Support Repository Design, Construction, and Operations**
  - Support Underground Layout and Drift Design
  - Support Ventilation and Drainage Systems Design
  - Support Access Shafts/Drifts Design
  - Support Backfill Design
  - Support Seal System Design
  - Support Ground Support Design
  - Support Power Supply Design
  - Support Waste Canister Design
  - Support Operations
- **Support Repository System Technical Bases**
  - Support EBS Technical Basis
  - Support Geosphere Technical Basis (including Site Characterization)
  - Support Biosphere Technical Basis
- **Support Preclosure Safety Evaluation**
- **Support Postclosure Safety Evaluation**
  - Support Performance Assessment Model
- **Support Confidence-Building**
  - Support Peer Review
  - Support International Collaborations
  - Support In Situ Testing and Demonstrations
  - Support Natural and Anthropogenic Analogues
  - Support Verification, Validation, and Traceability

Fig. 4. More detailed safety case objectives hierarchy.

DECISION-MAKING FRAMEWORK

An index ranking and/or numerical "figure of merit" for each proposed RD&D activity could be formulated by assigning (1) a "value" rating to each RD&D activity relative to each objective in Fig. 3, combined with (2) a normalized importance weight assigned to each of these five objectives. This evaluation exercise could also be done at the first sublevel of objectives shown Fig. 4, such as "Support EBS Technical Basis"—see [25] for an example of this type of multi-attribute utility analysis (MUA). A similar RD&D prioritization exercise has previously been carried out within the DOE UFD Campaign for a set of generic RD&D "issues" applicable to the four main repository concepts, with a numerical value or utility assigned to each issue [7, App. B]. In the present study specific to bedded salt, and in the Salt RD&D Workshop [11] conducted to support this study, a less formal prioritization approach has been adopted, using a three-level descriptive ("high," "medium," "low") rating scheme, rather than a numerical rating scheme. Future prioritization efforts for salt RD&D can also be expected to use decision analysis methodology, either descriptive or numerical, but with the evaluation of safety case objectives supported by future quantitative performance assessments [9, Sec. 4.5].

It is important to point out the difference between an RD&D "issue" and an RD&D "activity," as used in this methodology. The term "issue" is used to represent some type of remaining uncertainty that should be addressed to enhance safety confidence or, as described by [7, Sec. 2], an "opportunity to conduct R&D to fill information needs and knowledge gaps." The term "activity" is used in the present study to represent some type of work to resolve the issue or to advance the state of knowledge about the issue, with the goal being to reduce uncertainty and to build confidence in safety. In the methodology described here, the metric used to evaluate the importance of RD&D activities was actually applied to the associated RD&D issue, instead. For example, one relevant RD&D issue (see TABLE IV) is "Mechanical response of host rock due to excavation," while an example RD&D activity that could reduce uncertainty surrounding this issue would be a "Single Heater Test," e.g., see [11, Table H-2]. Additional tests/activities could also be proposed to evaluate this particular issue and each "issue-activity pair" could be evaluated against suitable metrics. However, for simplicity at this stage of planning, only RD&D *issues* have been evaluated and assigned importance ratings. This implies that any RD&D *activity* designed to address a given issue will inherit or assume the importance rating assigned to its underlying issue. Because only the underlying RD&D issues have been evaluated, the metric(s) used to evaluate RD&D issues is considered to be a *proxy* metric(s) for evaluating or rating the importance of the associated R&D activities. (Recall that it is the actual RD&D activities that support or build confidence in the safety case.) This approach of using a proxy or indirect measurement of an objective is often adopted in decision analysis, when a *direct* metric cannot easily be assessed [26]. This same approach is adopted here, i.e., the importance ratings for salt RD&D issues is used as a proxy for the importance of the associated RD&D activities (testing, modeling, etc.) needed to resolve the issues.

As described in more detail below, at this stage of planning and prioritization the only "quantitative" metric used to evaluate issue importance is "Importance to Postclosure Safety," which is discretized on a coarse descriptive scale of high ("H") importance, medium ("M") importance, or low ("L") importance—based on the impact of the underlying RD&D issue to a set of four repository safety/design functions (see TABLE I). As noted by the [27, p. 53], "performance assessment is arguably the most important part of the safety case...," and it is not unreasonable at this stage of RD&D planning to emphasize a metric related to the postclosure safety objective, in order to prioritize science and engineering activities. However, even though this is the sole "quantitative" metric applied, other safety objectives in Fig. 3, such as "confidence-building," have been given strong consideration (see below), since a safety case must present multiple lines of evidence and reasoning to support all aspects of repository safety.

Besides an importance evaluation with respect to the objectives hierarchy in Figs. 3 and 4, other types of information are either formally or informally used in the prioritization of RD&D activities. One of these is an evaluation of the current state-of-the-art or current state of knowledge for a particular RD&D issue. Issues or FEPs that have had little previous research conducted on them but are considered highly important to postclosure safety will be given a higher priority than either (1) issues with a lower importance to safety or (2) issues that may be highly important to safety but already have had extensive research conducted (such that associated uncertainties are minimal). Based on the foregoing discussion, a schematic illustration of the major steps in the decision-making process is shown in Fig. 5. (The definition of system *functions* [28] and their use in defining the "importance to postclosure safety" metric are discussed below.)

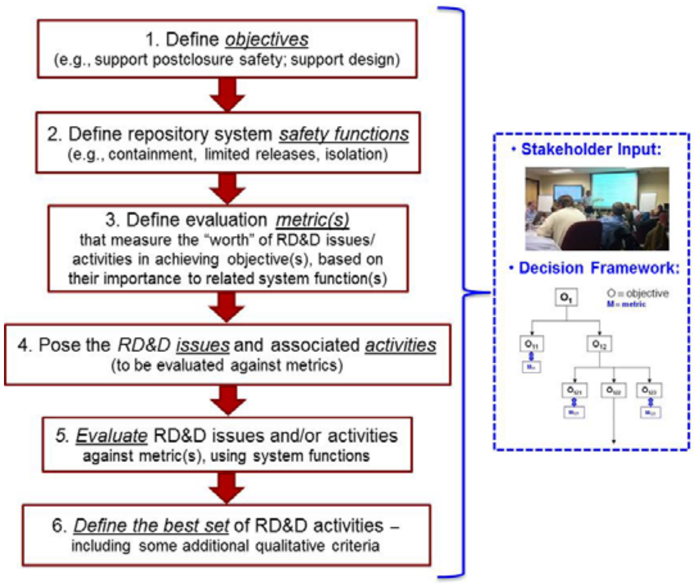

Fig. 5. Decision-making process for evaluating salt RD&D issues/activities.

Repository Safety Functions

An assessment of repository safety after closure addresses the ability of a site and repository facility to meet safety standards and to provide for the safety *functions* [14] of the engineered and/or geological components, such as containment of radionuclides by engineered and natural barriers or reduction in the rate of movement of radionuclides in the engineered and natural barriers (cf. 10 CFR 63.2 and 40 CFR 191.13/14). Confidence in the long-term operation of *safety functions* is part of a successful safety strategy (Fig. 2). Substantiation of the successful operation of the safety functions is provided by a quantitative postclosure safety assessment calculation [19], which is an integral part of the volume of evidence presented in the safety case. In the methodology described here, these postclosure safety functions, as well as one design function, are used as a basis for rating the relative importance of RD&D issues and, by proxy, the testing/modeling activities proposed to reduce uncertainties associated with these issues.

Safety functions identify key attributes of material barriers that are relied upon to prevent or limit contact of the emplaced waste with the biosphere, i.e., with humans, animals, and plants. These physical barriers fall into two major categories: natural (e.g., the host rock formation) and engineered (i.e., the waste container and other man-made barriers). Robust performance of physical barriers is facilitated when they work together, each complementing the other, which is the "multiple barrier" or "multi-barrier" concept identified in various regulations (e.g., 10 CFR 63.102h) and safety cases [12]. The contributions of the various natural and engineered barriers to safety confidence can be organized according to multiple safety functions:

> "The host environment shall be selected, the engineered barriers of the disposal facility shall be designed and the facility shall be operated to ensure that safety is provided by means of multiple safety functions. Containment and isolation of the waste shall be provided by means of a number of physical barriers of the disposal system. The performance of these physical barriers shall be achieved by means of diverse physical and chemical processes together with various operational controls. The capability of the individual barriers and controls together with that of the overall disposal system to perform as assumed in the safety case shall be demonstrated." [2]

While different terminology is used in different countries, safety functions fall into some general categories, as described by [14]:

- *Stability/Isolation Safety Function*—Two subgroupings are identified:
  - Isolating the waste from non-anthropogenic future events and climate changes, and which thus contributes to the stability of the repository's near-field conditions and to the longevity of the natural barriers.
  - Reducing the probability of and consequences from anthropogenic events such as future human actions that might result in inadvertent intrusions into the sealed repository.
- *Containment*—The prevention of groundwater from coming into contact with the waste. In the case of disposal in hard rock or argillaceous formations this safety function is provided by the engineered barrier system (EBS). In the case of disposal in salt formations much of the containment function is provided by the natural barrier system. If groundwater does not contact the waste there is, in general, no mobilization or release mechanism to transport radionuclides from the repository to the accessible environment, although gas-phase transport is a potentially minor release mechanism that must be investigated. {Note: An alternative definition of containment is provided at 10 CFR 60.2: "Containment means the confinement of radioactive waste within a designated boundary."}
- *Limited or Delayed Releases*—This represents mechanisms/processes/components that delay or reduce mobilization and migration of radionuclides. This safety function begins to dominate once the *containment* function deteriorates, e.g. for example when waste packages are breached as a result of corrosion. This is a major function of the natural barrier system as well as of various components of the EBS and ensures the long-term barrier capability of geologic disposal (cf. "barrier" definition at 10 CFR Part 63.2).

Evaluation of "Importance to Postclosure Safety" Metric

The importance value rating or "value level" of each salt RD&D issue relative to the postclosure safety objective is a function of two attributes: (1) the "impact" of the issue on one or more of the four postclosure safety or design functions defined in TABLE I and (2) the "function level" (either "primary" or "secondary") of the safety/design function relative to postclosure performance. These two attributes ("impact" and "function level") may be combined to produce importance value ratings for the "Importance to Postclosure Safety" metric, as indicated schematically below:

$$\frac{\text{Importance}}{\text{of RD\&D Issue}} = \frac{\text{Impact of RD\&D Issue}}{\text{on a Safety Function}} \cup \frac{\text{Function Level of}}{\text{the Safety Function}} \qquad \text{(Eq. 1)}$$

In particular, there are three impact levels for the issues, as defined in TABLE II: direct (but potentially significant), indirect (but potentially significant), or weak (regardless of whether it is a direct or indirect impact). These impact levels apply to both (1) the performance of a function (for the first 30 FEP-type issues shown in TABLE IV) or (2) confidence in the ability to demonstrate that performance, through either modeling or *in situ* testing (for the 8 modeling issues and the 4 *in situ* testing issues, respectively, in

TABLE IV). Regarding the two "function levels" defined in TABLE I, either primary or secondary, a secondary function plays a subsidiary role to a primary function or plays no role until the primary function "fails." For example, the *limited or delayed releases* safety function is not important while the containment function is uncompromised. Each safety/design function in TABLE I is also associated with one or more key parameters or characteristics, which help better explain the purpose and operation of the particular function.

TABLE I. Postclosure safety and design functions.

Function	Type	Function Level[a]	Definition	Examples of Key Associated Parameter(s) or Characteristic(s)
Isolation/stability	Safety	Primary (P)	Aspects of the repository and geologic environment that isolate the waste from external events or changes, and therefore help maintain the integrity and longevity of the barriers.	• (high) seal integrity • (thick) host rock zone • (non-) communication between salt beds and interbeds
Containment	Safety	Primary (P)	Aspects of the repository that prevent fluid contact with the waste.	• (very low or zero) permeability
Limited or delayed releases	Safety	Secondary (S)	Aspects of the repository that delay or reduce the transfer of radionuclides to the accessible environment after the containment function is compromised.	• (high) sorption • (low) solubility • (low) dissolution rates
Retrievability	Design	Primary (P)	Aspects of the repository that allow for retrievability of the emplaced waste without any releases, for a specified period of time after closure.	• (sufficient) WP thickness

[a] This is called the "significance level" in [11].

TABLE II. Impact of an RD&D issue on performance of a safety/design function (for feature/process issues—see TABLE IV), or on confidence in the ability to demonstrate that performance (for modeling or *in situ* testing issues).

Impact of an RD&D Issue	
D	Direct and potentially significant impact on the success of a safety or design function
I	Indirect but potentially significant impact on the success of a safety or design function
W	Weak impact (whether direct or indirect) on the success of a safety or design function

The impact of an RD&D issue on a safety/design function combined with the function level of the particular safety/design function provides a *value* rating ("H", "M", or "L") for each RD&D issue, defined in TABLE III. It should be noted that the importance rating methodology shown in TABLES I through III could easily be adapted to a finer level of discretization than defined in TABLE III. For example, as written, the matrix in TABLE III allows for six different value levels, so that numerical values of "1" through "6" (as an example) could be assigned to the six different combinations of impact and function level, instead of just the three values of "H", "M", and "L" in the first column. Or, the impact levels in TABLE II could be more finely subdivided, say into five levels such as "very high," "medium-high," "medium," "medium-low," and "low" impact, which combined with the two function levels would create a set of $5 \times 2 = 10$ importance values (e.g., "1" through "10") in TABLE III. However, at this stage of generic research, a set of three value ratings ("H", "M", "L") is deemed to be sufficient.

TABLE III. Importance value ratings for RD&D issues (i.e., value levels for the "Importance to Postclosure Safety" metric).

Importance Value Rating	= Impact	+ Function Level
High: H=(D,P)	Direct (D)	Primary (P)
Medium: M=(I,P)	Indirect (I)	Primary (P)
Low: L=(W,P)	Weak (W)	Primary (P)
Low: L=(D,S)	Direct (D)	Secondary (S)
Low: L=(I,S)	Indirect (I)	Secondary (S)
Low: L=(W,S)	Weak (W)	Secondary (S)

{Note: An RD&D issue receives an importance rating according to its highest function-impact combination, i.e., it may receive an "L" rating for one function/impact but if it gets an "H" for another function/impact, it inherits that highest rating—see TABLE IV.}

REMAINING SALT RD&D ISSUES/NEEDS

A key part of the overall safety case is a demonstration of the ability of the safety functions to continue to operate throughout the postclosure regulatory period. This requires demonstrable scientific knowledge about these evolutionary processes and the associated parameters that quantify the processes. While a large knowledge base exists for the emplacement of radioactive waste in salt—built on existing technical information from prior investigations in the U.S. and abroad [29, 30, 31], including the multiple performance assessment iterations at WIPP [32, 33, 34]—there are still some important issues remaining with respect to repository evolution for heat-generating, high-activity waste. Prioritization of these remaining RD&D issues, according to their importance to the safety functions, is a key goal in establishing a successful salt RD&D program that will enhance safety confidence.

An initial compilation of potential "issues" was taken from a FEPs list for generic repositories [7, App. A], but modified slightly to be more specific for salt repositories [35, App. A]. This list from [35] was then culled to primarily those technical issues or FEPs related to Geosphere and EBS processes, to focus continuing and new salt RD&D activities on those issues most amenable to the type of generic research being conducted at this time. In addition, a number of other literature sources and previous salt research and testing were accounted for in the compilation of the candidate list of salt RD&D issues to be investigated in the current context of generic repository investigations [3, Table 4; 36; 37].

The evaluation of each RD&D issue, according to the methodology in TABLES I to III, along with the brief explanation of the basis for their designated importance ratings is given in TABLE IV. {Note: The confidence-building "issues" listed at the end of TABLE IV are not amenable to the rating method given in TABLES I to III, but are rated instead by expert opinion.} The initial ("pre-workshop") importance ratings developed here are based on the expected repository performance for the nominal evolution scenario, i.e., for the scenario that does not have any human intrusions into the repository, such as borehole drilling, and does not encounter any natural disruptive events, such as seismicity or volcanism. While the work described here primarily focuses on the undisturbed scenario, which is appropriate at this stage of generic repository investigations, it is important to initiate and/or continue work on issues that may become important for disruptive scenarios. During the Salt RD&D Workshop [11], human intrusion was considered to be a representative disruptive scenario and the RD&D issues were evaluated relative to the key safety function operative for the disruptive human-intrusion scenario, which is *limited or delayed releases*—since the *containment* function has been compromised in this scenario [11, Table 7-1].

TABLE IV. Consolidated salt RD&D technical issues and their pre-workshop importance ratings for the nominal scenario and high heat load [11, Table 5-4]. {High "H" importance issues shaded in "light orange."}

Salt RD&D Technical Issue	Issue Importance Rating	Explanation of Issue Importance Rating
Wastes and Engineered Features (EBS) Feature/Process Issues		
1. Inventory and WP Loading	M (= I,P)	Indirectly related to limited and delayed releases through elemental composition of inventory (L = I,S), but also indirectly related to containment (permeability) through heat loading density and associated affects (M = I,P)
2. Physical-chemical properties of crushed salt backfill at emplacement	M (= I,P)	Indirectly related to the final state of the backfill permeability (containment function of the backfill)
3. Changes in physical-chemical properties of crushed salt backfill after waste emplacement	H (= D,P)	Directly related to maintaining the containment function of the backfill by directly changing its permeability
4. Changes in chemical characteristics of brine in the backfill and EBS	M (= I,P)	Indirectly related to backfill permeability through WP corrosion and subsequent gas generation (M) Indirectly related to limited and delayed releases (L)
5. Mechanical response of backfill	H (= D,P)	Directly related to host rock permeability in the EDZ and to backfill permeability (i.e., to containment)
6. Impact of mechanical loading on performance of the WP	H (= D,P)	Directly related to retrievability
7. Brine and vapor movement in the backfill and emplacement drift, including evaporation and condensation	H (= D, P)	Brine and vapor movement in the EBS are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to backfill permeability (containment)—through gas generation from WP corrosion or through trapping of water during consolidation
8. Corrosion performance of the waste package	M = (I,P)	Only indirectly related to retrievability; Also, the waste package is not designed for long-term postclosure containment or limited and delayed releases in a salt repository
9. Mechanical and chemical degradation of the waste forms	L (= D,S)	Both directly (chemical) and indirectly (mechanical) related to limited and delayed releases
10. Brine flow through waste package	L (= D,S)	Directly related to limited and delayed releases
11. Changes in chemical characteristics of brine in the waste package	L (= I,S)	Indirectly related to limited and delayed releases
12. Radionuclide solubility in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases
13. Radionuclide transport in the waste package and EBS	L (= D,S)	Directly related to limited and delayed releases
Natural Barriers (Geosphere: Host Rock and EDZ) Feature/Process Issues		
14. Stratigraphy and physical-chemical properties of host rock	H (= D,P)	Directly related to isolation; characteristics of interbeds and nature of underlying and overlying beds are important to design
15. Changes in physical-chemical properties of host rock due to excavation, thermal, hydrological, and chemical effects	H (= D,P)	Directly related to host rock and EDZ permeability (containment)
16. Mechanical response of host rock due to excavation (e.g., roof collapse, creep, drift deformation)	H (= D,P)	Directly related to host rock and EDZ permeability (containment)
17. The formation and evolution of the EDZ	H (= D,P)	Directly related to permeability (containment) of the EDZ host rock zone
18. Brine and vapor movement through the host rock and EDZ, including evaporation and condensation	H (= D, P)	Brine and vapor movement through the host rock and EDZ are directly related to containment by definition (fluid contact with waste), although this movement is much less likely after the backfill consolidates and the thermal period ends. Also, can indirectly result in changes to host rock and backfill permeability (containment) due to gas generation (from WP corrosion).
19. Chemical characteristics of brine in the host rock	L (= I,S)	Indirectly related to limited and delayed releases
20. Changes in chemical characteristics of brine in the host rock and EDZ	M (= I, P)	Indirectly related to limited and delayed releases (L) but also indirectly related to permeability (containment) through the possible effects of gas generation (fracturing)
21. Radionuclide solubility in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases
22. Radionuclide transport in the host rock and EDZ	L (= D,S)	Directly related to limited and delayed releases

TABLE IV. (continued)

Salt RD&D Technical Issue	Issue Importance Rating	Explanation of Issue Importance Rating
Repository System (EBS and Geosphere combined) Feature/Process Issues		
23. Thermal response of EBS and Geosphere (heat transfer from waste and waste packages into the EBS and Geosphere)	H (= D,P)	Constitutive behavior of salt is a strong function of temperature. Therefore, this issue has a direct effect on mechanical evolution of the EDZ and backfill, which strongly impacts permeability (containment).
24. Buoyancy of the waste packages	L (= W,P)	Weakly related to isolation
25. Gas generation and potential physical impacts to backfill, EDZ, and host rock	M = (I,P)	Indirectly related to permeability changes (i.e., to containment) through possible rock fracturing
26. Microbial activity in the waste package, EBS, and host rock (including EDZ)	L (= I,S)	Indirectly related to limited and delayed releases
27. Colloid formation and transport in the waste package, EBS, and host rock (including EDZ)	L (= D,S)	Directly related to limited and delayed releases
28. Performance of seal system	H (= D,P)	Directly related to isolation of the repository
29. Performance of ground support	L = (W,P,S)	Only weakly related to the safety and design functions
30. Performance and effects of ventilation	M (= I,P)	Indirectly related to containment (permeability) through the availability and movement of fluids, which may cause gas generation (and subsequent fracturing) Indirectly related to limited and delayed releases through the removal of fluid available for transport of radionuclides
Modeling Issues		
31. Appropriate constitutive models (e.g., Darcy flow; effective stress)	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions
32. Appropriate representation of coupled processes in process models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions
33. Appropriate representation of coupled processes in TSPA model	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions
34. Appropriate inclusion and scaling/representation of spatially and temporally varying processes and features in process and TSPA models	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions
35. Efficient and high performance computing of three-dimensional, spatially and temporally varying processes	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions
36. Efficient uncertainty quantification and sensitivity analysis methods	M (= I,P)	Indirect impact on demonstrating the importance of primary safety functions
37. Verification and validation	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions
38. Data and results management	H (= D,P)	Direct impact on confidence (QA)
***In-Situ* Testing/Design/Operations Issues**		
39. Development of accurate instrumentation and methods for *in situ* testing and characterization	H (= D,P)	Direct impact on the confidence in the demonstration (modeling) of performance of the containment safety function, through measurements of *in situ* stresses and rock movement (H) and brine and vapor/gas movement (M)
40. *In situ* demonstration and verification of repository design, with respect to its impact on the host rock and the ability to comply with preclosure and postclosure safety requirements.	H (= D,P)	Direct impact on the confidence in the demonstration of performance of the containment safety function
41. Demonstrate under representative conditions the integrated design functions of the waste package, backfill, host rock, and ventilation.	H (= D,P)	May not be possible in the time frame of an *in situ* test. Direct impact on the confidence in the demonstration of performance of the containment safety function
42. Provide a full-scale benchmark for understanding coupled THMC processes and comparing measured system responses with model predictions and assumptions	H (= D,P)	Similar to Issue 37, Verification and Validation. Direct impact on the confidence in the demonstration (modeling) of performance of primary safety functions

TABLE IV. (continued)

Salt RD&D Technical Issue	Issue Importance Rating	Explanation of Issue Importance Rating
Confidence-Building Issues		
43. Develop generic safety case	H	This is the fundamental documentation structure for demonstrating repository safety
44. Comparisons to natural and anthropogenic analogs	H	It is the best way to validate long time-scale processes
45. International peer review and collaboration	M	Adds credibility with the scientific community
46. In-situ testing and demonstrations	H	Adds credibility with the political and scientific communities. Was rated H in Items 39-42
47. Verification, validation, transparency, and traceability	H	Essential for all nuclear waste programs
48. Qualitative arguments about the intrinsic robustness of site and design	M	Helpful for understanding and transparency

The importance ratings presented in TABLE IV are based on a "high" heat load, i.e., a heat load more appropriate for hotter commercial HLW and UNF (at least above boiling at the outer wall of the waste container) than for cooler DOE-managed HLW and SNF. This makes sense because it is a more "inclusive" way to prioritize RD&D issues and develop associated RD&D activities, since higher heat loads cause more complex physical-chemical interactions that will affect the performance of a repository containing commercial radioactive waste.

CONFIDENCE-BUILDING CONSIDERATIONS

As indicated in Fig. 2, confidence-building plays a significant role in the safety case, and should be given due consideration in the proposal and design of testing and/or modeling work. Depending on the stage of repository development and the interest of stakeholders and regulators, the confidence-building objective in Fig. 3 may be given a higher weight than the postclosure safety objective for several types of RD&D activities. For example, for a repository concept that has a mature technical basis, such as bedded salt, large scale demonstration tests may be given a higher importance than further refinement of constitutive models. For a full-scale *in situ* demonstration test the goal may be less the acquirement of data to predict repository performance far into the future, than simply a demonstration that environmental conditions and physical-chemical processes stay within well-defined ranges. Or, the goal of the *in situ* test may be simply to demonstrate that heat-generating waste can be emplaced without any major adverse or unforeseen events. Fig. 6 shows the confidence-building objective and sub-objectives that were considered in the Salt RD&D Workshop.

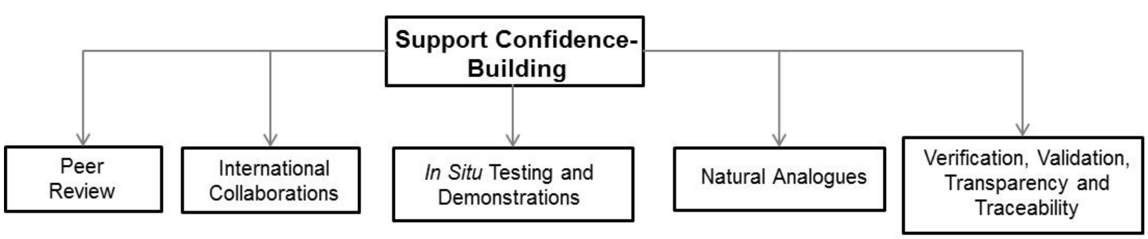

Fig. 6. Confidence-building objective and sub-objectives.

For the reasons noted above, related to the stage of repository development and the perceived importance of issues and activities to stakeholders and regulators, the confidence-building objective can be used to refine or revise the importance ratings in TABLE IV, e.g., to move an issue with an "M" rating to an "H" rating.

WORKSHOP

A planning workshop on “Advancing the Science and Engineering Supporting Deep Geologic Disposal of Nuclear Waste in Salt” was held March 6-7, 2013 at Sandia National Laboratories in Albuquerque, New Mexico, and was well attended by staff with expertise in repository sciences from SNL, LANL, LLNL, LBNL, and SRNL. Representatives from the U.S. DOE Offices of Nuclear Energy (NE), Environmental Management (EM), and the Carlsbad Field Office (CBFO) were also in attendance. This “Salt RD&D Workshop” [11] was two days in length and the overall goal of the workshop was to provide a basis for identifying RD&D activities that will have the greatest potential to contribute to the advancement of deep geologic disposal of nuclear waste in bedded salt, which is equivalent to the highest-level safety-case objective shown above in Fig. 3.

Importance ratings for the RD&D issues, as shown in TABLE IV, were reviewed by the workshop participants in two breakout sessions; one breakout group considered issues from a preclosure design/operations perspective and the other breakout focused on postclosure aspects of the disposal system. Of the thirty identified “feature/process” issues, about one-third of them (eleven) fell into the category of “high” importance for a nominal evolution scenario with high-heat load waste. The workshop participants also determined that for a human intrusion scenario another set of four issues, related to the waste form and associated chemical interactions, should be rated as “high” importance. It was noted that although these human intrusion issues might not warrant highest priority for the current generic research program (which is more focused on nominal performance), they need to be investigated at some level on a continuing basis, because they involve complex research programs that are difficult to set up. Workshop breakout groups also reviewed ratings for the twenty other RD&D issues (comprised of modeling issues, *in situ* testing issues, and confidence-building issues). Most of these were given high importance ratings, meaning that there is still some generic RD&D that could be completed with the goal of improving safety confidence.

The foregoing issue rating effort consumed the first day of the workshop. The second day of the workshop was devoted primarily to evaluating *in situ* field-testing activities (e.g., [5]) as to whether they could potentially support the primary safety case objectives described earlier. A post-workshop assignment, agreed to by the participants, was to suggest RD&D activities (lab, field, modeling) which would address the remaining RD&D issues that had been given a high or medium rating. Twenty-four such activities were proposed, of varying degrees of complexity [11, App. H].

CONCLUSIONS

This paper describes a decision methodology for evaluating the importance of additional RD&D activities needed to support a safety case for disposal of heat-generating radioactive waste in a generic bedded salt repository, given the current state of knowledge. The importance of any proposed RD&D activities (e.g., testing or modeling activities) is determined by evaluating the importance of the underlying technical issue (“RD&D issue”) relative to the objectives and goals of a safety case for a generic bedded salt repository. Technical issues are those primarily related to physical-chemical processes that might occur during the postclosure evolution of the repository.

An objectives hierarchy or “value tree,” which is a standard part of decision analysis, was created to evaluate the importance of remaining RD&D issues. Postclosure safety and four other objectives (repository design and construction, repository technical bases, preclosure safety, and confidence-building or enhancement) that map to the major elements of a successful safety case are considered to be the top-level objectives in the hierarchy. Of these five objectives, postclosure safety was the only one used at this stage to establish a semi-quantitative importance rating for the technical issues. However, the other objectives were considered with respect to how well they could be supported by *in situ* field-scale testing activities. Importance ratings assigned to remaining RD&D issues are based on an evaluation of these issues against three postclosure safety functions: isolation/stability, containment, and limited or delayed releases. These safety functions represent the key attributes of a multi-barrier repository system that will help achieve the objective of postclosure safety. Issue importance ratings can be combined with additional qualitative judgments to produce a more comprehensive prioritization of future RD&D activities. For example, the current state of knowledge for a particular RD&D issue, and the associated degree of uncertainty, will help determine both the necessity and focus of future RD&D.

REFERENCES

1. 66 FR (Federal Register) 55758. "Supplementary Information, III.3.8, Multiple Barriers and Defense in Depth" in *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada; Final Rule*, November 2, 2001, http://www.gpo.gov/fdsys/pkg/FR-2001-11-02/pdf/01-27157.pdf
2. IAEA. 2011. *Disposal of Radioactive Waste: Specific Safety Requirements,* IAEA Safety Standards Series No. SSR-5, International Atomic Energy Agency, Vienna, 2011.
3. Hansen, F.D. and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste*. SAND2011-0161, Sandia National Laboratories Albuquerque New Mexico.
4. EPA (U.S. Environmental Protection Agency). 2002. *Regulating the Safety of the WIPP: The Continuing Role of the U.S. Environmental Protection Agency*, U.S. EPA, Office of Air and Radiation (6608J), EPA-402-F-02-005, May 2002, http://www.epa.gov/radiation/docs/wipp/wippsafety1.pdf
5. Robinson, B. A., N. Z. Elkins, and J. T. Carter. 2012. "Development of U.S. Nuclear Waste Repository Research Program in Salt," *Nuclear Technology* **180**(1), pp. 122-138, October 2012.
6. Kuhlman, K. 2013. "Historic Testing Relevant to Disposal of Heat-Generating Waste in Salt," *Radwaste Solutions* **20**(4), September–October, 2013, pp. 22-28, American Nuclear Society (www.ans.org), La Grange Park, Illinois 60526.
7. DOE (U.S. Department of Energy). 2012. *Used Fuel Disposition Campaign Disposal Research and Development Roadmap.* FCR&D-USED-2011-000065, REV 1, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., September 2012.
8. BRC (Blue Ribbon Commission on America's Nuclear Future). 2012. *Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy*. January 2012.
9. MacKinnon, R. J., S. D. Sevougian, C. D. Leigh, and F. D. Hansen. 2012. *Towards a Defensible Safety Case for Deep Geologic Disposal of DOE HLW and DOE SNF in Bedded Salt.* SAND2011-6032. Albuquerque, NM: Sandia National Laboratories. July 2012.
10. NRC (National Research Council). 2003. *One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste*. Washington, DC: The National Academies Press.
11. Sevougian, S. D., R. J. MacKinnon, B. A. Robinson, C. D. Leigh, and D. J. Weaver. 2013. *RD&D Study Plan for Advancement of Science and Engineering Supporting Geologic Disposal in Bedded Salt—March 2013 Workshop Outcomes*, FCRD-UFD-2013-000161, Rev. 0, SAND2013-4386P, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., May 31, 2013, http://www.energy.gov/ne/listings/document-library.
12. NEA (Nuclear Energy Agency). 2013. *The Nature and Purpose of the Post-closure Safety Cases for Geological Repositories*, NEA Report No. 78121, Radioactive Waste Management, NEA/RWM/R(2013)1, February 2013, www.oecd-nea.org, Paris, France: OECD 2013.
13. NEA (Nuclear Energy Agency). 2009. *International Experiences in Safety Case for Geological Repositories (INTESC)*, NEA Report No. 6251, Paris, France: OECD 2009.
14. Bailey, L., Becker, D., Beuth, T., Capouet, M., Cormenzana, J.L., Cuñado, M., Galson, D.A., Griffault, L., Marivoet, J., and C. Serres. 2011. *PAMINA (Performance Assessment Methodologies*

in Application to Guide the Development of the Safety Case): *European Handbook of the state-of-the-art of safety assessments of geological repositories—Part 1*. European Commission. January 31, 2011. http://www.ip-pamina.eu/

15. Schneider J., L. Bailey, L. Griffault, H. Makino, K.-J. Röhlig, and P.A. Smith. 2011. *Safety Assessment and Safety Case Flowcharts,* OECD/NEA Project on the Methods of Safety Assessment (MeSA). MeSA Issue Paper # 2 Final. May 2011.
16. Sevougian, S. D., R. J. MacKinnon, C. D. Leigh, and F. D. Hansen. 2013. "A Safety Case Approach for Deep Geologic Disposal of DOE HLW and DOE SNF in Bedded Salt – 13350," in *Proceedings of the WM2013 Conference*, February 24 – 28, 2013, Phoenix, Arizona USA.
17. Freeze, G., M. Voegele, P. Vaughn, J. Prouty, W.M. Nutt, E. Hardin, and S.D. Sevougian. 2013. *Generic Deep Geologic Disposal Safety Case*, FCRD-UFD-2012-000146 Rev. 1, SAND2013-0974P, Sandia National Laboratories, Albuquerque, NM, August 2013.
18. Freeze, G., S.D. Sevougian, C. Leigh, M. Gross, J. Wolf, J. Mönig, and D. Buhmann. 2014. "A New Approach for Feature, Event, and Process (FEP) Analysis of UNF/HLW Disposal–14314," in *Proceedings of the WM2014 Conference*, March 2 – 6, 2014, Phoenix, Arizona USA.
19. NEA (Nuclear Energy Agency). 2012. *Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste: Outcomes of the NEA MeSA Initiative*. NEA Report No. 6923. Paris, France: OECD/NEA. ISBN 978-92-64-99190-3. http://www.oecd-nea.org/rwm/reports/2012/nea6923-MESA-initiative.pdf
20. Keeney R. L. and H. Raiffa. 1993. *Decisions with Multiple Objectives,* 2nd Edition, Cambridge University Press, New York, 1993.
21. von Winterfeld D. and W. Edwards. 1986. *Decision Analysis and Behavioral Research,* Cambridge University Press.
22. Weil R. and G. E. Apostolakis. 2001. "A Methodology for the Prioritization of Operating Experience in Nuclear Power Plants," *Reliability Engineering and System Safety*, **74**, 23–42.
23. Keeney, R. L. 1980. *Siting Energy Facilities*, Academic Press, New York.
24. Keeney, R. L. 1992. *Value-Focused Thinking: A Path to Creative Decision-Making*. Cambridge, Massachusetts: Harvard University Press.
25. Merkhofer, M. W. and R. L. Keeney. 1987. "A Multiattribute Utility Analysis of Alternative Sites for the Disposal of Nuclear Waste," *Risk Anal.* **7**(2), 173-194.
26. Keeney, R. L. and R. S. Gregory. 2005. "Selecting Attributes to Measure the Achievement of Objectives," *Oper. Res.* **53**(1), 1-11.
27. NWTRB (U.S. Nuclear Waste Technical Review Board). 2011. *Technical Advancements and Issues Associated with the Permanent Disposal Of High-Activity Wastes: Lessons Learned from Yucca Mountain and Other Programs, A Report to Congress and the Secretary of Energy*. June 2011. http://www.nwtrb.gov/reports/reports.html
28. Price R. R., B. Singh, R. J. MacKinnon, and S. D. Sevougian. 2013. "The Application of Systems Engineering Principles to the Prioritization of Sustainable Nuclear Fuel Cycle Options," *J. of Energy Policy*, 53(2013), 205-217.
29. Kuhlman K., S. Wagner, D. Kicker, R. Kirkes, C. Herrick, and D. Guerin. 2012. *Review and Evaluation of Salt R&D Data for Disposal of Nuclear Waste in Salt*, FCRD-UFD-2012-000380 and SAND2012-8808P, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., September 28, 2012.
30. Kuhlman, K. 2013. "Historic Testing Relevant to Disposal of Heat-Generating Waste in Salt," in *Proceedings of the 2013 International High-Level Radioactive Waste Management Conference*, Albuquerque, NM, April 28 – May 2, 2013, American Nuclear Society (www.ans.org), La Grange Park, Illinois 60526.

31. GRS (Gesellschaft für Anlagen und Reaktorshicherheit mbH). 2012. *Vorläufige Sicherheitsanalyse für den Standort Gorleben.* Köln. http://www.grs.de/vorlaeufige-sicherheitsanalyse-gorleben-vsg
32. DOE (U.S. Department of Energy). 1996. *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant.* DOE/CAO-1996-2184.
33. DOE (U.S. Department of Energy). 2004. *Waste Isolation Pilot Plant Compliance Recertification Application.* DOE/WIPP 2004-3231. March 2004.
34. DOE (U.S. Department of Energy). 2009. *Waste Isolation pilot Plant Compliance Recertification Application.* DOE 2009-24-34. March 2009.
35. Sevougian, S. D., G. A. Freeze, M. B. Gross, J. Lee, C. D. Leigh, P. Mariner, R. J. MacKinnon, and P. Vaughn. 2012. *TSPA Model Development and Sensitivity Analysis of Processes Affecting Performance of a Salt Repository for Disposal of Heat-Generating Nuclear Waste*, FCRD-UFD-2012-000320, Rev. 0, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., September 28, 2012.
36. Hansen, F.D. 2013. "Underground Salt Research Laboratory at the Waste Isolation Pilot Plant," in *Proceedings of the 2013 International High-Level Radioactive Waste Management Conference*, Albuquerque, NM, April 28 – May 2, 2013, American Nuclear Society (www.ans.org), La Grange Park, Illinois 60526.
37. Hansen, F.D., K. Kuhlman, W. Steininger, and E. Biurrun. 2013. *Proceedings of 3rd US/German Workshop on Salt Repository Research, Design and Operation*, FCRD-UFD-2013-000100, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C. SAND2013-1231P, Albuquerque, NM: Sandia National Laboratories. February 14, 2013.

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The statements expressed in this article are those of the authors and do not necessarily reflect the views or policies of the United States Department of Energy or Sandia National Laboratories. This paper is Sandia publication SAND2013-9491C.