A Safety Case Approach for Deep Geologic Disposal of DOE HLW and DOE SNF in Bedded Salt – 13350

S. David Sevougian*, Robert J. MacKinnon**, Christi D. Leigh***, and Frank D. Hansen****
*Advanced Nuclear Energy Programs Group, sdsevou@sandia.gov
**Advanced Nuclear Energy Programs Group, rjmacki@sandia.gov
***Defense Waste Management Programs Group, cdleigh@sandia.gov
****Geoscience Research and Applications Group, fdhanse@sandia.gov
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

ABSTRACT

The primary objective of this study is to investigate the feasibility and utility of developing a defensible safety case for disposal of United States Department of Energy (U.S. DOE) high-level waste (HLW) and DOE spent nuclear fuel (SNF) in a conceptual deep geologic repository that is assumed to be located in a bedded salt formation of the Delaware Basin [1]. A *safety case* is a formal compilation of evidence, analyses, and arguments that substantiate and demonstrate the safety of a proposed or conceptual repository. We conclude that a strong initial safety case for potential licensing can be readily compiled by capitalizing on the extensive technical basis that exists from prior work on the Waste Isolation Pilot Plant (WIPP), other U.S. repository development programs, and the work published through international efforts in salt repository programs such as in Germany. The potential benefits of developing a safety case include leveraging previous investments in WIPP to reduce future new repository costs, enhancing the ability to effectively plan for a repository and its licensing, and possibly expediting a schedule for a repository. A safety case will provide the necessary structure for organizing and synthesizing existing salt repository science and identifying any issues and gaps pertaining to safe disposal of DOE HLW and DOE SNF in bedded salt. The safety case synthesis will help DOE to plan its future R&D activities for investigating salt disposal using a risk-informed approach that prioritizes test activities that include laboratory, field, and underground investigations. It should be emphasized that the DOE has not made any decisions regarding the disposition of DOE HLW and DOE SNF. Furthermore, the safety case discussed herein is not intended to either site a repository in the Delaware Basin or preclude siting in other media at other locations. Rather, this study simply presents an approach for accelerated development of a safety case for a potential DOE HLW and DOE SNF repository using the currently available technical basis for bedded salt. This approach includes a summary of the regulatory environment relevant to disposal of DOE HLW and DOE SNF in a deep geologic repository, the key elements of a safety case, the evolution of the safety case through the successive phases of repository development and licensing, and the existing technical basis that could be used to substantiate the safety of a geologic repository if it were to be sited in the Delaware Basin. We also discuss the potential role of an underground research laboratory (URL).

INTRODUCTION

Investigating the feasibility and value of developing a defensible safety case for DOE HLW and DOE SNF at this time, based on existing technical information, is motivated by the fact that the previously existing pathway for disposal (Yucca Mountain) has been halted. The emphasis of this study is on DOE HLW and DOE SNF, in part because of its limited economic value as an energy resource, but also to further the development of geologic repository science and engineering, while the Nation endeavors to reach a consensus on the disposition of commercial SNF [2].

The development of any geologic repository will take place over a period of years and will generally include the following phases: site selection and characterization (including facility design), licensing, construction, operation, closure, and postclosure [3, Sec. 3.1]. However, as noted by the Nuclear Energy Agency [4]: "An initial safety case can be established early in the course of a repository project. The safety case becomes, however, more comprehensive and rigorous as a result of work carried out, experience gained and information obtained throughout the project…" The key point here is that the rigor needed for a safety case for DOE waste in bedded salt is already in large part available, due to the amount of work previously related to waste disposal in salt, both domestically and internationally. That is, many of the major elements of a safety case could be addressed with existing technical bases and experience from prior salt repository work.

Other benefits of utilizing prior salt R&D activities include potentially reducing future repository development costs and shortening the schedule for such a repository by leveraging the U.S. repository experience on the Waste Isolation Pilot Plant (WIPP) and the Yucca Mountain Project (YMP), various historical investigations at other potential salt repository sites in the U.S. (such as Lyons, Kansas and Deaf Smith County, Texas), and collaborations with the German salt repository program. This experience includes many key aspects of siting, repository development, operations, safety assessment, and licensing, including repository and seal system design, preclosure safety analysis, and application of performance assessment (PA) methodology [5, 6, 7, 8].

The safety case will provide the necessary structure for organizing and synthesizing existing salt repository science and identifying any issues and gaps pertaining to safe disposal of heat-generating nuclear waste in salt. This safety case synthesis will help DOE to plan its future research and development (R&D) activities for improving the defensibility of the safety case using a risk-informed approach, based in part on performance assessment modeling. Future activities, if deemed necessary, to increase the confidence in the arguments that form the basis of the safety case, may include a limited set of additional laboratory, field, and/or site investigations to reduce uncertainties in the events, processes, and properties associated with the evolution of heat-generating waste emplaced in salt. Also, even if the eventual site of a DOE repository is located outside of the Delaware Basin, but still in bedded salt, the relevance of the WIPP experience and other technical bases would nonetheless contribute significantly to the associated safety case.

REGULATORY BASIS FOR A DOE HLW/SNF DEEP GEOLOGIC REPOSITORY

The safety standards and implementing regulations governing development of a geologic repository are the important bases for judging the safety of a conceptual DOE HLW/SNF geologic repository. The site-specific Environmental Protection Agency (EPA) and U.S. Nuclear Regulatory Commission (U.S. NRC) regulations for Yucca Mountain, 40 CFR 197 and 10 CFR 63, are not applicable to a separate DOE HLW/SNF repository, but existing EPA and U.S. NRC regulations for disposal of high-level radioactive wastes in geologic repositories remain in effect, i.e., 40 CFR 191 and 10 CFR 60. However, these existing regulations would likely be superseded for a DOE HLW/SNF repository, since they were developed almost 30 years ago and are not consistent with the more recent thinking on regulating geologic repositories that embraces a risk-informed, performance-based approach [9], such as that represented in the site-specific regulations for Yucca Mountain. Despite this uncertainty regarding applicable safety standards, a robust safety case can still be developed based on either the existing standards (40 CFR 191 and 10 CFR 60) or on generic standards that incorporate dose or risk metrics recognized internationally to be important to establishing repository safety. Examples of the latter are compiled in Bailey et al. [10, Sec. 6.2], e.g., the French requirement that the dose rate should be less than 0.25mSv/yr.

Another important regulatory issue that influences the safety case is the specific waste inventory to be disposed in a DOE HLW/SNF repository [11, 12]. The safety case described herein assumes that the inventory would be a "non-NWPA" inventory consistent with Sec. 8(c) of the Nuclear Waste Policy Act[1] [13] and would be similar to one of the inventories considered by Carter et al. [2] [14].

If DOE decides to ultimately pursue the development of a deep geologic repository for disposal of DOE HLW and DOE SNF, other requirements may have to be satisfied, such as the National Environmental Policy Act (NEPA) (40 CFR 1500-1508). A NEPA-mandated Environmental Impact Statement (EIS) for a repository, if it were to be sited in the Delaware Basin, could be developed by leveraging the EIS for WIPP [15] and much of the technical basis identified here. Finally, the WIPP Land Withdrawal Act [16] does not allow for the disposal of HLW or SNF at the WIPP site. However, the Salado bedded salts of the Delaware Basin are extensive in southeast New Mexico, implying that most of the technical basis developed for the WIPP site can be used at other potential salt repository sites in the Delaware Basin.

SAFETY CASE CONCEPT

The Nuclear Waste Technical Review Board [17, Section 4.4] has suggested that the U.S. repository program would benefit from international work [4, 18, 19, 20] regarding "what a safety case should look like and how a national program might advance it." A *safety case* is an integrated collection of evidence, analyses, and other qualitative and quantitative arguments used to demonstrate the safety of the repository. Two of its major roles are as a management tool to guide the work of the implementer (e.g., DOE) through the various phases of repository development and to communicate the understanding of safety to a broad audience of stakeholders [3]. With regard to the former, because of various technical uncertainties associated with a complex one-of-a-kind repository project, the safety understanding and basis evolves through time. The safety case provides the framework to assist in prioritizing the technical work in the next phase of development, in order to reduce these uncertainties and to enhance the confidence in safety. This will be in the context of various defined decision points that may or may not result in construction and operation of the repository. As noted by the Nuclear Energy Agency [4, p. 7]:

> "A detailed safety case, presented in the form of a structured set of documents, is typically required at major decision points in repository planning and implementation, including decisions that require the granting of licenses. A license to operate, close, and in most cases even to begin construction of a facility, will be granted only if the developer has produced a safety case that is accepted by the regulator as demonstrating compliance with applicable standards and requirements."

With regard to the role of the safety case in the communication of safety arguments to a diverse group of stakeholders, the National Research Council's Committee on Principles and Operational Strategies for Staged Repository Systems [3, p. 126] has stated:

> "The safety case is also used to develop a program with features such as robustness and conservatism and to convince the implementer itself, the regulator, stakeholders, and the general public that there is a sensible and defensible set of arguments showing that the repository will be safe. The safety case includes a broad and understandable (to stakeholders and the general public) explanation of how safety is achieved and a

[1] The NWPA Sec. 8(c) states that "The provisions of this Act shall apply with respect to any repository not used exclusively for the disposal of high-level radioactive waste or spent nuclear fuel resulting from atomic energy defense activities, research and development activities of the Secretary, or both." [also see 13, Sec. 101].

[2] Some inventory owned and managed by DOE is not included in Carter et al. [14], such as 275 HLW canisters from the West Valley, NY reprocessing facility. Because these wastes are related to commercial energy production, it is not clear if these wastes are part of the non-NWPA waste inventory mentioned above that could be disposed of in a facility dedicated "exclusively" to atomic energy defense activities and DOE R&D activities [12].

> similar discussion of the uncertainties that result from limitations in the scientific understanding of system behavior."

As mentioned in the previous section, the current and applicable regulations for any new geologic repository, including a DOE HLW/SNF repository, are subject to being superseded as part of the development of the nation's policy for managing the back end of the fuel cycle. However, the purpose of the safety case would not be to replace or expand upon requirements of the licensing process, but rather to make the rationale for decisions about the facility accessible and understandable to the public and to a wider range of decision makers (e.g., Congress, state and local governments) beyond the regulatory experts who already have the technical expertise to make judgments about safety. Much of the safety rationale can be developed prior to the finalization of new regulations (if applicable), based on past DOE repository experience (Yucca Mountain and WIPP), as well as on commonly proposed safety indicators and metrics in the international arena, e.g., as described by Becker et al. [21]. Thus, regardless of the presence or absence of either general or site-specific regulatory guidance, the safety case structure and concept, as described here, is the recommended vehicle for articulating and communicating the safety of a DOE HLW/SNF repository.

Elements of the Safety Case

Although the scope of a safety case, and the definitions and terminology used therein, differ somewhat across the various international programs [4, 10, 22, 23], they all have the same goal of understanding and substantiating the safety of a disposal system. In this study, the major elements of the safety case are patterned after the NEA postclosure safety case [4], but include aspects of preclosure safety:

- *Statement of Purpose*. Describes the current stage or decision point within the 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 safe disposal, and includes (a) an overall management strategy, (b) a siting and design strategy, and (c) an assessment strategy. Two important principles of the safety strategy are (1) public and stakeholder involvement in key aspects of siting, design, and assessment and (2) alignment of the safety case with the existing legal and regulatory framework.
- *Site Characterization and Repository Design*. This contains key portions of the *assessment basis* that is described in some safety case concepts [4], and includes a description of (a) the primary characteristics and features of the repository site, (b) the location and layout of the repository, (c) a description of the engineered barriers, and (d) a discussion of how the engineered and natural barriers (i.e., the multiple-barrier concept) will function synergistically. In the earliest phases of the repository program it includes the site selection process and associated selection criteria/guidelines.
- *Preclosure and Postclosure Safety Evaluation*. This includes a quantitative safety assessment of potential radiological consequences associated with a range of possible evolutions of the system over time, i.e., for a range of scenarios, both before and after repository closure. It also includes qualitative arguments related to the intrinsic robustness of the site and design, insights gained from the behavior of natural and anthropogenic analogues, and sensitivity and uncertainty analyses to quantify key remaining uncertainties, which may be addressed with future R&D, if necessary.
- *Statement of Confidence and Synthesis of Evidence*. The statement of confidence is based on a synthesis of safety arguments and analyses, and includes a discussion of completeness to ensure that no important issues have been overlooked in the safety case. The statement of confidence recognizes the existence of any open issues and residual uncertainties, and perspectives about

how they can be addressed in the next phase(s) of repository development, if they are considered to be important to establishing safety.

Phased Development of the Safety Case

The development of a geologic repository will take place over a period of years and will generally include the following phases: site selection and characterization (including facility design), licensing, construction, operation, closure, and postclosure [3]. The relationship between the phases of repository development and the evolution of the safety case is illustrated in Fig. 1.

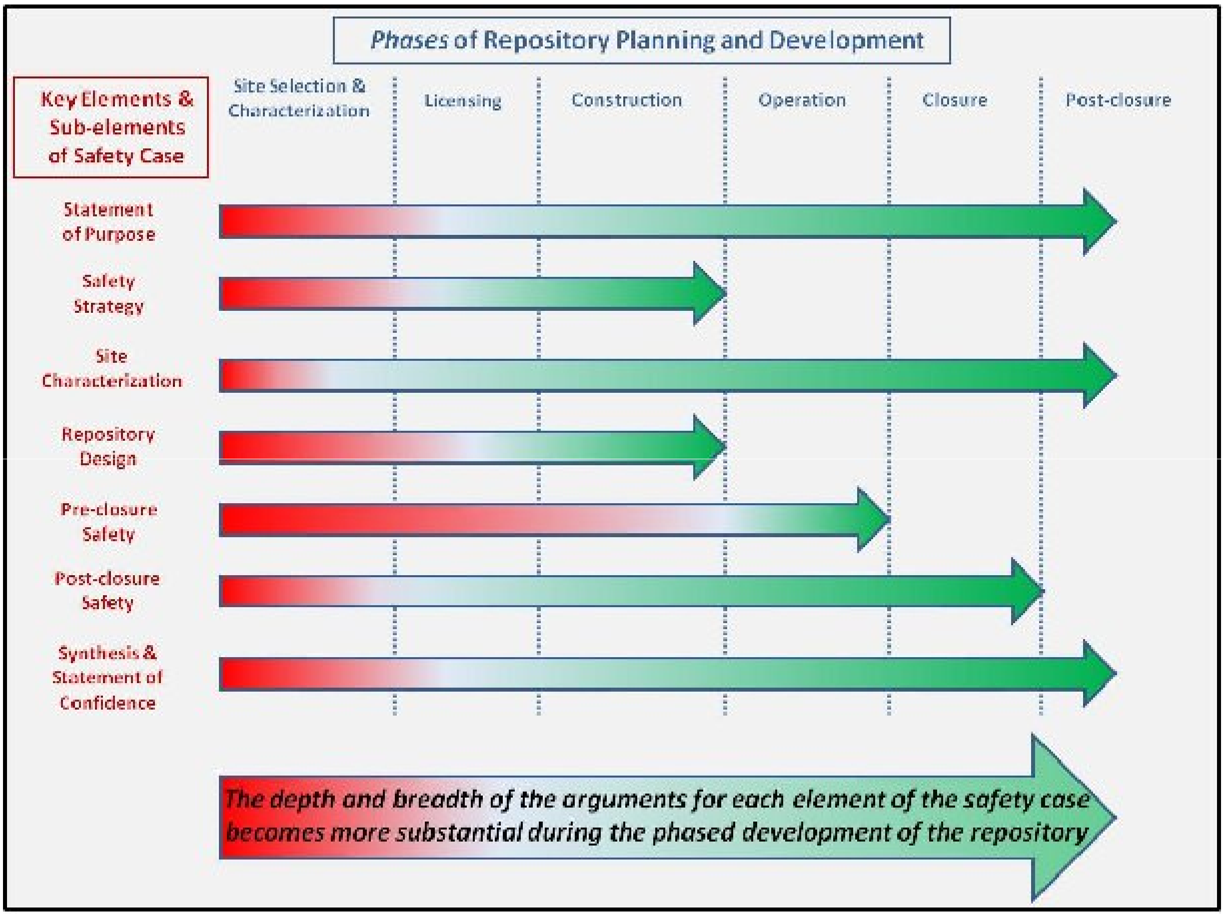

Fig. 1. Evolution of the Safety Case as Part of a Phased Approach to Repository Development.

Typical phases and decision points in the development of a repository are shown across the top of the figure, while key elements of the safety case are shown along the side. As the repository program evolves from siting to licensing to closure, the required level of completeness and rigor increases and the associated safety case becomes more detailed with the addition of more 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 phase feeds site characterization and design at the next phase. Public and other stakeholder participation are important in each phase, before proceeding to the next phase of development. With respect to the staged repository development shown in Fig. 1, because of the existing salt information basis from the WIPP repository and internationally, it is possible to accelerate the development of a defensible safety case for the site selection to licensing phases for a repository of DOE HLW/SNF in bedded salt. This safety case will not only provide decision makers and stakeholders with a concise summary of existing technical information mapped to the elements of the safety case, but also the basis for beginning the process of licensing and conducting public and regulator interactions. It will also provide a basis for identifying and prioritizing those activities necessary to finalize the safety case and license application.

EXISTING TECHNICAL BASIS FOR A SALT REPOSITORY

The concept of radioactive waste disposal in salt was recognized by the National Academy of Sciences as early as 1957 when they identified salt as the most promising method for high-level waste disposal [24]. An operational radioactive waste disposal facility for defense-generated transuranic (TRU) waste (i.e., WIPP) has since been sited in the Delaware Basin of Southeast New Mexico in the U.S., demonstrating this concept. Lessons learned from siting and operating this facility can be used to support the development of an HLW/SNF disposal facility in salt, particularly since the original design concepts and siting requirements for WIPP were based on the intent to dispose of HLW in addition to TRU waste [25; 26, pp. 2-9].

Disposal of DOE HLW/SNF in a suitable salt formation is attractive because the material is essentially impermeable, self-sealing, thermally conductive, and a significant experience base exists from earlier studies. A salt repository could potentially achieve complete containment, with no releases to the environment in undisturbed scenarios for as long as the region is geologically stable [27]. This complete containment goal could be further supported if it were decided to site a repository in the areally extensive and thick sequence of bedded salt and associated evaporites in the Delaware Basin, a sub-element of the Permian Basin of Southeast New Mexico and West Texas. However, it should be noted that phenomena caused by heat from HLW and SNF could add some potentially beneficial and/or detrimental FEPs that are not necessarily important for the significantly cooler TRU waste that is disposed at WIPP. This consideration also applies to FEPs related to the physical and chemical characteristics of DOE HLW and DOE SNF, since these characteristics are likely to be appreciably different than TRU waste. In addition, site-specific considerations and differences in the disposal concept, container types, and performance period could give rise to potentially important FEPs. Further, new human intrusion FEPs may need to be considered because of the different characteristics of DOE HLW/SNF. Overall, a FEPs analysis would be required in order to move forward with a safety case, and many of the FEPs screening results performed for WIPP will still be applicable.

A specific example of a potentially detrimental FEP that was determined to be unimportant for TRU waste, which may be important for heat-generating waste like HLW and SNF, is the reaction of acidic brines with metal waste containers. Acid-producing reactions were found to occur in a WIPP-representative brine subjected to elevated temperatures [28] implying that, if an acidic brine was available in sufficient quantity under repository conditions, it could be potentially detrimental to waste container performance. In fact, DOE has recently funded studies of waste container material performance to provide information applicable to a potential salt repository for SNF or HLW [29]. As an example of site-specific FEPs that should be considered if a repository were to be sited in the Delaware Basin, the potential impact of karst processes on repository performance would need to be evaluated depending on the site location and regulatory compliance period, since these processes are prevalent in some regions of the Permian Basin, including the Delaware Basin [30].

The remainder of this section reviews those key elements of the safety case to which most of the prior salt R&D was directed: siting, repository design, and safety assessment. It describes those aspects of the existing technical and knowledge bases that are relevant if a repository for disposing DOE waste were to be sited in Delaware Basin bedded salt. However, it only includes example references to prior research on disposal of heat-generating waste in salt. A much more complete review of the relevant technical bases for bedded salt produced hundreds of relevant references, as documented in MacKinnon et al. [1, App. B]. These have been included in a MySQL database [31], which actually includes over 10,000 potentially relevant references related to salt. Based on keyword searches of this database [31, Table 3], several hundred of these references are ranked high for their relevance to disposal of heat-generating waste in salt [31, App. A].

Site Selection

During the site selection process, the organization responsible for repository siting and development investigates one or more sites to determine suitability with respect to various screening criteria and guidelines [3]. Preliminary site investigations, such as seismic mapping or exploratory borehole drilling, will produce a variety of technical data, including geologic, hydrologic, geochemical, and geophysical data at the candidate sites, which can then be used to evaluate a site's fulfillment of technical siting criteria. In addition to technical criteria and data, other criteria and data related to health and safety, environmental, socioeconomic, and economic considerations [32] should be gathered during the siting process.

These types of criteria were used during the WIPP site selection process, and can be used to inform a possible future site selection for a DOE HLW/SNF repository in the Delaware Basin. In particular, the WIPP site selection was conducted "utilizing siting factors appropriate for a high-level waste repository in order to provide as much flexibility for future options as possible." [33]. Thus, even though the WIPP Land Withdrawal Act [16] later precluded the use of WIPP as an HLW repository, the original site selection process developed for bedded salt during the WIPP siting phase may be useful for siting of a DOE HLW/SNF repository elsewhere in the Delaware Basin.

At early stages of repository site selection, both the geologic media (e.g., salt, shale, or granite) and the location or setting (e.g., salt domes or bedded salt) are part of the down-selection process. At later stages, after a specific medium and/or setting is established, the criteria become specific to the medium and setting. Oak Ridge National Laboratory and the U.S. Geological Survey determined in the early 1970s that a repository in bedded salt of the northern portion of the Delaware Basin would be suitable for radioactive waste [26, Sec. 2.3.1; 31, Sec. 3; 34, p. 10; 35). Once this was determined, more specific siting criteria were applied to help site an exact repository location, including [26, Sec. 2.3.6]:

- *Geology criterion*. Includes the following factors: topography, depth, thickness, lateral extent, lithology, stratigraphy, structure, and erosion
- *Hydrology criterion*. Includes the following factors: surface waters, aquifers, dissolution, subsidence, hydrologic transport, climatic fluctuations, and man-made penetrations
- *Tectonic stability criterion*. Includes the following factors: seismic activity, faulting/fracturing, salt flow/anticlines, diapirism, regional stability, igneous activity, and geothermal gradient
- *Physico-chemical compatibility criterion*. Includes the following factors: fluid content, thermal properties, mechanical properties, chemical properties/mineralogy, radiation effects, permeability, nuclide mobility
- *Economic/social compatibility criterion*. Includes the following factors: natural resources, man-made penetrations, transportation, accessibility, land jurisdiction, population density, ecological effects, and sociological impacts

A more specific implementation of these criteria, such as "a minimum depth to suitable salt of 1,000 ft," led to the choice of the Los Medaños region as the best site for the WIPP TRU waste repository [26, 33, 34]. Since that time, much work has been done on the characterization of the land surface, particularly with respect to the flora and fauna present in the Delaware Basin. With that work as a basis, the WIPP

Disposal Phase Final EIS [15] discussed potential environmental impacts from the construction and operation of the facility, including impacts to flora and fauna. No significant environmental impacts were identified. Furthermore, any realized impacts have been manageable, as demonstrated by the construction and operation of WIPP. Thus, for development of a safety case for licensing an HLW/SNF repository, were it to be sited in the Delaware Basin, it could confidently be assumed that potential environmental impacts to flora and fauna will be minimal.

The nature and extent of commercially mined natural resources in the Delaware Basin, like oil, natural gas, and potash, are also known [36, App. DATA] and have been addressed both in the WIPP EIS [15, 37] and in the many performance assessments and compliance applications developed for WIPP [6, 36, 38, 39, 40, 41]. This compendium of information indicates that while extraction of natural resources for commercial purposes will likely continue in the presence of the existing and any future radioactive waste repository located in the bedded salt formation of the Delaware Basin, the dual use of this regional area is workable and can be managed so that repository performance would not be adversely affected.

The foregoing siting basis for WIPP and other, similar criteria and associated factors could be used if a repository for DOE HLW/SNF were to be sited in the Delaware Basin. In addition, the methodology from other site-screening studies for radioactive waste, e.g., for commercial HLW/SNF [42], is applicable to decisions about siting a DOE HLW/SNF repository.

Site Characterization

The region surrounding the WIPP site has been studied extensively for many years. Geophysical logs, cores, basic data reports, geochemical sampling and testing, and hydrological testing and analyses are reported by the DOE and Sandia National Laboratories (SNL) in numerous public documents [6, Ch. 2; 31]. Numerous additional studies have also been conducted by DOE and SNL since the initial WIPP certification. Many of these documents could form the technical basis for a safety case for a DOE HLW/SNF repository were it to be sited in Delaware Basin bedded salt [27 and references therein; 36; 41].

The geology of southeastern New Mexico has also been discussed or described extensively in professional journals or technical documents from many different sources other than DOE and SNL, primarily because of the exploration of both potash and hydrocarbon deposits in the region. These types of articles are another source of site characterization information for a possible Delaware Basin repository site. Elements of the geology presented in such sources have been the subject of specific DOE-sponsored studies [6, Ch. 2].

Repository Design and Waste Characteristics

As mentioned by Hansen and Leigh [27], a salt repository can be engineered to accommodate a broad spectrum of waste volumes, types, and decay heat. The engineered barrier system (EBS) design and repository layout are less dependent on emplaced waste characteristics than in other media because of the robustness of the natural barrier, i.e., the impermeability of salt and its ability to encapsulate the waste after disposal, thereby lessening the dependency of the safety case on the functioning of engineered barriers and the waste container.

<u>DOE HLW/SNF Waste Characteristics</u>

DOE nuclear waste materials that need to be permanently disposed, including HLW and SNF, have been well characterized [7, 43] and would be further evaluated during the development of this safety case. DOE SNF was primarily generated by DOE production reactors, but also includes naval SNF. DOE SNF generated in production reactors supported weapons and other isotope production programs. An example of SNF existing today from production reactors is the N-Reactor fuel stored at the Hanford site. Radionuclide inventories for DOE SNF vary widely depending on the history and fuel design [44]. Projections for the number of SNF canisters that would need to be disposed of vary depending on the fuel types, treatment and packaging arrangements and may possibly be a function of the repository design [7, 14].

HLW generated from the processing of defense-related SNF will be disposed of either in the form of borosilicate glass or calcine waste [14]. The borosilicate glass is formed by mixing HLW with a combination of silica sand and other constituents or with glass-forming chemicals that are melted together and poured into stainless steel canisters. Once the material vitrifies, the canister is sealed. Previously calcined HLW will be further treated by hot isostatic pressing (HIP) to reduce its volume and the number of required disposal canisters [14]. A loaded, sealed HLW canister and its contents constitute the final, to be disposed, waste form. Well over 20,000 HLW canisters would have to be disposed in various sizes with a range of inventories and heat generation rates depending on where the HLW originated and its age [7, 14, 43]. The majority of both DOE HLW and DOE SNF is currently stored at three DOE sites: Hanford, Savannah River, and the Idaho National Laboratory.

Repository Design

A mine layout for HLW and SNF disposal in salt can be quite flexible [27]. For example, the concept of operations utilized at WIPP includes stacking of contact-handled (CH) waste on the floor and horizontal disposal of remotely handled (RH) waste in boreholes in pillars. Initial designs for WIPP considered placement of HLW in vertical boreholes in the floor of the repository. Internationally, Germany has taken a leading role in underground waste disposal in rock salt formations with two repositories, one in a former salt mine (Asse) in north-central Germany that was operated between 1967 and 1978, and another in the Bartensleben salt mine in Morsleben, Germany that was used from 1972–1998. The Asse mine was also used as a research facility for a number of years. The feasibility of both borehole and drift disposal concepts has been demonstrated by about 30 years of testing in the Asse mine [45].[3] Although no country has a repository for HLW in salt, the previous experiments and disposal demonstrations attest to the flexibility of the concept of disposal operations.

The safety case outlined in this paper could be based on the recent design concept for a defense waste salt repository [14] that was derived from a conceptual salt repository study for recycled commercial light water reactor (LWR) fuel in a hypothetical closed fuel cycle [46]. The waste in the original study [46] was assumed to be generated by a conventional recycling facility which recovers uranium (U) and plutonium (Pu) for reuse and produces a vitrified high-level waste containing the high-decay-heat radionuclides. The repository design concept for this conceptual salt repository for commercial HLW consists of panels with individual rooms containing a series of alcoves. The disposal strategy assumes placement of one canister at the end of each alcove to be covered by crushed salt backfill for radiation shielding of personnel accessing adjacent alcoves. By providing spacing between adjacent canisters the areal heat loading of the salt is controlled. Defense-related and other DOE waste generally has a much

[3] It should be noted that the Asse mine is currently being decommissioned as a radioactive waste repository [47]. This is primarily a result of two detrimental factors: mechanical instability and brine influx. In particular, contrary to the WIPP site or to a new DOE HLW/SNF repository, the Asse site was not originally developed as a waste repository but as a potash mine, beginning in 1909. Therefore, care was not taken to ensure appropriate thickness for the repository horizon, and in some places the overlying rock (the source of brine influx) is within 5 meters of mine chambers. Some radioactive contaminated liquid is also found in the mine, due to poor isolation practices and spills during emplacement activities (but not due to the current influx of salt-saturated fluid).

lower heat load than the commercial HLW assumed in Carter et al. [46]. Evaluation of the DOE waste inventory in Carter et al. [14] revealed that the vast majority of the packages would be less than 100 watts each, which allows a much more efficient underground emplacement approach. Alcove emplacement of individual waste packages is not required. Instead, an in-room, on-the-floor disposal approach was proposed, with variable spacing, to accommodate waste packages with varying heat loads. Most waste packages are closely spaced, with a minimum spacing of 1 foot between canisters (3 feet centerline spacing) to allow for a run-of-mine salt backfill and to ensure packages are not displaced from their intended location as additional waste packages are emplaced. Thermal calculations demonstrated that a maximum temperature of 95°C could be assured for DOE HLW waste packages, even in a densely packed disposal scenario, while a temperature of less than 250°C could be maintained for DOE SNF waste packages by appropriate spacing and/or repackaging.

Because of the extremely low permeability of intact or healed salt [27], the geologic disposal concept for salt does not require long-term waste package containment integrity. However, a defense-in-depth philosophy may result in regulations that require the waste package to retain its isolation capability through the thermal period [27, Sec. 2.5.1] when brine migration processes are most active around the waste package, prior to reconsolidation of the crushed salt backfill around the waste package. This is likely to be less than 200 years [48], so carbon steel is a reasonable choice for the disposal overpack material. Carbon steel is susceptible to general corrosion of exposed surfaces, but not localized corrosion, which makes its degradation easier to represent in performance assessment models.

Another important component of salt repository design is the shaft sealing system. The shaft sealing system designed for WIPP, which has been reviewed and certified by EPA, would be the starting point for a salt repository safety case. Any modifications to the WIPP seal design envisioned for a repository for DOE HLW/SNF were it to be sited in Delaware Basin bedded salt would enhance the basic functions for which the WIPP shaft seal system was designed [1, Sec. 4.3.2].

Other aspects of repository design and siting in a bedded salt formation that are necessary to run preliminary performance assessment calculations have been discussed by Sevougian et al. [49].

Preclosure Safety

Demonstrating confidence in preclosure safety is also an important element of the safety case and includes transportation safety and operational safety. These aspects of preclosure safety should be described and analyzed in a safety case, and made available to decision makers and the public as transportation and disposal systems mature. Transportation of SNF and HLW, potential transportation routes, potential risks of transporting SNF and HLW, and potential transportation accidents and consequences should be described and evaluated. Operational safety should include a description of surface facilities and their operation, a description of the preclosure *safety assessment* methodology, and an assessment of potential occupational and public health and safety. The preclosure safety assessment identifies the potential natural and operational hazards for the preclosure period; assesses potential initiating events and event sequences and their consequences; and identifies the structures, systems, and components (SSCs) and procedural safety controls intended to prevent or reduce the probability of an event sequence or mitigate the consequences of an event sequence, should it occur [7, Chapter 1].

In this case of disposal in bedded salt the preclosure safety analysis will be supported by data from real packaging, transportation and operational experiences. In particular, operational information gained from experience at WIPP, the Asse mine, and Morsleben can all be inputs to an assessment of safety before closure. Probably the most relevant information from ongoing WIPP operations includes safe waste packaging/handling at the generator sites, safe transportation practices while moving waste from the generator site to the disposal site, and safe mining practices at the disposal site [8]. In addition, experience and analyses gained over the lifetime of the Yucca Mountain Project, specifically related to packaging and transportation of HLW/SNF and the potential vulnerability of waste packages [7, Chapter 1], can also be used in preclosure safety analyses.

Conceptual design information for the repository design discussed in the previous section could be used to identify initiating events and to conduct preliminary event sequence analyses. Representative waste containers, rather than those of specific designs or specific suppliers, can be analyzed for their failure potential associated with these event sequences. In addition, a range of container dimensions and materials can be considered within the set of representative preclosure safety analyses for the safety case. Conceptual design information on locations and amounts of radioactive material at various locations in the repository could be used in performing consequence and criticality analyses.

Additional site information relevant to a preclosure safety analysis for a conceptual Delaware Basin repository site, such as wind patterns, precipitation, environmental conditions and impacts, are available from the latest WIPP Annual Site Environmental Report [50] and the WIPP EIS [15].

Postclosure Safety

The postclosure *safety assessment*, which in the U.S. program and regulations is generally referred to as the postclosure *performance assessment* (e.g., see 40 CFR 191, the currently applicable standard for all geologic repositories in the U.S. other than Yucca Mountain and the standard under which WIPP is certified), is a key part of the safety case. As stated by the NWTRB [17, p. 53]: "Performance assessment is arguably the most important part of the safety case..." 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 of the engineered and/or geological components, e.g., containment 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). A complete safety assessment includes quantification of the long-term, postclosure performance of the repository and an analysis of the associated uncertainties in this prediction of performance. Such an assessment requires conceptual and computational models that include the relevant features, events, and processes (FEPs) that are or could be important to safety.

The knowledge base for performance assessments in the U.S. is extensive. For example, PA methodology has been used successfully to certify the WIPP repository and to develop the Yucca Mountain license application, and has been applied to many other waste disposal projects in the U.S. and internationally, beginning in the 1970s [51]. This methodology is directly applicable now for estimating the potential performance of a DOE HLW/SNF repository in bedded salt against relevant safety criteria. Meacham et al. [51, Fig. 2] have illustrated the steps in the performance assessment (PA) methodology that was used successfully to certify the WIPP defense TRU waste repository [6, 36, 41] and develop the Yucca Mountain License Application [7]. It has also been applied to many other waste management projects, dating back to the 1970s, including uranium mill tailings landfills and "greater confinement disposal (GCD)" of LLW at the Nevada National Security Site. This same PA methodology could be readily applied in an assessment of safety after repository closure for a bedded salt repository for DOE HLW/SNF if it were to be sited in the Delaware basin. This PA methodology organizes a variety of types of information that build confidence in postclosure system safety, including (1) the underlying technical bases for the safety assessment models (a component of the *assessment basis* in some safety case concepts, e.g., [4]), (2) the scenario and FEPs analysis that ensure a comprehensive assessment of postclosure performance, (3) a quantitative and qualitative description of barrier capability (which promotes the defense-in-depth concept), and (4) uncertainty and sensitivity analyses that help quantify where additional information is needed for the next stage of repository development.

Consideration of uncertainty in the evaluation of safety after repository closure is a well-developed science [52, 53] that categorizes uncertainty into two major types: uncertainty related to the inherent randomness of the problem (such as random external events that affect safety, e.g., seismicity) and uncertainty related to lack of measurement data (such as the uncertain composition of the current inventory of spent fuel and high-level waste). The former type of inherent or irreducible uncertainty is often called *aleatory* uncertainty and the latter type of measurement or reducible uncertainty is often called *epistemic* uncertainty [54]. Epistemic uncertainties can be reduced by data-gathering methods, including additional site characterization, design studies, fabrication and other demonstration tests, and other experiments both in the laboratory and in underground test facilities.

Sensitivity analyses from the postclosure safety assessment provide the basis for defining the types of tests and studies needed to reduce epistemic uncertainty and for assigning priorities for further R&D work in the next stage of repository development. This is a key feature of the PA methodology, which results from the iterative nature of the process wherein the current performance assessment informs the research and development agenda necessary for the next phase of system characterization, design, and/or implementation. This iterative principle has been applied to several very different disposal concepts that advanced to licensing: WIPP [6], Yucca Mountain [7], and Greater Confinement Disposal [55]. As recommended by the Nuclear Waste Technical Review Board [17, p. 53]: "Future repository programs should use probabilistic performance assessments throughout the life of a program to help set priorities among site-characterization activities, i.e., to guide the research portfolio."

UNDERGROUND RESEARCH LABORATORY

The safety case supports all aspects of disposal concept development and provides a framework for identifying and prioritizing work in those areas where further understanding is needed to build confidence and ensure the safety of the geological facility. An underground research laboratory (URL) could be used to build additional confidence in those areas that would be better examined at a large scale, such as aspects of different design options regarding ventilation and cooling systems, operational efficiency, and safety. Examining coupled physical and chemical processes at a field scale can also help reduce residual uncertainty in these processes because they would be examined at a scale close to the actual scale of a repository.

Although a field-scale disposal demonstration in a URL is not needed to initiate a strong safety case for disposal of DOE HLW and DOE SNF if it were to be sited in Delaware Basin bedded salt, there can be benefit in using an appropriately designed underground test for building additional confidence for the safety case. Such *in situ* testing in a URL should be "risk-informed" in a systematic fashion by the current version of the safety case and any associated performance assessment analyses, such as uncertainty and sensitivity analyses which determine the parameters and processes that most affect repository performance. Any specific underground test used to support the safety case should be assigned a priority based on how much it builds confidence and reduces uncertainties. Furthermore, the sequencing of tests and demonstrations, data acquisition systems, synergism or interference between and among tests, and the method for evolving from initial tests (say of a single disposal demonstration) to a long-term URL of use to the international salt science community, all need to be addressed prior to any underground testing.

CONCLUSIONS

Based on the wealth of existing technical information from prior repository investigations in the U.S. and abroad, including the multiple performance assessment iterations at WIPP, a strong initial safety case can be developed expeditiously for a geologic repository for DOE HLW and DOE SNF waste if it were to be sited in Delaware Basin bedded salt. This conclusion is derived from the following factors:

- The Nation has an extensive knowledge base in salt repository science that indicates that salt is a suitable disposal medium for radioactive waste; this basis stems from prior work on WIPP, work on past U.S. repository development programs such as the Salt Repository Project [56], and the work published through international efforts in salt repository programs such as in Germany
- Performance assessment (PA) methodology for nuclear waste disposal has been developed, matured, and applied successfully in the certification of WIPP
- DOE has the experience to develop the safety case and associated licensing basis:
  - Managed and developed the WIPP Compliance Certification
  - Managed and developed the Safety Analysis Report and License Application for Yucca Mountain
  - Is actively involved in international safety case projects
- DOE has the experience needed for the construction and operation of a repository:
  - Managed materials and wastes within EPA, U.S. NRC, and DOE regulatory frameworks
  - Transported SNF between sites
  - Developed and operated a geologic repository (WIPP)

The potential benefits of developing a safety case include leveraging previous investments in WIPP to reduce future new repository costs, enhancing the ability to effectively plan for a repository and its licensing, and possibly expediting a schedule for a repository. A safety case will provide the necessary structure for organizing and synthesizing existing salt repository science and identifying any issues and gaps pertaining to safe disposal of DOE HLW and DOE SNF in bedded salt. The safety case synthesis will help DOE to plan its future R&D activities for investigating salt disposal using a risk-informed approach that prioritizes test activities that include laboratory, field, and underground investigations.

It should be emphasized that the DOE has not made any decisions regarding the disposition of DOE HLW and DOE SNF and is presently studying options. This study provides additional information that could be used to inform DOE's decision making regarding management of this waste. Furthermore, the safety case discussed herein is not intended to either site a repository in the Delaware Basin or preclude siting in other media at other locations. Rather, this study simply presents an approach for accelerated development of a safety case for a potential DOE HLW and DOE SNF repository using the presently available technical basis for bedded salt if it were to be sited in the Delaware Basin. Experience gained from development of this safety case will also be beneficial if a DOE waste repository is sited outside of the Delaware Basin in either bedded or domal salt.

REFERENCES

1. 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.
2. 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.
3. 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.
4. NEA (Nuclear Energy Agency). 2004. *Post-closure Safety Case for Geological Repositories, Nature and Purpose.* NEA Report No. 3679. Paris, France: OECD/NEA. 2004.

5. Cranwell, R.M., J.E. Campbell, J.C. Helton, R.L. Iman, D.E. Longsine, N.R. Ortiz, G.E. Runkle, and M.J. Shortencarier. 1987. *Risk Methodology for Disposal of Radioactive Waste: Final Report.* SAND81-2573, NUREG/CR-2452. Albuquerque, NM: Sandia National Laboratories.

6. 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.

7. DOE (U.S. Department of Energy). 2008. *Yucca Mountain Repository License Application: Safety Analysis Report.* DOE/RW-0573, Revision 0. http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/yucca-lic-app-safety-report.html#1.

8. DOE (U.S. Department of Energy). 2011. 10000th Shipment Celebrated at WIPP. Press release, http://www.wipp.energy.gov/pr/2011/10,000th_Shipment_Commemoration_Release_Final.pdf

9. U.S. NRC (U.S. Nuclear Regulatory Commission). 2012. *A Proposed Risk Management Regulatory Framework (NUREG-2150),* April 30, 2012, ADAMS Accession #ML12109A277, http://adams.nrc.gov/wba/.

10. Bailey, L., Becker, D., Beuth, T., Capouet, M., Cormenzana, J.L., Cuñado, M., Galson, D.A., Griffault, L., Marivoet, J., and Serres, C. 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/

11. BRC (Blue Ribbon Commission on America's Nuclear Future). 2011. "Blue Ribbon Commission Ad-Hoc Subcommittee on Commingling of Wastes." Presentation. December 2, 2011 http://brc.gov/sites/default/files/meetings/presentations/ commingling_subcomm_pres_-_final_compatibility_mode.pdf

12. BRC Staff (Staff Report for the Blue Ribbon Commission on America's Nuclear Future). 2011. "Background Paper on Commingling of Defense and Commercial Waste." November 17, 2011. http://brc.gov/sites/default/files/documents/defense_waste_policy_issue_paper_final.pdf

13. NWPA (Nuclear Waste Policy Act). 1983. Public Law 97-425; 96 Stat. 2201, as amended by P.L. 100-203. December 22, 1987.

14. Carter, J.T., P.O. Rodwell, B. Robinson, and B. Kehrman. 2012. *Defense Waste Salt Repository.* FCRD-UFD-2012-0001 13. May 15, 2012.

15. DOE (U.S. Department of Energy). 1997. *Waste Isolation Pilot Plant Disposal Phase Final Environmental Impact Statement: Summary.* DOE/EIS-0026-S-2. September 1997.

16. WIPP (Waste Isolation Pilot Plant). 1992. *WIPP Land Withdrawal Act.* Public Law 102-579, 106 Stat. 4777, October 30, 1992, as amended by P.L. 104-201, 110 Stat. 2422, September 23, 1996.

17. 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.

18. NEA (Nuclear Energy Agency). 1999. *Confidence in the Long-term Safety of Deep Geological Repositories: Its Development and Communication*, NEA 01809. Paris, France: OECD Nuclear Energy Agency.

19. NEA (Nuclear Energy Agency). 2008. Safety Cases for Deep Geological Disposal of Radioactive Waste: Where Do We Stand? *Symposium Proceedings, Paris, France (23-25 January 2007).* Nuclear Energy Agency Organization for Economic Cooperation and Development.

20. IAEA (International Atomic Energy Agency). 2011. *Disposal of Radioactive Waste, Specific Safety Requirements.* IAEA Safety Series No. SSR-5. Vienna, Austria: International Atomic Energy Agency.
21. Becker, D.-A., et al. 2002. *Testing of Safety and Performance Indicators (SPIN)*. Final Report. EUR 19965 EN. European Commission, Nuclear Science and Technology.
22. 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.
23. NEA (Nuclear Energy Agency). 2009. *International Experiences in Safety Case for Geological Repositories (INTESC).* NEA Report No. 6251. Paris, France: OECD/NEA.
24. NRC (National Research Council). 1957. *The Disposal of Radioactive Waste on Land: Report of the Committee on Waste Disposal of the Division of Earth Sciences*. Publication 519. National Academy of Science.
25. Weart, W.D. 1975. *Radioactive Waste Disposal Pilot Plant Concept for a New Mexico Site.* SAND75-5929A. Albuquerque, NM: Sandia National Laboratories.
26. Powers, D.W., S.J. Lambert, S. Shaffer, L.R. Hill, and W.D. Weart, Editors. 1978. *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico, Volume 1.* SAND78-1596. Albuquerque, NM: Sandia National Laboratories. August 1978. In *Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, Appendix GCR.* DOE/CAO 1996-2184. October 1996.
27. Hansen F.D., and C.D. Leigh. 2011. *Salt Disposal of Heat-Generating Nuclear Waste.* SAND2011-0161. Albuquerque, NM: Sandia National Laboratories. January 2011.
28. Molecke, M.A. 1983. *A Comparison of Brines Relevant to Nuclear Waste Experimentation.* SAND83-0516. Albuquerque, NM: Sandia National Laboratories. May 1983.
29. Bryan, C.R., D.G. Enos, L. Brush,A. Miller, and K. Norman, and N. R. Brown. 2011. *Engineered Materials Performance: Gap Analysis and Status of Existing Work.* FCRD-USED-2011-000407, SAND 2011-7896P. October 27, 2011.
30. Johnson, K.S. 2008. "Evaporite-Karst Problems and Studies in the USA." *Environ Geol* **53**: 937–943.
31. 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,* SAND2012-8808P. Albuquerque, NM: Sandia National Laboratories. September 28, 2012.
32. Keeney, R.L. 1980. *Siting Energy Facilities.* New York: Academic Press.
33. Weart, W.D. 1978. "Evaluation of Salt Beds in New Mexico as a Geologic Repository for Nuclear Wastes." SAND78-2086C, DOE/EV-0046, UC-11. Albuquerque, NM: Sandia National Laboratories. In *Proceedings of the U.S. Department of Energy Environmental Control Symposium, Vol. 1, Plenary Session and Fossil Fuels*, Washington, DC (November 28-30, 1978).
34. Griswold, G.B. 1977. *Site Selection and Evaluation Studies of the Waste Isolation Pilot Plant (WIPP), Los Medaños, Eddy County, NM.* SAND77-0946. Albuquerque, NM: Sandia National Laboratories.
35. Rechard R.P. 2000. *Milestones for Disposal of Radioactive Waste at the Waste Isolation Pilot Plant (WIPP) in the United States.* SAND98-0072 Revision March 2000. Albuquerque, NM: Sandia National Laboratories.

36. DOE (U.S. Department of Energy). 2009. *Waste Isolation Pilot Plant Compliance Recertification Application.* DOE 2009-24-34. March 2009.

37. DOE (U.S. Department of Energy). 1980. *Waste Isolation Pilot Plant Final Environmental Impact Statement*. DOE/EIS-0026. October 1980.

38. SNL (Sandia National Laboratories). 1990. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant.* December 1990. SAND90-2347. Albuquerque, NM: Sandia National Laboratories.

39. SNL (Sandia National Laboratories). 1991. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant.* December 1991. SAND91-0893/1-4. Albuquerque, NM: Sandia National Laboratories.

40. SNL (Sandia National Laboratories). 1992. *Preliminary Performance Assessment for the Waste Isolation Pilot Plant.* December 1992. SAND92-0700/1-5. Albuquerque, NM: Sandia National Laboratories.

41. DOE (U.S. Department of Energy). 2004. *Waste Isolation Pilot Plant Compliance Recertification Application.* DOE/WIPP 2004-3231. March 2004.

42. 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.

43. DOE (U.S. Department of Energy). 2002. Appendix A, "Inventory and Characteristics of Spent Nuclear Fuel, High-Level Radioactive Waste, and Other Materials." *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada.* DOE/EIS-0250 Office of Civilian Radioactive Waste Management. February 2002. ADAMS Accession #ML032690552, http://adams.nrc.gov/wba/ .

44. Carter, J. T., A. J. Luptak, J. Gastelum, C. Stockman, and A. Miller. 2012. *Fuel Cycle Potential Waste Inventory for Disposition*. FCRD-USED-2010-000031, Rev. 5. July, 2012.

45. Brewitz, W., and T. Rothfuchs. 2007. "Concepts and Technologies for Radioactive Waste Disposal in Rock Salt." *Acta Montanistica Slovaca Ročník* **12**(1): 67–74.

46. Carter, J.T., F.D. Hansen, R. Kehrman, and T.A. Hayes. 2011. *A Generic Salt Repository for Disposal of Waste from a Spent Fuel Recycling Facility.* SRNL-RP-2011-00149. Savannah River National Laboratory.

47. BfS (Bundesamt für Strahlenschutz). 2012. German Federal Office for Radiation Protection. BfS Info Asse, Am Walde 1, Remlingen, Germany. http://www.endlager-asse.de/EN/1_Home/home_node.html

48. Clayton, D.J., J.G. Arguello Jr., E.L. Hardin, F.D. Hansen, and J.E. Bean. 2012. "Thermal-Mechanical Modeling of a Generic High-Level Waste Salt Repository." In: SALTVII, 7th Conference on the Mechanical Behavior of Salt, Paris, France. April 16-19, 2012. (www.saltmech7.com), SAND2012-2741C.

49. 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. Department of Energy, Office of Nuclear Energy, Office of Used Nuclear Fuel Disposition, Washington, D.C., September 28, 2012.

50. DOE (U.S. Department of Energy). 2011. *Waste Isolation Pilot Plant Annual Site Environmental Report for 2010*. DOE/WIPP-11-2225.

51. Meacham P.G., D.R. Anderson, E.J. Bonano, and M.G. Marietta. 2011. *Sandia National Laboratories Performance Assessment Methodology for Long-Term Environmental Programs: The History of Nuclear Waste Management.* SAND2011-8270. Albuquerque, NM: Sandia National Laboratories. November 2011.

52. Helton, J.C. and C.J. Sallaberry. 2009. "Conceptual basis for the definition and calculation of expected dose in performance assessments for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada," *Reliability Engineering and System Safety* **94** (2009) pp. 677- 698.

53. Helton, J.C. and C.J. Sallaberry. 2009. "Computational implementation of sampling-based approaches to the calculation of expected dose in performance assessments for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada," *Reliability Engineering and System Safety* **94** (2009) pp. 699- 721.

54. Helton, J.C., J.E. Bean, J.W. Berglund, F.J. Davis, K. Economy, J.W. Garner, J.D. Johnson, R.J. MacKinnon, J. Miller, D.G. O'Brien, J.L. Ramsey, J.D. Schreiber, A. Shinta, L.N. Smith, D.M. Stoelzel, C. Stockman, and P. Vaughn. 1998. *Uncertainty and Sensitivity Analysis Results Obtained in the 1996 Performance Assessment for the Waste Isolation Pilot Plant.* SAND98-0365. Albuquerque, NM: Sandia National Laboratories. September 1998.

55. Cochran, J.R., W.E. Beyeler, D.A. Brosseau, L.H. Brush, T.J. Brown, B. Crowe, S.H. Conrad, P.A. Davis, T. Ehrhorn, T. Feeney, B. Fogleman, D.P. Gallegos, R. Haaker, E. Kalinina, L.L. Price, D.P. Thomas, and S. Wirth. 2001. *Compliance Assessment Document for the Transuranic Wastes in the Greater Confinement Disposal Boreholes at the Nevada Test Site: Volume 2: Performance Assessment: Version 2.* SAND2001-2977. Albuquerque, NM: Sandia National Laboratories. September 2001.

56. ONWI (Office of Nuclear Waste Isolation). 1987. *Conceptual Designs for Waste Packages for Horizontal or Vertical Emplacement in a Repository in Salt.* BMI/ONWI/C-145 (OSTI ID: 6915229). Columbus, OH: Office of Nuclear Waste Isolation, Battle Memorial Institute. June, 1987.

ACKNOWLEDGEMENTS

The authors would like to acknowledge technical contributions from Kris Kuhlman, Mike Schuhen, and Steve Wagner, as well as Laura Connolly's assistance in document production. 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 SAND2012-9766C.