# Back to the Future

## A Rationalized Rock Salt Repository

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In 1789, Benjamin Franklin wrote to a friend: "In this world nothing can be said to be certain, except death and taxes." Since then, scientific and technological advances have added a third certainty to this list: with time, the radioactivity of every single isotope will come to an end. Addressing this time factor, however, has become one of the most challenging socio-political issues in attempting to safely dispose of these isotopes.

Multinational organizations have been established to protect mankind and the environment from harmful exposure to doses of radiation. As well, a great many scientists and engineers have been devoted to developing safe disposal places for long-lived radioisotopes. [For the purposes of this article, the term "long-lived radioisotopes" includes greater-than-Class C (GTCC) and GTCC-like low-level waste, sealed sources, transuranic (TRU) waste, and used and spent nuclear fuel or other high-level radioactive waste.]

**A look at going "back to the future" of rock salt geologic structure as the preferred approach to effecting a final HLW repository in the United States.**

Based on more than 50 years of research and analyses, the general consensus among these groups and individuals is that deep geological disposal is the most promising and safest solution. Number five of the 10 safety principles and technical criteria for underground disposal of HLW defined in 1989 by the International Atomic Energy Agency states the following: "A high-level radioactive waste repository shall be designed, constructed, operated, and closed in such a way that the postsealing functions of the host rock and its relevant surroundings are preserved." (For the purposes of this article, the term HLW includes both spent and used nuclear fuel. Furthermore, all radioactive waste categories mentioned herein are in solid state.)

The confidence in deep geological disposal of HLW was reiterated by the European Commission in its proposed Nuclear Waste Directive on November 3, 2010. Even so, Finland is currently the first nation in line to open a deep geological disposal system (repository), in 2020, followed by France and Sweden, in 2025[1]—that is, the opening of the world's first HLW repository is still at least 10 years away.

### The Sad Tale of Yucca Mountain

The United States' first HLW repository, which in 1983 was projected to open in January 1998,[2] has experienced several delays and gone from a most likely operational date of 2020[3] to not very likely to open anytime in the foreseeable future.[4–7]

The January/February 2010 issue of *Radwaste Solutions* contained an article summarizing the perceived status and future prospects of the Swedish and U.S. HLW repository programs at the end of 2009, in which the Swedish HLW repository program was judged to be a success relative to the U.S. HLW repository program.[8] The article also illuminated some of the key reasons for the success of the Waste Isolation Pilot Plant (WIPP) repository for defense program–generated, long-lived TRU radioactive wastes meeting specific criteria (see Fig. 1) and reiterated a suggestion that the WIPP mission could be expanded to accommodate the safe disposal of other long-lived radioactive waste categories.[9,10] Specifically, the article suggested that the following four proven remedies could mitigate the perilous future and escalating costs of the U.S. HLW disposal program:

- Transferring the responsibility for safe disposal of commercial spent fuel to a utilities-funded, not-for-profit, independent corporation, which would unify the nation's

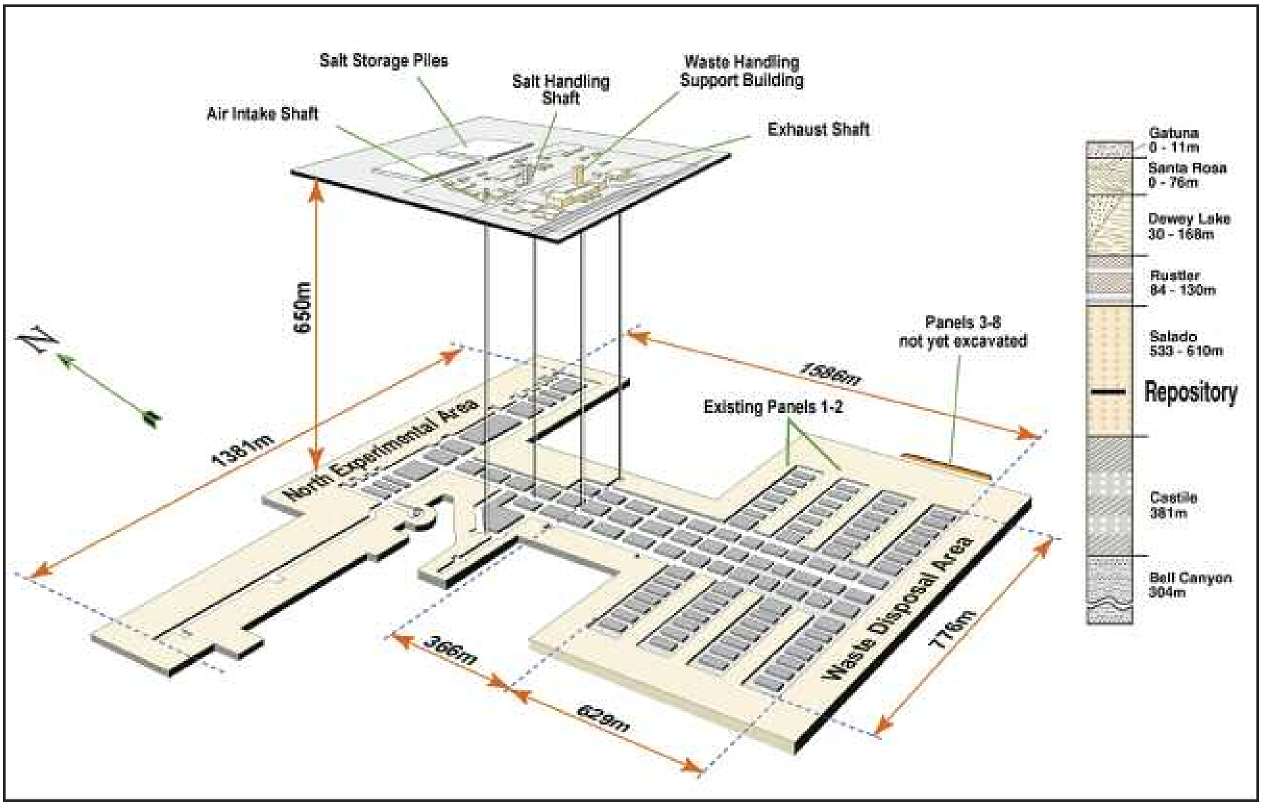



*Fig. 1. Schematic illustration (not to scale) of the layout of surface and subsurface facilities and the stratigraphic column of the WIPP site. At the end of 2010, panels 1–4 (to the east) and 5 have been filled, panel 6 is being filled, panel 7 is being excavated, and panel 8 (opposite from panel 1) is to be excavated. Each panel has seven 4-m-high, 10-m-high,*

management and disposal of commercial spent fuel under one entity that would work with, rather than for, the ever-changing political community.

- Promulgating and implementing nationwide uniform HLW disposal regulations/standards.
- Employing a repository siting approach based on voluntary host communities where the majority of the local residents are in favor of hosting a repository in their "backyard."
- Establishing at least one federal HLW storage facility to accommodate the multiyear legal process required for the three previous remedies and any required modification to the U.S. Nuclear Regulatory Commission's Nuclear Waste Confidence Rule. The Waste Confidence Rule is the basis for the NRC's ability to issue new and renewing reactor and HLW-storage licenses. It is currently predicated on reasonable NRC assurance that safe disposal of HLW in a geologic repository is technically feasible by 2025.

In the interval between publication of that *Radwaste Solutions* article and today, politically motivated actions taken by congressional leadership and the regulatory authority following the Obama administration's announcement in February 2009[11] that "the Yucca Mountain Program will be scaled back to those costs necessary to answer inquiries from the NRC, while the administration devises a new strategy toward nuclear disposal" have virtually demobilized and canceled the Yucca Mountain project.[4–7] The Yucca Mountain site hosts the only candidate HLW repository (Fig. 2) under consideration in the United States since 1987,[12] and it currently represents a financial investment in excess of $10 billion.

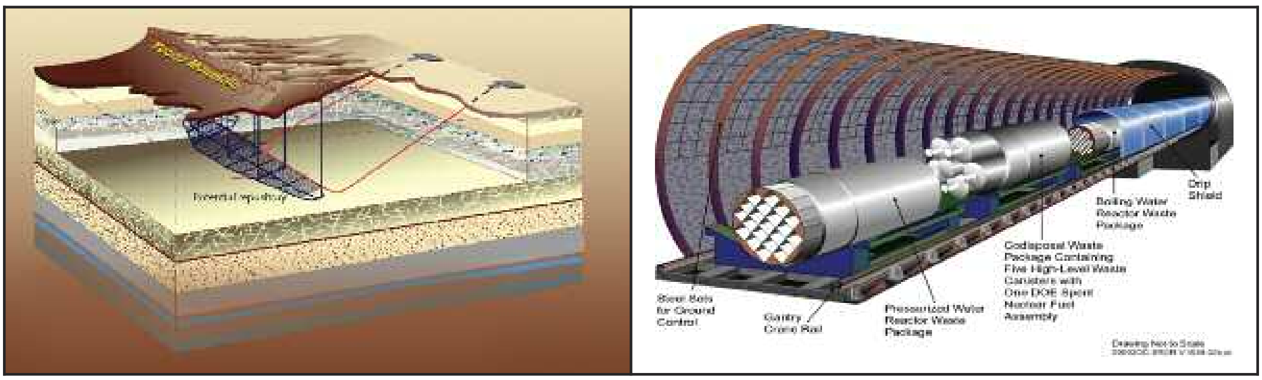
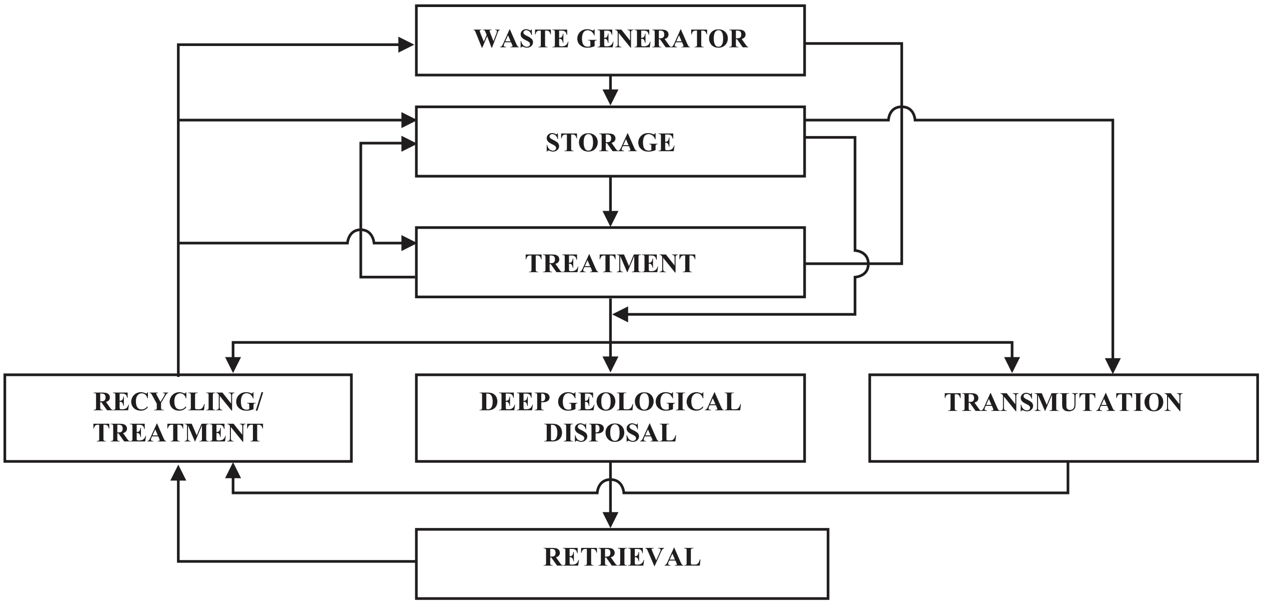



*Fig. 2. Schematic illustration of the layouts of the Yucca Mountain HLW repository (in blue) and the underground re-*




## The Blue Ribbon Commission

In January 2010, the secretary of energy announced the establishment of the politically handpicked 15-member Blue Ribbon Commission on America's Nuclear Future to report no later than August 2012, including a draft report no later than January 2012, on the following charter:

"To conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste, and materials derived from nuclear activities." (For more information on the Blue Ribbon Commission, see www.brc.gov.)

Considering that it took approximately five years for 33 renowned subject-matter experts hand-picked by the National Research Council of the National Academies and the Institute of Medicine[13] to get their arms around the technologies for separation and transmutation shown in Fig. 3,[14] the Blue Ribbon Commission's task is daunting, given the allocated time and the resident expertise on the commission in geological disposal of long-lived radioisotopes and what other repository programs have accomplished since 1987. Absent a timely attainable, fully integrated, national nuclear fuel cycle,[14,15] the eulogy of the pending Blue Ribbon Commission reports might read as follows: "They gave birth astride a grave, the light gleams an instant, then it's night once again."—Samuel Becket, 1953.

In March 2010, the energy secretary approved the establishment of the following three commission subcommittees: Reactor and Fuel Cycle Technology, Transportation and Storage, and Disposal. The charter of the Disposal Subcommittee was stipulated as follows: "How can the U.S. go about establishing one or more disposal sites for high-level wastes in a manner that is technically, politically, and socially acceptable?"(www.brc.gov).

While politics and legal challenges will always dictate the progress and, in some cases, the outcome of a radioactive waste disposal program, there is one successful U.S. repository program, WIPP, that can provide some instructive domestic lessons-learned about how to move toward a successful project in a highly charged socio-political environment and that also offer other useful analogues for consideration. For example, the broad-based acceptance of the WIPP concept since 1973; the successful certification of the WIPP repository in May 1998, i.e., license to operate; its March 1999 opening; and the ensuing more than 11 years of safe waste shipments across the United States and safe site operations, including two recertifications of the WIPP repository operations—these provide a readily-available, full-scale domestic analogue that should be harvested by the Blue Ribbon Commission for unique information on how the Disposal Subcommittee assignment could be successfully resolved.

## Where We Are Today

At the end of 2010, the future of the nation's HLW disposal program seems to depend upon the following:

- The pending reports from the Blue Ribbon Commission.
- The NRC Atomic Safety and Licensing Board's (ASLB's) unanimous rejection on June 29, 2010, of the U.S. Department of Energy's motion to withdraw its June 3, 2008, license application to construct a 70 000 metric ton HLW repository at the Yucca Mountain site (Fig. 2). The ASLB's reason for the decision was that in its opinion, the secretary of energy lacked the authority required to overrule the related congressional process defined in Public Law 97-425,[2] as amended, e.g., in Public Law 100-203[12] and the *Federal Advisory Committee Act of 1972.*[5]
- Several lawsuits filed in the U.S. Court of Appeals for the District of Columbia Circuit challenging the legality of the DOE's motion to withdraw the Yucca Mountain license application.[5]
- The congressional restructuring prompted by the November 2010 midterm elections, particularly in the House of Representatives, which could block/reverse the current politically motivated cancellation of the Yucca Mountain program.

In the event the current political effort to cancel the Yucca Mountain HLW repository is successful or the NRC rejects either the construction license application or the subsequent license application to receive HLW at the Yucca Mountain site or grants the DOE's motion for withdrawal of the construction license application, the opening of the nation's first HLW repository could be delayed at least 20 years,[1,4] i.e., well beyond the current 2025 Waste Confidence Rule milestone. Indeed, even if the Yucca Mountain HLW repository survives both the current cancellation efforts and the NRC's pending rulings on the license applications, it still may not be able to open by 2025. In addition, the current statutory capacity of the Yucca Mountain repository is already too small to accommodate the existing amount of HLW.[3,16] In other words, there is an imminent need for additional HLW disposal capacity in the United States.

## Disposal in Salt

Drawing on our combined more than 60 years of involvement in and monitoring of radioactive waste management disposal programs in the United States and abroad, we submit that a carefully selected and designed repository in rock salt offers an ideal solution. It also is the most timely and least costly solution for disposal of other long-lived, highly active radioisotopes in the United States. Our confidence in and promotion of rock salt as a repository host rock for safe disposal of these wastes develop from the following factors:

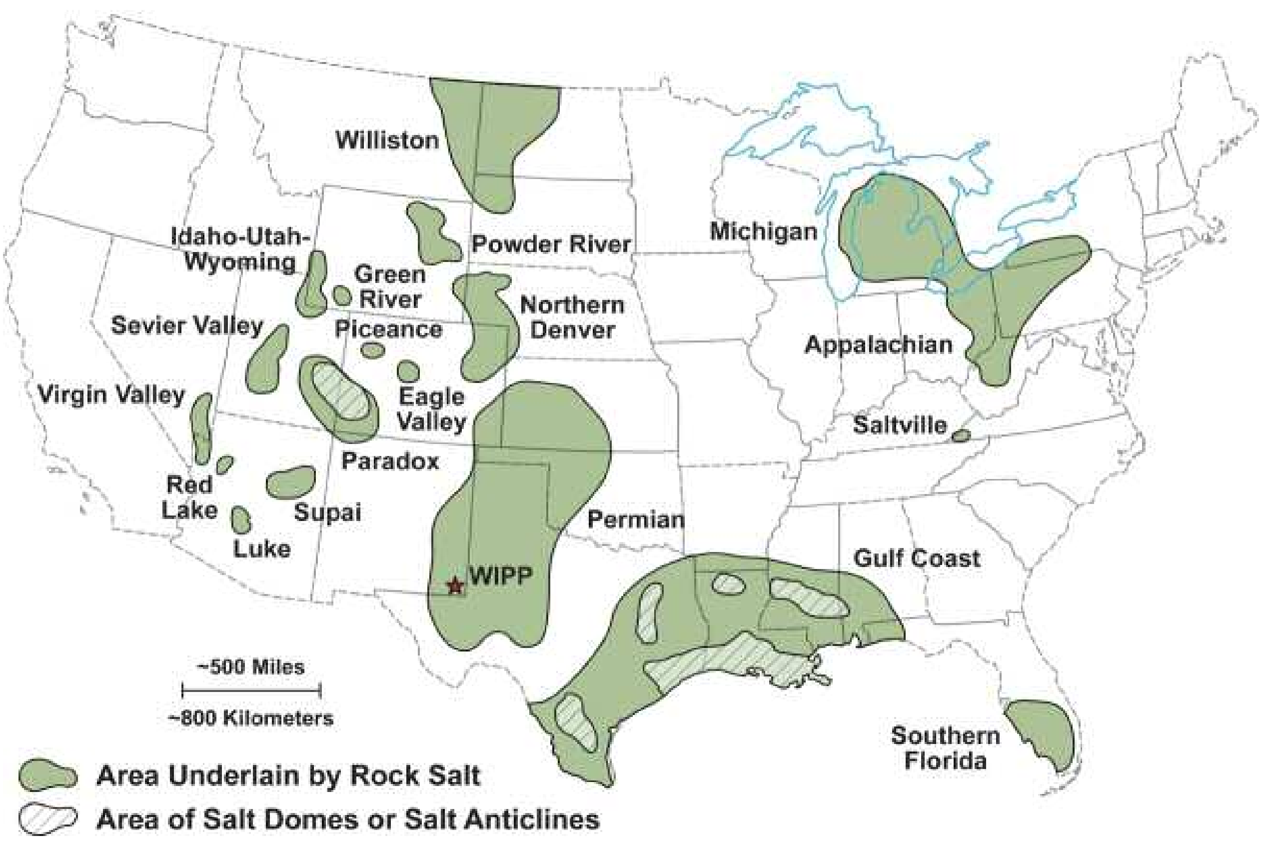
1. The abundance of salt rocks in the United States (see Fig. 4). Mississippi alone has 53 known salt domes located within 2000 meters of the ground surface, of which three, the Richton, Vacherie, and Cypress Creek domes, were considered for HLW disposal prior to 1987. Several others are used for storage of natural and liquefied gas.[17]

2. The abundance of the domestic scientific and engineering/technical expertise and experience required for repository siting and development in rock salt resulting from the more than 50-year-long focus on rock salt as a potential host rock for safe disposal of long-lived, highly active radioisotopes in the United States (see item 4 on next page); site characterization and evaluation processes at the WIPP site; recertification applications every five years, including updated postclosure performance and safety analyses; and 11 years of safe operation of the WIPP site/repository.

3. The well-known inherent material characteristics of rock salt.[17–22] For example, in 1955 the National Research Council of the National Academies assembled a committee of geologists and geophysics at the request of the Atomic Energy Commission "to consider the possibilities of disposing of HLW in quantity within the continental limits of the USA." Two years later, the committee released a report including the following conclusion:[18]

> The most promising method of disposal of high-level waste at the present time seems to be in salt deposits. The great advantage here is that no water can pass through the salt. Fractures are self-sealing.

Today, the long-term performance of both pristine (undisturbed) rock salt and rock-salt bodies subjected to human intrusion and elevated temperatures, e.g., excavation/mining and a broad range of utilizations of rock salt



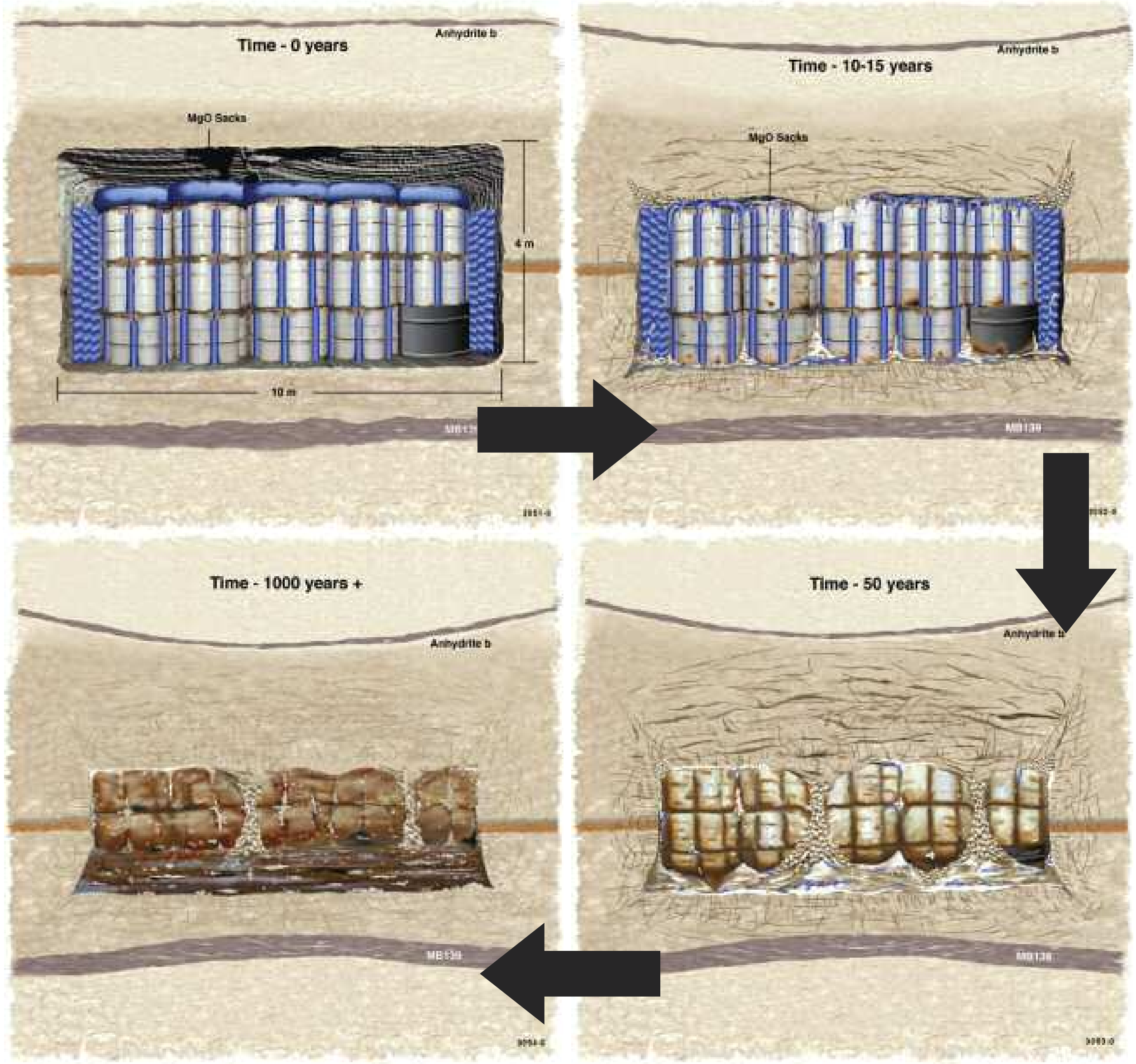



*Fig. 5. Clockwise schematic illustration of the behavior of a disposal room in rock salt with time. As illustrated in the sequence, the rock salt will encapsulate the waste containers and close all void spaces, which, in turn, will prevent solids*

caverns/openings, is very well understood largely because of the 53 years of detailed studies and analyses[17,19–22] following the 1957 National Academies conclusions.[18] The three most promising inherent material characteristics of rock salt important to the long-term containment and isolation of any emplaced radioactive waste are its (a) self-sealing characteristics (see Fig. 5); (b) imperviousness, i.e., very low porosity and hydraulic conductivity; and (c) high thermal-conductivity coefficient relative to other candidate repository host rocks pursued in the world today, e.g., argillites/mudstones, granite, and tuff. One of the unique benefits of the inherent material characteristics of rock salt is that *no* postclosure near-field engineered barrier system would be required for complying with current radionuclide containment and isolation regulations and standards.

Indeed, if postclosure safety, i.e., radionuclide containment and isolation, is the primary objective, it is the ideal rock for meeting the following objective:

"The art is not to overmaster nature by means of technology, but—with a deeper knowledge of geology—to adopt the engineering to nature."—Carl-Olof Morfeldt.[23]

4. The vast supply of related and supplementary repository experience and data in Germany, which, in addition to having a long-standing radioactive waste disposal program based essentially on rock salt, has 174 active rock salt caverns with another 106 planned or under construction.[17,21] For example, in 2007, Germany was storing 6.8 billion $m^3$ of gas in 158 salt caverns at 17 sites and was adding 54 caverns accommodating an additional 3.5 billion $m^3$ of gas,[22] which verifies the impervious nature of rock salt because if the product were lost, this industrial praxis/application would not continue.

We submit that adequately large, stable bodies of rock salt with well-known pedigrees are potentially very well suited to safely contain and isolate a broad range of long-lived radioactive waste categories, including those having heat-generating radioisotopes. As indicated in item 3, rock salt is by no means the only potentially suitable host rock for an HLW repository. It is, however, in our opinion still[18] the most promising repository host rock in the United States due to its inherent material characteristics and the perceived time and cost it would require to site, license, and open a *new* HLW repository in the United States under adequate financial resources and engaged leadership. However, local public and political acceptance needs to be recognized and addressed from the outset.[1,8,23,24]

## Challenges Ahead

As mentioned previously, the time it takes for radioisotopes to become harmless to humans, other forms of life, and the environment is a major challenge to all repository developments. The reasoned safety and performance assessments conducted today to project computationally the safe performance of a repository until the radioactive waste it contains is rendered harmless involve spatial and temporal scales and scientific and engineering concepts beyond the comprehension of most people. Typically, these projections are based on a broad range of features, events, and processes (FEPs) combined into a large number of possible scenarios evolving during at least the first 10 000 years and up to the first one million years after repository closure. These include the following five main categories of FEPs:

1. FEPs we know we know.
2. FEPs we think we know.
3. FEPs we know we don't know.
4. FEPs we think we don't know.
5. FEPs we don't know we don't know.

In addition to being incomprehensible to most people and meaningless numerical simulation games beyond a few hundreds or thousands of years to others, the projections of the postclosure performance and safety of an HLW repository embody uncertainty. The results are thus always susceptible to the individual's confidence in the messenger. They also often result in "what if" questions and scenarios that typically have marginal probability of occurrence but require time-consuming and costly efforts to address and often remain unresolved. As Mark Twain cautioned, "It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so."

### *Heat Loading*

The response of rock salt to heat loading is one such what-if question. Clearly, the timeline shown in Fig. 5 would be much shorter if the emplaced waste induced a strong thermal pulse. In other words, existing discontinuities/fractures and openings in the rock salt in the vicinity of the heat-generating waste would close faster, but the closure rate would depend upon the magnitude of the thermal pulse and the site-specific characteristics of the salt. Two heat-related "urban legends" are often used to discredit rock salt as a repository host rock:

1. Brine moving toward a heat source and thereby threatening the integrity of the waste canister.
2. Hot canisters sinking or rising after burial in rock salt.

From Project Salt Vault in the 1970s until the premature demise of the salt repository program in December 1987,[12] several studies of brine migration were conducted both in the United States and Germany under a broad range of boundary conditions.[19] The first observations of brine migration from Project Salt Vault were somewhat unfortunate in that they gave birth to the urban legend that brine would move toward a heat source. In this case, brine was released when the electrical power to the heater was shut down, which reversed temperature gradients around the heat source and reduced the tangential compressive stress at the wall of the vertical test borehole hosting the heater: conditions that allowed the brine to accumulate in the heater-test borehole. Brine would not flow toward the canister as long as it generates radiological heat. Because the radiological heating emanating from the emplaced waste cannot be abruptly terminated unless the waste canister is removed, this urban legend is based on a false premise.[19]

It has been suggested that buoyant forces due to thermally produced density differences may initiate convection cells in a plastic medium like rock salt that would cause movement of heat-generating canisters buried in it. Sandia National Laboratories has used a thermo-mechanically coupled formulation for creeping, viscous flow and heat transfer to predict canister motion. The large-deformation creeping behavior of the salt over long periods of time was represented as a viscous fluid with temperature-dependent viscosity. Temperature-dependent thermal conductivity was included in the analyses. Coupling between the flow field and temperature distribution resulted from temperature-dependent material properties, temperature-dependent body forces, viscous dissipation, and changes in the system geometry.[25]

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The Boussinesq approximation was applied in these analyses so that changes in the salt density affected only the body forces in the equilibrium equation. Free expansion of the rock salt with temperature rises was assumed for the purpose of computing these body forces. This assumption led to the largest density differences and therefore the greatest driving forces for upward salt flow. The analyses reported by Dawson and Tillerson[25] in 1978 indicated that very little canister movement would result during the heat-producing life of the waste canisters. The transient analyses showed that initially, the canister will sink. Due to the formation of a convective cell in the rock salt from heating by the wastes, the canister would then rise. Eventually, as the convective cell diminished, the canister began to sink again. Predicted displacements were less than a canister length during this process. The steady-state analyses provided upper bounds on the magnitudes of upward velocity possible during heating. In all cases, the velocities were sufficiently small to indicate very little movement will occur while the canister is capable of producing heat. However, these analyses are more than 30 years old, and advanced multiphysics modeling could probably more transparently demonstrate the phenomena associated with potential movements of emplaced HLW canisters.[19,22].

### *Waste Retrieval*

One concept affected by the two afore-mentioned urban legends is postclosure removal of emplaced waste. Although removal of waste disposed of in rock salt has been demonstrated at WIPP,[26] it requires specially designed techniques. Simply stated, postclosure retrieval of waste can be done in rock salt; however, it involves a trade-off between canister designs and ease of recovery.

## WIPP-2?

A frequently posed question is "Could the WIPP repository be expanded to accommodate additional waste?" As indicated previously and discussed to a greater level of detail in other papers presented by the authors (e.g., Refs. 4,9, and 10), the simple answer is "yes" for two reasons:

1. Several regulator-reviewed and -approved performance and safety assessments have been conducted in support of the WIPP repository during the past 15 years, and they all show that a fully loaded TRU waste repository, even if breached by a given combination of hypothetical boreholes with extremely low probability of occurrence, would still be at least one order of magnitude safer than that required by the applicable radiation protection standards.

2. There is plenty of room both laterally and vertically in the 600-m-thick Salado Formation to modify and expand the current WIPP repository layout (see Fig. 1). Indeed, in the late 1970s and early 1980s, the WIPP site was considered and evaluated for disposal of both TRU waste and HLW, including the HLW being emplaced deeper than the TRU waste in the Infra-Cowden unit of the Salado Formation.[10,19]

Indeed, WIPP would likely be the optimal temporal and financial disposal solutions for a broad range of radioactive waste categories currently lacking a disposal solution in the United States. However, the current legal and regulatory frameworks for WIPP and perhaps its regulatory oversight would need to be modified, as well as the current onsite facilities, operations, and logistics. This, in turn, would likely require site and operations modifications that would impose severe disruptions on the current successful operations. It thus seems more logical and less disruptive to ongoing operations to maintain a defense-oriented mission for WIPP.

**The WIPP region remains particularly attractive for radioactive waste repository developments due to the existing long-standing radioactive waste transportation and disposal experience, nuclear facility safety culture, and subject-matter knowledge vested in the local residents and politicians.**

One major reason for separating commercially generated HLW from defense-generated HLW put forth in the 2010 *Radwaste Solutions* article[8] was that defense waste typically does not have any significant redeeming value; i.e., it would not be an economically attractive source material for recycling, or it has already been stabilized/solidified in a form that is not conducive to recycling. The vastly different objectives and cultures of the afore-mentioned two groups of HLW generators, the performance objectives of the related waste management organizations, their respective different legal and regulatory frameworks and financing vehicles, and, last but not least, the volumes involved are other compelling reasons for separating the management and disposal of commercial and defense waste. But we must also remind ourselves that the radionuclides do not know in which program they reside and therefore act in predictable ways that are identical, which means that going "back to the future" of rock salt geologic structure as the preferred approach[18] to effecting a societally and politically acceptable HLW repository in the United States would likely suit both programs equally well. Fortunately, as illustrated in Fig. 4, there is an abundance of rock salt formations both in the WIPP region and in the United States as a whole. The WIPP region remains particularly attractive due to the existing long-standing radioactive waste transportation and disposal experience, nuclear facility safety culture, and subject-matter knowledge vested in the local residents and politicians.

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