Recommendations for radioactive waste management in the United States

Jens-Erik Lund Snee

March 2017

Summary

After more than three decades of formal effort, progress has stalled to dispose of the large volume of radioactive waste produced in the United States by commercial and defense programs. Here I build upon learnings from the American and international experiences of successes and failures with the repository siting and design process, and I propose a set of principles that should guide the future of American radioactive waste disposal. The great size and geologic, cultural, and political diversity of the United States provide many potentially suitable repository sites. My recommendations are based on the view that even an imperfect repository is vastly better than the *status quo* of dispersed, above-ground, temporary storage. Thus, at its core, the siting and approval process should be designed to select the *best* site(s) out of a list of strong contenders, rather than prescribing standards that may not be attainable and/or preemptively identifying sites that may not be able to meet the standards. In addition, my recommendations recognize the need to elevate stakeholder approval to the same level as technical and legal considerations. This document provides a radically different approach to stakeholder involvement than has been applied heretofore in this context in the United States.

1 Introduction

In the United States, >60,000 metric tonnes of spent nuclear fuel (SNF) is awaiting disposal at 72 dispersed commercial sites, and it is growing at a rate of 2000 tonnes per year (United States Department of Energy, 2013, 2014). In addition, very large volumes and activities of high-level (HLW) and other types of radioactive waste associated with the United States nuclear weapons program, together with significant amounts of surplus weapons-grade plutonium and uranium, are stored at a handful of federal government facilities. It is the near-unanimous view of technical and policy experts involved with United States nuclear waste management that most or all of this waste should be promptly disposed of in a subterranean (geologic) repository (e.g., Bredehoeft et al., 1978; National Research Council, 1978; Hamilton et al., 2012; Ewing et al., 2016).

In brief, the current process in the United States for building a geologic repository required the development of standards and regulations for such a site by the Nuclear Regulatory Commission (NRC) and Environmental Protection Agency (EPA). The Department of Energy (DOE) is tasked with developing an application to build a repository using specified containment mechanisms at a certain site. The application is to be submitted to NRC and EPA for license approval before the site can become operational.

Efforts to develop a radioactive waste repository were formally initiated in 1982 and subsequently progressed through several technical and legal steps, including the identification of the

Yucca Mountain facility in southern Nevada as the single repository choice as an act of Congress in 1987 (see, e.g., Ewing, 2011, for a summary of events). Unfortunately, that progress has stalled, as manifest most decisively by the 2009 decision by DOE to withdraw its permit application for the Yucca Mountain site (see Hamilton et al., 2012).

The purpose of this document is to provide my views of the major issues facing radioactive waste disposal in the United States and to propose steps for achieving its successful and safe long-term geologic disposal. First I summarize what I regard as the main factors contributing to the failure to construct a repository thus far, and then I provide general and specific prescriptions for developing a waste siting plan for the future in light of these past failures. A silver lining that has emerged from the relatively slow progress on repository siting in the United States is the opportunity to learn from countries that have successfully achieved certain portions of their own repository siting process.

2 Factors contributing to the failure to construct a repository

The opportunity to learn from our own failures is an additional silver lining—albeit a perverse one—associated with the United States' inability thus far to build a repository for its radioactive waste. In my view, the process that gradually emerged for siting a geologic repository all but assured early failure; Congress in 1987 mandated the evaluation of a single site (the Yucca Mountain facility), prior to successful approval of a permitting application or even the completion of standards for that site. Resistance by Nevada ensured a lengthy and contentious legal process to construct the site, and Congress failed to recognize the possibility for a changing political landscape that resulted in the elevation of Nevada from political weakness to a nationally powerful state. More specifically, I attribute the failure to develop a geologic repository to the following.

- A failure to move waste into interim storage under federal custody, which resulted in large penalties to taxpayers.
- The decision not to investigate multiple facilities simultaneously, which led to a lack of backup options in the event that the one site failed. This also led to great pressure associated with the licensing process, and probably resulted in suspicions that standards and the licensing process were tailored to make the single site succeed (see Hamilton et al., 2012).
- Selection of a site with serious technical weaknesses (e.g., a volcanically active area experiencing a relatively high tectonic strain rate, in which the waste would be hosted within fractured, relatively permeable rocks, and an oxidizing chemical environment that could lead to more rapid corrosion of the waste package).

- The requirement that the selected site meet a set of quantitative, risk-based standards, rather than evaluating and comparing the activity release rate between multiple sites in multiple rock types (see Ewing, 2011).
- An absence of serious consideration of the needs and concerns of affected individuals, communities, and states.
- A lack of incentives for potentially affected individuals, communities, and states.
- Congressional action that effectively removed access to the Nuclear Waste Fund (NWF) for financing the process of licensing and operating the repository.
- Inappropriate Executive Branch interference in the licensing process, which short-circuited the established procedures by instructing DOE to withdraw the license application for the Yucca Mountain facility (see Carter et al., 2010).

3 Key learnings from international cases

There is a wealth of information to be gained from the scientific research and progress toward repository siting and the development of regulations that has occurred in Finland, Sweden, Canada, France, Switzerland, Belgium, Spain, and also the United States. Here I summarize some of the most important learnings that should be applied to the American case.

- The Swedish effort provides an excellent learning opportunity for ways to effectively engage with and obtain consent from stakeholders, most notably locally affected populations. Nevertheless, some modifications are needed when applying this model to the United States case in order to accommodate large political and social differences between the two countries, as described below.
- International research has provided the United States with evidence that several rock types that it has in abundance (e.g., granite, clay rocks, and salt) may prove to be effective hosts for long-term geologic repositories. Studies such as those by Grambow (2016) and von Berlepsch and Haverkamp (2016) concisely lay out technical arguments in favor of using these rock types in international cases.
- The International Atomic Energy Agency (IAEA) has developed its own set of institutions, regulations, and recommendations that may help guide the progress of repository design and siting in the United States. For example, as cited by the Blue Ribbon Commission on America's

Nuclear Future (BRC), IAEA in 2003 issued its own baseline standards for repository design and siting.

4 Proposed guiding principles for repository siting, permitting, construction, and operation

1. It should be assumed that any site can and may fail to progress through the permitting process, either for technical, legal, or social reasons. Consequently, multiple sites should be evaluated in parallel and compared with one another. This approach has been employed, with some degree of success, in places like Sweden.

2. Generous incentives should be offered to potentially affected individuals, communities, and states. These incentives should be based in part upon results of surveying the communities about their concerns about the proposed repository, as well as their stated desires.

3. Congress should be involved early in the process in order to draft and approve legislation authorizing the new framework advocated by BRC and here. However, Congress should avoid being involved later, in order to provide predictability to the process, and to ensure that technical strength and local considerations dominate, rather than remote, partisan ones.

4. Laws enabling the approach described here and by BRC should be formulated to anticipate court challenges; the legislation should be written such that lawsuits and court orders are unlikely to derail site selection, permitting, construction, and operation, provided that specified procedures are followed. Senior Executive Branch involvement should also be avoided.

5. As recommended by BRC, responsibility for site selection, application, and construction should be removed from DOE. A new organization should be formed and tasked with these responsibilities (referred to by DOE as the "waste management and disposal organization," MDO). I take no position on whether this organization should be public (a federal government entity) or private (a utility-owned corporation). The organization structure should be chosen on the basis of strategic policy reasoning as well as continued surveying of populations in potential site locations to determine their views and relative levels of trust in various types of entities.

6. In order to simplify the process of developing site standards, this responsibility should be placed under a single federal regulatory agency, perhaps EPA or a new entity that is a collaboration between NRC and EPA (currently standards are formulated by both NRC and EPA). In the recent past, failure by EPA to adopt standards consistent with that of NRC resulted in

several years of lost time toward repository siting. Consolidating these regulatory functions under a single agency was also recommended by Ewing (2011).

7. An independent organization (here called the Stakeholder Support Organization, SSO) should be formed to represent citizens and communities potentially affected by the disposal site and its construction. SSO should receive ample and stable federal funding but be insulated from influence by other federal agencies and from Congress.

8. A paid, part-time citizen stakeholder committee (here called the Repository Consideration Board, RCB) that is part of SSO should be formed to interact on a more frequent, technical basis with SSO and MDO.

9. MDO and SSO should operate semi-independent radiation and heavy metal monitoring arrays as soon as operations begin at the selected site. Stakeholders must have meaningful input regarding array design, and results must be immediately available to the local populations.

10. Planning for accidental early release should be part of site planning. Stakeholders should be involved with the drafting of contingency plans.

5 Immediate action to develop consolidated temporary storage

The slow progress toward developing a geologic repository in the United States has created numerous serious problems, one of the most urgent of which is annual payment by taxpayers to the companies that store the orphaned SNF as a consequence of DOE's failure to construct a repository. The total judgments will reach 20.8 billion dollars if no repository is in existence to accept waste by 2020, and it will increase annually by 500 million dollars after that (Hamilton et al., 2012). The fiscal problem is compounded by recent Congressional actions that render the approximately 28 billion dollars remaining in the NWF essentially inaccessible for use constructing a repository. Therefore, I support recent BRC (Hamilton et al., 2012) and DOE (United States Department of Energy, 2013) recommendations to comprehensively modify the legal framework governing NWF monies and approximately 750 million dollars of annual nuclear energy production fees such that these funds would become available for repository permitting, construction, and operation.

Nevertheless, BRC's legal recommendations require substantial Congressional action and they do not resolve the issue of the payment of damages to utilities. A much more beneficial step, in my view, would be to do away with the government's liabilities to utilities by quickly constructing consolidated temporary waste facilities. These sites should be aboveground in order to speed permitting

and construction, and also to reduce suspicions that they could become *de facto* long-term repositories. Nevertheless, it is obviously of critical security importance that these facilities be hardened against natural disasters and also terrorist attacks such as bombings, crash-landings by airplanes, theft of radioactive materials, or other sabotage (e.g., cyberattacks to disable cooling systems).

To prepare for development of consolidated interim storage, DOE should immediately begin designing such facilities and study safety issues associated with transporting large amounts of radioactive waste across the country (also recommended by BRC). If required, DOE should also immediately begin preparing permitting applications to EPA and/or NRC to house the waste. Ideally, Congress would not only authorize the interim storage but also bypass any usual full-scale environmental impact statement or nuclear safety review and permitting processes, both in the interest of timeliness and under the assumption that consolidated federal storage would be vastly safer than the *status quo* of dispersed, temporary radioactive waste storage under the management of many private companies. Instead of requiring a lengthy permitting process, NRC and/or EPA could simply issue reasonable, cost-effective, and achievable regulations to ensure the safety of SNF during transportation and interim storage. To further expedite this process, interim storage facilities should most likely be housed at or near existing federal facilities that already contain HLW.

6 Scientific standards for repository design

The *status quo* of dispersed temporary surface storage for United States nuclear waste presents overwhelming problems and risks to humans today and into the future. For this reason, constructing a robust consolidated geologic storage of the waste using existing technologies and within the present-day geological and social options in the United States is vastly better than seeking failing to find a *perfect* repository site. Therefore, I support the recommendations of BRC (Hamilton et al., 2012) and Ewing (2011) that standards should be reformulated to be generic and applicable to any site, finalized before the formal site selection process begins, and attainable using modern technologies. I agree further that the requirement of strict, quantitative, total-system, population-based dosage limits should be relaxed to be less opaque, less reliant on cascading, uncertain models, and to account for more qualitative ("common-sense") factors.

The guiding principle of repository standards should be relaxed and generalized to based upon those articulated by IAEA in 2003, to ensure "sufficient isolation of the waste from human beings and other biota and thereby provide the required assurance of the safe disposal of the waste" (International Atomic Energy Agency, 2003). Balance clearly needs to be struck between setting robust baseline standards versus allowing qualitatively different sites to compete with one another in the technical realm such that the strongest contender(s) win(s) out.

It is tempting to recommend that standards be abolished altogether and replaced by a process by which technical and social considerations for several sites are compared side-by-side with the purpose of selecting the best site. This would be inappropriate, however, because some baseline criteria clearly must be achieved to warrant the cost and risk of constructing a mined repository in the first place. It is my position that the use of more generalized standards and regulations, like those articulated by International Atomic Energy Agency (2003), will impose minimum safety standards and will also help guide the site comparison process toward desired outcomes. Furthermore, I find the current approach, in which radionuclide release is considered with respect to arbitrary facility boundaries, to be nonsensical because future populations will not necessarily know the present-day boundaries of the repository.

Specifically, attainable standards should be set, and these standards should no longer be based on quantitative dose limits at the site boundary, but instead on radionuclide release or migration rates in the target formation, and release times given the formation thickness. This approach would enable more direct comparisons of breakthough times between different rock types, waste package designs, and repository structures. In addition, as recommended by BRC (Hamilton et al., 2012) the compliance period should be set to a reasonable time frame, such as 10 kyr or 100 kyr. Nevertheless, site performance should still be quantified for much longer time spans, perhaps to the order of 10 Myr, so as to provide an *approximate* sense for the relative performance of various sites over the lifespan of the longer-lived radionuclides. Although nominally quantitative, these long-term release or mobility rate estimates should be considered qualitative due to the immense uncertainties involved.

As an aside, I agree with BRC (Hamilton et al., 2012) that research to evaluate the potential of deep borehole disposal should commence immediately. However, I am concerned that research in this presently more speculative realm could become a distraction to more serious and promising efforts to pursue research and development toward a mined repository.

7 Cultural site characterization

Serious mistrust has developed between DOE and local stakeholders during the history of attempts to site a geologic repository (e.g., Hamilton et al., 2012). I concur with BRC's recommendation that the responsibility for interacting with communities and designing, siting, and operating a repository should be removed from DOE and placed under the new MDO organization.

Furthermore, dramatically greater emphasis should be placed upon identifying stakeholder interests and concerns, and on working with local populations to meet many of their desires for a repository site. This effort should be modeled in part upon the positive example that SKB in Swe-

den has set for interactions between the applicant organization and the affected public. However, as noted previously, major cultural differences between Sweden and the United States make it unlikely that SKB's model can be directly applied in the United States. Specifically, Americans have fairly low and declining levels of trust in institutions (Twenge et al., 2014). In addition, many Americans are susceptible to misinformation (Weeks and Garrett, 2014; Weeks, 2015) and, particularly in the rural areas where repository sites are most likely to be considered, have relatively low levels of educational attainment (Provasnik et al., 2007; Breslau et al., 2014), which could challenge efforts to discuss the scientific merits and risks of a proposed repository. Early during the site characterization process, surveys conducted by MDO should evaluate the local public's cultural characteristics, including its susceptibility to misinformation and its amenability to fact-based, scientific arguments.

To account for important American cultural considerations, one or more organizations should be formed exclusively to represent citizen stakeholders (referred to here as the Stakeholder Support Organization, SSO) and provide them with resources to assist with evaluating sites before, during, and after the permitting process. SSO should receive stable and ample funding from the federal government but have a great deal of autonomy. It should be insulated from influence from MDO, DOE, and other federal agencies, but it should be accountable to taxpayers through statutes.

SSO should act in part as an advocacy group representing local communities, thus providing individuals with organizing power to achieve certain aims and obtain desired information and assurances. It should be staffed in part with scientists well versed in communicating with the public, and also in part by lawyers and community outreach professionals. SSO should interact heavily with MDO to evaluate and provide comment to their proposed site designs. It should be a vehicle for citizen feedback to MDO about aspects of site design and community incentives. If a single organization, SSO should be divided into divisions defined by the different sites under consideration. As sites drop out of consideration during the evaluation process, it is hoped that momentum will be gathering toward the remaining sites, so employees of divisions that have closed can transfer to the remaining divisions to accommodate the need for increasing staff numbers at the remaining sites.

In addition to its regular employees and management, SSO should be advised in part by a Repository Consideration Board (RCB) for each community, composed of community representatives elected by members of the potentially affected areas. RCB members will commit 10–20 hours per week to becoming comprehensively briefed in technical aspects of the proposed site design as well as to interacting with their community constituents. RCB members will be paid for their time, earning the equivalent of a part-time salary at a professional job (perhaps $10,000–40,000 year, depending on the cost of living and hours served). Candidates for RCB positions should be residents of the affected area. They should also be screened for conflicts of interest and be able to demonstrate no income for the past 5–10 years from nuclear energy companies or contractors that could

benefit from site approval. RCB members are intended to be highly informed and also highly credible members of the local population who can communicate community desires to SSO and MDO, and can convey summaries of technical information to the community at a level that is appropriate. RCB members should be exposed to re-election every two years. Minimal campaign funds will be provided by SSO to candidates receiving sufficient in-state signatures. No outside campaign funds will be permitted in order to ensure that RCB members serve their fellow community members instead of financial interests.

The licensing agency, MDO (formerly DOE), should engage heavily with communities and members of potential host state and county governments starting at early stages. Before sites have even been identified, it should launch nationwide, quantitative surveys to identify areas that are most amenable to having a nuclear waste repository. Surveying should also assess the types of compensation that individuals would expect in exchange for hosting a radioactive waste repository site near their homes, as well as their perceptions of benefits and risks of obtaining such a facility. The results of this surveying should then be compared with the results of country-scale geologic rock type and tectonic setting characterization that should be done in large part by the U.S. Geological Survey (USGS), as described below.

Subsequently, MDO should conduct detailed, qualitative and quantitative, community-scale surveying in areas that have been recognized as having suitable geology and potential social acceptance. It will be at this stage that SSO starts a division representing a possible community of interest. If initial community-scale surveying further suggests that an area may be amenable to allowing a site to be built nearby, then MDO should prepare to engage in more participatory surveying and analysis. As part of this later stage, representatives of MDO should identify and form relationships with key local leaders, such as heads of community organizations and churches, nonprofits, city- and county-level government, RCB members, and others who hold high regard in the community. MDO should forge alliances with these key individuals in an effort to learn about the needs and characteristics of the community, and to make a case for the building the repository in that area.

Simultaneously, MDO representatives should meet with a large proportion of the potentially affected population, in part to provide a human face to the applicant organization but also to conduct in-person surveying to gain insight into community concerns and desires. Most likely, a strong economic case could be made for constructing a repository in a remote area, because it would provide a substantial number of stable jobs. In fact, some job types might last throughout the entire construction and operations periods, which could span decades. Thus successful completion of each phase of repository siting, construction, and operations could ensure the continuation of specific jobs for additional years, which could act as an incentive for a community to support a proposed site through to completion. Nevertheless, it should be expected that some community members will be

strongly opposed to a radioactive waste repository of any type and in any part of the country, so MDO should work early in the process to identify and meet with potential sources of opposition in the community. During the community engagement process, MDO should begin drafting initial site plans to eventually present to the community for comment, taking into account early responses from community members.

Once MDO has identified a handful of sites (approximately 8–15, and certainly more than 4) that are not only geologically advantageous (see below) but also have potentially supportive local populations, it should present its draft site plan to the populations for comment in written and town hall settings attended also by SSO staff and RCB members. Community members should be given non-monetary incentives to attend these events, perhaps including grocery store gift cards or meals. Child care should be provided to all attendees to ensure equal participation across socioeconomic groups. Communities should all be made fully aware of the several other locations that are simultaneously in consideration, and that only one or two sites will be constructed in the end.

MDO should be prepared to spend substantial amounts of money engaging with the community, providing tangible incentives to stakeholders, and conducting robust surveys. Although this is not similar to the approach that has been conducted in the United States in the past, portions of it have precedent in Europe (notably Sweden). In addition, the enormous expenditures to date on the stalled Yucca Mountain facility emphasize that the costs of failure are far higher than would be incurred from engaging with affected taxpayers at the community level.

It is my view that applicant organization's (MDO) internal employee incentives must be structured to encourage collaboration between it and communities, while also rewarding speedy progress toward completing repository construction according to the generic standards. All professional employees and managers at MDO should be eligible for modest but appreciable annual bonuses based mostly upon two factors: 1.) stakeholders' stated approval with and trust in MDO, and 2.) the degree of progress that MDO demonstrates relative to annual goals toward siting and constructing a repository. Employee incentive structures of this nature will help ensure the high level of flexibility desired by BRC and may also improve employee morale.

During operation of a successfully constructed repository, and subsequently into the post-closure phase, MDO should operate and fund a monitoring network designed with input from SSO and community members. The network should monitor both air and groundwater for radionuclides and other hazardous materials that could be migrating from the site. In addition, in recognition of the history of mistrust between the operator/applicant and the public, SSO should independently operate its own monitoring array that supplements that of MDO. To ensure trust, SSO and community members should have unrestricted and immediate access to monitoring results from both arrays.

An important aspect of site planning will be the development by MDO—in concert with SSO and community members—of contingency plans for a range of accidents, natural disasters, or other hazards. It will be the responsibility of MDO to negotiate suitable contingency plans with SSO and community members that are cost-effective and reasonable. In addition, the federal government should be obliged to compensate any individuals for accidental releases or repository workplace accidents that could impair human health or livelihoods.

It must be noted that a major obstacle to siting the Yucca Mountain facility has been strong opposition from the majority of Nevada outside Nye County. There is an obvious risk that any repository site, no matter how well received by the local community, could face bitter opposition by the host state, which could result in crippling political and legal challenges. Thus, state governments and more distant communities within the host state must also be brought into the siting and permitting process at an early stage. MDO should offer state-wide incentives to compensate citizens and allay some of their concerns. In addition, credible representatives of communities from outside the area immediately affected by the repository should be invited to panel discussions and town halls. A few people from outside the affected community but within the host state should sit on the RCB.

8 Scientific site characterization

Prior to identification of specific sites, the USGS should be tasked with providing the scientific assessment to identify the ideal geologic settings for hosting a long-term geologic repository. The USGS is the logical and ideal organization to handle this process because of its role as the federal government's impartial geoscience research agency; its extensive history studying seismic and volcanic hazards, mineral resources, and basement structure of the United States; and its prior experience with studying geologic repositories (e.g. Bredehoeft et al., 1978). The USGS is also the steward of the nation's geologic maps and understanding of its rock types and tectonic settings. The USGS should be explicitly tasked with evaluating the merits of rock types and geologic settings considered by the United States and other countries, drawing in part upon the wealth of work in this realm (e.g., von Berlepsch and Haverkamp, 2016; Grambow, 2016; Swift and Bonano, 2016; Yardley et al., 2016). This study need not identify or characterize specific repository sites, but it should summarize the nation's distribution of suitable rock types (e.g., clay, granite, basalt) and tectonic settings (e.g., cratonic, low strain rate, low volcanic activity). The USGS assessment should also provide qualitative evaluations of the suitability of the host rock in these broad areas; for example, drawing upon available research on clay rocks, the USGS might note advantages or disadvantages of certain clay formations in a particular basin relative to those considered for waste storage in other countries from the perspective of permeability, depth, grain size, or geochemistry.

During and following the course of these USGS assessments, MDO should begin its own process to evaluate potential sites. There should be no legal requirement that MDO's site selection agree with the USGS assessment, but MDO should be required to provide written explanation for its choice of potential sites, particularly in cases where the site selection appears to be at odds with the USGS assessment of favorable rock type and tectonic settings.

MDO should identify some 8–15 sites that have both potentially interested populations and a strong chance of meeting the generic release standards. As mentioned previously, MDO should evaluate each of these sites in parallel and be prepared to abandon weak sites (and also add newly identified sites) as soon as it is clear that either they are not likely to meet the standards or that they are not as strong as other contenders. In order to ensure an efficient site selection process, it might be necessary to stipulate that a certain number of sites be disqualified every few years until only perhaps 4 sites remain. The final remaining sites will be evaluated more intensively and compared both quantitatively and qualitatively with one another, on the basis of their technical merits and on their costs, the cooperation of local communities, and the ease of designing, constructing, and operating each site given the specifications that each community has negotiated. The latter consideration will help modulate the cost and effort required to meet stakeholder demands; stakeholders will be aware that their site, together with any jobs and other incentives guaranteed as part of its successful construction, may not win out if their demands are unduly burdensome to MDO and taxpayers.

Finally, I argue that the greatest potential for early release will come in the form of unexpected events. The recent accident at the WIPP plant in New Mexico provides a clear example. Therefore, much attention should be given to contingency planning during the site selection, design, and community engagement process. Obviously, MDO should strive to achieve a culture of safety, but this alone is not sufficient; it will be the responsibility of SSO, the organization representing stakeholders, to hold MDO to a high safety standard and to continuously probe for avenues of failure.

9 Personal views about Yucca Mountain and ideal repository sites

As a personal aside, it is my opinion that the Yucca Mountain facility should be abandoned as a radioactive waste repository. From a geologic point of view, the Yucca Mountain facility is plagued by several problems that could result in early radionuclide release. Notably, its oxidizing geochemistry and heavy reliance upon the containment mechanism, its location within strong, fractured rock, and the area's unstable tectonic environment (National Research Council, 1995; Ewing and Macfarlane, 2002; Long and Ewing, 2004; Swift and Bonano, 2016) provide major potential weaknesses compared with other rock types present in abundance across the United States.

From a social point of view, the designation by Congress in 1987 that the Yucca Mountain fa-

cility will serve as the sole site considered for the nation's repository (circumventing portions of the established site permitting process), together with elements of DOE's style of interaction with local stakeholders, provoked strong suspicions, fears, resentments, and a fundamental lack of trust between the federal agencies and stakeholders in Nevada (Hamilton et al., 2012). The Obama Administration's decision to remove the permit application may have further tainted the process by injecting additional partisan political overtones to an issue of such emotional poignance by those living in Nevada or near the repository (Carter et al., 2010).

Nevertheless, formal abandonment of Yucca Mountain would represent a major failure in the process originally set forth in the Nuclear Waste Policy Act of 1982, and it would represent a vast waste of taxpayer money. However, the excavated areas within Yucca Mountain may remain useful for other purposes. DOE should initiate a request for proposals from the state of Nevada, Nye County, and local stakeholders regarding their desires for the site. Other types of hazardous may be suitable for storage in that area, and local populations should be consulted to gauge their interest in housing such a facility, which would generate jobs during the construction and operation phases.

I consider it inappropriate for me to take a strong position about the relative merits of rock types considered for repository siting elsewhere. Strong cases have been made for salt, clay rocks/shale, and crystalline rocks such as granite or basalt. In general, however, I am persuaded that rocks with very low permeabilities and that provide a reducing geochemical environment are ideal for repository siting (e.g., Ewing and Macfarlane, 2002). These criteria would generally exclude welded but fractured ignimbrites in oxidizing environments, such as those at Yucca Mountain. For similar reasons, I am somewhat skeptical about granite and other crystalline rocks such as quartzite; the high strength of these rocks typically results in higher differential stresses and the presence of fractures that heal slowly if at all. In contrast, Grambow (2016) provided convincing arguments in favor of disposal in clay-rich rocks. He compellingly showed that migration rates in the Callovian–Oxfordian clay rock in the Paris Basin are extremely low for many elements of interest, and that waste stored in the center of merely 100 m of this clay unit, in reducing conditions, would be unlikely to escape the formation for 100,000 years or possibly much longer, depending on the element and its oxidation state. Unfortunately, many well-understood clay rock units in the United States are located in hydrocarbon-producing areas, which should be avoided to reduce the risk of accidental well interceptions. This restriction limits the availability of clay rock units to be considered, but the large size and diverse geology of the United States presents many advantages for hosting ideal sites.

10 Conclusion

In light of recent failures in the United States and elsewhere, there is reason for pessimism about humanity's ability to safely dispose of waste produced during nuclear energy and weapons production (see Ramana, 2017). On the other hand, progress continues to be made toward siting repositories throughout the world, including at the WIPP facility in the United States, and many substantial social and scientific lessons have been learned. In addition, the threat of anthropogenic climate change, and humanity's slow response to addressing it (Wise et al., 2014), arguably underscores the urgency of finding a solution to the back-end of the nuclear power cycle.

Together, these arguments, and the views expressed throughout this document, demonstrate the need for a major shift in the American approach to siting and permitting radioactive waste repositories. Above I have outlined a series of recommended changes to the legal, technical, and social aspects of this process. I draw from previous work that argues in favor of immediate consolidation of waste into temporary storage facilities, more generic, release-based site selection standards and regulations, evaluation of many sites simultaneously, and a consent-based approach to interacting with communities.

However, I move beyond the simple consent-based structure articulated by BRC, and I propose a dramatically different approach to interactions with stakeholders. Stakeholders should have ultimate power over whether to accept construction of a site, and their interests should be organized, represented, and informed by a powerful, well-funded, technically competent advocacy agency (SSO). Stakeholders should be compensated for the time and effort they expend considering whether to approve a site, and they should receive substantial incentives in the event that their area is selected based on its technical and social merits. The applicant and site construction organization (MDO) should conduct extensive surveying of local populations, interact closely with community members and their leaders, and be prepared to reasonably modify the site design according to stakeholder desires. These modifications, particularly to the social aspects of site approval, would represent a dramatic shift in the approach that the United States has employed heretofore, and it would clearly be associated with appreciable expenditures to support local incentive programs, community engagement, and agency staff. Despite the costs associated with funding a new organization to represent local stakeholders, and for stakeholder incentives and compensation, the Yucca Mountain case provides a painful example of the extreme costs that can be incurred by failing to adequately engage affected communities.

References

Bredehoeft, J.D., England, A.W., Stewart, D.B., Trask, N.J., and Winograd, I.J., 1978, Geologic disposal of high-level radioactive wastes: Earth-science perspectives: Geological Survey Circular 779.

Breslau, J., Marshall, G.N., Pincus, H.A., and Brown, R.A., 2014, Are mental disorders more common in urban than rural areas of the United States ?: Journal of Psychiatric Research, v. 56, p. 50–55, doi:10.1016/j.jpsychires.2014.05.004.

Carter, L.J., Barrett, L.H., and Rogers, K.C., 2010, Nuclear Waste Disposal Showdown at Yucca Mountain: Issues in Science and Technology, v. 27, no. 1, p. 80–84.

Ewing, R.C., 2011, Standards & Regulations for the Geologic Disposal of Spent Nuclear Fuel and High-Level Waste Standards & Regulations for the Geologic Disposal of Spent Nuclear Fuel and High-Level Waste,

Ewing, R.C., and Macfarlane, A., 2002, Yucca Mountain: Science, v. 296, p. 659.

Ewing, R.C., Whittleston, R.A., and Yardley, B.W.D., 2016, Geological disposal of nuclear waste: A primer: Elements, v. 12, no. 4, p. 233–237, doi:10.2113/gselements.12.4.233.

Grambow, B., 2016, Geological Disposal of Radioactive Waste in Clay: Elements, v. 12, no. 4, p. 239–245, doi: 10.2113/gselements.12.4.239.

Hamilton, L.H., Scowcroft, B., Ayers, M.H., Bailey, V.A., Carnesale, A., Domenici, P.V., Eisenhower, S., Hagel, C., Lash, J., Macfarlane, A.M., and Others, 2012, Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy: Blue Ribbon Commission on America's Nuclear Future (BRC), Washington, DC, p. 20,585.

International Atomic Energy Agency, 2003, Technical considerations in the design of near surface disposal facilities for radioactive waste: Technical Reports Series no. 417.

Long, J.C., and Ewing, R.C., 2004, Yucca Mountain: Earth-Science Issues at a Geologic Repository for High-Level Nuclear Waste: Annual Review of Earth and Planetary Sciences, v. 32, no. 1, p. 363–401, doi: 10.1146/annurev.earth.32.092203.122444.

National Research Council, 1978, Geological criteria for repositories for high-level radioactive wastes, 201258.

National Research Council, 1995, Technical bases for Yucca Mountain standards, , Committee on Technical Bases for Yucca Mountain Standards.

Provasnik, S., KewalRamani, A., Coleman, M.M., Gilbertson, L., Herring, W., and Xie, Q., 2007, Status of Education in Rural America, , United States Department of Education, Washington, D. C.

Ramana, M.V., 2017, An Enduring Problem: Radioactive Waste From Nuclear Energy [Point of View]: Proceedings of the IEEE, v. 105, no. 3, p. 415–418, doi:10.1109/JPROC.2017.2661518.

Swift, P.N., and Bonano, E.J., 2016, Geological disposal of nuclear waste in tuff: Yucca Mountain (USA): Elements, v. 12, no. 4, p. 263–268, doi:10.2113/gselements.12.4.263.

Twenge, J.M., Campbell, W.K., and Carter, N.T., 2014, Declines in Trust in Others and Confidence in Institutions Among American Adults and Late Adolescents , 1972 – 2012: Psychological Science, v. 25, no. 10, p. 1914–1923, doi:10.1177/0956797614545133.

United States Department of Energy, 2013, Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste, January.

United States Department of Energy, 2014, Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel, October.

von Berlepsch, T., and Haverkamp, B., 2016, Salt as a Host Rock for the Geological Repository for Nuclear Waste: Elements, v. 12, no. 4, p. 257–262, doi:10.2113/gselements.12.4.257.

Weeks, B.E., 2015, Emotions , Partisanship , and Misperceptions : How Anger and Anxiety Moderate the Effect of Partisan Bias on Susceptibility to Political Misinformation: Journal of Communication, v. 65, p. 699–719, doi: 10.1111/jcom.12164.

Weeks, B.E., and Garrett, R.K., 2014, Electoral Consequences of Political Rumors: Motivated Reasoning, Candidate Rumors, and Vote Choice during the 2008 U.S. Presidential Election: International Journal of Public Opinion Research, v. 26, no. 4, p. 401–422, doi:10.1093/ijpor/edu005.

Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer Van Garderen, E.R.M., and Campbell, B., 2014, Reconceptualising adaptation to climate change as part of pathways of change and response: Global Environmental Change, v. 28, p. 325–336, doi:10.1016/j.gloenvcha.2013.12.002.

Yardley, B.W.D., Ewing, R.C., Whittleston, R.A., and Editors, G., 2016, Deep-Mined Geological Disposal: Elements, v. 12, no. 4.