Geologic Disposal Options in the USA-11299

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ABSTRACT

The contiguous forty-eight states contain many geologic formations that are likely to be technically suitable for deep geologic disposal of nuclear waste. Given appropriate repository designs, there is substantial confidence that compliance with regulatory standards for waste isolation can be demonstrated for several geologic settings, disposal concepts, and rock types, including salt, shale, volcanic rock, granite, and deep boreholes. Potential repository environments are evaluated with respect to first-order attributes that relate to repository development and performance. Discriminating characteristics of each geologic setting and associated variations in disposal methodology are highlighted. Based on international programs and decades of experience in repository development, it is highly likely that a suitable, compliant repository can be developed within any of these geologic surroundings.

The availability of potentially suitable geologic formations is illustrated by maps showing the occurrence of granite, shale, and salt geology in the USA. As our nation considers future nuclear waste disposal necessities, multiple geologic media will receive attention, as was the case before enactment of the Nuclear Waste Policy Act of 1982. General disposal concepts are described for each geologic setting, recognizing that site specific disposal concepts would result from future design and analysis efforts. A broad comparison and summary of attributes for each concept are provided. International and domestic experience suggests that any of the options discussed in this paper could be implemented with high confidence, to yield a technically adequate repository compliant with performance standards.

INTRODUCTION

The contiguous forty eight states in the USA enjoy many geologic settings likely to be technically suitable for deep geologic disposal of nuclear waste. Given suitable operational designs, there is substantial confidence that compliance with regulatory standards for human and environmental protection can be demonstrated for several geologic venues, disposal concepts and rock types including salt, shale, volcanic rock, granite, and deep boreholes. Discriminating characteristics of each geologic disposal concept and variations in methodology are highlighted in this paper.

The available geologic formations are illustrated by maps showing occurrences of granite, shale, and salt. Sandia has recently published in-depth technical reports on the performance of conceptual high-level waste repositories in shale, salt, and deep boreholes. The disposal option in volcanic rock at Yucca Mountain site has been extensively described in many documents supporting the June 2009 License Application for repository construction. Other countries, as listed in Appendix A, have also advanced repository sciences in granite, shale and salt, which afford additional perspectives for various disposal concepts.

As our nation considers future nuclear waste repository needs, all geologic options will receive attention, as was the case before enactment of the Nuclear Waste Policy Act (NWPA) of 1982[1]. The USA pursued conventional deep geologic repository programs in granite, also referred to as igneous or crystalline rocks, shale, salt, and volcanic rock in the years leading up to the NWPA. Granite programs included a full-scale emplacement demonstration in an underground research laboratory at the Climax Stock on the Nevada Test Site. Shale programs were supported by laboratory testing, literature studies, and limited field testing, but no underground research laboratory was developed nor was any disposal demonstration conducted in shale in the USA. Extensive underground research labs as well as full-scale underground disposal demonstrations were undertaken at several salt sites, including Lyons in Kansas, Avery Island in Louisiana, and Carlsbad in New Mexico. As directed by the 1987 amendment to the NWPA (NWPAA), the volcanic rock at the Yucca Mountain Nevada was characterized in detail sufficient to support a license application for construction authorization. There have been literature studies, engineering and safety analyses performed for deep borehole disposal, sub-seabed disposal, and a few deep crustal exploration programs, but none of these disposal concepts has been demonstrated by the USA. Five of the aforementioned geologic disposal possibilities on land encompass the scope of this paper. References to international repository programs augment the technical basis for repository disposal concepts, where direct domestic experience might be limited.

The paper begins with an overview of the extant formations of granite, shale and salt in the USA. A general concept for disposal in each lithology is put forward, recognizing an actual disposal concept for implementation would be the result of a site-specific design and analysis effort at some future date. General attributes for each disposal concept are summarized in the concluding section. International and domestic experiences suggest that implementing any of the options discussed in this paper could yield high-confidence that a technically adequate repository could be built and operated, compliant with existing repository safety and performance standards in the USA and abroad.

SITING AND GEOLOGIC FORMATIONS

Suitable host rocks for deep geologic repositories would, typically, exhibit some basic favorable physical characteristics, such as depth, thickness and tectonic stability and, preferably, other key geologic characteristics limiting dissolution and radionuclide transport. The US Department of Energy issued guidelines for preliminary screening of potential sites for a nuclear waste repository and the Nuclear Regulatory Commission issued other technical criteria for disposal of high-level waste in a geologic repository. These regulations guided previous work on site evaluation and provided relevant detail on favorable and adverse characteristics. Key physical characteristics[2] to consider in siting mined geologic repositories might include:

- **Depth** – The disposal horizon should be determined based on site-specific conditions. Geologic isolation is attained by ensuring significant separation between the repository and the biosphere, which would provide extensive zones for robust seal systems. Rock strength characteristics would also determine a practical and functional mining depth. For deep borehole concepts, proposed disposal zone depths are 2-5 km.

- **Thickness** – Maximal thickness of the isolation medium is desired to ensure radionuclide migration does not exceed regulatory criteria or boundaries. Various "minimal" thicknesses have been put forward, generally of the order of 100 m. However, the thickness of the formation is less important than its uniformity and structure.

- **Uniformity and Structure** – The potential repository interval and surrounding rock should be reasonably homogeneous both vertically and horizontally. The related benefits are simpler and more transparent characterization and performance assessments and safer repository mining and operations.

- **Seismicity** –Seismically quiescent regions favor repository design, operations, and long term performance.

Key geologic and hydrologic attributes of the host rock should also include:

- **Hydrogeology** – Low hydraulic conductivity ($\sim 10^{-12}$ m/sec or lower).

- **Self-sealing** –Rocks with plastic deformation characteristics reestablish a diffusion-dominated transport system.

- **Hydrogeochemistry** – Reducing chemical conditions minimize corrosion of engineered barriers and waste forms, reduce most radionuclide solubility, and improve sorption. Oxidizing environments are also possible but would require very low hydraulic flux as found in desert environments.

Possible regulatory considerations for future anthropogenic activities such as human intrusion and sociopolitical considerations such as proximity to population centers are not mentioned above. These deliberations would, however, come into play as the screening for potential sites progress. As demonstrated at Yucca Mountain, in a democratic society one can only advance site screening to the point of potentially suitable sites before there is a need to actively involve potential host communities and states. Each characteristic mentioned above would reflect positively or negatively with regard to the siting and development of a repository. The site-specific intrinsic factors should be used to develop an accurate safety assessment and to strengthen the safety case for a particular repository location. However, local public and political acceptance is a prerequisite for site selection.

Granite. The 48 conterminous states have an abundance of granitic formations. Several countries have determined that granite formations are adequate for mined geologic disposal. Figure 1 illustrates granitic outcrops in the USA. As discussed below, deep borehole disposal in a generic granite could be located virtually anywhere the Pre-Cambrian basement rock is within about 2 km of the ground surface.

Following the 1982 NWPA, USA had an active second-repository program considering granite formations. The NWPAA in 1987 legally terminated all other domestic repository programs in favor of a repository in volcanic tuff at the Yucca Mountain site in Nevada. In the meantime, Finland, Sweden, and Switzerland have successfully pursued repositories in granite currently scheduled to open in 2020 in Finland and 2025 in Sweden. Granite is also seriously considered by several other nations, e.g., China, Japan, and the United Kingdom. USA has a natural geologic variety that includes many potential granite sites for a mined nuclear waste repository or deep borehole disposal of nuclear waste.

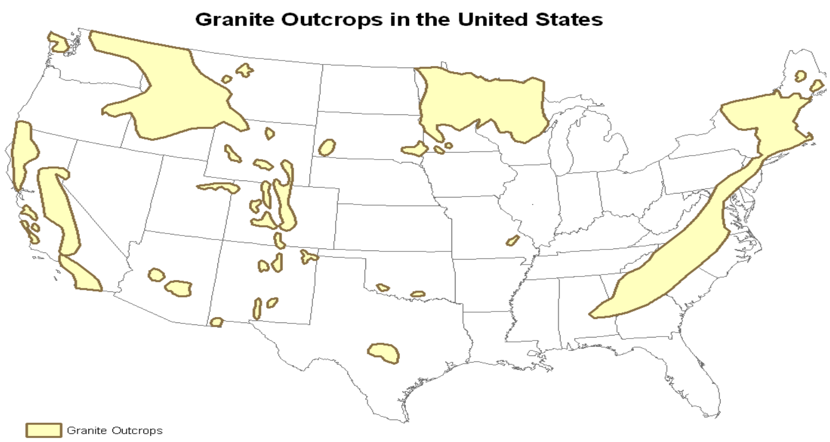

Figure 1. Granite outcrops in the United States[3].

Shale. As shown in Figure 2, shale formations meeting the general guidelines for depth, thickness, and other criteria summarized above are also common in the USA. There are potentially significant differences in rock characteristics included in this category of sedimentary rock, as discussed in a recent study of the performance of shale repositories for high-level waste (HLW) in the USA[4]. Shale includes a spectrum of rocks with different characteristics grading from unconsolidated clay stone, to lightly indurated mudstone having shale texture and composition, to a compact argillite. Because high clay content is needed to ensure low permeability and plasticity, the term “argillaceous rock” is also appropriate for this general rock type.

Gonzales and Johnson concluded that the most desirable host rocks should be between 300 and 900 m below ground level, at least 75 m thick, relatively homogeneous in composition, and in an area of low seismicity and favorable hydrology that is not likely to be intensively exploited for subsurface resources. Figure 2 shows distribution of principal shale formations by general geologic age and region.

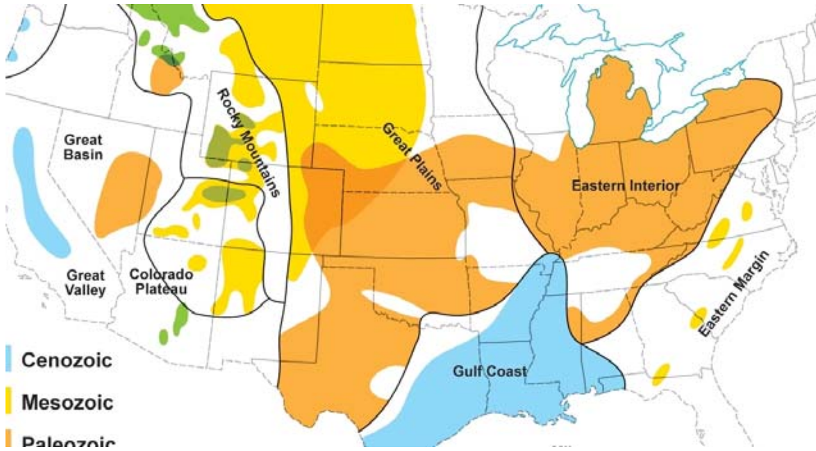

Figure 2. Shale Provinces in the United States[5].

Characterization of possible shale formations for HLW repositories in USA has not been undertaken. However, from the 1970s until the mid 1980s Oak Ridge National Laboratory (ORNL) led the USA research and development efforts for shale repository investigations. ORNL directed testing programs specifically to characterize a few accessible shale formations, collecting repository-relevant physical, mechanical, mineralogical, and hydrological information. Testing efforts to characterize thermomechanical responses of selected shale formations were elementary. More lab and field work would be needed to characterize any particular shale site, and may necessitate development of an underground research laboratory. Until such time as the USA repository program advances to the stage of developing an underground research laboratory in a shale formation, international communications and collaborations with France and Switzerland may be a key source of information.

Shale formations that could host a HLW repository in the USA span a range of lithologies with different physical, mechanical, hydrological, chemical, and mineralogical properties. Two primary concerns for evaluating the effects of repository construction, operation and long-term waste isolation performance are geomechanical response and fluid flow. The specific properties that control these important rock characteristics would be among those closely examined at the time of site selection and characterization.

Salt. Use of salt formations for nuclear waste disposal has been a widely embraced concept for more than 50 years. Disposal of nuclear waste in salt remains a viable concept in the USA, as has been successfully demonstrated by virtue of more than 11 years of successful operations at the Waste Isolation Pilot Plant near Carlsbad in New Mexico[6]. As shown in Figure 3, the conterminous USA has many large salt formations, including bedded and domal salt. Four major regions of the US where salt formations are found include: 1) the Gulf Coast; 2) the Permian Basin; 3) the Michigan-Appalachian Region; and 4) the Williston Basin. Domal salts are found in the Gulf Coast region and Paradox Basin, and bedded salts are present in the remaining three major salt regions of North America.

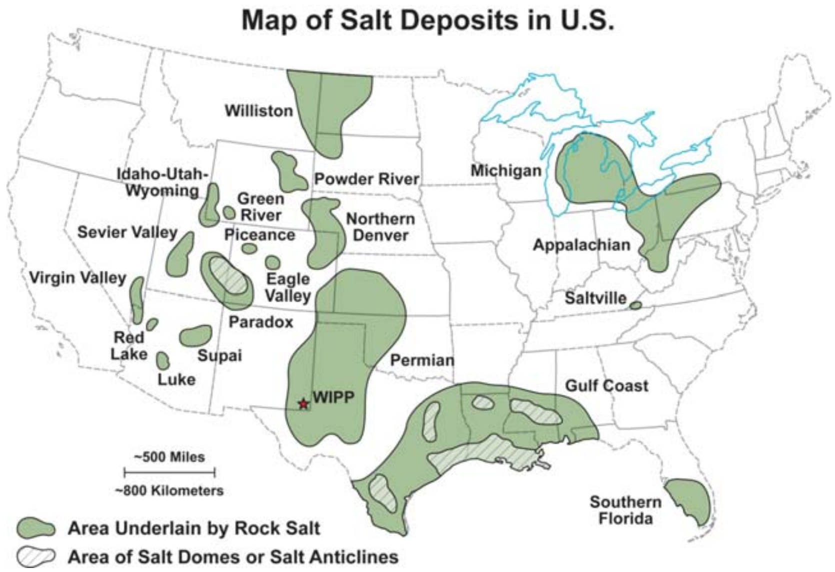

Figure 3. Map of Salt Deposits in the United States[7].

Screening of the entire US in the 1960s and 1970s identified large regions underlain by rock salt of sufficient depth and thickness to accommodate a repository.

Salt domes in the Gulf Coast. The primary screening factors used to identify potentially favorable locations were the depth to the top of the dome and present use for gas storage or hydrocarbon production. Siting guidelines and the related evaluation reduced the list of over 500 salt domes to seven potential repository locations, with further screening resulting in the identification of the Cypress Creek, Richton, and Vacherie domes as potentially acceptable sites.

Bedded salt in Utah. The primary screening factors used to identify potentially favorable locations were the depth to the salt, the thickness of the salt, proximity to faults and boreholes, and proximity to the boundaries of the dedicated lands. The thickness of the salt, the thickness of the layers above and below the depth of a repository, and the minimum distance to salt-dissolution features were considered the most critical geologic discriminators. Davis Canyon and Lavender Canyon were identified as potentially acceptable sites.

Bedded salt in west Texas and southeastern New Mexico. The Permian bedded-salt deposits in the Texas Panhandle and western Oklahoma had been identified as potentially suitable for waste disposal. The primary screening factors were the depth to and the thickness of the salt, faults, seismic activity, salt dissolution, preexisting boreholes, underground mines, proximity to aquifers, mineral resources, and conflicting land uses, such as historical sites and state or national parks. All the evaluated sub-basins contain salt beds of adequate thickness and depth. Following considerable study, DOE decided to focus on locations in northeastern Deaf Smith and north-central Swisher counties in Texas.

In 1985, the Secretary of Energy nominated three salt sites among the five sites considered for further consideration: the Deaf Smith County, the Davis Canyon, and the Richton Dome sites. The President subsequently selected the Deaf Smith County site as one of the three sites to fully characterize prior to the 1987 enactment of the NWPAA, which left only the Yucca Mountain site for full characterization.

Deep Borehole. Deep borehole disposal presents a favorable prospect, in part due to the wide expanse of basement crystalline rock at design depth in the lower 48 states. Figure 4 shows a contour map depicting depth to crystalline basement. Low permeability, high salinity, and geochemically reducing conditions at many locations in the deep crystalline basement rock limit significant fluid flow and radionuclide transport. Though the relatively high temperatures and salinities of deep fluids should accelerate the corrosion of steel pipes, fuel assemblies, and the waste itself, the scarcity of oxygen might slow the oxidation of spent fuel. The geochemical behavior of the projected waste inventory in the deep borehole environment sets limits on the stability of the uranium in the spent fuel matrix and on radionuclide transport to the biosphere.

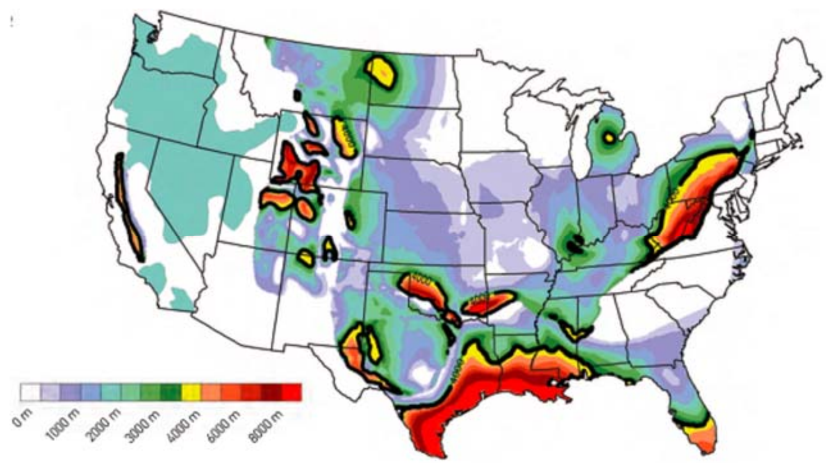

Figure 4. Depth to basement crystalline rock in the United States[8].

CONCEPTS OF DISPOSAL

Concepts of geologic disposal have been well developed in several countries. Full-scale underground research laboratories have been used for site characterization in several media by several different nations (see Appendix A). These studies provide a basis for launching a new repository program in the USA, particularly if any site other than Yucca Mountain is considered. Note that the Yucca Mountain disposal concept is not included here, but its development is contemporary and well documented[9]. In this section, examples of disposal concepts are given for deep borehole disposal, as well as for mined deep geologic repositories in granite, shale and salt.

Granite. Mined deep geologic disposal in granite is a mature option. The schematic shown in Figure 5 illustrates vertical (SKB3-V) and horizontal (SKB3-H) placement concepts being investigated and developed by Sweden and Finland. Figure 6 is a photograph of the full-scale demonstration of spent nuclear fuel disposal executed in a quartz monzonite (granitic rock) at the Nevada Test Site in the 1980s[10]. The mature designs advanced by international programs and the demonstration at Climax provide confidence that an acceptable disposal concept in granite could be readily developed should the USA opt for mined disposal in granite.

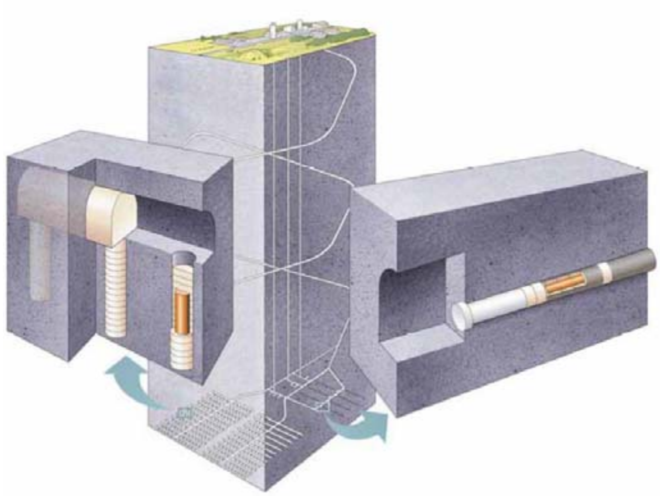

Figure 5. Representative disposal concept for mined granite repository[11].

Figure 6. Waste disposal demonstration in granite at the Nevada Test Site[10].

Deep boreholes. Emplacing intact spent fuel assemblages, without pre-consolidation, is one of the simplest approaches to borehole disposal, and is the one evaluated by Arnold et al.[12]. Figure 7 illustrates the deep borehole concept. A vertical borehole with an estimated diameter of 45 cm is drilled into the crystalline basement rock down to a total depth of 5 km, or so, below the ground surface. The borehole is assessed for stress conditions, stability and fluid pressure. A string of waste containers is then placed in the lower 2 km of the borehole. The borehole is sealed in the upper 3 km of penetration. Potentially acceptable basement rock is relatively common at depths of 2 to 5 km.

A canister made of standard oilfield casing 5 m in length and having an inner diameter of 32 cm and an outside diameter of 34 cm could hold one pressurized water reactor (PWR) fuel assembly. Welded end-caps would seal the canisters after the waste is inserted. The disposal canister must be strong enough to prevent radionuclide releases and exposures through the waste emplacement phase, including recovery operations for canisters that become stuck or damaged during emplacement. The canisters could be emplaced one at a time or as part of a canister string – a grouping of 10 or 20 canisters. Crushing of underlying canisters during the operational period would be prevented by bridge plugs in the borehole. As illustrated in Figure 7, the canisters would be surrounded by bentonite slurry and the upper 3 km of the borehole would be sealed by a combination of compacted bentonite elements, asphalt, and concrete plugs.

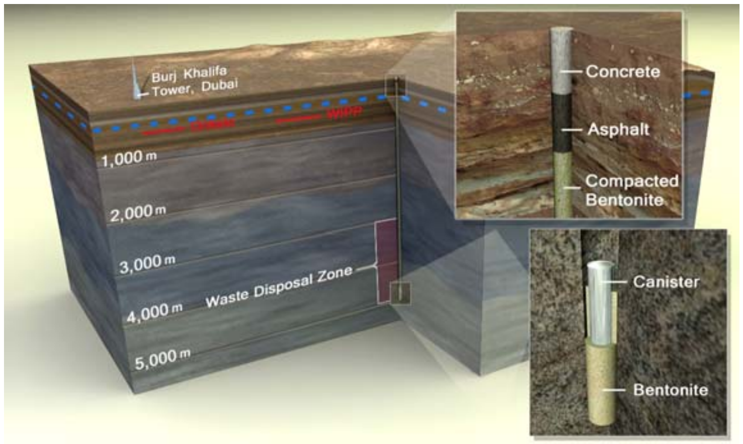

Figure 7. Deep borehole disposal concept[12].

Shale. Figure 8 illustrates shale disposal concepts for the three comparable European repository studies and a representation of possible disposal in a clay/shale formation in the USA[4]. Disposal boreholes would be spaced far enough apart to limit interaction of neighboring boreholes. The access drifts are conceived to be 5 m in diameter, which would accommodate waste packages. These dimensions are generally consistent with the French layout shown in Figure 8 but could be changed in response to site-specific analyses.

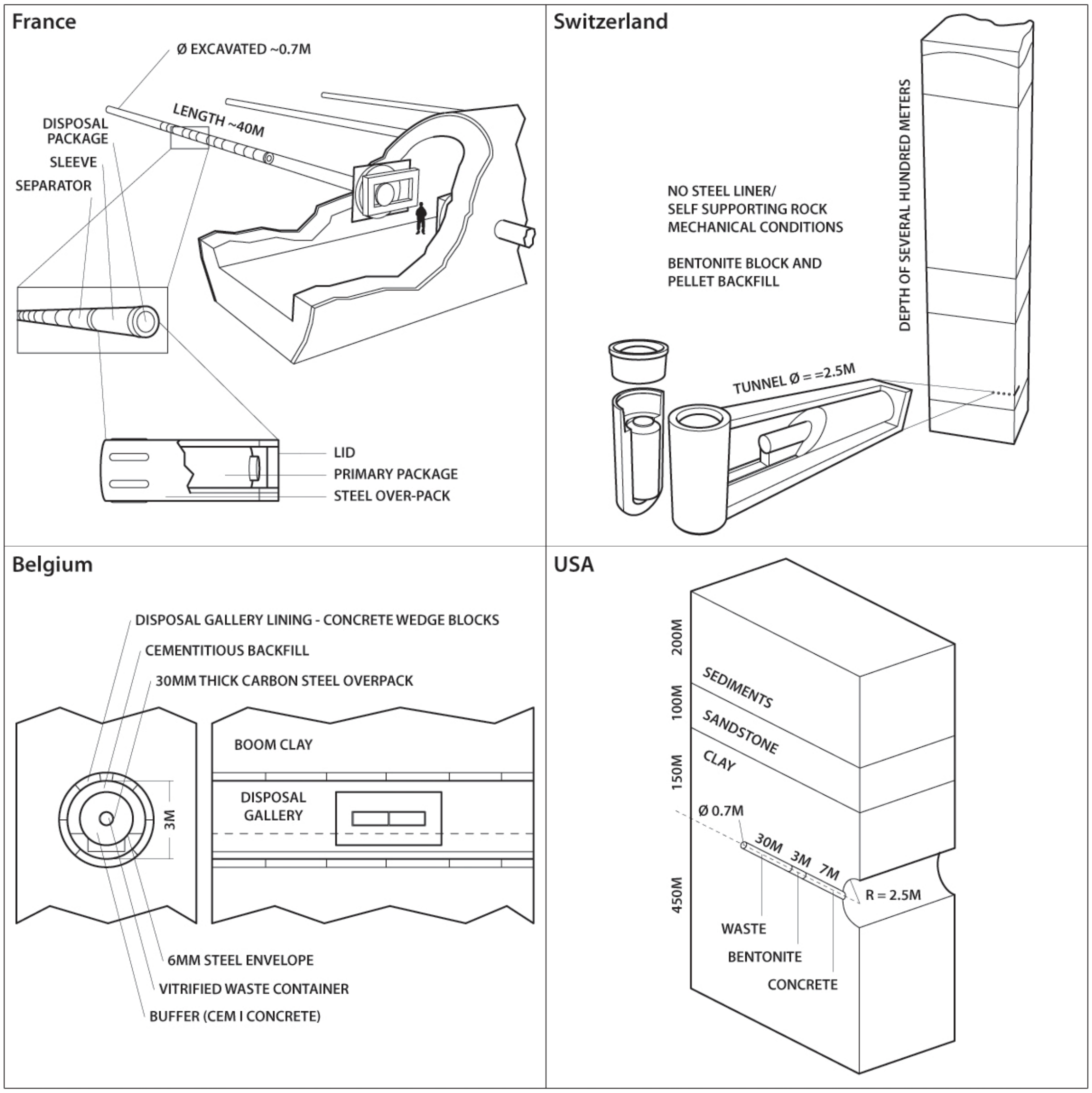

Figure 8. Schematic of shale disposal concepts (France: [13]; Switzerland: [14]; Belgium: [15]; and USA: [4]).

Salt. Disposal concepts in salt have been demonstrated in several full-scale field tests. Figure 9 shows how waste containers are emplaced in the Waste Isolation Pilot Plant (WIPP) repository. Single canisters of remote-handled (RH) TRUW are placed in horizontal boreholes, whereas the more benign contact-handled (CH) TRUW is stacked in the disposal room. Figure 10 shows the heated room tests at WIPP that simulated defense-HLW emplacement. This test assumes vertical emplacement of the waste in drilled boreholes in the floor. Other disposal concepts would be considered if a salt repository were selected as an option for disposal of heat-generating waste.

Figure 9. Disposal configuration for transuranic waste at the WIPP.

Figure 10. Vertical placement of heaters simulating HLW at WIPP[16].

CONCLUDING REMARKS

Given the developments at the Yucca Mountain Project and the establishment in January 2010 of the Blue Ribbon Commission on America's Nuclear Future, it is prudent to anticipate that the USA will develop a new radioactive waste management policy in 2012. Many of the policy issues debated in the 1970s and early 1980s will be revisited. The suitability of a particular disposal concept would need a regulatory framework against which to judge long-term safety and performance.

This paper provides a summary of geologic disposal options available in the 48 states in the conterminous USA. Table 1 compares relative attributes for four options besides Yucca Mountain. Not all of the properties listed in Table 1 are of equal concern; however this type of table is often constructed for general considerations in repository related papers. Details, characteristics and attributes in Table 1 could be expanded extensively and some readers no doubt will argue the relative merits designated in our table. Other factors of the geologic environment and domain noted previously would be considered during site screening. Suitability as used in this report is a qualitative safety case argument, other sites could be included or specific sites excluded depending upon the regulatory criteria established. Based on international programs and decades of experience in repository development, it is highly probable that a suitable repository can be developed for any of the four options.

Table 1. Relative Attributes of Disposal Options[1]

Property	Salt	Shale	Granite	Deep boreholes
Thermal conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on decade scale	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemical	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology*	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

Favorable property   Average   Unfavorable property

*** See figures in text.**

[1]Portions of this table are after BMWi[17].

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APPENDIX A

Geologic Disposal Options of Advanced National Repository Programs

Country	Potential Geology
Belgium	Scheduled to open the nation's first HLW repository in the Boom **clay** at Mol/Dessel. Has operated an underground research laboratory (URL) in the Boom **clay** since 1984.
Canada	Restarting the repository siting program. Hosted multi-national research on **granite** in the 1980s and 1990s in the now closed Pinawa URL.
Finland	Scheduled to open the nation's first HLW repository in **granite** in 2020 in the voluntary host municipality of Eurajoki. Opened the near-by Onkalo URL in **granite** in 2010.
France	Scheduled to open the nation's first HLW repository in Callovo-Oxfordian argillite **shale** in 2025 in the voluntary host communities of Meuse and Haute Marne. Operates the Bure URL.
Germany	Gorleben **salt** dome is the only current candidate HLW repository site. Has terminated ILW-disposal facilities in **salt** at Morsleben and Asse as well as a URL at Asse.
Japan	Pursuing voluntary candidate repository sites with an expressed interest in **granite**. Operates URLs in **clay** and **granite**.
Sweden	Scheduled to open the nation's first repository for HLW in **granite** at Forsmark in the voluntary host community of Oesthammar in 2025. Hosted Stripa experiments in 1970's and operates a multi-national URL at Äspö.
Switzerland	Explores **shale** (the Opalinus Clay formation) in the Mont Terri URL and **granite** in the Grimsel URL. Has not selected the first repository site.
The Netherlands	Current UNF-management policy/strategy is based on 100 years of central storage in the Habog facility.
United States of America	Has operated URLs in **basalt, granite, salt**, and **tuff**. Operates a mined, deep geological repository for long-lived radioactive waste in **salt** (WIPP) since 1999. Pending policy recommendations in 2012 from the Blue Ribbon Commission on America's Nuclear Future, repository developments are virtually dormant and subjected to complicated legal and financial challenges.

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