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LLNL Input to SNL L2 MS: Report on the Basis for Selection of Disposal Options

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Introduction

This mid-year deliverable has two parts. The first part is a synopsis of J. Blink's interview of the former Nevada Attorney General, Frankie Sue Del Papa, which was done in preparation for the May 18-19, 2010 Legal and Regulatory Framework Workshop held in Albuquerque.

The second part is a series of sections written as input for the SNL L2 Milestone M21UF033701, which is due March 31, 2011. The section numbering of the second part follows the outline developed by the multi-laboratory team. Placeholder section titles are shown for sections not in LLNL's scope).

Interview of Former Nevada Attorney General, Frankie Sue Del Papa

In preparation for the May 18-19, 2010 workshop on the Legal and Regulatory Framework, James Blink interviewed Nevada's former Attorney General (AG), Frankie Sue Del Papa, on March 19, 2010, at her home in Reno, NV. Dr. Blink and General Del Papa attended college together in the late 1960s, and Dr. Blink's wife is a first cousin of General Del Papa; hence, the interview had a relaxed, non-confrontational tone that sought to understand the perception of the DOE program at Yucca Mountain from the perspective of the senior levels of Nevada State government.

General Del Papa was Attorney General from 1990 to 2002, serving under Governors Bryan, Miller, and Guinn. She served as Secretary of State from 1987 to 1990, and was a member of the University of Nevada System Board of Regents from 1980 to 1987. This experience provides a rare opportunity to observe, in hindsight, the reactions of state political leaders during the contentious process of developing Yucca Mountain.

General Del Papa concluded that it is critical to reach out to State-level leadership as a project is planned and developed, and that the State Constitutional Officers are key to the discussion. She noted that these types of projects are much more of a State decision, rather than a decision of a local county. The Congressional action to amend the Nuclear Waste Policy Act (NWPA) in 1987, to focus on only a single site, was unilateral on the Federal level, and left very bitter feelings in Nevada government. The NWPAA (NWPA as Amended) is commonly referred to as the "Screw Nevada Bill" within Nevada. General Del Papa believes the NWPA Amendment resulted in strong opposition across Nevada and helped to doom the project.

The perception in Nevada state government was that, following the NWPAA, DOE pushed the repository "come hell or high water", forced the science to fit preconceived conclusions, ignored scientific evidence unfavorable to the project, and generally did not give a fair hearing to scientific evidence. She noted that this perception was exacerbated by problems DOE had at a number of sites, such as Hanford (leaks) and Savannah River. She believes that DOE's representation of safety and quality did not match information coming out across the DOE complex of facilities.

General Del Papa noted that, during her tenure as a Constitutional Officer (Secretary of State and Attorney General), the entire leadership consistently opposed Yucca Mountain. When asked if it could have gone differently if DOE's approach had been different, she said that the NWPAA poisoned the relationship, and that all subsequent DOE efforts to include the State in the process were doomed because of the Congressional action.

A couple of AG Deputies worked full time on Yucca Mountain matters over an extended period. They raised, internally within the AG Office, concerns about radionuclide transport, groundwater contamination, and seismic activity. She noted Nevada is the third most seismically active state. Also, concerns arose about transportation to the repository, and General Del Papa noted that 80% of the waste would originate east of the Mississippi River. This raised regional equity issues in addition to scientific issues. On the scientific front, Governor Bryan suggested leaving waste in dry casks for centuries, while we "wait for science to catch up" with disposal feasibility issues.

A telling experience was the wet walls 1,500 feet underground in the Climax Mine at the Nevada Test Site. Although this mine was in a different geological medium than Yucca Mountain, it was being used for repository tests and hence the wetness was noted (whether fairly or not). Due to the poisoned relationship, State officials did not visit the Yucca Mountain Exploratory Studies Facility, but if they had, they could have seen some localized wetness that would have reinforced the (incorrect) perception that repository tunnels would not be dry in the repository.

We discussed the involvement of the two State Universities (UNR and UNLV) on the project. General Del Papa said that, in general, the university involvement was a positive aspect of the project, but that it also resulted in some difficult relationships.

Following 9-11, the concerns about terrorism added to the concern about Yucca Mountain becoming a repository, with transportation and surface facility activities being potentially vulnerable. The concern continues to this day, with General Del Papa reminding me of CIA Director Panetta stating to Congress, in February 2010, that Al-Qaeda can be expected to attempt an attack on the United States in the next three to six months.

Dr. Blink turned the interview toward a hypothetical Federal project, and how the Federal government could effectively include State governments in project planning and development. General Del Papa said that States would begin with the principles that there needs to be a basic sense of fairness, that it is a privilege to live in the United States, and that all States want to do their share. She noted that pre-selection of a site for a large project and then selling it to the host State and community is the wrong approach. Instead, there needs to be a process that is above-board and fair, and that is carried through in a predictable manner. The process should start with the State's Congressional delegation and Constitutional officers. The Federal agency should reason with them in a fair and above-board manner. The process should start with perhaps a half-dozen States, rather than just two or three. Discussions should include pros and cons, mitigation, and the process that would be followed. General Del Papa noted that the opposite has historically occurred, citing the MX Missile Project as being secretive and heavy handed, as another example beyond Yucca Mountain.

It is interesting that the scientific issue that resonated with credibility with General Del Papa was an article in the New York Times on the Szymanski theories about ground water flow at Yucca Mountain. Jerry Szymanski, a DOE employee on Yucca Mountain, hypothesized that the ground water table had risen by several hundred meters in the past and that it could again rise. Multiple peer reviews have since concluded that the near-surface mineral deposits cited by Szymanski resulted from percolating rainwater rather than seismically driven water table rise. General Del Papa, at the time and apparently to this day, credits the New York Times as having more credibility than the DOE reports, including those from independent peer review panels.

The distrust of DOE sponsored work, and the adoption by the State of critical discussion (even if only preliminary) from credible media sources, is a strong impediment to implementing the hypothetical process discussed by General Del Papa. The interview followed up on this aspect, to try to determine a reasonable path forward on the hypothetical federal project we were discussing. General Del Papa said that what is needed are straight-up independent analyses. She suggests three parties (independent studier, project proponent, and regulator) could be better than two (proponent/studier and regulator). She noted that the State perception of the DOE process being "Decide – Announce – Defend" (DAD) taints the process. She said that down-selection to a number of potential sites greater than three would have been better, rather than DOE's three or Congress's one. She concluded that no stone should be left unturned, and there must be the fairest of reviews. A schedule-driven project is artificial and leads to a push rather than an impartial review. She characterized DOE's strategy as "reaction to delays by creating short term deadlines", and that this strategy resulted in further distrust within the State. The NWPAA was a similar reaction at the Congressional level, and it created a similar but even stronger result, she concluded that obtaining project support in Nevada was hopeless from then on.

Sections to be Integrated into the SNL L2 Milestone M21UF033701

I. Introduction

Disposal of high-level radioactive waste is categorized in this review into several categories. Section II discusses *alternatives to geologic disposal*: space, ice-sheets, and an engineered mountain or mausoleum. Section III discusses *alternative locations for mined geologic disposal*: islands, coastlines, mid-continent, and saturated versus unsaturated zone. Section IV discusses *geologic disposal alternatives other than emplacement in a mine:* well injection, rock melt, sub-seabed, and deep boreholes in igneous or metamorphic basement rock. Finally, Section V discusses *alternative media for mined geologic disposal*: basalt, tuff, granite and other igneous/metamorphic rock, alluvium, sandstone, carbonates and chalk, shale and clay, and salt.

A number of reviews of this subject have been undertaken in the past forty years. These include Kubo and Rose (1973), Battelle Pacific Northwest Laboratories (BNWL, 1974), Energy Research and Development Administration (ERDA, 1976), the DOE Environmental Impact Statement for waste disposal (DOE, 1980), Lomenick (1996), the National Academy of Sciences (NAS, 2001), McKinley (2007), EPRI (2010, four volumes), and Whipple (2010).

II. Alternatives to Geologic Disposal

Disposal of high-level radioactive waste by methods other than geologic burial has been discussed in most overviews of the subject. In this review, three alternatives are discussed: space, ice-sheets, and an engineered mountain or mausoleum

1. Space

The extra-terrestrial disposal of nuclear waste was the subject of several reviews largely in the 1970s and 1980s. The specific concepts varied from solar incineration or solar system escape, to lunar placement or high Earth orbit. Not surprisingly, the concept has been widely investigated by researchers at NASA and Boeing, with findings documented in several reports including BNWL (1974), ERDA (1976), Boeing (1981), and Rice and Priest (1981).

One of the most recent reports to discuss the subject (NAS, 2001) summarizes the disposal option as not currently feasible due to the scientific, technical, and economic challenges, citing trade-offs between cost and safety discussed in Rice and Priest (1981). Table II.1-1, which is based on NAS (2001, Tables 1 and 2) and ERDA (1976, Table 26.1), lists the advantages and disadvantages of a range of space disposal concepts. Rice and Priest (1981), citing Burns (1978), ranked space disposal options, with solar orbit > lunar surface > solar system escape > lunar orbit > high Earth orbit > solar impact. Orbits in the inner solar system change over time-periods shorter than that of the lifetime of the waste, suggesting that waste may not remain in a stationary orbit while hazardous. Solar incineration guarantees that the waste is destroyed forever, but the massive amounts of energy required to send a heavy and regularly launched payload as far as the sun makes incineration highly cost-prohibitive. Consequently, a space disposal option would likely be considered a *complementary* alternative, utilizing terrestrial disposal together with separation and reprocessing, and sending only long-lived radionuclides into space. Additional space disposal concepts are discussed in Boeing (1981), including landings on Venus, Jupiter, and asteroids.

Key characteristics of extra-terrestrial disposal include: rescue options (for deployment malfunctions), long-term risk of Earth re-encounter, long-term containment requirements, cost, orbit velocity, propulsion requirements, vehicle re-use options, launch window requirements, retrieval (of properly deployed waste), passive monitoring, and implications for future use. (Here, it is interesting to note that from an energy/resource perspective, “future use” traditionally refers to the possibility of using what is currently considered waste; in this specific example, “future use” refers to use of the *location*, e.g. moon bases, space stations etc). Orbit velocity (ΔV) is the additional velocity required for an object to leave a low-Earth orbit; the value can be considered a direct indication of propulsion energy (and therefore the size and cost) required.

High-profile space shuttle disasters such as Challenger in 1986 and Columbia in 2003 highlight the immediate or short-term risks, but, provided the orbit is correctly selected and maintained, the long-term risk is significantly lower than any terrestrial disposal option. Using waste forms such as cermets may prevent dispersion of radionuclides should a catastrophic failure occur before the waste reaches its destination.

Table II.1-1. Advantages and disadvantages for specific space disposal design concepts.

Rice and Priest (1981) Rank, Destination	**ΔV, km/s**	**Advantages**	**Disadvantages**
5 High-Earth orbit	4.11	• Low ΔV • Launch any day • Passive waste package (no post-launch burn) • Can be rescued • Can be retrieved	• Long-term container integrity required • Orbit lifetime not proven • Not permanent • Public controversy
4 Lunar orbit	4.25	• Low ΔV • Can be rescued • Can be retrieved	• Orbital stability uncertain • Complex flight profile
2 Lunar surface (soft landing)	6.05	• Can be rescued • Can be retrieved • Permanent disposal • No orbit issues	• Potential for lunar contamination • Complex flight profile • Public and scientific controversy
Solar orbits via:			
1 Single burn to beyond Earth escape	3.65	• Low ΔV • Launch any day • Passive waste package	• Long-term container integrity required • Earth re-encounter possible (may not be able to prove otherwise) • Controlled abort not possible past Earth escape vel. • Rescue difficult
1 Circular solar orbit	4.11	• Low ΔV • Launch any day	• Long-term container integrity required • Orbit stability not proven • Controlled abort not possible past Earth escape vel. • Rescue difficult
1 Venus or Mars swingby	4.11	• Low ΔV	• Long-term container integrity required • Launch opportunity (3-4 of every 19-24 months) • Requires midcourse systems • Need space propulsion or have possibility of unplanned encounter
Solar system escape:			
3 Jupiter swingby	7.01	• Removed from solar system • Potential high public acceptance	• High ΔV • Limited launch opportunity (2-3 of every 13 months) • Requires midcourse systems • Controlled abort not possible past Earth escape vel.
3 Direct	8.75	• Launch any day • Passive waste package • Removed from solar system, potential high public acceptance • Operationally simple	• High ΔV • Controlled abort not possible past Earth escape vel.
Solar impact:			
6 Jupiter swingby	7.62	• Package destroyed	• High ΔV • Limited launch opportunity (2-3 of every 13 months) • Requires midcourse systems • Controlled abort not possible past Earth escape vel. • Potential to return a small fraction of the waste to Earth
6 Direct	24.08	• Package destroyed • Launch any day • Passive waste package • Operationally simple	• Extremely high ΔV • Controlled abort not possible past Earth escape vel. • Potential to return a small fraction of the waste to Earth

2. Ice-Sheets

As with extraterrestrial disposal, ice-sheet disposal has been well documented in numerous reports published in the 1970s and 1980s (BNWL, 1974; EDRA, 1976, Vol. 4, Section 25.3). The two main proposed locations are Antarctica and Greenland, both of which have significant ice caps.

Antarctica is one of the most remote locations on Earth, uninhabited by humans, perhaps providing enhanced isolation of nuclear waste from both the biosphere and intruders. Philberth (1958, 1961) first proposed the concept of ice-sheet disposal of nuclear waste in Antarctica. A multi-national Antarctic Treaty signed by 48 nations specifically forbids the disposal of radioactive waste (ATS, 1959). A potential nuclear waste facility in Antarctica would likely be an international site where many countries would send their nuclear waste, may require ratification by all Antarctic Treaty System (ATS) states, and would draw much criticism from environmental groups worldwide.

Alternatively, the Greenland ice cap is more accessible to transportation via shipping, and the environment is less harsh than Antarctica. However, Greenland is Danish Territory and houses several settlements (Zeller, 1976), making international repository collaboration and minimization of risks to local population more difficult.

The concept utilizes the long-term stability of ice-sheets and their remote geographical location. For example, the continent of Antarctica has been glaciated for more than 200 million years (Budd, 1971) and ice has been present even during periods of interglacial warming. Scientists believe that the ice cap would not melt within the next 250,000 - 500,000 years (Angino, 1976). Specific design concepts include melt-down (free-flow), anchored emplacement, and surface storage.

In the melt-down design, each waste canister has a single shaft in the ice, predrilled to 50-100 meters. The ice provides shielding. An example of proposed shaft spacing is 1 km, which limits heat source interference. The emplaced canister melts down through the ice at a rate of 1 to 1.5 meters per day (Aamot, 1967) and may reach bedrock after 5 to 10 years. The shape of canister can be engineered to either enhance or hinder the vertical path through the ice. Paterson (1976) notes that this concept involves hot waste packages reaching the bedrock and that may result in increased slip rates along the bedrock, and subsequent ice deposition into the ocean much earlier than expected. He instead prefers an anchored approach where the waste follows the path of ice-flow nearer the ice surface.

For anchored emplacement, the specific design concept is similar to melt-down, but provides for retrievability at a depth of (for example) 200 to 500 meters. Anchor cables connected to the waste package are tied to surface plates. As fresh snow is deposited on the surface of the ice-sheet, the anchor plates will become increasingly covered. Estimates for retrievability are 200 to 400 years (ERDA, 1976, Section 25.3.1.2), with an estimated 20,000 to 30,000 years to reach the bedrock. This is considerably longer than that estimated for the melt-down design, resulting in a much cooler waste package reaching the bedrock and subsequently a reduced likelihood of thermal effects increasing slip.

Additionally, the remote and cold locations offered by ice-sheets can provide for surface storage options. One example is a large above-surface vault facility supported by jack-up pilings that rest on load-bearing plates just below (or on the surface of) the ice. The facility would be air-cooled and allowed to remain above the ice surface for as long as possible before being consumed by the ice when the jack-up legs reach their maximum extension. This option, like anchored emplacement, could provide retrievability for approximately 400 years (ERDA, 1976, Section 25.3.1.3).

The advantages and disadvantages of ice-sheet disposal are given in Table II.2-1. The remote nature of ice sheets necessitates the need for marine and over-ice or air transportation. The transportation costs, logistics, the short operating season, and waste monitoring and maintenance factors may affect decisions supporting and developing such a waste facility. In the 1970s, discussion of a potential repository in Antarctica called for international collaboration to characterize and build the site, with costs shared among nations wishing to dispose of their waste. The IAEA released documents (IAEA, 1998; IAEA, 2004) providing a list of important technical, institutional, and economic factors; frameworks; and scenarios for developing a multinational radioactive waste repository.

A panel of international scientists (Bull, 1975) concluded that Antarctic ice sheets were not suitable for protecting the biosphere for several hundred thousand years from emplaced radioactive waste. The panel also concluded that a complete understanding of the current ***and*** future climate changes, geothermal flux, and sea level is needed before ice sheet disposal should be seriously considered as an option. Currently, research in Greenland by scientists from Sweden, Finland, and Canada (the Greenland Analogue Project, GAP) aims to increase knowledge of the groundwater flow and the water chemistry adjacent to a continental ice sheet. Sub-projects focus on ice-sheet hydrology, groundwater formation, sub-glacial hydrology, hydro-geochemistry, and hydrogeology. A report detailing the results and conclusions reached by GAP is expected in 2013.

Table II.2-1. Advantages and disadvantages of ice sheet disposal (BNWL, 1973; BNWL, 1974).

Advantages	**Disadvantages**
Geographical isolation	Extensive new data on all facets of ice sheet physics will have to be obtained
Relative isolation and containment of wastes by the ice in the event of leakage or canister failure	The harsh environment and unpredictability of conditions on ice sheets will present severe problems in establishing safe operations
Low temperatures and high heat dissipation capacity	Ice sheet areas are inaccessible during much of the year (8-11 months) because of storms, long periods of winter darkness, and freezing of surrounding seas
Relative safety from damage by storms, sabotage, and other hazards once the waste is emplaced	Monitoring and evaluating waste disposal operations would be difficult
Self emplacement	Recovery from an unforeseen occurrence during transport to the disposal site would be difficult

3. Engineered Mountain/Mausoleum

Kubo and Rose (1973) provide information on the use of engineered near-surface structures. They state that such a facility is designed specifically for temporary storage (not disposal) with the explicit intent of future retrieval. The use of near-surface facilities comes at the expense of increased surveillance and increased vulnerability to both natures' harsh conditions and human sabotage.

There was informal discussion among Yucca Mountain staff in the Site Recommendation phase about the potential of replacing an in situ mountain, such as Yucca Mountain, with an engineered mountain. Essentially, the existing mountain would be removed, using technology associated with large-scale open pit mining. Then, barriers below the emplacement level would be installed, followed by the waste emplacement. Finally, barriers above the emplacement level would be installed. The three layers would have the same roles as the engineered barrier system and the natural barriers above and below emplacement level. It was conjectured that engineering a well-drained artificial mountain that is essentially perfectly characterized by design could be more certain and less expensive than the "no stone unturned" approach to site characterization.

III. Alternative Locations for Geologic Disposal

This section discusses four alternative location categories for geologic disposals. Locations under remote islands, in coastline areas, and in mid-continental areas are discussed. A final section covers the important distinction between disposal in the saturated zone versus the unsaturated zone (below or above the water table).

1. Islands

The concept of remote island repository sites was discussed in the Final Environmental Impact Statement, Management of Commercially Generated Radioactive Waste (DOE, 1980, Sections 1.4.3 and 6.1.3) and further discussed in NAS (2001, Section 7). Small, remote, or uninhabited islands would combine the advantages of both seabed disposal and geologic repositories. A repository may include conventional drifts or shafts from the island surface to below the island or adjacent ocean floor. As with any other geologic facility, the rock-type and behavior would need to be characterized and well understood. The concept provides a reduced risk of intrusion because small islands are not generally a potential resource to be mined. For islands not near continental coastlines, the hydrogeology is not connected to ground water used by large populations, and the large volume of the ocean can dilute minor radionuclide migration from the site before it enters the food chain. However, it should be noted that relying on ocean dilution as a barrier is contrary to the underlying principle of nuclear waste disposal, which is "*isolation*". Significant reliance on ocean dilution would use the opposite principle ("*dilution is the solution to pollution*") historically used for fossil fuel combustion gaseous waste.

An alternative to using naturally occurring remote islands is to construct a man-made island in a shallow part of the ocean, with location and rock properties selected and engineered for optimum performance and lowest risk.

In the mid to late 1990s, several groups focused on the use of remote islands as a host for a disposal site. The background is summarized in an IAEA document addressing infrastructural framework and cooperation scenarios associated with the development of multinational radioactive waste repositories (IAEA, 2004, Section 3.2.2).

From 1946 to 1958, the US tested nuclear weapons in the Marshall Islands area of the Pacific Ocean, resulting in some islands being contaminated with radioactive material. In 1995, Amata Kabua, President of the Marshall Islands, proposed to the US government that a nuclear waste storage and disposal facility be built on one island. His proposal was that payment for hosting such a facility be used in part to remediate historical radiological contamination on the islands, and his government amended the law to include importing nuclear waste. Neighboring Pacific islands were vehemently opposed to the idea, and opposition to the concept also included the US government. In 1997, following the death of Kabua, the concept was rejected by the new government of the islands (IAEA, 2004, Section 3.2.2).

In the mid 1990s, a consortium of interested parties, including US Fuel and Security and Russian Minatom, proposed both storage and leasing of fuel on a Pacific island, possibly Wake Island. The consortium tried unsuccessfully to purchase Palmyra Island in 1996, and Wake Island in 1997. The US government strongly opposed the concept, and interested parties shifted their desired location to Russian territory (IAEA, 2004, Section 3.2.2).

2. Coastline

In an evaluation of the suitability of all potential geologic formations and rock types in the continental US for permanent repositories, McClain (1975) examined hydrological and structural characteristics of caverns constructed in the major US physiographic provinces. A major finding of the study was that the five caverns constructed at a single site in the Atlantic Coastal Plain (Triassic red shale) had possibly been subject to metamorphism. The fracture system provided a route for high water flux into the cavern. McClain concluded that “in general, the Atlantic Coastal Plain is not particularly favorable for the construction of mined storage caverns; the thick, unconsolidated, young materials, which are deposited unconformably on older crystalline rock, do not, for the most part, present candidate zones of sufficient structural strength or impermeability.”

BNWL (1974, Vol. 1, Section 1.7.1) addresses various hydrogeologic factors that should be considered when evaluating potential sites for disposal. The most important factor is hydrologic isolation, particularly “far removed from major drainages, lakes and oceans”. Of those considered particularly unsuitable in BNWL (1974), areas subject to possible rise in sea level or changes in drainage patterns are unfavorable. The authors also note that sites that could be inundated by 60 to 150 m sea level rises (especially those below the 60 m level) should be reviewed critically. In the Pacific coastal area, considerable seismic activity is observed, making Pacific coast disposal sites unsuitable.

3. Mid-Continent

Mid-continent repository locations must consider potential groundwater contamination from releases in both nominal and disruptive event scenarios, and also from human intrusion.

There was intense opposition to the Deaf Smith County site in the Texas panhandle due to the overlying Ogallala aquifer (which extends across 8 states from South Dakota to Texas). The key technical factor was whether water moved upward (from the repository horizon) to the aquifer, or downward away from it. Bair (1987) concluded the water moved downward, when the fluid density as a function of elevation was included (the opposite conclusion from earlier analyses that only considered fresh water density). In situations in which opposing conclusions can result from reasonable changes in models, opponents and the media focus on the conclusion they want and on the disagreement among scientists. There was vigorous opposition in Texas to the site, with potential contamination of the aquifer being a major argument by the opponents, as can be seen with a simple internet search. The debate was terminated when Congress, in the NWPAA, narrowed the site characterization to the single site at Yucca Mountain, Nevada.

In Nevada, the performance assessment results were dominated by disruptive events, both igneous and seismic. Groundwater contamination due to disruption of both natural and engineered barriers was a key issue for opponents of the site. Conversely, at Yucca Mountain, the closed groundwater basin (that supplied water to only a small population) was a positive factor for proponents of the repository (DOE, 1984, Sections 1.2.3.2 and 3.3.3).

Human Intrusion could potentially disrupt both engineered and natural barriers in a repository. For mid-continent locations, the primary cause of such intrusions would be drilling for mineral or water resources. Therefore, site characterization must assess the presence of minerals (or indicators that could lead a future prospector to expect their presence) (DOE, 1984, Section 3.2.4).

4. Saturated Zone versus Unsaturated Zone

The National Academy of Science (NAS, 1983) provided a list of design criteria as required by the NWPA (and subsequently became part of 10 CFR 60.122). The list included desirable characteristics for both saturated zone (SZ) and unsaturated zone (UZ) sites. Specifically, for hydrogeologic conditions in the SZ, a site should provide:

- A host rock with low permeability
- A downward or dominantly horizontal hydraulic gradient in the host rock and surrounding hydrogeologic units
- A low vertical permeability and hydraulic gradient between the host rock and the surrounding hydrogeologic units.

Similarly, for disposal in the UZ, hydrogeologic conditions should provide:

- A water table sufficiently below the repository that saturated voids do not encounter the underground facility
- A low moisture flux in the host rock and surrounding units
- A laterally extensive low-permeability hydrogeologic unit above the host rock that would inhibit or divert downward moving water to a location beyond the limits of the underground facility
- A host rock that provides for free drainage, or a climatic regime in which the average annual precipitation is a small percentage of the average annual evaporation.

In a paper by Winograd (1974), detailed discussion of the characteristics of high level waste (HLW) disposal in the UZ is given, particularly relating to the very thick formations found in the Southwestern US. Rocks confined within the UZ contain interstitial water ranging from a few percent of the pore volume in highly porous rocks (sand, gravel, and sandstone) to 90% in low permeability rocks (clay, shale, and tuff). In the Southwest, the deep water table is due to a combination of moderate to high relief, aridity, relatively permeable rocks, and regional aquifers with surface outlets. Key to radionuclide isolation in the UZ, water moves from the coarser permeable strata to the fine-grain sediments constituting the gravel pack, impeding water movement away from a repository. The bulk capillarity between strata in the UZ favors horizontal distribution of water, impeding vertical transport either to the biosphere or to a water table below. The thick nature of UZ rocks in the Southwest also offers extensive sorption capacity to hinder the transport of released radionuclides.

In regard to rising water tables in the UZ, Winograd (1974) concludes that if UZ storage is "acceptable under present climatic conditions, it may also be adequate under pluvial conditions, provided that future pluvials are not considerably wetter than past ones and provided that precautions are taken in site selection." Additionally, Winograd states that a rising water table is not likely to inundate shallowly buried waste packages beneath carefully selected mesas, plateaus and valleys. And if such water table rise did occur, the effects would be diminished as a result of the properties of a UZ repository, namely gravel-pack, sorption processes, depth of water table, and retarded vertical flow by stratification.

Advantages ("assets") and disadvantages ("liabilities") of the UZ for HLW storage are given in Table III.3-1 (Winograd, 1974). EPRI (2010, Vol. 1, Section 3.3) also notes that a UZ site implies an oxidizing atmosphere within the repository, which is a potentially adverse geochemical condition with respect to radionuclide release and mobility compared to the more favorable reducing geochemical condition of most saturated sites.

Table III.3-1. Assets and liabilities UZ as a HLW site (Winograd, 1974).

Assets	Liabilities
Exhumation of wastes by erosion unlikely in the time frame of 1,000 - 10,000 years	Potential for exhumation of wastes by erosion in the time frame of 10,000 - 100,000 years is difficult to assess
Transport of dissolved radionuclides to deep water tables is unlikely under present climatic conditions	Potential for transport of dissolved radionuclides to the water table under pluvial climatic conditions is difficult to assess
Potential availability of remote federal lands with thick UZ	Extensive field and laboratory studies needed to evaluate the stresses caused by the placement of a major heat source in the UZ
Relative ease of placement and retrieval in the event of design miscalculation or development of a superior storage or disposal system	Nominal monitoring of the surface of a storage site is mandatory

However, Whipple (2010) points out that the trade-off between sites in the UZ and SZ is not as simple as looking at the generic effects of the local environment, since Tc-99, I-129 and Np-237 can be highly mobile and soluble in both UZ and SZ environments.

IV. Alternatives to Mined Geologic Disposal

Geologic disposal of high-level radioactive waste by methods other than excavated mines has been proposed in a number of overviews of the subject. In this review, four alternatives are discussed: well injection, rock melt, sub-seabed, and deep boreholes in igneous or metamorphic basement rock

1. Well Injection

Injection, also known as hydrofracture (or commonly "hydrofrac") has been used as a method of stimulating oil, gas, and well water production since the 1940s, with roots back to the shallow use of TNT in the 1860s (Montgomery, 2010). Information on injection as a concept for nuclear waste disposal is given in several references, including (Perkins, 1982; Lomenick, 1996, Sections 2.1.3 and C.3.3; BNWL, 1974 Vol. 1, Sections 1.6.1.10 and 3.2.3.1; ERDA, 1976 Vol. 4, Section 25.1) - the latter provides excellent background reading and forms the basis of much of this section.

The use of hydrofracturing for disposal of radioactive waste was first applied at ORNL in 1959, where wastes were injected into Conasauga shale at 700-1000 feet (De Laguna, 1968; Weeren, 1974). Similar proof of concept tests have been conducted for West Valley in New York (De Laguna, 1972; Sun, 1974) and several other locations in the U.S (Perkins, 1982).

The geological formation must be fractured along the bedding planes. This is achieved by pumping a fluid containing a gelling agent and propping agent into the formation. The propping agent holds the fractures open. An anti-gelling agent is then injected and the fluids are removed. The waste can then be injected in the form of a cement or grout, which hardens within a few days to form a sheet of solid cemented waste typically 3 mm in thickness and 350 m in diameter around the well (BNWL, 1974, Vol. 1, Section 1.6.1.10). Several layers of emplacement in fractured rock can be achieved on top of the previous fracture plane. Subsequently, the access hole is sealed with cement/backfill, and another well location is chosen. As an example, BNWL (1974, Vol. 1, Section 3.2.3.1) also identifies the need for thirty 15-centimeter diameter wells approximately 1,000 meters deep to handle the waste from an 1,825 MT/year plant over its 25- year life, cooling by liquid storage prior to emplacement.

The ORNL site serves as a test case with a half century of post-emplacement evolution. Longer-term understanding of the waste containment, and of the effects of possible resulting seismic activity, are major concerns with this disposal concept. The concept also offers poor retrievability. Ideally, the site of injection would be at (or close to) the site of waste generation, minimizing or even removing the need (and costs) for transportation. Thus, well injection can be one of the simplest and cheapest concepts (BNWL, 1974, Vol. 1, Section 3.2.3.1). However, this depends on the local geology meeting the requirements. Additionally, there would be the need to dissipate the significant heat generated by the waste, and the system would need to be protected from corrosion and radiation damage (Lomenick, 1996, Section 2.1.3).

Deep well injection (1,000 – 5,000 m) is another industry-proven method of liquid waste disposal (LeGros, 1972; Warner, 1972; Trevorrow, 1977). This method differs from hydrofracturing in that no fractures are induced prior to injecting the waste; rather, the waste is pumped directly into deep-mined wells in geologic formations.

Porosities of 10-30% are usually recommended (Johnson, 1973) and impervious strata must border the site both above and below the waste location. The site must also not be connected to water-transmitting faults or aquifers.

2. Rock Melt

This concept relies on using the heat from the waste to melt the near-field rock. High-level waste in liquid or slurry form would be placed into underground cavities. Heat from the waste would evaporate the water and melt the surrounding rock if the radionuclide heat content is high enough (Patterson, 1980). Chemical reactions of the molten rock and waste would form a complex waste form that would eventually solidify, in perhaps 1,000 years, into a relatively insoluble matrix (DOE, 1980, Sections 1.4.2 and 6.1.2).

To develop this concept, a designer would need to specify a very high thermal loading of liquid or slurry waste. Therefore, the waste would need to be relatively "young" (short time after reactor use), separated from structural materials such as cladding and fuel assembly components, and converted to liquid form. In addition, the waste would need to be placed in a localized region in order to reduce the heat loss (i.e. in a quasi-spherical cavity). Finally, the liquid or slurry waste would need to be contained within the cavity for the period in which the near-field rock would heat to the melting point, and the containment means would need to be functional during the heating, melting, and resolidification period. These factors were considered in the Environmental Impact Statement (DOE, 1980, Sections 1.4.2 and 6.1.2)

Due to uncertainties associated with criticality and heat generation rate, DOE (1980, Section 6.1.2) did not consider direct disposal of spent fuel using the rock melt concept, instead, reprocessed fuel would be disposed. The fuel reprocessing plant would be located at each disposal site, thereby eliminating cross-country transport of liquid waste (BNWL, 1973). The waste would be emplaced in phases (DOE, 1980, Section 6.1.2). In the charging phase, high-level waste in aqueous solution would be injected into the mined cavity, which would be sized at about 6,000 m^3 (11 m radius) to dispose of the high-level waste and transuranics from about 40,000 MTIHM of reprocessed spent fuel. The solution would boil during the charging period, with steam piped to the surface, resulting in enough latent heat removal to prevent rock melt, with the condensate recirculated to the cavity. Late in the charging period, liquid transuranic wastes would be added to the cavity. After about 25 years, charging would be complete, and the cavity would be sealed. Until that time, the cavity would be at atmospheric pressure, resulting in groundwater flow toward the cavity, minimizing leakage of radionuclides. After sealing, the temperature would rise above the rock melting point (600-1,200˚C, depending on rock type), with peak melt occurring in about 65 years, reaching a radius of 80 m. A heat barrier to ground water flow into the cavity was postulated to prevent leaching of the radionuclides during the 1,000 years of slow cooling that would result in the final product: a silicate rock conglomerate with a highly leach-resistant matrix (DOE, 1980, Section 6.1.2).

Variations of this concept include the use of unlined rubble-filled cavities made by nuclear explosives, and the use of drilled holes (such as in the Deep Borehole Concept discussed in Section IV.4 below) instead of cavities (BNWL, 1973). A report by Lawrence Livermore Laboratory in 1972 (Lewis, 1972) showed thermal calculations for an 11 m radius cavity or chimney consistent with a 5 kT nuclear detonation at a depth of 2,000 m, as well as alternatives using conventional explosives or mining techniques. That report discussed use of a shale rock for generation of the cavity, due to its low permeability and fracture healing properties. The shale was a layer within larger silicate rock in which the melting would occur. The report used 1,050°C for the rock melting point. The authors noted that low carbonate content was desirable to avoid generation of carbon dioxide during the melting phase. The report went on to note that the high viscosity of silicate rock near the melting point would result in low radionuclide loading near the periphery of the melt zone.

3. Subseabed (not LLNL)

4. Deep Boreholes in Igneous/Metamorphic Basement Rock (not LLNL)

V. Alternative Media for Mined Geologic Disposal (not LLNL)

1. Basalt (2-3 pages) (not LLNL)

2. Tuff (2-3 pages) (not LLNL)

3. Granite and other Igneous/Metamorphic Rock (3-4 pages) (not LLNL)

4. Alluvium (2-3 pages) (not LLNL)

5. Sandstone (1 page) (not LLNL)

6. Carbonates and Chalk (not LLNL)

7. Shale/Clay (not LLNL)

8. Salt (not LLNL)

VI. Conclusions (not LLNL)

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