

# What has Happened to the U.S. Nuclear Waste Disposal Program?

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**Introduction** One of science's strongest abilities is to be able to reduce uncertainties in a problem.

If left to itself, science usually does this very well. But it's rarely left to itself. Science exists within the larger framework of society and has to deal with the realities of politics, economics, history and even religion. Nowhere is this more obvious than with nuclear waste disposal. For this problem, the question we want to know with a fair degree of certainty is:

*If we put nuclear waste in this spot, what's likely to happen to it in 10,000 or 100,000 years? Will it contaminate the environment before it decays away? What are the risks to humans and the ecosystem?*

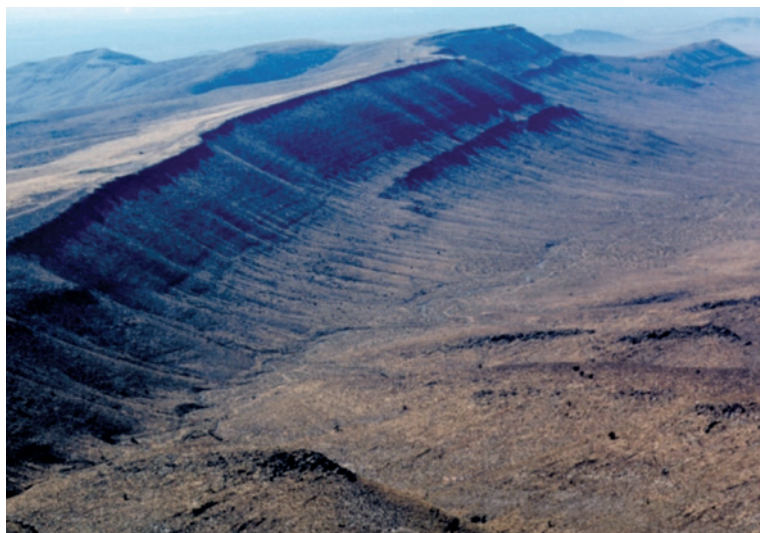
Unfortunately, even though we in the scientific community have answered these questions pretty well, our nuclear waste program is presently in shambles.

The nuclear waste program in America began during WWII and the making of the Bomb. The production and reprocessing of fuel from weapons reactors to make Pu resulted in the first significant amount of nuclear waste beginning in 1944.

With the increase in weapons production, and the advent of commercial power reactors in the 1950s, it became obvious that we needed a place to put this material away for ever and ever.

The federal government asked the National Academy of Sciences (NAS) to come up with the best strategy and, in 1957, they reported that deep geologic disposal (half-a-mile or so below the Earth's surface) was best (National Academy of Sciences, 1957). And they had a particular rock in mind (NAS, 1957), the massive Permian salt, which is the best rock for isolating anything for a very long time. And a rock that is pretty common around the world, especially in North America.

This recommendation led directly to the only operating deep geologic repository in the world, the Waste Isolation Pilot Plant (WIPP) in New Mexico (Conca, 2017). A splinter strategy in the 1970s, involving retrievability of spent nuclear fuel from the depths, then led to the 1982 Nuclear Waste Policy Act (NWPA,



**Fig. 1.**

The Yucca Mountain site was chosen in 1987 to be the first of two high level and spent nuclear fuel repositories in America, but the basis for the final decision was quite political, causing large uncertainties in the performance and the cost, as well as political resistance by the State of Nevada. DOE

1982) and its 1987 Amendment. That legislation chose Yucca Mountain (**Figure 1**), mainly through political means, as the only repository for spent nuclear fuel (SNF) and high-level waste (HLW). The State of Nevada has fought that decision ever since.

We submitted a license application for Yucca Mt in 2008, but in 2009, the Obama Administration terminated the project and formed the Blue Ribbon Commission (BRC) to recommend alternative paths.

Meanwhile, WIPP continued on in the salt (**Figure 2**), with its license and permit curtailed to include only transuranic waste (TRU), the other

type of nuclear bomb waste, that is mainly Pu, U, Am and other actinide elements along with other nasties (WIPP Land Withdrawal Act, 1992). The LWA set aside 16 square miles for nuclear waste disposal.

Periodically, attempts are made to resuscitate the Yucca Mt. project, as is being done once again as of this writing. At the same time, attempts are made to return WIPP to its original NAS mission which was to dispose of all nuclear waste – SNF, HLW and TRU – for which it was designed and built.

Finally, attempts are being made to site an interim storage facility for SNF near WIPP, either in New Mexico or just across the border in West Texas, under the regulatory umbrella of 10 CFR Part 72. SNF would be stored in dry casks (**Figure 3**) after removal from the spent fuel water pools where the short-lived radionuclides are allowed to decay away.

## Nuclear Waste

The United States has over 80,000 tons each of spent nuclear fuel (SNF) and high-level nuclear waste (HLW) although the forms of each are quite different (**Figure 4**). SNF from reactors is in a solid form that is easily handled and easily stored in dry casks



**Fig. 2.**

The Waste Isolation Pilot Plant (WIPP), the only operating deep geologic nuclear waste repository, is located 700 meters (2,130 ft) below the surface in the massive salt of the Salado Formation, and has been operating successfully since 1999. The Salado Salt was chosen originally based entirely on science. DOE



Fig. 3.

When spent fuel is removed from the reactor it requires about five years in water to cool off and allow the short-lived radionuclides to decay away. It can then transferred to dry cask storage (shown here) until needed, e.g., burned in Generation IV or V fast reactors in the near-future, or disposed of more easily in a deep geologic repository as it will be significantly cooler and less radioactive. NRC

once it is removed from the cooling pools after about five years. HLW is in different liquid, sludge and solid forms in various containments such as the 90 million gallons stored in large tanks at Hanford, Savannah River and other DOE facilities. HLW needs to be solidified and packaged by various methods including grouting (cementing), vitrifying (glassification) or steam reforming (mineralization). When dewatered, solidified and repackaged, this HLW will have somewhat over 80,000 metric tons of heavy metals, referred to as MTHM.

In addition to SNF and HLW, a minor amount of other wastes are included in the discussion of a deep geologic repository and include nuclear navy waste, weapons proliferation-related international waste, research materials and greater than Class C radioactive waste (GTCC). GTCC includes activated metals from decommissioned power plants, some sealed sources from the irradiation, medical and energy industries, and nondefense-related transuranic (TRU) waste.

However, spent nuclear fuel may not actually be waste since it can be re-used in various forms in present and future reactors, with or without additional reprocessing depending upon the reactor design. Since the economics of re-use is in question, SNF should be placed in an interim storage facility at the surface where it can be safely stored until needed, a conclusion agreed upon by the scientific community and the BRC. Whatever use is made of SNF, there

will be eventual waste from it, even if it is disposed of ultimately without being re-used. So there will be a need for the final repository regardless of the future use of SNF. Interim storage truly is interim, even if it could be a hundred years. SNF, or its waste after re-use, will be disposed in a deep geologic repository at some point in time.

On the other hand, HLW is waste that should be permanently disposed as soon as possible since it was generated primarily from reprocessing spent fuel from old weapons reactors and has no future value or use. The decision to co-mingle SNF and HLW administratively and physically in the

same repository led to the concept of retrievability of the SNF, i.e., we might change our minds about throwing something so valuable away, so we should construct the repository so that we are able to get only the SNF back out in 50 years or so.

Unfortunately, retrievability makes a deep geologic permanent repository into a deep geologic interim storage facility that we attempt to engineer or morph into a deep geologic permanent repository after we retrieve the waste or decide to leave it in place. The engineering and logistics then becomes extremely difficult and costly. However, since SNF, or its waste after re-use, needs a repository in the long run, co-mingling the eventual waste may not be a problem in the manner in which it is presently considered, as there will not be a retrievability issue at that time. This is the problem that interim storage solves – SNF is not physically co-mingled during disposal of HLW in the same repository but is disposed in the same repository decades later – co-mingled in space but not time.

The critical aspect about nuclear waste, unknown to the general public and their elected officials, is that there is not much of it. All the nuclear waste generated in the United States from its nuclear power fleet in the last 60 years can fit in a single soccer field – using a light-water reactor assembly dimension of 21.5 cm x 21.5 cm, approximately 100,000 used assemblies, and a regulation soccer field of 100 x 60 meters. Including all high-level defense waste in the U.S. more

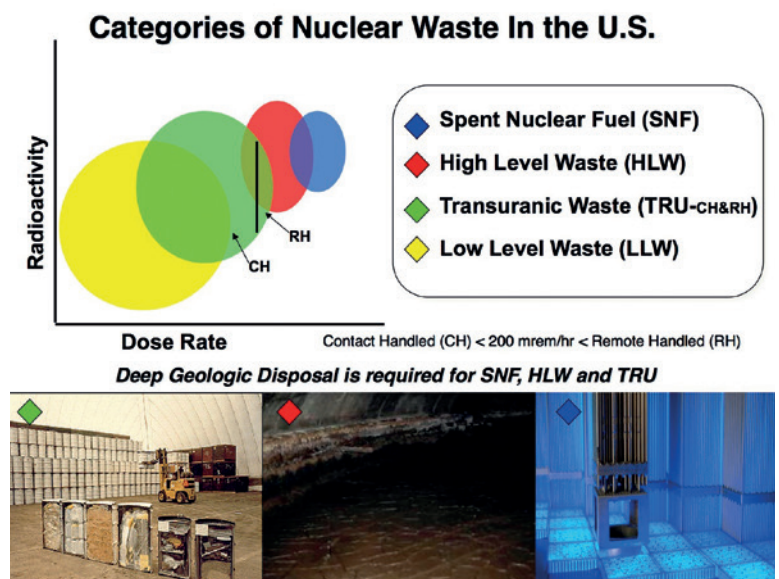


Fig. 4.

Four categories of nuclear and radioactive waste, their relative amounts and radioactivity, and an example of SNF, HLW, and TRU, the three categories that require permanent deep geologic disposal by law. DOE CBFO



than doubles that but it still would fit in the field with some in the stadium.

Compared to that, the over 400 million tons of solid waste and billion tons of CO<sub>2</sub> generated from coal-fired power plants each year is staggering. Even worse is the greater than 500 million tons of solid chemical and sanitary waste generated each year, and the 2 quadrillion gallons of water requiring waste treatment each year. These are large waste volumes that require thousands of disposal sites, if they are regulated at all. On the other hand, all of the nuclear waste generated in the United States in a thousand years could fit into one repository. Yes, it's bizarre material, but easy to handle and relatively easy to dispose.

Another critical aspect of the defense HLW is that most of it is no longer high level, except in name only. So much time has passed that significant amounts of radionuclides have decayed away, and several campaigns to remove the most radioactive constituents (<sup>137</sup>Cs and <sup>90</sup>Sr) have left most of the HLW tank waste with such low radioactivity that is now falls into the category of TRU-waste or LLW (Conca, 2014). But bureaucratically and legally, it is still considered HLW. Embracing the ramifications of this development will change our approach to this problem in ways that would dramatically speed up disposal and reduce costs over our present path. DOE has pursued this reclassification but public and state opposition has slowed it dramatically.

Most importantly, no one has ever died in the U.S. from handling, transporting or disposing of nuclear waste, and no one has ever died in the U.S. at an operating nuclear power plant, a tribute to our technical, industrial and regulatory system. Because nuclear waste is sufficiently odd and long-lasting, scientific opinion has long considered deep geologic burial to be the optimal method for permanent disposal (National Academy of Sciences, 1957; BRC 2011). The earth is the only system that can operate as expected for millions of years, and we understand geologic processes sufficiently to be able to choose an optimal place to dispose of these materials.

### Optimal Characteristics Of A Deep Geologic Repository

Characteristics of a suitable geologic repository for the disposal of nuclear

waste include the following favorable characteristics (McEwen 1995, EPRI 2006):

- i. a simple hydrogeology,
- ii. a simple geologic history,
- iii. a tectonically interpretable area,
- iv. isolation robustly assured for all types of wastes (no difficult or exotic processing needed),
- v. minimal reliance on engineered barriers to avoid extravagant costs and long time extrapolations of models for certain types of performance,
- vi. performance that is independent of the canister, i.e., canister and container requirements are only for transportation, handling and emplacement in the repository,
- vii. a geographic region that has an existing and sufficient socio-political and economic infrastructure that can carry out operations without proximity to a potentially rapidly growing metropolis (unlikely to ever have dense human habitation near the site).

Two rock types that fit these characteristics are argillaceous rocks (claystones and shales) and bedded or massive salts. Many studies have focused on argillaceous sites, particularly in Canada and Europe, with some strong technical arguments (Nuclear Energy Agency 2001); similarly for salt deposits (McEwen 1995, National Academy of Sciences 1970). The primary difference between salt and argillites is that, while both have extremely low permeability (the ability to conduct water) and the contaminants dissolved in it), argillites have much higher porosity (the total amount of pore space, usually filled with water) and molecular diffusion coefficients (the ability of molecules and dissolved contaminants to “randomly walk” through the material independent of the flow of water).

Massive salts have extremely low porosity, molecular diffusion coefficients and permeability. In fact, in massive salt, permeability and diffusion at the depths of a repository are vanishingly small, so nothing moves appreciably over millions of years. As an example, in the massive salt of the Delaware Basin spanning the borders of New Mexico and Texas, a half-mile below the surface it takes water, and any contaminants in it, a billion years to move an inch (Beauheim and Roberts 2002; Conca et al. 1993). Although salt deposits exist throughout the world (Zharkov 1984), many are not sufficiently massive, have too

many clastic interbeds, are tectonically affected (faulted and folded), or are near population centers.

Salt domes and interbedded salts are less optimal than massive bedded formations from a hydrologic standpoint, particularly within the United States where diapiric movement can exceed 1 mm/yr (McEwen 1995) and vertical spline fractures can act as hydraulic conduits. Still, there are many viable salt deposits in the U.S. and globally that meet these criteria (Zharkov 1984, Waughough & Urquhart 1983, Karalby 1983). The United States does not have optimal argillites for this purpose. It should be noted that volcanic tuffs, like those at Yucca Mountain, do not generally satisfy these criteria. The Yucca Mountain tuffs have a complicated dual-porosity oxidizing hydrogeology, a complex geologic and active tectonic history, and a heavy reliance on engineered barriers for the performance of a repository.

Finally, it is a mistake for disposal programs in any country to attempt to use old abandoned mines, even in an otherwise good rock. Mines dug for profit do not necessarily possess the correct structure or depth for optimal disposal. Simply taking what an old mine gives you is not wise and doesn't save enough money to justify the risk of failure. This was one problem with the German Asse Salt Repository. Any repository should be designed and built strictly with the disposal of nuclear waste in mind.

### Uncertainty

The ultimate basis for any choice of rock and location is to maximize properties you think are good, and minimize properties you think are bad. The best way to do this is to use natural systems that have already minimized these uncertainties by minimizing or eliminating the properties themselves. Pick a site where almost nothing has been happening for a long time, and where almost nothing will happen in the future.

This was WIPP.

Alternatively, you can try to impose certainty on the system through engineering, forcing each uncertain variable to become practically zero. Unfortunately, the Earth is a large, active and open system that resists long-term control by human engineering schemes and our understanding and control of these processes has always been limited.

This was Yucca Mountain.

Yes, the Great Pyramids are fantastic but that's about all humans have made that has lasted anywhere near what we think of as geologic time, and what we want for long-term disposal of nuclear waste.

Beginning in 1982, the Yucca Mountain Project hoped those variables that cropped up were sufficiently minor that they could be handled by changing the design as we discovered them.

Instead, what we did was just add more variables with bigger uncertainties. We addressed many by testing and redesigning, or discovering new information, over the years between 1987 and 2000, but the uncertainties just grew. And because of that, so did the projected cost.

There are many factors and properties of a situation that contribute to risk. For geologic containment, the most important properties are the characteristics of the rock itself, especially the permeability, chemical composition, strength, thermal conductivity, density, porosity, and pore water chemistry. These characteristics determine which radionuclides move in the subsurface, in what chemical species they exist, and how fast they migrate.

The host rock for the Yucca Mountain repository, the Topopah Spring tuff, is a highly fractured, dual

porosity and variably saturated volcanic rock with highly oxidizing pore water, that sits along the edge of a tectonically-active region called the Las Vegas Shear Zone in which the Mojave Block is being rotated between the San Andreas fault along the south and the Garlock Fault along the north.

The permeability of water, or hydraulic conductivity, varies from  $10^{-10}$  cm/s to  $10^{-4}$  cm/s in the tuff matrix, from  $10^{-4}$  cm/s to  $10^{-2}$  cm/s in small fractures, and greater than  $10^{-1}$  cm/s in large fractures and faults. The ionic diffusion coefficient in the pore space varies from about  $10^{-10}$  cm/s<sup>2</sup> to  $10^{-6}$  cm/s<sup>2</sup> depending upon the volumetric water content which varies from a few percent to 10 % depending upon the position, degree of saturation and recent rainfall. Perched water tables exist. In some of the proposed engineered barriers around the waste, the volumetric water content would exceed 30 %.

The redox potential of the pore water at Yucca Mountain is oxidizing, with Eh (oxidation potential) values greater than +200 mV, and causing redox-sensitive radionuclides, like Np, Se and Tc, to be under constant threat of becoming mobile. This aspect dominates the performance assessment of Yucca Mountain.

Yucca Mountain now has several engineered barriers that are supposed to reduce the effects of particular

properties, like the tuff's relatively large flux of oxidizing water, in the hope of reducing their uncertainties. These include reducing inverts, shotcrete, robust waste containers with copper and ceramic coatings, titanium drip shields, vitrification of HLW, waste package supports and reducing gravel backfill (**Figure 5**).

Unfortunately, these have only added uncertainty to the repository, since their correct emplacement, rates of degradation and time period for optimal performance are themselves uncertain.

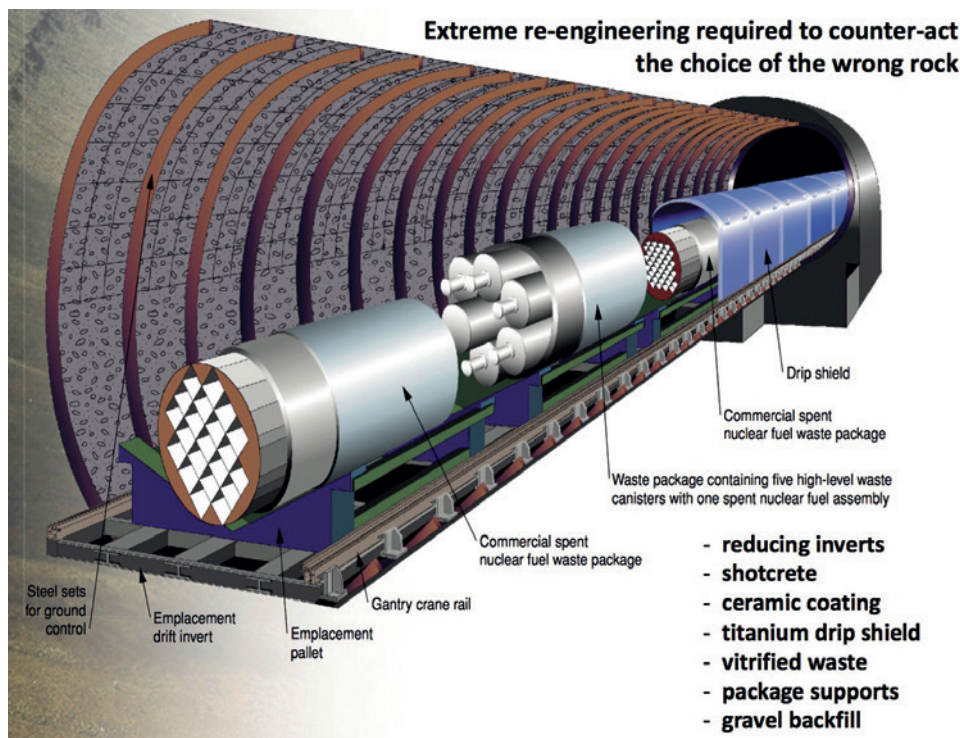
On the other hand, a better way to reduce uncertainty is to pick a situation that has few variables or where those variables have values that naturally approach zero, which is what the NAS did when they chose Permian Salt in 1957. The Atomic Energy Commission, and later the Department of Energy, searched for a suitable site in Permian Salt and, after several failed attempts, was invited by the local community in Carlsbad, New Mexico to investigate their proposed site.

Carlsbad was settled in the 1880s by German miners mining salt above what is the most optimal rock in the United States for this purpose – the massive Permian Salado Salt formation. The miners and geologists in Carlsbad understood the engineering needs of the nuclear repository better than the DOE, and understood that the Salado Salt Formation near Carlsbad would provide all of the performance required even without any engineered barriers.

The Waste Isolation Pilot Project (WIPP) repository was sited in the Delaware sub-basin of the Permian salt in southeast New Mexico and West Texas. It was designed and built for all nuclear waste of any type. Later, after the 1982 NWPA, WIPP was licensed and permitted only for transuranic nuclear weapons waste, or TRU waste (**Figure 6**).

WIPP is just one place that has ideal massive salt deposits. Although the following discussion uses data from the Salado Salt at the WIPP site, we have well over 100,000 square miles of appropriate massive salt deposits in America with similar optimal rock properties that would suffice for nuclear waste disposal, 10,000 square miles of Salado itself (**Figure 7**).

One particularly important property of massive salt is something called creep closure. At depth, under the pressure of the overlying rocks, the salt cannot maintain an opening,



**Fig. 5.**

A schematic of the engineered barriers proposed for the waste emplacement drifts at Yucca Mountain. The emplacement of the barriers correctly is an extremely difficult and expensive logistical activity. The titanium alone for the drip shields will probably exceed \$30 billion. DOE YMP





**Fig. 6.**

Over 10,000 nuclear waste drums and standard waste boxes fills 1 of 56 rooms to be filled at WIPP over its original 30-year mission, although more rooms are planned. Over 45 rooms have been filled as of this writing. Note the high-activity remote handled waste (RH) robotically plunged into boreholes in the wall to the left and plugged, while the contact handled waste (CH) fills the bulk of the room. 15 years of operation – 100,000 cubic meters of TRU waste disposed. After 20 years of operation, over 120,000 cubic meters of TRU waste have been disposed, over 600,000 fifty-five gallon drum equivalents, 21 storage sites have been cleaned of legacy waste, no deaths, with only one minor release to the environment that resulted in no lasting effects or people contaminated. DOE CBFO

fracture or pore space. It's why the salt is essentially impermeable, e.g., the trapped water in the salt hasn't migrated an inch in 270 million years.

The permeability of water, or the hydraulic conductivity, is less than  $10^{-14}$  cm/s, and the aqueous diffusion coefficient is less than  $10^{-15}$  cm/s<sup>2</sup>, amazingly low values that are, for all practical purposes, zero. Water just won't move in this rock and, therefore, neither will radionuclides.

The redox potential of the pore water in this salt is exceptionally reducing, one of the most reducing in the country, with Eh values less than -500 mV. This makes redox-sensitive radionuclides such as Pu, U, Tc, Np, Se, and I, immobile and unlikely to migrate out of the repository in the highly unlikely event that there is a path out.

Which is unlikely in the extreme. If a fracture does occur in the salt, or if we dig out an opening to put waste in, the salt creeps closed over a relatively short time, tens of years depending on the cut of the space. The more asymmetric the cut, like the long rectangles of the disposal rooms, close quickly, in years to tens of years. The more symmetric the cut, like circles or squares, close in decades. During this process, the salt naturally recompacts, or re-anneals, so there is no open space and the salt becomes essentially impermeable again.

In fact, any disturbance in rock properties from a cut only goes out about 14 feet from the wall of the

repository anyway. Beyond that, the rock isn't even disturbed. And these formations are thousands of feet thick. At WIPP, the Salado salt formation is 2000 feet thick over an area of about 10,000 square miles.

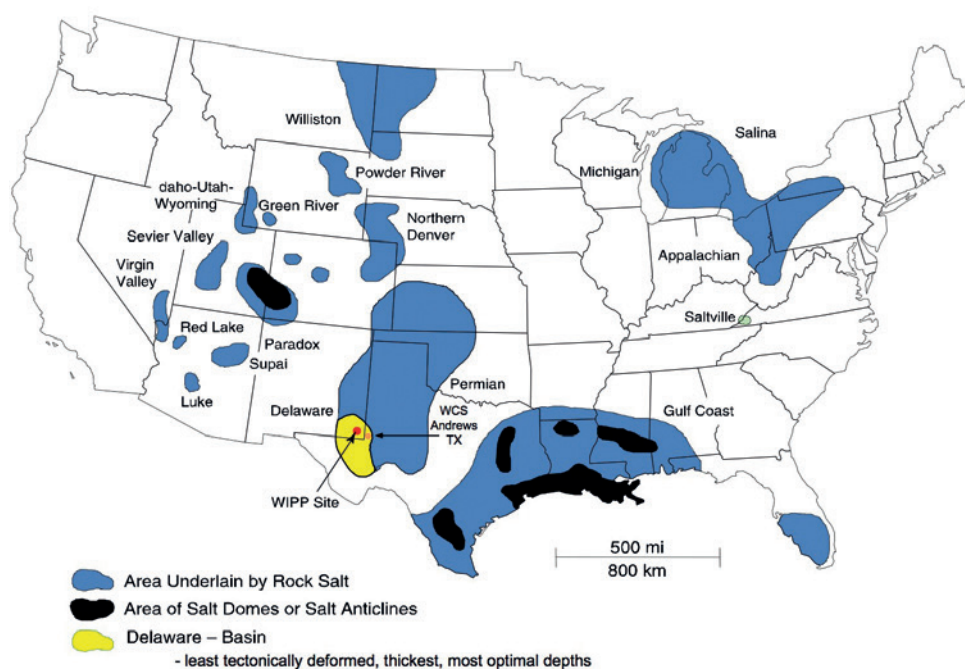
Two to three of those square miles could hold all of the waste destined for Yucca Mountain. WIPP already contains more nuclear waste by volume than everything that was supposed to go into Yucca Mountain total, some of it as radioactive as high-level waste.

In addition, the Salado Salt Formation in this region has never been subjected to any adverse geological processes – no volcanism, no folding or faulting, not even any tilting after 270 million years, quite unusual. There was only some regional uplift. In fact, this area is tectonically the quietest region in America and will be for the next 200 million years.

Which is why the National Academy of Sciences picked this rock in the first place. All the adverse properties and possible processes are either practically zero or non-existent. Which means the uncertainties are few and small, and come mainly from the mining operation or future human activities that we can never predict or control. The NAS recommendation for a salt host rock still stands and, in fact, has been borne out by 20 years of successful WIPP operations.

The Nuclear Waste Policy Act and its Amendments established a 0.1 cent per kilowatt-hour users fee on nuclear generated electricity to pay for the repository and associated costs, called the Nuclear Waste Fund (NWFund). The NWFund will have received about \$100 billion by the end of this century depending on how nuclear energy evolves in America.

However, recent reports from the Government Accounting Office (GAO) have shown how the projected costs for Yucca Mt, including waste preparation unique to YMP, have risen from \$80 billion to well over \$400 billion. The NWFund will certainly not cover



**Fig. 7.**

Locations of geologic salt deposits in the United States. The Delaware Basin salts (yellow) are the least tectonically deformed, are the thickest, and are at the most optimal depths for nuclear repository purposes. DOE CBFO

these expenses, and taxpayers or ratepayers would have to step in, which is highly unlikely.

On the other hand, the cost of a repository in a host rock like the Permian salt will only be about \$30 billion, easily handled by the NWFund. That's because the cost is actually a function of the choice of rock, and the science that should be determining which site is best.

No one envisioned that a political choice, like the one that selected Yucca Mountain, would have such a profound cost effect because in 1982 no one understood the many aspects and costs of a deep geologic repository. But uncertainty increases cost.

The 30-year study of Yucca Mt by all of us scientists and engineers led to an amazing understanding of how water and contaminants move through the Earth's subsurface and how we can affect that to our benefit. The \$12 billion spent on that study from the NWFund was not wasted at all, most of it is useful no matter where we put this waste.

Almost all of that information is useable elsewhere no matter what rock we pick. Our understanding of corrosion, transportation, permeability and subsurface contaminant migration, engineered barriers, shielding, packaging, waste form development and material science, among others, have been increased enormously by studying Yucca Mt.

Using science as the basis of the decision doesn't just give you reduced uncertainty, it also means getting the lowest cost. That's how science is supposed to help society.

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