Technology of the Deep Isolation Repository

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Introduction

Deep Isolation proposes that spent nuclear fuel and other high-level nuclear waste can be disposed in deep horizontal drillholes. In this document we describe the basic technology of this method, and give a brief introduction to the issues that must be addressed to satisfy safety requirements.

We expect that many readers will be familiar with nuclear issues, or with drilling methods, but few will know both. It is the surprising combination of these two technologies that makes the Deep Isolation concept attractive. We start with two key observations. First, spent nuclear fuel is amazingly compact, with a density of 10 gm/cm^3, and it will fit easily in narrow drillholes. Second: drilling technology has advanced so remarkably in the last two decades that long horizontal drillholes have become so common that there are many companies which, under contract, can drill a well to our specifications.

Disposal of radioactive waste in deep drillholes is not a new idea. For decades, the use of vertical drillholes in deep crystalline basement rock (e.g. granite) has been advocated and studied by Michael J. Driscoll, a professor of nuclear science and engineering at MIT. In 2016, his concept was further developed by the U.S. Department of Energy (DOE) under Secretary Ernest Moniz, who was a former MIT colleague of Driscoll. Moniz initiated an experimental program under the guidance of Sandia National Laboratories. The program was abruptly canceled in 2017.

The Deep Isolation approach was directly inspired by the DOE borehole program, but it differs in several important aspects. The DOE program involved purely vertical holes drilled 3 miles deep into basement rock, which is the metamorphic or igneous rock that typically underlies sedimentary formations. The waste was to be disposed in the bottom mile of the borehole, at a depth between 2 and 3 miles. In contrast, the Deep Isolation method disposes of the waste in the horizontal section of a deep drillhole, typically in sedimentary rock that overlies the basement, although any rock can be used if we determine it has been isolated from the biosphere for hundreds of thousands to millions of years. Sedimentary rock has the advantage of enormous drilling experience in the industry, and the extensive logging of drillholes around the U.S. whose records have been made public.

To quote Richard Feynman (out of context), “there is plenty of room at the bottom.” A 1 gigawatt (1000 megawatt) nuclear reactor produces, typically, 20 tons of spent nuclear fuel every year, but that waste is so dense (consisting primarily of uranium dioxide ceramic pellets) that it occupies only 2 cubic meters of volume. As another example, two horizontal drillholes would be sufficient to store all of the strontium-90 and cesium-137 defense waste that current sits in pools near the surface at the Hanford Waste Encapsulation and Storage Facility in Washington State.

Essential to the Deep Isolation approach is the technology for inexpensive but precise directional drilling. Horizontal drillholes a mile deep and two miles long are routinely drilled into sedimentary rock. In many such formations there are layers of shale that have held volatile gases for tens of millions of years. The presence of such gases provides prima facie evidence that the rock below is well isolated from the surface. Over 50,000 such horizontal holes have been drilled, although for nuclear waste, the diameter of the horizontal holes must be expanded from the typical value of 9 inches to a wider 18 inches. The basic design is shown in Figure 1.

The drillhole is lined with a casing, a continuous pipe made of carbon steel, consisting typically of 30-foot sections screwed together.

In the United States, there are currently about 80,000 tons of nuclear waste from commercial nuclear power plants at the power plants themselves. There has not yet been any *disposal* of spent nuclear fuel. It is currently stored at or near the surface at over 80 locations around the U.S. This is called “interim” storage, and is not meant (nor licensed) to be permanent. About 2/3 of this waste is currently in cooling pools, and about 1/3 has been transferred to “dry cask” storage in which continued cooling is by gas flow rather than by water. In the coming years, until a permanent disposal facility is available, the remaining fuel in pools will gradually be moved to dry casks, usually at the same location, or possibly at a “consolidated interim storage facility”. Sites for consolidated (but still temporary) storage have been proposed in New Mexico and Texas. Currently, about a third of the U.S. population lives within 50 miles of an interim storage facility, mostly in the eastern U.S.

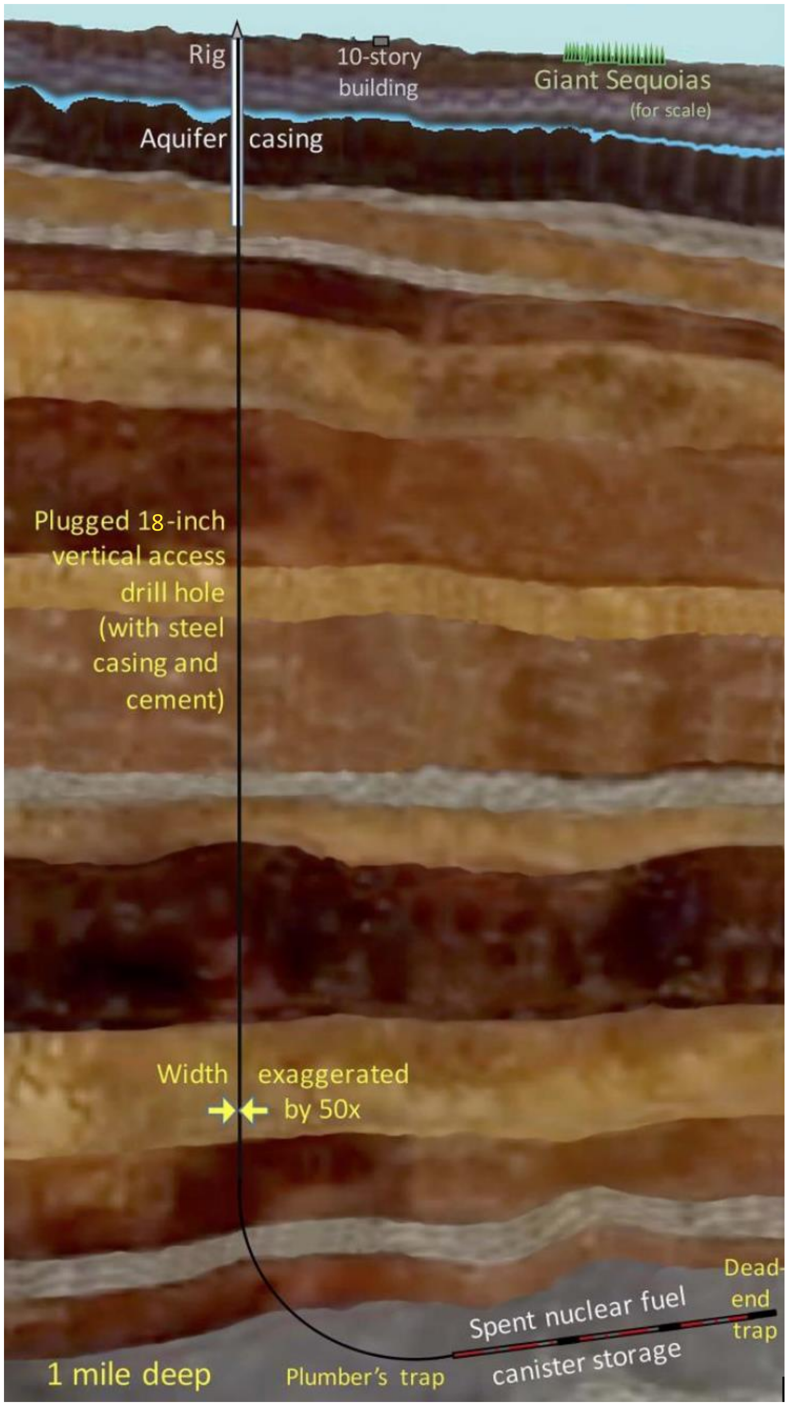

Figure 1. Deep Isolation Repository Baseline Design
This diagram shows a relatively short horizontal section; in practice, it could be 1 to 3 km long.

For this commercial spent nuclear fuel, the Deep Isolation disposal method takes the unmodified fuel assemblies, with no reprocessing or repackaging, and places them in canisters made of a corrosion resistant alloy. Excess space inside the canister is filled with a sand-like material to provide additional safety against damage from shaking and impact. The canister is brought to the drilling rig surrounded by a concrete radiation shield for protection of surface workers. It is lowered (out of the shield) into the vertical access borehole. Starting at the *kickoff* depth, the hole gradually curves to a nearly horizontal direction. The drillholes are sufficiently wide and the curved section is sufficiently gradual (e.g. 8° turn per 100 feet) that no bending moment is ever applied to the canisters. The horizontal part of the hole, which might be 1 to 3 kilometers long and 18 inches in diameter, is the disposal section. The canisters are placed end-to-end. When the horizontal section is full, and all performance confirmation tests complete, the vertical hole is sealed with rock and bentonite.

In the United States, there are about 250,000 such assemblies currently holding spent nuclear fuel. These assemblies have diameters of 8 inches (for boiling water reactors) to 12 inches (for pressurized water reactors), and length typically 14 feet. Placing these assemblies end-to-end amounts to 600 miles. They could fit in fewer than 400 horizontal drillholes, each about 2 miles long. The spent fuel for a gigawatt reactor for a 50 year lifetime would require three such drillholes.

The Department of Energy also has about 2000 capsules holding concentrated strontium-90 and cesium-137 from the national defense program. This waste is even more radioactive than are the commercial fuel assemblies. The capsule is under 3.5-inches in diameter, and less than 2-feet in length. They could all be disposed in less than a mile of a single horizontal drillhole.

Modular Disposal: NIMBY and NoTAMS

A horizontal drillhole disposal facility could be consolidated at a single location, or it could be modular, with smaller facilities placed at or near the current interim sites. A natural concern is that local residents would object to permanent storage in their states. Deep Isolation commissioned the firm GfK to survey people living in 23 states that have interim storage facilities. The results were remarkable: 82% would prefer to have the waste buried deep underground at or near the existing interim storage site, rather than have it transported out of their state across local roads. Although we at Deep Isolation believe that transportation can and is being done safely, it is evident that the public does not. The NIMBY acronym, “Not In My Backyard”, is contradicted here. Perhaps the operating acronym should be NoTAMS: No Transportation Across My State.

In part because of these survey results, the Deep Isolation concept is currently focusing on modular local rather than consolidated disposal. We would expect to put our first Deep Isolation repositories at locations that have suitable geology for safe disposal at or near the current surface interim facilities. Many nuclear reactor plants which have interim storage on-site have suitable geology directly beneath, and no transportation beyond their current fences would be necessary.

Our original concept was to place it in or under clay-rich shale formations which contain natural gas and yet are unsuitable for hydraulic fracturing. Gas in these formations was generated millions of years ago, and its retention provides evidence that the formations below are highly isolated from the surface. But any geologic formation that has evidence of similar isolation is a good location.

Yucca Mountain Repository

Most people in the nuclear waste industry are familiar with the partially-built Yucca Mountain repository, so it is worthwhile pointing out the difference between that approach and the one proposed by Deep Isolation.

The Yucca Mountain repository is planned to have about 7 miles of tunnels, typically 17 to 25 feet in diameter, about 1000 feet below the surface. The tunnels will be in the "unsaturated zone" meaning that the pores of the rock at and above the formation are not completely filled with water but contain air. The repository is sited above an existing aquifer. Because of the presence of air, the environment is oxidizing; this is important for the chemistry of certain radioisotopes that were produced by fission. For example, in an oxygenated environment C-14 forms the gas CO_2, and Tc-99 forms TcO_4, a soluble compound. The unsaturated rock could be a leakage path for gases. The rock "breathes" as outside atmospheric pressure changes. Another leakage path comes from rainwater percolating down through the fractured rock and dripping into the waste emplacement drifts. If the water breaches the containment canisters, it could dissolve chemicals such as TcO_4 and carry them to the aquifer below. The groundwater in the aquifer might then, in turn, transport these radioisotopes to a drinking-water well or directly to the surface. Much of the effort on the Yucca Mountain facility has been to develop sufficient engineered barriers, including titanium drip shields, to assure that this will not happen.

Deep Isolation locations will be deeper, typically between 2,000 and 8,000 feet. They will be in the saturated zone, which means that the rock pores are filled with brine. Gas transport, through diffusion or a breathing mode, will be suppressed. The horizontal disposal section will be in a reducing environment. This helps to suppress corrosion of the engineered barriers, and suppress the formation of some of the chemical compounds that dissolve readily in water. The primary leakage to the surface, assuming that the engineered barrier of the canister fails, would be from dissolution of radioisotopes in the deep brine and transport to the surface from flow of that brine. A key to assure that the waste will not harm human health or the environment is the determination of the isolation of the deep brine from potable aquifers.

Surrounding both the tunnels of Yucca Mountain and the drillholes of Deep Isolation, there is a region of *disturbed* rock. This is rock that has been cracked or otherwise affected by the excavation process, and may be affected by the heat generated by the spent nuclear fuel. The disturbed zone typically extends beyond the walls to about one hole radius. For Yucca Mountain, this is about 10 feet although it can be more; for Deep Isolation, it is about 9 inches. In Yucca Mountain, the tunnels are filled with air; in Deep Isolation, brine from the rock quickly fills the region between the rock and the casing. The space between the casing and the canisters can be filled with de-oxygenated water, brine, or mud. The water throughout the drillhole water will be at hydrostatic pressure at that depth, 1 atmosphere for every 30 feet of depth, or about 100 atmospheres for a drillhole that is 3000 feet deep. The water near the tunnel in Yucca Mountain, in contrast, has the pressure of the air, about one atmosphere.

When the fuel is emplaced, the temperature in the rock initially rises and then decreases as the short-lived radioisotopes decay and heat is conducted away. For Yucca Mountain, the temperature rises high enough to boil any water in the tunnels and to dry out nearby rock. In contrast, the water in a Deep Isolation repository does not boil because of the high pressure at depth.

For both repositories, elevated temperatures in the rock create thermal stresses and lead to differences in water density which may induce fluid flow. Temperature changes also affect reaction kinetics and the chemical composition of the water, and may lead to dissolution and precipitation of minerals that affect corrosion rates. We are currently analyzing these phenomena for the Deep Isolation drillhole.

The fact that our storage sections will be in a reducing environment enables us to obtain extremely long expected lifetimes for the canisters. An investigation of this issue by Dr. Joe Payer (Chief Scientist of National Center for Education and Research on Corrosion and Materials Performance) will be published separately; preliminary estimates are that a 1-cm-thick canister made of the proper corrosion resistant alloy will take 50,000 years to corrode half-way through.

The proposed Yucca Mountain repository is currently limited, by statute, to dispose of no more than 63,000 tons of commercial spent nuclear fuel; as mentioned earlier the United States already has nearly 80,000 tons sitting in interim storage. Moreover, the amount of this waste is growing by about 2,000 tons each year. To provide for the extra spent nuclear fuel (above 63,000 tons), federal laws need be passed, either to allow for the expansion of Yucca Mountain, or to build a second repository (such as Deep Isolation) or to do both. The Nuclear Waste Policy Act, currently in force, does not allow a second repository until the Yucca Mountain facility is completed. There is no similar restriction for the disposal of defense waste, such as the Cs/Sr capsules currently stored at Hanford.

Leakage Paths

As mentioned above, the main mechanism by which radioactive isotopes may migrate from the repository to freshwater aquifers in the near surface (usually less than 500 ft from the surface) or the biosphere is the transport of dissolved radioisotopes by advection or diffusion in pore water. A hydrogeological characterization of the host rock and overlying formations and cap rocks will determine the properties of the heterogeneous rock, specifically its ability to transmit water in response to local and regional pressure gradients. Shale formations are characterized by very low hydraulic permeabilities, preventing deepwater flow or reducing it to very small velocities. Flow most likely occurs in networks of small or medium-sized fractures and potentially larger geologic features, such as contacts between hydrostratigraphic layers, faults, and other discontinuities. Should radionuclides escape the near-field of the repository and migrate along such features, they are likely retarded by adsorption onto mineral surfaces and diffusion into stagnant pore water in the surrounding rock matrix. In our reducing environment such transport is going to be significantly different than it would be in the unsaturated oxygenated environment of Yucca Mountain.

As mentioned above, the main mechanism by which radioactive isotopes may migrate from the repository to freshwater aquifers in the near surface (usually less than 500 ft from the surface) or the biosphere is the transport of dissolved radioisotopes by advection or diffusion in pore brines. A hydrological characterization of the host rock and overlying formations will determine the properties of the rock, specifically its ability to transmit the brines in response to local and regional pressure gradients. Shale formations are characterized by very low hydraulic permeabilities, preventing brine flow or reducing it to very small velocities. Flow most likely occurs in networks of small or medium-sized fractures and potentially larger geologic features, such as contacts between hydrostratigraphic layers, faults, and other discontinuities. Should radionuclides escape the near-field of the repository and migrate along such features, they are likely retarded by adsorption onto mineral surfaces and diffusion into stagnant pore water in the surrounding rock matrix. In our reducing environment such transport is going to be significantly different than it would be in the unsaturated oxygenated environment of Yucca Mountain.

The driving forces behind advective groundwater flow are mainly pressure gradients, which are controlled by the rock properties and regional hydrological conditions, including topography, recharge rates, as well as upflow and convection of hydrothermal fluids. Some of these boundary conditions may change as a result of natural or human-induced climate change impacts. Pressure gradients may develop locally due to differences in fluid densities caused by changes in temperature, salinity, or corrosion-gas generation. Finally, rocks with high clay content may exhibit osmotic effects.

There is also the possibility of failure of the plugging of the vertical access hole. Following ideas developed at the Sandia National Laboratories, we expect to begin the sealing of this hole by removing the casing, and then filling the hole will rock, gravel, and where appropriate, bentonite. Where the hole passes through shale or salt layers, we can fill it with similar materials; both clay-rich rocks and salt creep to fill small cracks and spaces, which helps make a good seal.

A small upward tilt to the horizontal disposal section might have some benefit, and we are studying this concept. The distant “dead-end” of the hole would be at a slightly shallower depth. This geometry could help isolate the sealed vertical access hole from the storage region, at least for light materials that tend to rise within the disturbed zone. We are currently performing computer simulations to see if this tilt, or some alternative (e.g. a repeated up and down undulation) has value.

Given the overall low permeability of the host rock, molecular diffusion of dissolved radionuclides is expected to be the dominant transport mechanism, albeit with very slow migration rates. Diffusion is driven by concentration gradients, which decrease substantially at even short distances from the disposal drillhole. The small porosity and tortuosity of the pore space considerably reduce the effective diffusivity compared to that in free water. Diffusing radionuclides reach very low concentrations after short distances as they are diluted and spread over a radially increasing volume of pore water.

Initial calculations lead us to believe that the assessments comprising the safety case will likely demonstrate that all of these features and effects have either very low occurrence probabilities or low consequences, or that they do not compromise the safety of the repository even when making conservative assumptions and accounting for inherent and irreducible uncertainties. The Deep Isolation disposal concept takes advantage of geological formations with very high barrier performance, integrated into a robust multi-engineered barrier waste disposal system.

Spent Nuclear Fuel (SNF)

Although the waste from a commercial nuclear reactor could be repackaged or even reprocessed, the Deep Isolation concept allows waste to be kept in the same fuel assemblies that hold it in the nuclear reactor. There is no need to reprocess the waste, or to reconfigure the fuel rods. The fuel assembly is shown in the center of Fig. 2; the individual pellets are shown on the right side. As we mentioned earlier, the spent nuclear fuel consists of small, hard and dense (10 g/cm^3) pellets, made primarily of uranium dioxide.

For a boiling water reactor, the diagonal width of the fuel assembly is typically under 8 inches; the diagonal in Figure 2 is 7.24 inches. For pressurized water reactors, a typical diagonal is 11.9 inches. These assemblies can be placed in canisters that will fit in standard casings with 13-inch inner diameters. The canister walls will be about 0.4 inches (1 cm) thick, resulting in a canister diameter of 9 to 14 inches. The handling required includes removal of the individual assemblies from the cooling pools or from the dry casks, placement in the canisters, sealing of the canisters, transport to the drill rig location, and then lowering of the canister into the drillhole.

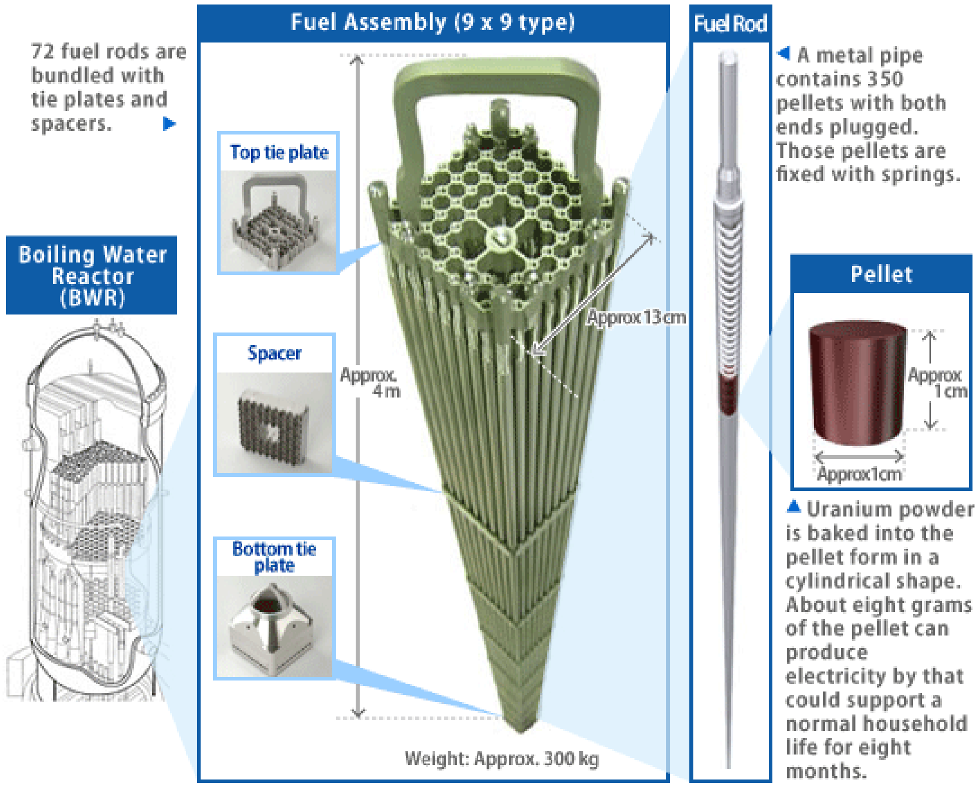

Figure 2. Spent nuclear fuel
(diagram from Westinghouse)

The Deep Isolation approach can be used for disposal of commercial spent nuclear fuel, or for key components of the defense waste currently stored by the Department of Energy. This includes the separated and concentrated Cs-137 (in the form of CsCl solid) and Sr-90 (in the form of SrF_2 powder). The capsules currently holding this waste are double and triple walled containers, less than 3.5 inches in diameter, less than 2 feet long, and weighing 6 to 9 kg. These capsules will be placed within Deep Isolation canisters.

For spent nuclear fuel, the uranium dioxide pellets contain unburned U-238 (about 96% of the pellet), unburned U-235 (less than 1%), fission products (e.g. H-3, Sr-90, Cs-137, I-129, Tc-99) and transuranic elements created in the reactor from neutron absorption (e.g. Pu-239, Pu-240, Am-241, Np-237, typically about 1%), and other elements created by the decays of the parent radionuclides. The fission fragments (about 3% by mass) are responsible for the high intensity of the initial radioactivity over the first few centuries, and the transuranics are responsible for much of the long-lived radioactivity.

In nuclear reactor operations, each fuel assembly is handled as a unit. It may spend 3 to 5 years in a reactor, at which time it is replaced with an assembly containing fresh fuel. To do the removal, the reactor is typically shut down, the lid of the reactor removed, and one fuel assembly at a time is moved to a cooling pool, and then lowered into water. Even though the chain reaction has stopped, the initial heat production of the fuel assembly is almost 7% of that when the reactor was operating. As the short-lived radioisotopes decay, so does the rate of heat production. After ten minutes it has decayed from 7% to 2% of the operating power, and after a day to about 0.5%.

The Deep Isolation Directional Drillhole Configuration

Here we describe, once again but with more detail, a Deep Isolation repository drillhole configuration with typical parameters. (Refer again to Figure 1.) After several thousand feet of drilling, when the bit reaches the kickoff depth, the bit takes a gradually curving path, ultimately reaching a near-horizontal direction. It then can continue for a long distance; there are tens of thousands of horizontal drillholes in oil and gas fields that extend 2 miles or longer. This near-horizontal section is the location for the canister storage and disposal. The horizontal section of the drillhole could have a diameter of 8 inches for Cs/Sr waste, or 18-inches for spent nuclear fuel.

A continuous pipe called a casing is inserted into the length of the hole. This casing consists of 30-foot segments typically of carbon steel that are screwed together at the rig and then lowered into the hole. In the reducing environment of the Deep Isolation drillhole, the casing should provide an engineered barrier for several hundred years. The canister itself is made from a corrosion resistant alloy that is expected to last 50,000 years or longer in the hole environment. The curved part of the hole typically has a radius of 700 feet, so even a 1⁄2-inch thick steel casing bends easily around the curve. The corrosion resistant canisters with the nuclear waste are then lowered into the casing and pushed (using a wireline tractor, coiled tubing, or drill pipe) along the horizontal section, and then released.

The inner diameter of the casing is chosen to allow the canisters to move around the curved section freely, with no bending stress put on the canister. For a typical hole curvature, 8° per 100 feet, an inch of clearance is more than sufficient.

The vertical section of the hole will typically have a larger diameter. The largest casing at the top is called the conductor casing and is followed by the surface casing, both of which are cemented into place to provide two levels of isolation from freshwater aquifers. Its larger diameter allows the upper casing to be in place before the lower casing is installed through it.

In typical shale gas/oil operations, the space between the casing and rock is cemented, in part for stability when it conveys moving fluids, but primarily to separate different “stages” in which high pressure water is injected to fracture the rock. We have no need for fracking, and there will be no rapidly flowing material through the casing, so we might omit the cementing stage.

In Figure 1, the nominally horizontal repository section has a slight upward tilt, 1° to 3°, as it stretches away from the vertical access drillhole. This tilt could provide an additional isolation from the vertical hole; any leakage mechanism that transports radioisotopes in an upward direction (e.g. gas flow through the brine in the casing) would move towards the dead end of the storage section.

The horizontal drillhole concept might seem unique and technically challenging, but in fact it has become standard in the shale gas/oil drilling industry. This is illustrated in Figure 3, which is a map of well locations in part of North Dakota. Each dot represents a well, and each line emanating from a dot represents a horizontal drillhole, typically one to two miles deep and two miles long. The lines are mostly parallel because fracking is typically done perpendicular to the direction of maximum stress in the rock.

There are over 50,000 such drillholes in the US. They have become a commodity, and most oil and gas companies hire specialized companies to drill the holes. Deep Isolation would not use existing drillholes but rather custom ones. There is no significant advantage using holes that have been fracked; the cost of drilling is not high, and drilling allows us to place them where we want.

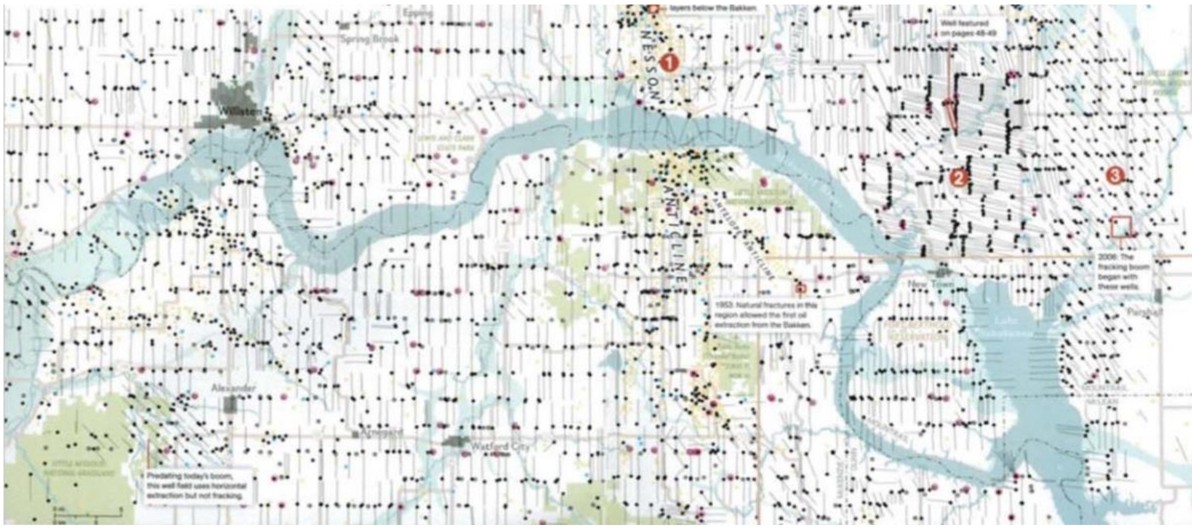

Figure 3: A Map of Horizontal Drillholes in North Dakota

There is an important qualification, however. The horizontal sections of these existing drillholes are typically 8 inches in diameter, too small to accommodate commercial fuel canisters, although adequate for the canisters that hold the 3.5-inch capsules of the Hanford Cs/Sr waste. We have been in discussions with several drilling companies, and they have assured us that larger horizontal holes do not present any substantial difficulty. They are used routinely for horizontal wells in deep water drilling but are not needed for shale gas and oil recovery.

The Radioactivity of Spent Nuclear Fuel

The fresh fuel inserted into a nuclear reactor is radioactive, primarily from the U-238 and U-235 it contains. But these have exceptionally long half-lives, 4.5 and 0.7 billion years respectively, so the radioactivity (decays per second) is low, and the fuel rods are relatively easy to handle. Once in the reactor, the situation changes. When uranium fissions, it splits into two or more fission fragments, and these are typically very radioactive due to their much shorter half-lives.

After a few years, the most problematical of the remaining fission fragments are strontium-90 (Sr-90) and cesium-137 (Cs-137), both with half-lives of about 30 years. Two other important fission fragments that challenge nuclear waste disposal methods are Tc-99 (half-life of 210,000 years) and I-129 (half-life of 16 million years). These radioisotopes endure long enough that even very slow processes that bring them to the surface must be considered.

A third source of radioactivity is in the production of new isotopes when materials in the reactor are exposed to the high neutron flux that makes the reactors operate. The most troublesome of these are the transuranics, elements heavier than uranium. These include Pu-239, a result of neutron bombardment of uranium. Pu-239 is also fissionable, and in defense reactors is chemically separated for use in nuclear weapons.

These processes make for a complex mix. Remarkably, the radioisotopes with very short half-lives cause little long-term concern because they go away so quickly. Similarly, the isotopes with very long half-lives, such as U-238, decay so slowly that they pose minimum danger. It is the intermediate half-lives that present the challenges.

An example of the radioactive components of spent nuclear fuel for a typical reactor is shown in Table 1. There will be differences for different reactors that depend on initial enrichment, amount of burnup, age of the waste, and other factors. But the table offers an illustrative example. Columns 5 through 13 show the change in the radioactivity for each radioisotope vs time.

This table contains far too much information to allow a full discussion here; besides, it is only representative, and a specific chart needs be created for each set of spent nuclear fuel. But a discussion of some of the salient features is worthwhile, and several rows and columns have been darkened to draw attention. The columns for 10,000 and for 1,000,000 years indicate the containment time required by two key federal regulations: 10CFR60 (the original NRC regulation for nuclear waste) and 10CFR63 (regulations for the Yucca Mountain repository).

In a disposal repository, nuclear waste is confined by both engineered barriers (pellets, cladding, canisters, casks, casing) and by geologic barriers. The engineered barriers might have a lifetime of hundreds to tens of thousands of years, but ultimately, we depend on the geologic barriers for the very long term. Some radioactive components are gaseous, some are solid, some dissolve in water. Ordinary diffusion of solids through rock is very slow. The greatest danger of radioactive material reaching the biosphere is through fast-paths.

At Yucca Mountain, one such fast path has following scenario. Assume engineered barrier failure, possibly through unexpectedly high corrosion of the titanium drip shields, canisters, and casks. Then rainwater dripping onto the exposed fuel pellets dissolves Tc-99 and I-129, and carries it to the aquifers below and to drinking water supplies within a few thousand years. That is a scenario that has received a great deal of attention.

For Deep Isolation, a possible fast path might arise from the following scenario. We assume that the canister corrosion was much faster than anticipated, so that the fuel pellets are sitting in brine within the horizontal disposal section. Next, postulate the sudden breaking of a previously unknown “major water-conductivity fault”, a fault that creates a fast path for brine to near-surface aquifers. This could allow radioisotopes in the brine to come up; particularly of concern would be dissolved Cl-36 and I-129.

Isotope	half-life (years)	initial Curies/ton	initial Curies/m BWR	Later Ci/m (values < 0.001 set to blank) years 30	100	300	1,000	3,000	10CFR60 10,000	50,000	100,000	200,000	10CFR63 1,000,000
H-3	12.30	574	57	10.6	0.20								
C-14	5730.000	4.800	0.480	0.478	0.474	0.463	0.425	0.334	0.143				
Cl-36	310000.000	0.011	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
Se-79	327,000	0.064	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.004	0.001
Kr-85	10.73	11,100	1,110	160	1.7								
Sr-89	0.14	1,060,000	106,000										
Sr-90	29.000	84300.000	8430.000	4115.449	772.313	6.482							
Y-90	0.007	88,500	8,850										
Y-91	0.16	1,260,000	126,000										
Zr-95	0.18	1,640,000	164,000										
Nb-95	0.01	1,560,000	156,000										
Mo-99	0.01	1,880,000	188,000										
Tc-99m	0.0007	1,620,000	162,000										
Tc-99	210000.000	14.400	1.440	1.440	1.440	1.439	1.435	1.426	1.393	1.221	1.035	0.744	0.053
Ru-103	0.11	1,560,000	156,000										
Ru-106	1.01	494,000	49,400										
Rh-103m	0.0001	1,560,000	156,000										
Ag-111	0.02	53,800	5,380										
Cd-115m	0.12	1,480	148										
Sn-125	0.026	10,800	1,080.00										
Sn-126	100,000	5	0.48	0.480	0.480	0.479	0.477	0.470	0.448	0.339	0.240	0.120	
Sb-124	0.16	415	42										
Sb-125	2.73	9,930	993	0.49									
Te-125m	0.16	1,980	198										
Te-127m	0.30	13,800	1,380										
Te-127	0.0011	99,200	9,920										
Te-129m	0.092	85,100	8,510										
Te-129	0.0001	321,000	32,100										
Te-132	0.009	1,490,000	149,000										
I-129	15,900,000	0.032	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
I-131	0.022	1,030,000	103,000										
I-132	0.0003	1,510,000	151,000										
Xe-133	0.014	2,100,000	210,000										
Cs-134	2.06	272,000	27,200	1.124									
Cs-135	2,300,000	1.440	0.144	0.144	0.144	0.144	0.144	0.144	0.144	0.142	0.140	0.136	0.107
Cs-136	0.036	69,600	6,960										
Cs-137	30.100	112000.000	11200.000	5612.911	1119.743	11.192							
Ba-140	0.035	1,950,000	195,000										
La-140	0.0046	2,020,000	202,000										
Ce-141	0.089	1,780,000	178,000										
Ce-144	0.78	1,230,000	123,000										
Pr-143	0.037	1,660,000	166,000										
Nd-147	0.030	790,000	79,000										
Pm-147	2.62	103,000	10,300	3.7									
Pm-149	0.006	392,000	39,200										
Sm-151	93	866	87	69	41	9.3	0.05						
Eu-152	13.4	7.84	0.78	0.17	0.004								
Eu-155	4.80	2,540	254	3.3									
Tb-160	0.20	1,420	142										
Ra-226	1602.000	129600.000	12960.000	12792.863	12411.210	11382.361	8408.067	3538.983	171				
Ra-228	2.7		0.54										
Ac-227	21.6	10.8	1.08										
Np-237	2,140,000	0.032	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.002
Th-229	7,340	from Pu and Am						0.003	0.005	0.010	0.032	0.031	0.030
Th-230	80,000	from U and Pu					0.001	0.007	0.029	0.644	0.966	1.063	0.966
U-232	68.9	0.011	0.001										
U-233	159,200	32	3.22	3.2									
U-234	245,500	3	0.32	0.3	0.3	0.3	0.3	0.3	0.313	0.280	0.2	0.2	0.019
U-235	703,800,000	336	34	33.6	33.6	33.6	33.6	33.6	33.600	33.598	33.6	33.6	33.567
U-236	23,480,000	48	4.8	4.8	4.8	4.8	4.8	4.8	4.799	4.793	4.8	4.8	4.660
U-238	4,468,000,000	0.011	0.001										
Pu-238	87.8	2,900	290	229	132	27	0.11						
Pu-239	24400.000	325.000	32.500	32.472	32.408	32.224	31.590	29.845	24.463	7.853	1.897	0.111	
Pu-240	6,540	484	48	48	48	47	44	35	17	0.242	0.001		
Pu-241	15	110,000	11,000	2750	108	0.01							
Pu-242	24,110	0											
Am-241	433	80.2	8	7.6	6.8	5.0	1.6	0.07					
Am-243	7,370	0.89	0.09	0.1	0.1	0.1	0.1	0.07	0.035	0.001			
Cm-242	0.45	36,700	3,670										
Cm-244	0.049	2,770	277										

Table 1. Spent Nuclear Fuel Radioisotope Inventory, from a typical nuclear reactor. The column showing curies per meter shows the radioactivity if the fuel assemblies from a boiling water reactor are laid end-to-end in a horizontal drillhole.

We can't rule out such a scenario, and it must be analyzed in a license application. Such analysis would include the likelihood of the rapid corrosion of our canisters, the

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probability of such a fault intersecting the disposal section, and estimates of the probability that brine would rise up the fault.

One of the important scenarios analyzed by Sandia for their vertical borehole program is flow along the excavation disturbed zone and the access borehole.
The geometry is significantly different for Deep Isolation, since the disturbed zone is horizontal. We are currently analyzing this issue for our configuration using the TOUGH2 code. This analysis could also help elucidate whether the small tilt away from vertical in the disposal section is beneficial. We are also considering other geometries, such as an undulating disposal region, with small upward and downward changes to the path along the nominally horizontal section.

Another scenario for Deep Isolation is the presence of an underground brine flow path that intersects the repository. Oil and gas companies have assured us that the brine at depths of several thousand feet "does not flow" but that only means is that any such flow is too slow to notice over a period up to several decades.

Note that the heavy elements that dominate the lower right of the table, the actinides of uranium, plutonium, actinium, americium, etc., are highly immobile in rock unless dissolved in water; they are also highly insoluble, except in the form of certain compounds. In our reducing environment, the usual culprits (oxides) are suppressed. We are studying the chemistry of the reducing environment to see what compounds could cause problems.

In the table, we have left blank all entries below 0.001 curies per meter. This was done because at such levels, the geometric spreading of these radioscopes dilutes them to a non-dangerous concentration. That does not mean that a fast path could not cause a problem, but it helps draw attention to the key radioisotopes of concern.

Note that some radioisotopes *increase* their concentration in the spent nuclear fuel as time passes, due to their production from the decay of heavier elements. This effect leads to a subtlety. To help illustrate this subtlety, consider Ra-226. Despite its half-life of 1602 years, its concentration in the fuel pellets remains high for over a million years; that's because although it decays, it is continually produced by decay of heavier actinides. But once it is produced, it is still located in the spent fuel. It has only 1602 years to reach the surface, not a million years, before half is decayed. If it takes 32,000 years—i.e. 20 half-lives—then less than one millionth of it reaches the surface. So it is the 1602 year value that is relevant, not the million-year one. Perhaps of greater concern is the possible fast path for this isotope. That doesn't mean there is no fast path for Ra-226, but it only points out that even radioisotopes that persist for a million years don't have a million years to reach the surface. The Ra-226 does have a role in producing other daughter radioisotopes, and they need to be studied separately. (Any Ra-226 that does move away from the disposal drillhole will initiate a daughter that then has a shorter distance to travel.) Other charts of isotopic decay in spent fuel often show the radium persisting beyond a million years, and it does, but that doesn't mean it has such a long time to make it to the surface.

Isolation of Deep Brines from Shallow Aquifers

There are many ways in isotope geochemistry to estimate the isolation of deep brines. Among the most important are measurements of C-14, Cl-36, and I-129. These are radioactive isotopes that are continuously produced by cosmic rays in the atmosphere, and that mix with surface water. Measurement of their presence in deep brines gives an estimate of the time that it took for that water to carry the radioisotopes downward. That time will generally be longer than the water travel time, because the radioisotopes are slowed by interaction with the surrounding rock, but they give a useful indication nevertheless.

The method for measuring concentrations of these isotopes is now highly developed and can be done with no more than a liter of sampled water. The technology is called "AMS", which stands for "accelerator mass spectrometry." [Note: the cofounder of Deep Isolation, Dr. Richard Muller, was the first person to suggest accelerators be used for radioisotopes, and the first to make a successful measurement and age determination using the technique.] The fact that this approach is well-developed does not mean it is easy. Extreme care must be taken with the samples to make sure that they are kept pristine. Small amounts of Cl-36 contamination in the laboratory can yield highly inaccurate and misleading results.

One also must take into account the "bomb pulse" effect. The C-14, Cl-36 and I-129 levels in the atmosphere increased dramatically when nuclear bombs were exploded above ground in the 1950s and early 1960s. At Yucca Mountain, this pulse was initially thought to have been observed in percolation water entering the tunnels, and led to a concern that the pathway for water from the surface took much less time than had been expected. However, those measurements are now in doubt; it is possible that the water samples may have been contaminated by extraneous Cl-36 in the laboratory.

We propose that any potential location for a Deep Isolation repository have its deep brines tested for the levels of C-14, Cl-36, and I-129. Any site that shows high levels (i.e. above the levels expected from production in the local rock formations) may have had recent contact with the biosphere. Of course, low levels don't prove that there is no fast path due to water flow upward, only that there is none downward, or that the fast-flow path carries small amounts of water that gets diluted by the time it reaches the measurement point. And other fast paths might exist that don't involve water. Nevertheless, the method is a useful indicator of recent mixing of surface water with the deep brines.

Decay Heat

The radiation from the spent nuclear fuel is converted to heat in the fuel pellets, the canisters, the casing and the rock. This heat production, initially about 11 kW per ton of spent nuclear fuel, decreases with time as the radionuclides decay, as shown in Figure 4. (The decay heat for Cs/Sr capsules is typically 15 to 18 kW per ton.)

The result is that the temperature of the canister and the rock around it rises and then, as the radioactivity drops and as the rock continues to conduct heat away, the temperature drops. A simulation done by Stefan Finsterle using the TOUGH2 code for a boiling water reactor fuel assembly is shown in Figure 5. (Dr. Finsterle was the main developer of the key iTOUGH2 simulation-optimization framework and is the co-developer of the TOUGH suite of nonisothermal multiphase flow and transport codes used by the U.S. government and others to analyze underground flow.)

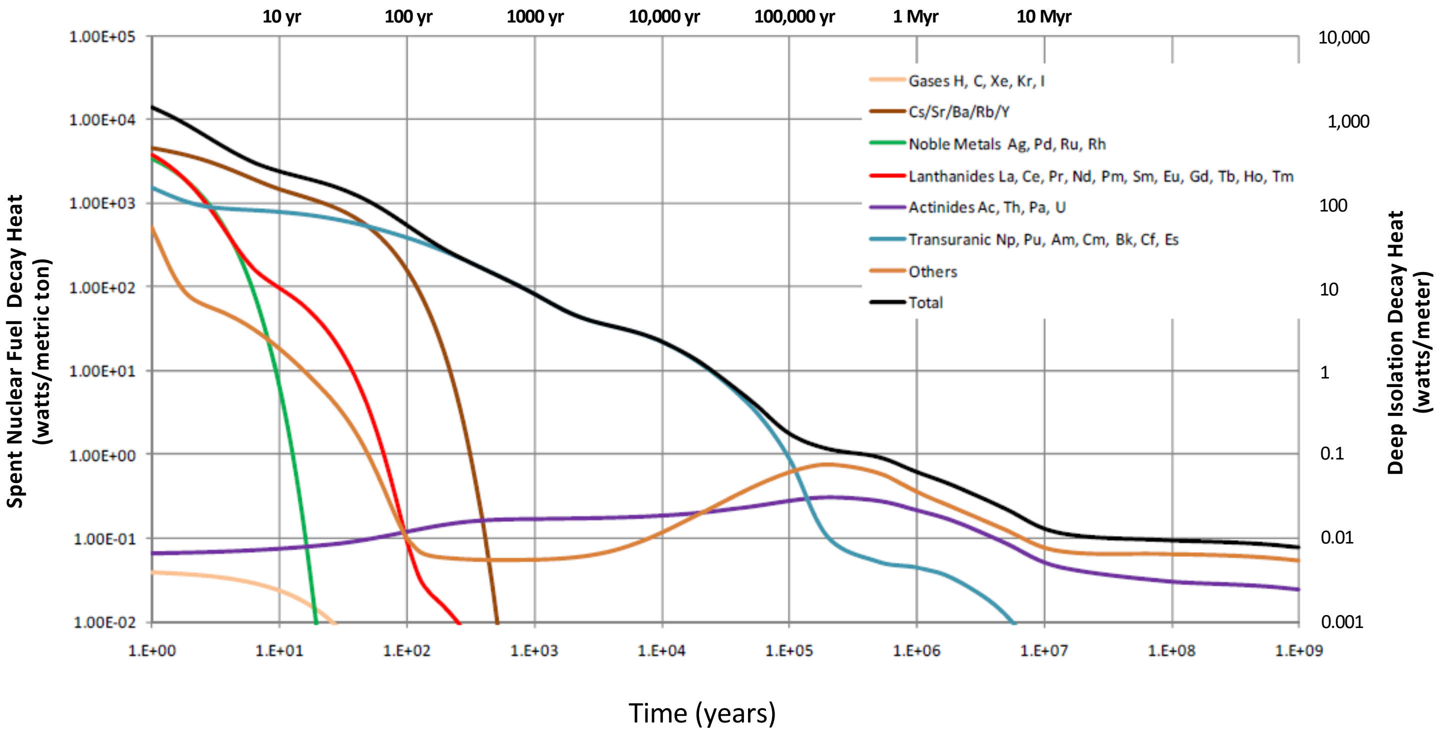

Figure 4. Heat vs time from spent nuclear fuel. The left scale shows the heat generated per metric ton; the right scale shows the heat generated per meter for the proposed Deep Isolation canisters. (Adapted from Sandia report FCRD-UFD-2012-000146 SAND2013-0974P, with the right and upper scales added.)

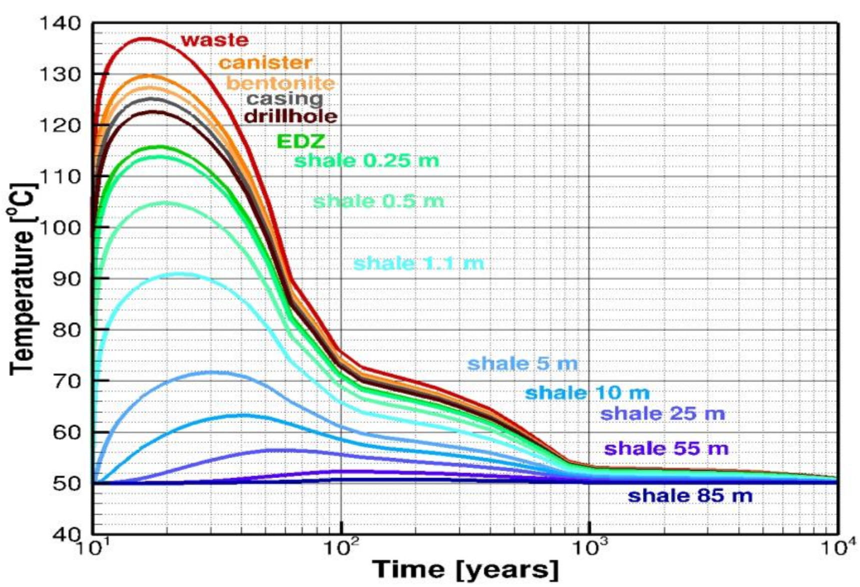

Figure 5. Temperature vs time in a Deep Isolation disposal drillhole. The calculation was done by Stefan Finsterle using the TOUGH2 code. It assumes BWR fuel assemblies in a nearly horizontal hole drilled in shale. (The details of this calculation will be submitted for publication.)

As Figure 5 shows, the maximum temperature rise in the waste and the canister is about 85°C above the ambient (assumed to be 50°C for a repository at 5000 ft depth). Although the temperature, 135°C, is above the boiling point of water at atmospheric pressure, it is well below the boiling point for a depth of 5,000 ft., which is about 350°C. (The ambient water pressure at this depth is given by the water load, not the rock load, and is about 170 atm.)

The maximum temperature on the canister is about 135°C, reached about 15 years after the waste is emplaced. This temperature is low enough that the corrosion resistant alloys would maintain their key corrosion properties and strength. Note that the temperature in the distant shale (in the diagram taken to be 85 meters away) peaks at about 140 years, with an insignificant temperature rise.

Engineered Barriers and Corrosion Resistance

The metal canister is an effective barrier to radionuclide transport until there has been a through-wall perforation. To delay perforation from corrosion, the canisters are made of nickel-chromium-molybdenum alloys which have remarkable stability in the expected hot, high radiation, reducing, chloride environments we will encounter in our disposal sections. Depending on the location, the rock brines can have multiple dissolved species and concentrations.

With modern corrosion resistant alloys, particularly alloy 625, laboratory measurements show that the rate of corrosion can be kept below 0.1-micron per year. Thus a 1-cm canister will provide a barrier for 50,000 years (assuming failure when the corrosion reaches 0.5 cm), even in the raised temperature environment of the underground repository. The details of this design, and its properties in the deep brine, have been carried out by Joe Payer, and have been submitted for publication in a refereed journal.

These casings, made of carbon steel, don't last as long, but they should provide a reliable and relatively smooth channel for the placement of waste canisters and for retrieval for the currently required 50 year period. In addition, in the reducing brine environment, we estimate that they will provide an engineered barrier for several hundred years.

Reducing Environment

In the event the canister is breached, and the spent fuel is exposed to the brine which saturates the host rock, all constituents of the spent fuel are likely to react with the brine and form new compounds of varying solubility. The subsequent migration of dissolved radionuclides is dependent on their chemistry, that of the formation host rock, the dissolved constituents in the brine, the ambient temperature, and on advective transport and diffusion.

In the broadest sense, the chemical factors that determine the extent of radionuclide migration can be divided into two parts:

1. Those that immobilize the radionuclide in stationary phases, inhibiting migration through (a) precipitation of minerals where the radionuclide is an "essential" component, i.e., it is an essential part of the mineral composition, (b) co-precipitation with an essential naturally occurring element with similar chemical properties in solid solution in a mineral, and (c) adsorption on host rock mineral surfaces, or ion exchange with existing minerals, especially clay minerals. All three processes can operate concurrently, but some are much slower or less important than others. The valence state of several radionuclides can differ depending on the ambient oxidation state, and in those cases, their chemical properties and ability to migrate can be substantially affected.

2. Those due to complexing with dissolved constituents in the brine, which could enhance migration. Most elements, if in solution in the cationic state, i.e., as positive ions, will complex with dissolved aqueous anions, thereby enhancing their solubility. Complexing anions in the brine can include chloride (Cl^-), carbonate or bicarbonate (CO_3^{2-}, HCO_3^-), sulfate (SO_4^{2-}), phosphate (HPO_4^{2-}), and others. Some radionuclides such as iodine, and technetium can form oxyanionic species, i.e., IO_3^- and TcO_4^-, respectively, under oxidizing conditions and have a limited capacity to complex. However, their potential to be immobilized in solid phases is also limited. Similarly, both CO_3^{2-}, or HCO_3^- and SO_4^{2-} can form organic carboxy and sulfide anions under highly reducing conditions, which will likewise affect the mobility of some radionuclides

All of the above processes are in competition, and predicting the actual migration of any given radionuclide depends on integrating the critical thermodynamic and kinetic parameters affecting its solubility in a geochemical simulator, which in turn can be incorporated in an appropriate advective transport model. Substantial progress in such modeling has been made in recent years, largely in other countries which are taking advantage of disposal in reducing environments. For example, France is planning its disposal in clay layers drilled out from an access tunnel. This prior work suggests to us that there is no show-stopper that would prevent a high level of confidence in predicting containment to the satisfaction of regulatory agencies and the public.

Retrieval of Canisters from a Repository

On November 15, 2018, Deep Isolation successfully placed a canister in a deep horizontal well, released it, withdrew the placement cable, and several hours later inserted a recovery cable, latched the canister, and brought it back to the surface. This was both a demonstration and a test; our goal was to see if anything unexpected happened. Nothing did. The project was carried out under contract for us by a drilling company at a previously drilled (but unfracked) horizontal borehole.

The canister was designed to be able to hold the capsules of Sr-90 and Cs-137 that are presently stored at Hanford. But in the test no radioactive waste was used; equivalent weights were substituted. The canister plus dummy load weighed 83 lb. The canister was attached to a "hanger" which had a releasable connector; the hanger was connected to a tractor with electrically-driven retractable wheels which pushed against the sides of the casing. The tractor was linked to the surface with a wireline cable.

The canister was lowered in the vertical section to the kickoff depth of 793 feet. From that depth the hole gradually turned until it was horizontal at a depth of 2263 feet. The canister was pushed 100 feet into the horizontal section by the tractor. The temperature at depth was 60°C (140°F). The canister and hanger were released, and the wireline cable and tractor were withdrawn to the surface.

A special latching device was installed on the end of the tractor and the assembly lowered into the drillhole. The tractor pulled the assembly back into the horizontal section. At the bottom, 3 hours and 43 minutes after the canister had been released, the latching mechanism engaged the canister/hanger combination, and they were pulled to the surface.

Figure 6 shows Deep Isolation's founders Elizabeth Muller and Richard Muller standing on the rig just above the drillhole just after the canister had been pulled to the surface. Their hands at the connection between the canister and the hanger. Their green hard hats indicate that they are observers, not actual riggers.

Figure 6. Canister Recovery Demonstration. Elizabeth Muller and Richard Muller on the rig after the successful recovery of a canister carrying a dummy load that had been placed in a horizontal drillhole at a depth of 2200 feet.

Although this was a test of the Deep Isolation concept, the drilling company considered it to be more of a *demonstration* since they were so confident that they could place and recover the canister. Yet they were doing what many people in the nuclear waste arena had assumed was impossible. It is widely but mistakenly believed by non-drillers that although waste canisters can readily be placed in drillholes, that there is no reliable method to retrieve them, and therefore drillhole disposal could not comply with NRC regulations which require recovery capability.

Mechanical placement and retrieval are highly developed in the oil industry. It can be done using wireline with a tractor (as we did), coiled tubing, or drill-pipe methods. Specialized "fishing" companies do this routinely, typically with "uncooperative" objects (such as detached instruments, broken drilling equipment, cement plugs, cement/casing remediation, and even sections of casing). Such fishing skill is important in the drilling industry, where a few days' delay can cost hundreds of thousands of dollars in extended rig rental costs.

We mentioned two alternatives to wireline: coiled tubing, and drill pipe. Coiled tubing consists of a long thin-walled tube, typically an inch in diameter, which can provide both tensile and compressive strength within a casing. Coiled tubing can be used to lower the canisters down the vertical access section, and then to both push and pull canisters along the horizontal part. The tubing is called "coiled" because it is thin enough that it can be wrapped around a spindle for convenient transportation to the drillhole.

Yet another alternative to coiled tubing is small drill pipe, perhaps an inch in diameter, with similar latching equipment installed on the end. It is not clear which approach, wireline, coiled tubing, or drill pipe, will prove most useful.

Earthquakes

We consider two issues: earthquakes caused by the drilling of the repository, and the danger that natural earthquakes could release radioactive materials from deep underground into the human environment.

When the public hears of the Deep Isolation approach, and that it uses the technology associated with fracking, they naturally worry whether we will induce earthquakes, since they believe fracking has done that. Indeed, earthquakes have been induced by fracking operations. However, it is important to note that none of those earthquakes were associated with the *drilling* of the boreholes. Small earthquakes did indeed occur when the rock was fracked (hydraulically fractured), but not from the drilling, and the fracking earthquakes were only magnitude 1. But since we don't frack, we will not even have these.

More substantial earthquakes associated with fracking operations have been triggered when large volumes of wastewater from the fracked holes have been injected into storage wells. The vast bulk of this wastewater comes from the injected water that fractures the rock, and from the "produced water" that comes out of the fracked rock along with the oil or gas being produced. Since we will not be fracking, we will not have either.

Let us now consider the effects of natural earthquakes on the integrity of the Deep Isolation repository. Intense shaking from an earthquake will not, by itself, release radionuclides from the canisters unless the canisters are damaged. Shaking could cause local collapse of the rock above the drillhole, although the canisters are designed to withstand such collapse; the corrosion-resistant alloy 625 has strength comparable to that of carbon steel.

After 50,000 years, when we presume the canisters have corroded, then the shaking of the earthquake *per se* does not accelerate penetration of the geologic barrier. Shaking is more important at Yucca Mountain, since the engineered barriers, particularly the drip shields, could lose their integrity.

There is also the danger that an earthquake fault could intersect the horizontal disposal drillhole and create a "major water-conductivity fault", a fault that provides a fast-path for brine to near-surface aquifers. This could allow radioisotopes in the brine to come up; particularly of concern would be dissolved Cl-36 and I-129. As we wrote above, we can't rule out the possibility of an unknown fault. For any given location, the license application must estimate the probability of such a fault intersecting the storage area, and estimate the probability that water would rise up the fault. Any site chosen for consideration for a Deep Isolation Repository will undergo detailed geologic study to assure that the likelihood of such faults is at an acceptable level.

Inadvertent Intrusion

The NRC regulation states that the licensee (assumed to be the DOE) must address the danger that the site could be penetrated "by exploratory drilling for resources". For Yucca Mountain, the regulations specifically state:

> "There is a single human intrusion as a result of exploratory drilling for groundwater.... The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository.... The drillers use the common techniques and practices that are currently employed in exploratory drilling for ground water in the region surrounding Yucca Mountain."

The geology of the Deep Isolation horizontal repository offers a natural protection against this kind of inadvertent intrusion. The spent nuclear fuel is stored many thousands of feet below any useful ground water, in an environment where the brine has no known value. Thus we automatically avoid the scenario that is written into the Yucca Mountain regulation.

What about deeper drilling, for mineral value? For many sites, the drillhole will be placed in a region that has no commercially viable natural resources. In some cases the horizontal disposal section will be located in or below a clay-rich highly ductile (not frackable) shale layer. Moreover, the narrow profile of the storage drillhole makes it unlikely that even a deep exploration borehole would actually encounter our horizontal disposal section. The horizontal disposal drill hole will be, typically, 18 inches in diameter and 2 miles long. In a 2-mile square surrounding the drillhole, the cross-sectional area is about 0.014% of the area of this square.

The NRC suggests a frequency of 30 boreholes per square kilometer (that would be 300 for a 2-mile square) be used as a standard. We believe that this number makes sense for aquifer drilling, but it is too high in the formations we consider, which contain no useful water at our depths. If, instead, we assume that one exploratory borehole is drilled into the brine, and nothing of value found, then no additional holes would be drilled. Then the probability of an inadvertent hit is reduced to 0.00014, a value close to the NRC requirement of 0.0001.

Regulations mandate that we place a long-term marker above the site. The marker would make inadvertent intrusion even less likely, for as long as the marker survives. The NRC requirement is for a period of 10,000 years, and an ordinary rock strip, placed along the entire length of the horizontal section, should easily last that long against erosion.

Note that intrusion would hit, at most, one canister. The canisters are designed to offer an engineered barrier expected to last (in the reducing environment of our drillholes) 50,000 years. Drilling into the canister would bring the fuel pellets inside that canister into contact with brine, which could then be accidentally pumped up the exploratory hole. This is a scenario that will require careful analysis in a license application.

Terrorist Intrusion

Deep geology provides a barrier that gives significant protection against a terrorist attempt to obtain spent nuclear fuel. Contrast the deep isolation storage location to either temporary storage in pools or dry cask interim storage on or near the surface.

Although the fuel is retrievable, removing even one canister requires setting up a (typically) 160-foot-tall rig, removing several thousand feet of vertical drillhole sealant (likely rock and bentonite), and operating a fishing system to pull up each canister. Of course, the canisters are highly radioactive when they breech the surface, so to prevent a rather quick death from radiation poisoning, the terrorists would have to rig shielding and safety equipment. This would typically require a concrete cylinder 6 feet in diameter, both to remove the canisters from the well, and to transport it.

Removal of the first canister would take an experienced crew, using a rig, about a week, at a cost of several million dollars. It does not lend itself to a surreptitious terrorist attack. Removing all the canisters would take months. Moreover, the equipment for the handling of the fuel is highly specialized. The canisters themselves do not provide radiation shielding, so any recovery would require a crew experienced not only in normal rig operations, but also in the handling of the highly radioactive canisters.

Criticality

Criticality refers to the danger that stored fuel will undergo a sustained chain reaction, made possible, perhaps, from the intrusion of ground water that could serve as a neutron moderator.

The danger of a disposed waste reaching criticality is best estimated by using computer codes designed for this issue. We have not yet done so, although we will do so for a license application. But we are confident that these computations will show that criticality is not a danger. The spent fuel rods are placed in a linear array, not side-by-side. The canisters holding the fuel assemblies will have empty space filled with a sand-like material, limiting the nearby water. If deemed necessary, this sand could have a high content of a neutron absorber such as boron; this will be used if the criticality codes show there is a danger.

Summary

In this section we'll summarize the key features of the Deep Isolation approach, and add a few points that were not previously mentioned.

Disposal is in sedimentary or metamorphic rock, at a depth of 2,000 to 8000 feet.

All the current US commercial spent nuclear fuel assemblies could be placed unmodified and disposed in fewer than 400 Deep Isolation repositories. If the fuel rods are repackaged, eliminating the gaps between them, they would fit in 100 wells.

Measurement of low levels of radioisotopes in the deep brine (C-14, Cl-36, I-129) will indicate that the deep brines have been isolated from the biosphere for thousands to millions of years.

Presence of a cap layer containing natural gas would indicate that the formation has been isolated from the biosphere for tens of millions of years. A cap layer of salt could also offer protection from leakage.

The disposal region is nearly horizontal, so the canisters sit end-to-end, not side by side. This configuration reduces heating (especially for the very hot Cs/Sr capsules) and reduces the possibility of a criticality event.

The disposal region is in the saturated zone, so diffusion leakage would be primarily through water, not gas.

Waste could be put in a consolidated repository, with many wells located near each other (spacing of 20 meters should be sufficient), but a possibly preferred implementation is modular, with facilities close to the locations where surface interim storage currently exists. Surveys in 23 states show that 82% of nearby residents prefer local disposal (to avoid transportation); for the same reason, we presume that they would object to additional waste being carried in from other regions. NIMBY is trumped by NoTAMS (No Transport Across My State).

The disposal region is in a chemically reducing environment in which resistant alloys corrode very slowly, and in which some mobile chemical species (e.g. CO_2, TcO_4) do not form.

The canisters are placed in carbon steel casings, offering reasonable recover (if desired) for 50 to several hundred years, and an additional engineered barrier for similar times.

The canisters made of corrosion resistant alloys, such as alloy 625, are expected to offer an engineered barrier for 50,000 years or more.

The nearly horizontal disposal sections can have lengths from a few thousand feet to 2 miles or more.

A slight upward tilt to the disposal region could help isolate upward-mobile radioisotopes from the vertical access hole.

Major costs for the repository will not be the drilling costs (expected to be under $10M for a 1-mile deep with a 2-mile long horizontal drillhole). Larger costs include the licensing expenses and the facilities for handing the waste.

The Deep Isolation technology offers a viable approach for the disposal of compact high-level waste. The modular approach and the relatively low technical costs reduce the financial barriers for entry, reduce the transportation challenge, and allow, perhaps, relatively quick implementation. It may be particularly attractive in states that prefer local disposal, or in countries that have a relatively small amount of nuclear waste.