

What's Wrong with Yucca Mountain?

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This is intended as an informal web essay on Yucca Mountain, the US Department of Energy's (DoE) intended repository for radioactive waste from the nation's commercial nuclear power reactors. The material is taken from various lectures the author has given at the University of Colorado. The objective here is to explain some of the history and technical arguments and issues for and against the establishment of a nuclear waste repository at Yucca Mountain for the educated citizens of the nation and the state of Nevada who need to make an informed collective decision about whether this project should proceed or not. The article assumes some basic technical literacy, but gives enough background to be readable for any educated person. The author was involved in the early parts of the project and so is familiar with the technical aspects, and having had no direct involvement for twenty years is able to offer a mature, scientific and relatively unbiased, or at least disinterested, view of the issues surrounding the project.

DoE Laboratory Culture

The Department of Energy is a bureaucracy that grew out of the former Atomic Energy Commission and is staffed with career civil

servants, many of whom have academic backgrounds in nuclear physics. In addition to energy research, the DoE is also responsible for the design and development of nuclear weapons, largely to keep them under civilian control. The DoE funds several 'national laboratories' and other research and engineering facilities, including Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Oak Ridge National Laboratory (ORNL), Sandia National Laboratory (SNL), and Idaho National Engineering Laboratory (INEL). The laboratories are all operated by various state and private entities under contract with DoE, so that the employees all serve at the pleasure of the contractor and can be terminated, generally with 30 days notice.

The culture within the labs is very much the cold-warrior-scientist paradigm. The structure is hierarchical with funding coming in at the top for the various large projects, and responsibilities delegated within the laboratory structure. Dissent is generally not tolerated, and discussion of technical issues is limited. Access to information within the classified areas is determined by 'need to know', and this mind set carries to non-classified areas as well. The DoE disciplines its

contractors by setting them in competition with each other. The labs compete fiercely with each other in weapons design as well as nearly all other projects. Despite any flaws, one has to give these cold warriors credit for making all-out nuclear war so unthinkable that the politicians and diplomats have been coerced into responsibility, and we have avoided it for nearly sixty years.

Project History

The Yucca Mountain Project began in 1977 as a U.S Department of Energy (DoE) initiative under the Carter administration. The project was initiated, partly as a way to maintain funding to The Nevada Test Site, which was facing an imminent test ban, and partly as a serious attempt to address the problem of what to do with the nations growing inventory of highly radioactive spent fuel elements from commercial nuclear power reactors. Political concerns have always been dominant over technical concerns in this project. The charge in the initial days of the project was to find a host rock at NTS that might be suitable for radioactive waste isolation, rather than to find the best place in the country to put the waste. The thinking was that DoE had control of this reservation, that it was in Nevada, which had a relatively sparse population, and that it was already contaminated with radioactive debris from decades of underground and above-ground nuclear weapons testing. In addition to its security infrastructure, it even had some facilities that might be useful such as a shielded high-bay facility for assembly of prototype nuclear-powered rockets. So if a suitable, or at least scientifically defensible, host rock at the site could be identified, it had among the best chances, politically, of being approved.

True-to-form, DoE divvied up the possible host rocks among the labs, and set them in competition to find the best one. Los Alamos got tuff, Livermore got granite, and Sandia got shale. We met in the back room of a casino in Las Vegas and duked it out over who would get what funding to do what experiments in what medium. It was the only time I ever won anything at a casino. Sandia got about a half a million dollars to string a power line across a few miles of desert, pour a small concrete pad, drill a few shallow holes, and put some heaters in the shale. Los Alamos got

Table 1. Fission Products in Spent Fuel Assemblies (after 10 years).

Isotope	Half-life	g/asby	Ci/asby
⁸⁵ Kr	10y	40	1,100.
⁹⁰ Sr	30y	170	13,000.
⁹³ Zr	10 ⁶ y	810	0.6
⁹⁹ Tc	2x10 ⁵ y	200	3.4
¹⁰⁷ Pd	7x10 ⁶ y	340	0.03
¹²⁶ Sn	10 ⁵ y	12	0.2
¹²⁹ I	2x10 ⁷ y	62	0.01
¹³⁵ Cs	2x10 ⁶ y	350	0.5
¹³⁷ Cs	30y	270	22,000.
¹⁵¹ Sm	93y	185	31.

about 300K to collect samples from existing drill holes and design some heating experiments for zeolitized and non-zeolitized tuffs. Livermore got some funding to design and build a heater experiment for the Climax Stock granite. There is not a lot of accessible granite at NTS, and what there is has been somewhat shattered by nuclear explosions, but there was an existing and maintained mine tunnel structure at Climax. With the labs competing for funding to investigate one rock medium or another, each lab was motivated to tell DoE what they thought DoE wanted to hear in order to increase their funding. No one was funded to point out the technical difficulties.

Nuclear Power

The Nevada site is intended to address the problem of waste from the commercial electric power reactors in the US. To put the radioactive waste problem in perspective, it is useful here to give some background on commercial nuclear power. Commercial nuclear power reactors produce about 15% of all U.S. electricity and account for about 5% of total energy production. The major objective of the Yucca Mountain project is to provide a repository for radioactive wastes from commercial nuclear power reactors. For the non-technical reader, it is appropriate to give some general background on the technical aspects of nuclear power. The U.S. uses light-water reactors in which ordinary water is used as

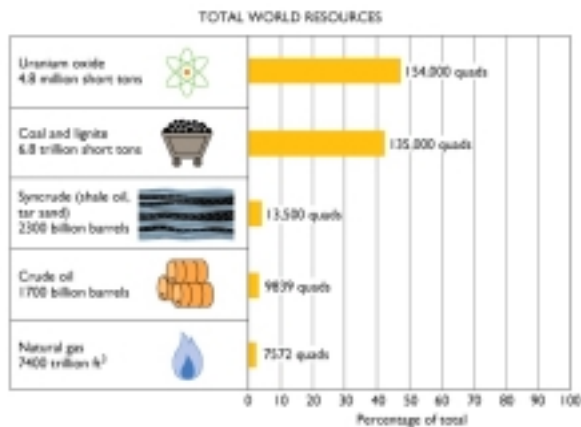


Figure 1. Relative sizes of Energy Resources. The uranium oxide option includes energy from converting ^{238}U to Pu (breeder reactors).

both the moderator to slow down the neutrons to sustain the nuclear fission reaction and as a heat exchange medium to produce steam to drive the generators. The fuel is uranium oxide with the fissile isotope, ^{235}U , enriched to about 3.3%, much lower than would be required to make an explosive weapon. The oxide fuel pellets are fabricated into fuel assemblies of a zirconium alloy metal weighing about 500kg. The fuel assemblies typically spend about three years in a reactor with half of them being replaced every 18 months or so. In the reactor, the uranium fuel is producing about 25 megawatts per metric ton, and a total 'burn' is about 25,000 megawatt days, roughly three years. The pressurized reactor vessel is enclosed within an outer vessel to contain the radiation in case of an accident, such as happened at Three Mile Island.

European countries use a different design or style of power reactor, called a high-temperature, gas-cooled, graphite-moderated reactor (HTGR). These reactors use highly enriched (read weapons-grade) uranium fuel. Reactors of this type in the former east-block countries generally lack an outer containment vessel to prevent escape of radioactive debris in case of accident such as happened with disastrous results at Chernobyl.

Canada uses a deuterium-moderated reactor that uses unenriched uranium fuel. Many other reactor designs are possible, including breeder reactors that convert ^{238}U to ^{239}Pu , another form of fuel, while producing power from ^{235}U . The

possibility of burning the abundant isotope of uranium, ^{238}U , in future reactors makes the spent fuel elements, a huge potential energy resource that rivals that available from all fossil fuels put together (Fig. 1).

Natural uranium is about 0.7% ^{235}U and 99.3% ^{238}U . Both isotopes are naturally radioactive with half-lives of 700 million and 4.5 billion years respectively, but with such very long half-lives, they are not highly radioactive. You can hold natural uranium in your hand for a short period without exceeding radiation exposure limits. It is not even warm to the touch. But once it has been in a reactor, you would need a foot of lead to protect you from the radiation to be in the same room with it. It requires active cooling to keep it from melting for the first ten years after it comes out of the reactor. Mining and milling of uranium has produced large amounts of very low-level radioactive waste. Enriching the uranium to 3.3% ^{235}U produces copious amounts of depleted ^{238}U that has found its way into armor-piercing military ammunition because of its high density and toughness.

Just being 'burned' once in a light water reactor, the fuel produces about 3 million times as much energy per gram as coal. The magnitude of the total energy resource in uranium for fission is larger than that of coal, and dwarfs that of all other fossil fuels. The relative sizes of the resources are compared in Figure 1. In addition to being a huge energy resource, nuclear fission power does not produce greenhouse gases that trap the sun's heat in Earth's atmosphere, as does the burning of coal and other fossil fuels. Unless we can scrub CO_2 from stack gases, fossil fuel usage will eventually have to be curtailed. Atmospheric CO_2 levels have increased by nearly 20% since 1960 (Fig. 3) from anthropogenic sources.

Nuclear Waste

The U.S. has decided it will not reprocess spent fuel assemblies to recover fissile plutonium and unreacted ^{235}U . This means that the U.S. will be seeking a repository to permanently dispose of spent fuel elements from light-water reactors.

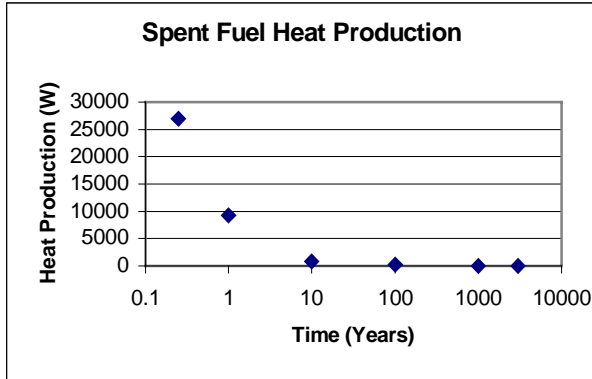


Fig. 2. Log-linear plot of heat production with time for spent fuel elements. The plot clearly shows the different regimes: 1 and 2 where water-cooling is required, 3 where air-cooling is recommended, and 4 where cooling in the rock formation is adequate.

Permanent disposal is deemed preferable because it will have a fixed cost that can be factored into the cost of the process and the price of the electricity. Almost all of the spent fuel elements that have been consumed by U.S. nuclear power reactors are still in lightly protected, water-cooled storage at the reactor sites where they were 'burned'. These spent fuel elements constitute a huge inventory of curies (unit of specific radioactivity) that dwarfs all of the military and research wastes put together, and they are located near large centers of population. In the light of the events of September 11, 2001, this must be seen as a significant potential terrorist target as well.

In the fission process, one nucleus of ^{235}U absorbs a slow neutron and splits into two lighter nuclei (fission products), one with an mass number about 140 and the other about 90, plus a few fast neutrons. The neutrons are slowed by the moderator so they can sustain the reaction, or they get absorbed by the ^{238}U to make ^{239}Pu and other transuranic elements (TUs). In addition to ^{238}U , and fissile ^{239}Pu and ^{235}U plus other heavier TUs, the spent fuel elements contain the highly radioactive fission products. A typical inventory of fission products and TUs in a spent fuel element is given in Table 1, along with their half-lives. After ten years out of the reactor, most of the heat is being generated by the decay of ^{90}Sr

and ^{137}Cs , both of which have half-lives of about 30 years, so that heat production of a typical spent fuel element will be down to about 100 W after 100 years. Heat production as a function of time is given in Table 2 and shown graphically in a log-linear plot in Fig 2.

For a low thermal conductivity medium like volcanic tuff, heat production and dissipation is a major critical limitation that will determine waste loading, that is, the total amount of waste that can be disposed of in a given amount of real estate.

At the atomic scale these fission-product atoms are mostly contained within the crystals of UO_2 . Some of these elements can be accommodated by the UO_2 (fluorite-structure) lattice, but most cannot, and being far from chemical equilibrium, will diffuse out of the crystals given sufficient time or heating. The UO_2 crystals themselves are also out of chemical equilibrium and will oxidize to U_3O_8 or soluble U^{6+} cations if stored in the oxidizing region above the water table. The task is to assure containment of these elements for up to 8 half-lives. Because oxidized uranium is soluble in water a major task will be to assure reducing conditions in the immediate vicinity of the fuel canister.

Permanent Versus Interim Storage

As mentioned earlier, the U.S. is seeking a repository for spent fuel elements from its light-water reactors. These fuel elements contain a large unused resource of ^{235}U , ^{239}Pu and ^{238}U that could potentially be utilized in future reactors. The total energy available from these elements is a factor of 50 to 100 times that derived in the first 'burn'. Whether this energy can be used economically in the future will depend on the price of uranium, the economic viability of nuclear fusion reactors, the economics of CO_2 scrubbing from coal-burning power plants, and the urgency of the CO_2 problem. *However, given the problem of heat generation and dissipation from ten-year-old spent fuel elements, there is not sufficient real estate available at Yucca Mountain to permanently dispose of all of the spent fuel elements currently being stored at U.S. light water reactor sites.* Further, the growing urgency of the terrorist threat to the wastes currently stored at

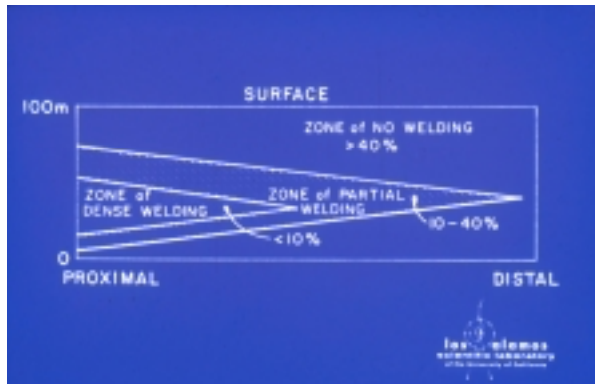


Fig.3. A schematic diagram of a single tuff cooling unit showing zones of relative degrees of welding. The densely welded portions approach granite in density and thermal conductivity, whereas the non-welded portions may have densities less than 1.0 and thermal conductivities less than 0.02 W/mK.

reactor sites adds some urgency to getting this material to a terrorist-proof underground site, permanent or otherwise.

Yucca Mountain Geology

The President has decided that we will go ahead and put our 'nuclear' [sic] waste at Yucca Mountain, so let me give some background on the geology and geography of the site. Yucca Mountain is located about 95 miles northwest of Las Vegas on the southwestern corner of the Nevada Test Site (NTS). The Yucca Mountain site actually spills over the western boundary of NTS onto a small corner of Nellis Air Force bombing range. The climate is arid with less than eight inches of rain per year. There is no permanent surface drainage in the area, and the ground water eventually drains to Death Valley. There is no drainage outlet to the ocean. The unsaturated (vadose) zone at the site extends down more than 300 m below the surface. The geology is predominantly volcanic with over 1000 meters of silicic volcanic tuff, which is (presumably) underlain by Paleozoic sedimentary rocks, limestone and shale.

Tuff is the product of an explosive volcanic eruption, such as happened at Mount Pinatubo in the Philippines and Mount St. Helens in Washington. At Yucca Mountain the tuff has approximately the same chemical composition as granite. There are ash-flow units deposited by large, hot eruption clouds and smaller air-fall units



Fig. 4. A single cooling unit outcrop of silicic tuff showing the black vitrophyre, the brown densely welded, devitrified zone above it, and the tan, non-welded portions above and below.

composed of pumice fragments that were deposited at cool temperatures. The larger ash-flow units are initially composed of tiny fragments of glass, sometimes with a small percentage of accessory feldspar or other crystals deposited by a hot volcanic cloud. The glass shards are the walls of the ruptured bubbles in a glass foam (pumice). If deposited at high temperature (above about 500 °C) the shards will compact and weld under the weight of the overlying deposit. If cooling is rapid, as near the bottom of a thick deposit, this densely welded material will form a dense, black glass deposit similar to obsidian called a vitrophyre. If cooling is slower as in the center of the deposit, the densely welded glass will crystallize (devitrify) to quartz and feldspar, forming essentially a very fine-grained granite with randomly distributed air pockets called lithophysal cavities. A schematic ash-flow-tuff cooling unit is illustrated in Figure 3, and a small typical outcrop with labeled units is shown in Figure 4. Farther from the vent, the glass shards are emplaced cool and do not weld or compact. These unconsolidated deposits, both ash-flow and air-fall, are easily and rapidly reworked and redeposited by water on the surface. An outcrop of bedded (reworked) tuffs is shown in Figure 5.

After the rocks are deposited and consolidated, the remaining glass will alter to clays or a variety of zeolite minerals under the influence of ground water and temperature. The zeolites, which form below the water table, can form an effective sorptive barrier to the migration of many of the dissolved fission product elements

in groundwater, particularly cesium and strontium. The zeolites can also tell us quite a bit about past geologic conditions in the area such as thermal gradients and ground water movements, because the different zeolite minerals have limited ranges of temperature and ground water chemistry in which they form. After the various rock units were deposited, the area was uplifted, faulted, and eroded. The faulting, together with the extreme variation in physical properties with welding, makes the geology of the site extremely complex.

One of the most recent geologic events at the site is the eruption of several small basalt lava flows and cinder cones in Crater Flat, just east and south of the site. The location of these small volcanoes is shown in Figure x and the beautifully intact and uneroded cinder cone of the youngest basalt, located about five miles south of the site is shown in Figure 5. The point of all this geology is that these rocks are extremely variable in physical properties (density, porosity, permeability, thermal conductivity, sorption capacity, and mineral make up). This makes the modeling of processes affecting waste isolation extremely difficult.

At Yucca Mountain the proposed repository is located in the thick Topopah Springs cooling unit of the Paintbrush Tuff. It is a densely welded and devitrified unit up to 300 m in thickness and located above the local water table in the unsaturated zone. It is overlain by another, partially welded cooling unit, called the Tiva Canyon member of the Paintbrush Tuff. Between the two welded cooling units is the thin, non-welded basal part of the Tiva Canyon with some small air-fall pumice horizons. It is this basal part of the Tiva Canyon member that makes thermal modeling of the repository so difficult.

Thermal Conductivity Issue

There is an issue with thermal conductivity at Yucca Mountain that is not yet fully resolved. This will determine how much waste can be emplaced at the site. We have a good understanding of heat transport by conduction, and it can be easily modeled by computer calculations, based on laboratory measurement of thermal conductivity and heat capacity. Heat transport by water vapor movement in the unsaturated zone will simply add on to the

conduction, but should be ignored for repository design because the formation is expected to dry out with time. The problem for modeling heat conduction in volcanic rocks is the extreme variability of thermal conductivity. Conductivities can vary by an order of magnitude over short distances (centimeters).

The standard international (SI) unit of thermal conductivity is watts per meter-kelvin (W/mK). For natural materials, quartz (SiO₂) and halite (NaCl) are among the most conductive with conductivities ranging from 4 to 6 W/mK, whereas volcanic pumice is about the least conductive with conductivities as low as 0.02 W/mK. Welded tuff is typically about 1 W/mK, and non-welded tuff about 0.2 W/mK. For thermal conduction models of temperature with time with known heat generation from the waste, a layer of abnormally low conductivity, such as a pumice horizon, has a large and controlling effect on the final temperature distribution. Because pumice horizons are somewhat delicate, they are easily destroyed and not always recovered in drill core. A 5 cm (2 in) pumice horizon would have a controlling effect on most models of thermal conduction and temperature distributions. There is a non-welded unit at the base of the Tiva Canyon Member of the Paintbrush Tuff with possible pumice horizons located above the proposed repository. What is required to show that a low conductivity horizon is not present above the repository horizon is a density profile with a resolution better than 2 cm. Otherwise one must assume that any unrecovered core interval from this part of the section has the very low thermal conductivity measured for pumices (~0.02 W/mK).

To this authors knowledge, this has not been done. Several thermal models of the repository have been done to determine possible emplacement densities for the waste. None of the models to date make this worst-case assumption for thermal conductivity.

Volcano Issue

As mentioned earlier, there are some very young basaltic volcanoes within 8 km of the site. The very young (<50000 yrs) LathropWells cone is shown in Fig. 5. In addition there are a few older cones in Crater Flat, closer to the site, and



Fig. 5. A view of the very young Lathrop Wells basalt cinder cone that is about 8 km south of the Yucca Mountain site.

basaltic dikes (intrusions) were encountered in some of the deep drill cores at the site. The possibility and consequences of a magma incursion into the repository must therefore be considered. This also has not been done.

Hydrology and Hot Springs

There also is evidence of ancient springs in the vicinity of the repository. We know that the region was much wetter during the recent glacial maximum that extended from about 100,000 to 10,000 years ago, and that permanent lakes were present in many of the closed basins of southern and eastern Nevada and southeastern California. From northern Nevada, Lake Bonneville stretched eastward to the Wasatch Front. There has been some discussion as to whether the surface travertine deposits near the repository are the result of springs and upward movement of groundwater, or whether they are soil caliche deposits resulting from downward movement of surface waters.

Looking at the drill cores and zeolite mineral zonation, we have strong evidence that geothermal gradients were significantly higher in the past. We know that the various zeolite minerals form at various specific temperature-ranges in specific ground water chemistries. In fresh, but slightly alkaline conditions and at low temperatures below about 65 °C, not much happens, and we have Zone I (unaltered glass). At temperatures from 65 °C up to about 125 °C the

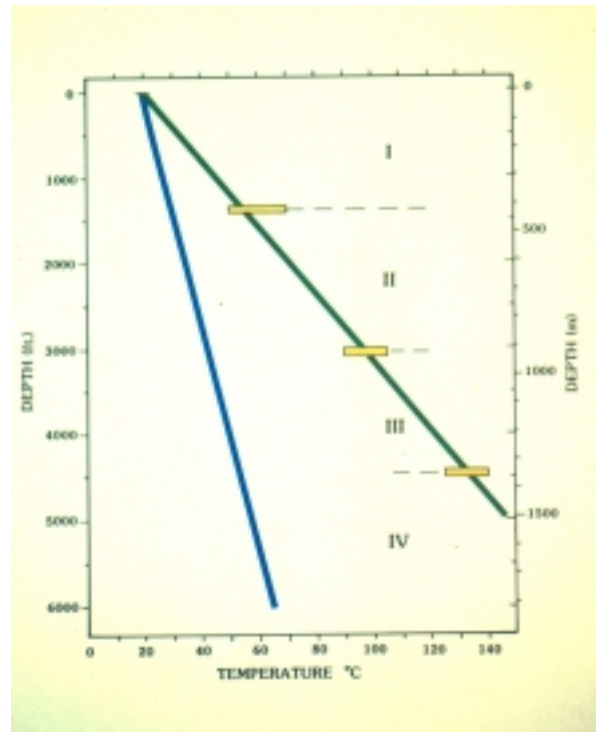


Fig. 6. A plot of zeolite zones (I =glass; II = clinoptilolite, III = analcime; and IV= albite) and boundaries. The temperatures of the boundaries imply a much higher geothermal gradient (green curve) in the past, than the observed gradient at the site (blue curve).

glass will alter to the zeolite mineral, clinoptilolite (Zone II). Above 125°C, the clinoptilolite will transform to analcime, another zeolite phase (Zone III). Above about 160°C the analcime will transform to albite, an anhydrous feldspar mineral (Zone IV). These zeolite zonations are observed in saline, alkaline lakes, in marine tuffs, and in continental tuffs, although the zone boundaries are shifted to lower temperatures with the higher salinities present in marine tuffs. Saline, alkaline lakes may have been present in the area in the geologic past, but there is no surficial evidence of lakes in the immediate vicinity. The current surface drainage is down the Amargosa River to Death Valley, and the water in Death Valley would have to rise several thousand feet to inundate the area. If the ground water chemistry has been roughly constant, then the observed zeolite zonations patterns may be presumed to result from temperature gradients that were considerably higher in the past. The temperatures inferred from the observed zeolite zonation

patterns are shown in Figure 6 along with a plot of the current geothermal gradient. In addition to the observed pervasive zeolite zone alteration shown in Fig. 6, there is evidence of short-term upward movement of heated ground water. In several of the drill holes, analcime is encountered deposited in fractures within the clinoptilolite zone. This means that the travertine deposits at the site may well be hot spring deposits. Such deposits could result from shallow basaltic intrusions below the site.

A Possible Alternative

One possible alternative to the permanent disposal of spent fuel at Yucca Mountain may be long-term interim storage of spent fuel at the site. The long-term interim storage concept would consist of two separate stages, one for the first ten years would be water cooled, and the second, lasting about ninety years, would be passively air cooled. Both could be underground at Yucca Mountain. The first stage of would consist of large, underground water cooling tanks and could accept spent fuel elements recently taken from their reactors after about one year of on-site water-cooling. Transport of spent fuel canisters would not be without risk, and would have to be after at least one-year of cooling on site. The second stage would place the spent fuel canisters in a large aluminum heat sink and allow air to convect around the heat sink to dissipate the heat. After 100 years of total storage, the tunnels could be backfilled for a permanent repository after 80 percent of their heat is dissipated, or they could be retrieved for reprocessing to utilize the ^{238}U resource if economics so demand.

There are numerous technical and political advantages to this concept over permanent disposal of spent fuel elements. The technical advantages include greatly increasing the possible density of waste emplacement, and keeping the large energy resource in the spent fuel available for future use. This would allow the site to accommodate all spent fuel generated and currently stored at reactor sites. The political advantages include reducing the current terrorist threat, and turning the waste repository at Yucca Mountain from a 'dump' to an industry with a long-term future.

By allowing a 90-year air-cooled storage period (three half-lives of ^{90}Sr and ^{137}Cs), the heat required to be dissipated through the rock is decreased by about a factor of five. This will allow waste loadings to be increased so that the site will be able to accommodate the entire US inventory of spent fuel through at least 2020. Through this period, the facility would have to be closely monitored and the waste retrievable in the event of any mishap, miscalculation, or increased need for the stored ^{238}U . To reduce terrorist threat to operating nuclear power facilities, the stored spent fuel should be moved to an underground site away from large population centers. An underground water-cooled facility could be constructed at Yucca Mountain or nearby. Finally, the people of Nevada are far more likely to be favorable to a whole new industry than to a dump.