NUCLEAR WASTE MANAGEMENT:

... a manageable task

NUCLEAR WASTE MANAGEMENT:

... a manageable task

Published by:

Westinghouse Advanced Power Systems
P.O. Box 158
Madison, PA 15663

Table of Contents

Sections:

Introduction

The current instabilities in the supply of imported oil reinforce the proposition that the United States must replace oil with other energy sources for central station power production. Based on the goals of lowest cost to the customer and minimum environmental impact, increased utilization of nuclear power is an essential element of our future electricity supply. Yet, the current controversy surrounding nuclear waste management has had and is having an effect on impeding the construction of this needed nuclear capacity.

Unfortunately, the discussions taking place in the United States today about nuclear waste management are dominated by misconceptions and misinformation —not facts. The purpose of this booklet is to provide documented information on the status of nuclear waste management technology based on the results of research programs in the U.S. and other countries. This includes recognition that waste storage and disposal facilities will be required regardless of the future growth of commercial nuclear power. Significant inventories of nuclear waste have already accumulated from existing Government and commercial activities.

The "problem" of nuclear waste management is not something recently discovered. Serious research has been ongoing both here and abroad for many years. Indeed, several foreign countries already have focused national programs. It is, therefore, extremely important that a clear understanding of the waste management process be fostered among the decision makers of this country. To assist in accomplishing that goal, a glossary of key terms and acronyms has been included in this booklet, along with a complete listing of references.

Background

The principal goals of nuclear waste management are to stabilize, shield and isolate the nuclear waste elements from the human environment. These goals must be met during each step of the waste management process, starting with the removal of spent fuel from the reactor.

- Stabilization is the process of immobilizing the radioactive material so that a liquid becomes a non-mobile solid when in water or air.
- Shielding is the process of reducing the radiation by putting barriers around the highly radioactive spent fuel or reprocessed waste. These can be water, lead, earth, concrete, etc., all of which attenuate radiation.
- Isolation is the process of removing access to the waste by putting barriers between the waste and humans. These barriers can be either passive (requiring no intervention by man) or active (requiring man's involvement).
- Nuclear waste management is concerned with storage of nuclear waste and spent fuel, transportation of nuclear waste and spent fuel, and the disposal of nuclear waste.

The purpose of this section is to provide background information on nuclear waste management. More detailed information on the interim storage, transportation and disposal of waste can be found behind subsequent tabs in this book.

Types of Nuclear Waste

- **High Level Waste (HLW):** This is the waste generated in the reprocessing of spent fuel. It contains virtually all of the fission products and most of the actinides not separated out during reprocessing. This waste is being considered for disposal in geologic repositories or by other technical options designed to provide long-term isolation from the biosphere. (Current Administration policies and proposed regulations define HLW to also include spent fuel assemblies. See Section 1, Interim Storage, for comments on spent fuel as a valuable resource.) [1,2]
- **Transuranic Waste (TRU):** This results predominately from spent fuel reprocessing, the fabrication of plutonium to produce nuclear weapons, and plutonium fuel fabrication for recycle in light water and breeder reactors. TRU waste is currently defined as material, other than HLW, containing more than ten nanocuries of transuranic activity per gram of material. This waste would be disposed of in a similar manner to that used for HLW. [2]
- **Low Level Waste (LLW):** LLW contains less than ten nanocuries of transuranic contaminants per gram of material, or it may be free of transuranic contaminants. It requires little or no shielding, has low, but potentially hazardous, concentrations or quantities of radionuclides. Low level waste is generated in almost all activities involving radioactive materials. LLW is presently being disposed of by shallow-land burial.
- **Uranium Mine and Mill Tailings:** These are the residues from uranium mining and milling operations. They contain low concentrations of naturally occurring radioactive materials. Tailings are generated in very large volumes and are stored at the site of mining and milling operations.
- **Gaseous Effluents:** These are released into the biosphere, where they become diluted and dispersed.

Sources of Nuclear Waste

Nuclear waste is produced as a by-product of operations which involve nuclear processes and materials. There are many operations that produce nuclear waste. In general, these operations can be divided into those performed by the Government (mostly defense) and those that are a part of commercial nuclear power and other civilian activities.

Government Activities

- Production and testing of nuclear weapons
- Operation of Government-owned reactors which support military and Government R&D programs
- Operation of naval reactors for ship propulsion
- Government-sponsored nuclear research programs

Commercial Activities

- Operation of commercial nuclear power plants
- Research programs, including operation of test reactors
- Production and use of radioactive materials for industrial and research application
- Production and use of radioactive materials for medical applications (e.g., cobalt sources for the treatment of cancer)

Radioactive elements from all of these sources which have been determined to have no value must be disposed of in a manner that poses no undue risk to public health and safety. Useful applications have been proposed for some nuclear waste, such as gamma radiation from cesium 137 to treat sewage. However, the quantities of nuclear waste produced, even by a large nuclear power industry, are too small to make these proposed applications economical. In time it may be economically desirable to remove certain materials in the waste, such as the rhodium, which becomes safe to use in only a few years. The isotopes used in industry and medicine are primarily produced in special isotope production reactors, rather than from the operation of military or nuclear power reactors. [2,3]

Nuclear Waste Inventories [4,5]

The current inventories of defense and commercial waste volumes are summarized in this chart.

- The commercial inventory consists of 2300 cubic meters of liquid HLW and more than 9000 spent fuel assemblies in water-basin storage, mostly at reactor sites.
- This volume would reduce to only about **142 cubic meters** after reprocessing and solidification.
- Over **90%** by volume of **all waste** accumulated to date resulted from defense activities.
- About **97%** by volume of the **HLW** accumulated to date resulted from defense activities.

CURRENT STORAGE INVENTORIES (1980)

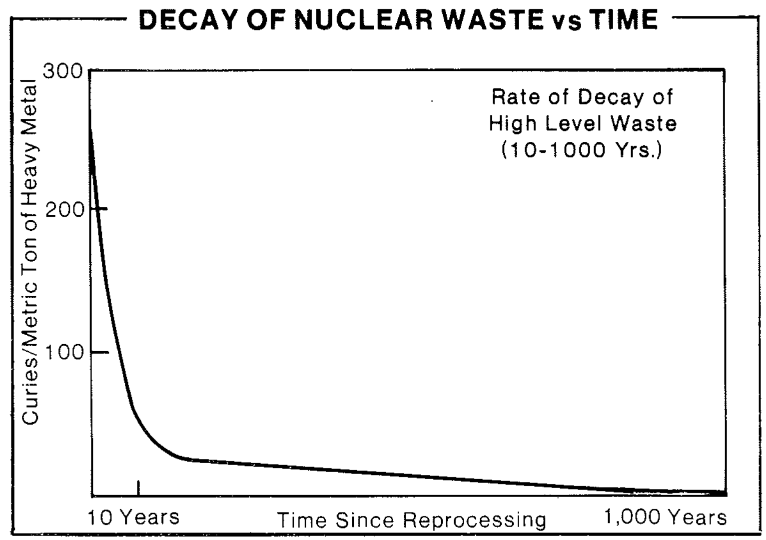
Defense	286,000 cubic meters HLW 1 billion curies
Commercial	2300 cubic meters HLW > 9000 spent fuel assemblies 1 billion curies*

* Increasing at 500 million curies/year

Radioactivity [4,5]

High level waste contains about 98% of the radioactivity produced by all nuclear waste. Properties of some of its more important constituents are shown in the list below.

- The HLW that results from reprocessing is highly radioactive.
- Reprocessing one pound of fuel material will produce HLW which contains about 2000 curies of radioactivity.
- More than 90% of this activity will decay away in 10 years, and more than 99% will be gone in 100 years.
- The current inventory of defense HLW amounts to about 1 billion curies.
- 1000 million curies of activity has accumulated from the operation of commercial nuclear power plants.
- It is important to remember that much of the radioactivity in HLW decays away in a few decades. Also, while much of the military HLW is over 20 years old, most of the spent fuel has been recently removed from operating nuclear power plants.



9/52

Low Level Waste

Low level waste is found in a wide variety of forms. Most of it remains radioactive for up to several hundred years. The current means of disposing of LLW is through shallow-land burial.

- The Government has 14 active and 2 closed LLW disposal sites.
- Commercial operators maintain 3 LLW disposal sites; there are 3 closed commercial LLW sites.
- The commercial facilities serve the nuclear power industry and other producers of nuclear waste, such as hospitals and research organizations.
- Projections indicate that the demand for commercial LLW disposal sites will increase dramatically in the decades ahead; nevertheless, only about 600 acres will be required for disposal through the year 2000.
- Currently, over 2 million cubic feet of LLW are disposed of each year at commercial sites; over 1 million cubic feet are disposed of at Government sites.
- Over 75% of all LLW produced have come from defense operations; about half of the commercial LLW is generated by hospitals, education and research facilities. [2,6,7,8]
- LLW only contains 2% of the total radioactivity contained in all nuclear waste. [9]

[Note: The remainder of this document will deal with the storage, transportation and disposal of HLW and TRU. Reference 10 provides a recent evaluation of LLW disposal technologies.]

Uranium Mill Tailings

Mining and milling extracts the uranium ore from the earth and prepares it for subsequent use in the nuclear fuel cycle. Tailing piles are accumulated, which are residues from the milling operations. These tailings contain low concentrations of naturally occurring radioactive materials.

- Compared with other types of nuclear waste, uranium mill tailings are generated in large volume (about 10-15 million tons annually).
- Although tailings are a natural product of mining and milling, they are hazardous because they contain long-lived radioisotopes, and because they have been left in waste piles where humans may come in contact with them.
- Radon and radium are two radioactive elements in this waste that are of particular environmental concern.
- Radon is a noble gas that escapes easily into the atmosphere from unstabilized mill tailings.
- Radium, the parent of radon, is a potential pollutant of surface water.
- Due to the long half-life of thorium 230, the parent of radium, the quantity of radon and radium in the tailings will diminish by only one-half in roughly 80,000 years.

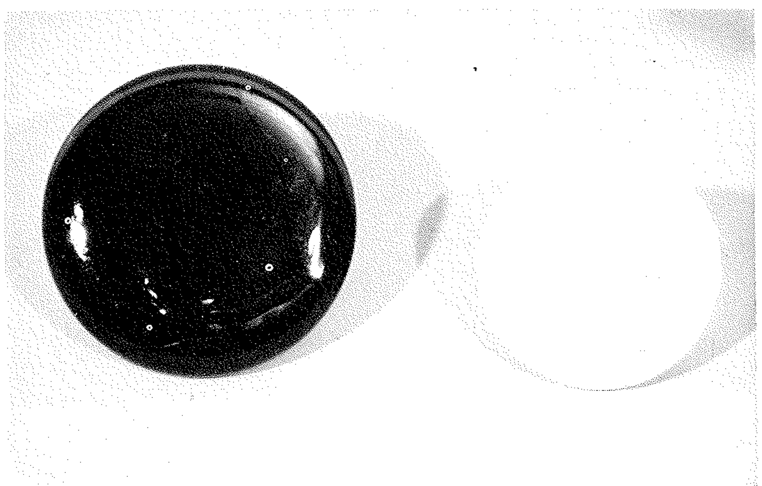
The Uranium Mill Tailings Reduction Control Act was enacted to improve control of tailings at mill sites. [11]

- The President's Interagency Review Group noted that technologies exist for the management and disposal of tailings. [2]
- The NRC has subsequently issued regulations on Uranium Mill Tailings Licensing, based on its Generic Environmental Impact Statement.
- These regulations will require that tailings be covered with at least 10 feet of earth, which will reduce radon emissions to meet EPA standards.
- For more detailed background on mill tailings, consult references 12 and 13.

Uranium Mill Tailings

Perspective

- The EPA estimates that about 60 million tons of hazardous waste of various kinds will be produced annually in the early 1980s. Less than 0.01% of this hazardous waste will come from commercial nuclear power plants. [14]
- After reprocessing and solidification, the volume of the resulting HLW from spent fuel assemblies accumulated through the year 2000 would cover a football field to a height less than 10 feet. (The actual disposal volume, however, would require about 2000 acres, since the solidified HLW would be contained in canisters, spaced at intervals to permit heat dissipation.) [15]
- Approximately 25 tons of fuel are utilized by a 1000 megawatt nuclear power plant per year. The amount of solidified HLW produced has a volume of about 70 cubic feet.
- This amount would fit under a dining room table. The electricity supplied while this waste is generated would be about 5-1/2 billion kilowatt hours. [16]
- The nuclear generated electricity used by one person over this lifetime will result in an amount of solidified HLW that is half the volume of a soft drink can.
- These small volumes make it possible to manage HLW so as to protect current and future generations without significantly affecting the cost of electricity from nuclear power plants.



High Level Waste for 1 Family, 1 Year

Interim Storage

Spent nuclear fuel is a valuable energy resource:

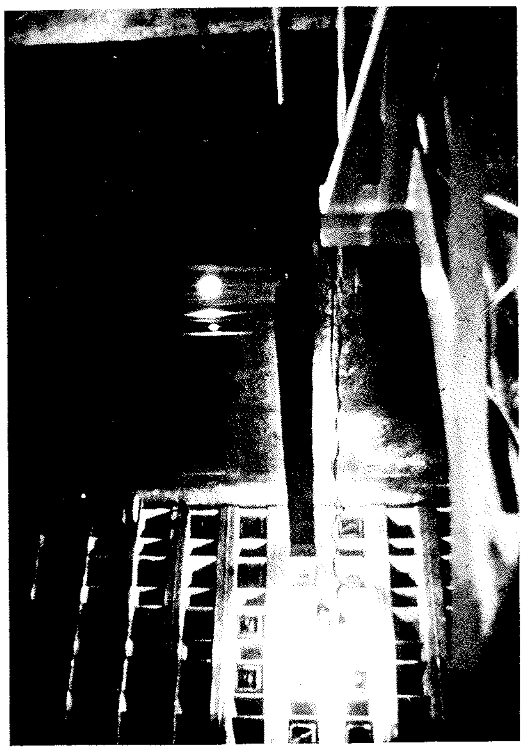
- Each spent fuel assembly represents an energy potential greater than 3 million barrels of oil if uranium and plutonium are recycled and used in breeder reactors.

Interim storage is required, and it currently is being accomplished worldwide at reactor sites and reprocessing plant sites.

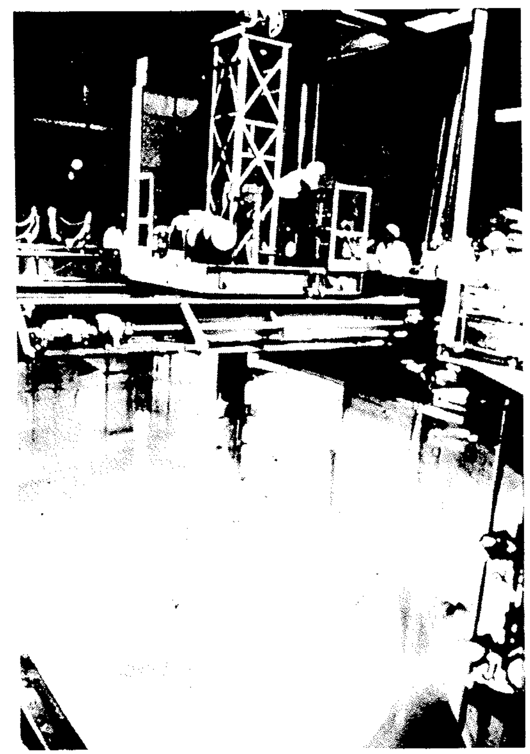
- Spent fuel, liquid high level waste and solid high level waste currently are being stored.
- Storage has been used for 25-30 years.
- Interim storage permits spent fuel or vitrified (glassified) waste to cool.

Water-basin storage facilities are used at all reactor sites. [2,17]

- These are massive concrete, water-filled cells lined with stainless steel.
- They are provided with cooling and cleanup systems.
- The water provides cooling, radiation shielding and a partial containment for any radioactive leakage.



Spent Fuel Pit

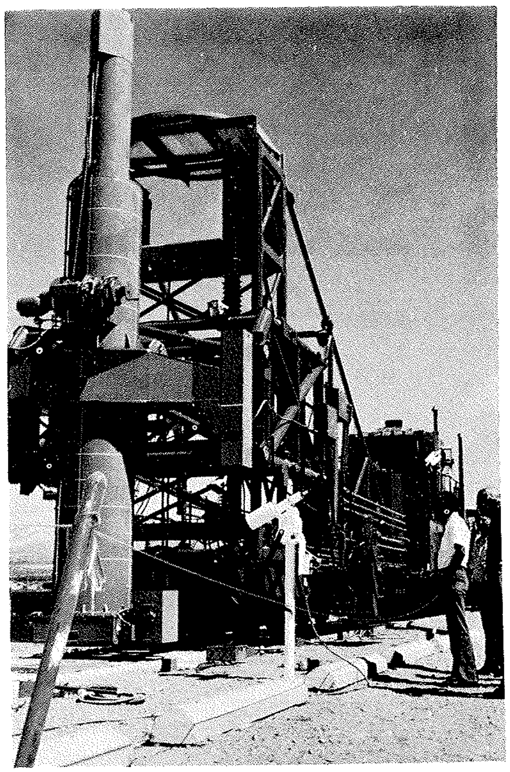


Fuel Handling Equipment

- Spent fuel has been stored for more than 30 years in water with no adverse effect.
- High level reprocessed waste, solidified and placed in canisters, can also be stored in water basins for cooling.

Several countries use various systems for interim storage:

- France is currently using an air-cooled vault at Marcoule for vitrified HLW. Similar storage is planned at La Hague. [18]



Assembly Being Transferred
(Dry Storage)

- Sweden, the United Kingdom and France are planning to use interim storage for at least 30 years to reduce heat loadings of vitrified waste prior to deep geologic disposal. [19]
- Canada is storing spent fuel at reactor plant sites. Experimental air-cooled surface silos have been under test since 1976. [20]
- The United States is storing spent fuel in reactor plant water pits and is planning to provide additional away-from-reactor (AFR) storage facilities. Dry storage systems are also being developed at DOE's E-MAD facility in Nevada.

Spent Fuel Storage

- As much as possible, spent fuel should be stored at reactor sites, expanding existing spent fuel pits as necessary.
- Some away-from-reactor (AFR) storage capacity will be required in the U.S. by the mid-1980s. [2]
- The need for this capacity will increase until repositories and/or reprocessing plants are available.
- The President's Interagency Review Group (IRG) concluded that spent fuel storage can be done safely. [2]
- The NRC concluded that storage of spent fuel in water pools has an insignificant impact on the environment—whether on or off-site. [17]
- The NRC also concluded that dry storage techniques appear to be equally acceptable.

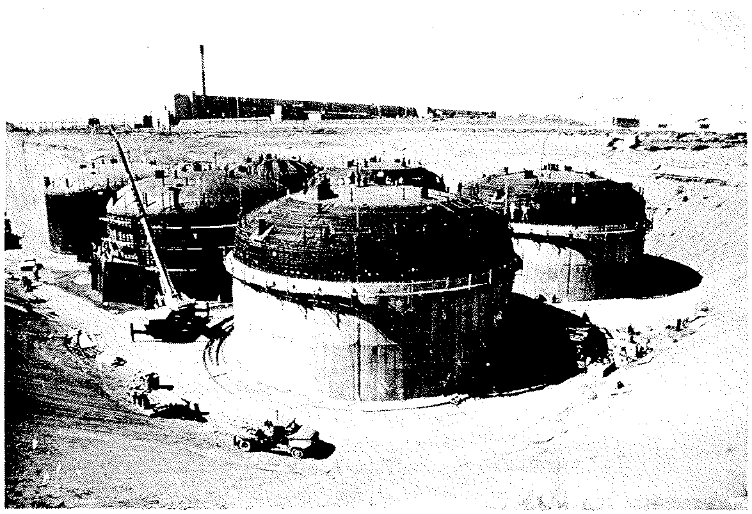
International Reprocessing

- Reprocessing is essential to obtaining the valuable fuel reserves remaining in spent fuel.
- There is a significant amount of foreign reprocessing experience with different sized plants, including several commercial plants. [15]
- United Reprocessors was formed in 1971 by the British, French and Germans to coordinate their future reprocessing capacity and to market reprocessing services.
- The Eurochemic reprocessing plant at Mol, Belgium, has operated during 1966-1976.
- The French have two reprocessing plants—one at Marcoule, operating since 1958; and one at La Hague, operating since 1967.
- The current output of La Hague is 400 tons of uranium per year.
- By 1987 the La Hague output per year will be about 1600 tons of uranium. [21]
- The British have had more than 25 years of successful reprocessing experience at Windscale.
- The United Kingdom has the capacity to reprocess 1650 tons per year of Magnox (magnesium covered natural uranium) fuel and 330 tons per year of LWR oxide fuel.
- More than 20,000 tons of Magnox fuel and 110 tons of oxide have been reprocessed. [22]
- British Nuclear Fuels, Ltd. has received approval to begin construction of a Thermal Oxide Reprocessing Plant (THORP), with a capacity to process 1200 tons per year. [23]
- The British also have a small test facility for reprocessing fuel from their prototype fast breeder reactor at Dounreay. [24]

Reprocessing in the United States

- Commercial nuclear fuel reprocessing is not permitted in the United States under current Administration policy.
- U.S. reprocessing is currently being performed at Government facilities essentially for defense operations.

- Liquid high level waste is produced as a chemical by-product of reprocessing. This material is being temporarily stored prior to its solidification.
- Defense HLW is now being stored at several Government-owned sites, mostly in improved design, double-walled, carbon steel tanks in Washington, South Carolina and Idaho.
- The double-walled storage tanks were designed to replace early design (1945) single-walled concrete tanks lined with carbon steel after leakage was reported at the Government's Hanford facility.



Hanford Storage Facility

- The value of natural barriers in preventing the spread of radioactive materials was demonstrated by the Hanford experience. The leaked waste was retained by the first few yards of dry sediment below the tanks.
- No leakage or serious problems have been encountered with the improved double-walled, carbon steel tanks. [25,26]
- The only operational U.S. commercial reprocessing facility, at West Valley, NY, is now shut down.
- About 600,000 gallons of liquid high level waste is in storage at this site. [2]
- Two-thirds of this material resulted from the reprocessing of defense spent fuel assemblies from the Hanford site.
- The Department of Energy has been authorized by Congress to prepare a plan to solidify the high level waste at West Valley.

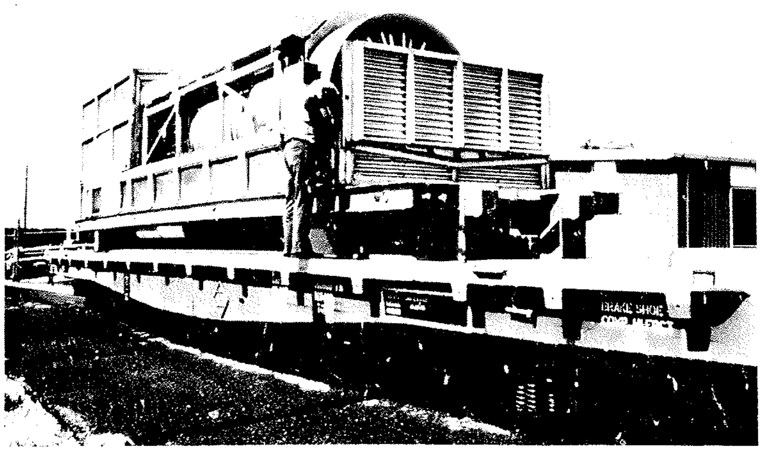
2 Transportation

There are approximately 500 billion packages of all commodities shipped each year in the United States.

- About 100 million involved hazardous materials (flammables, explosives, poisons, corrosives and radioactive materials).
- About 2 percent of these involve radioactive materials.

Radioactive materials transportation has an excellent record of safety.

- 1,000,000 shipments of nuclear materials to date (mostly radiopharmaceuticals), with a lower than average vehicle accident rate
- 4000 spent fuel assemblies transported to date (in U.S.) with a perfect public health and safety record. [27]
- Canada: More than 500 spent fuel shipments, with the same perfect record. [28]



Spent Fuel Shipping Cask

- Sweden: More than 700 tons of spent nuclear fuel transported to reprocessing plants in Europe, using both land and sea routes. [29]
- United Kingdom: A British newspaper comments, "Although transport operations have now been carried out throughout the world over a period of thirty years, there has not been a single death or injury due to the radioactive nature of these shipments." [30]
- Radioactive materials make up only 2 percent of the shipments of hazardous materials in the U.S. Only 0.5 percent of the accidents involve these materials, and almost all of these involved small packages which contained very little radioactivity.
- 33 percent of the radioactive shipments contain so little radioactive material that a license to transport is not required.
- 44 percent consists of licensed shipments for medical and industrial purposes.
- 13 percent are licensed shipments for the nuclear fuel cycle.
- 10 percent of the total shipments are nuclear waste. [31]

There are two basic approaches to protecting the health and safety of the public and workers in the transportation industry during the transport of radioactive materials [32] :

- Limiting the amount of the material in the package.
- Above certain limits, special testing of the package.

- Example: Up to 1 millicurie (mCi) of iodine 131, an isotope widely used in medicine, could be shipped without any special packaging. Shipping over 1 millicurie, but not over 3 mCi of iodine 131, would require a package designed to provide protection during normal freight handling, but not during accident conditions (Type A package). If over 3 mCi of iodine 131 is to be shipped, a package designed to provide protection during accidents is required (Type B package).

Some of the low level waste can be shipped in Type A containers, but all spent fuel and high level waste require Type B containers. Shipping casks must pass tests designed to simulate accident conditions, such as [33] :

- A 30-foot free drop onto a flat unyielding surface with the cask oriented such that maximum damage will occur.
- A 40-inch free drop onto the top end of a 6-inch diameter, 8-inch high mild steel bar with the cask oriented such that maximum damage will occur.
- Exposure to a 1475 °F fire for a 30-minute period, with no artificial post-fire cooling.
- Immersion of the entire cask in water to a depth of three feet for at least eight hours.

Spent fuel shipping casks are probably the most carefully designed shipping containers made by man:

- A very strong steel shell (1-inch thick)
- Surrounded by 8 to 12 inches of lead, which is protected by
- Another 4-1/2 inch steel shell.
- Radiant cooling fins are welded to the outer steel cylinder to remove any heat generated by the radioactivity in the fuel elements.

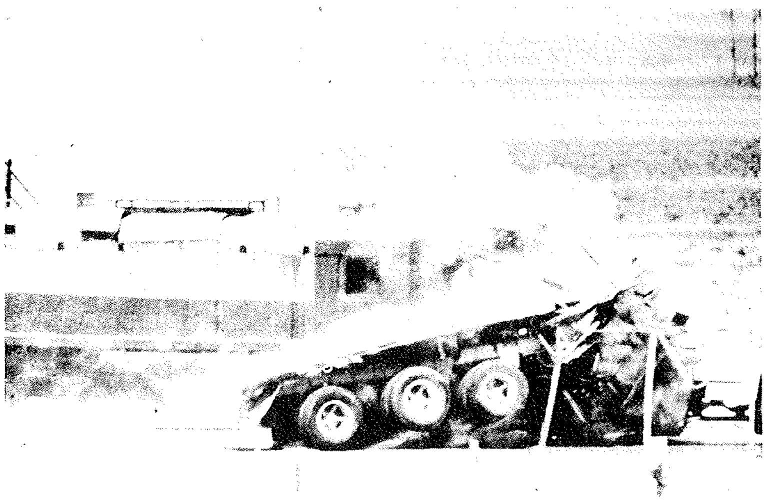
- Ends of outer cylinder have massive flanges designed to protect the finned sides.
- Entire cask weighs from 25 to 100 tons.

Many tests have already been performed on these shipping casks, including some extremely harsh ones:

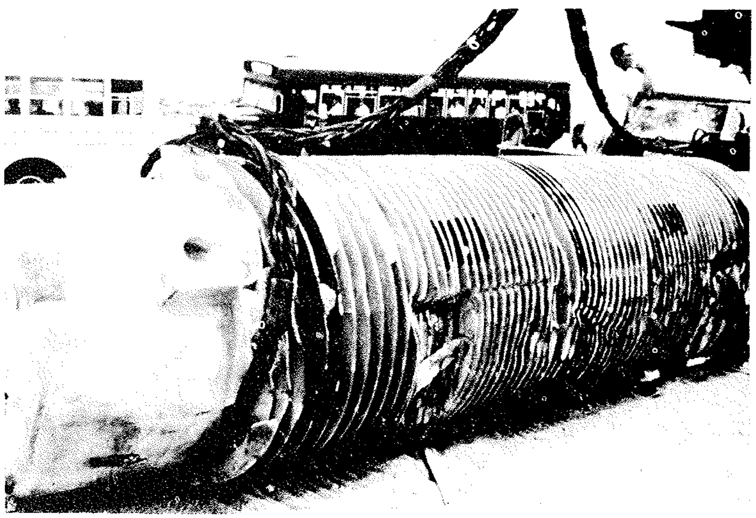
- Sandia Laboratories, New Mexico: A rocket-propelled locomotive was crashed at 80 mph into a cask to simulate an extreme accident. The truck-carrier and the locomotive were demolished, but there was no leakage detected from the cask. [34]

Each step of the nuclear fuel cycle involves the transportation of some radioactive material, ranging from very low levels of activity (enriched uranium to the fuel fabrication plant) to very high-activity materials (spent fuel to a reprocessing plant).

- The transport step for spent fuel and high level waste is expected to occur two or three times, or more, depending on the fuel cycle sequence.
- The transport and handling systems in use have been developed over 30 years of research and operation in both military and commercial programs.
- All nuclear shipments are regulated by the Department of Transportation (DOT), the Nuclear Regulatory Commission (NRC), and various state and local ordinances.



Locomotive Impact Test.



Shipping Cask after Impact.

3 Disposal

Disposal of Nuclear Waste

This section is concerned with the disposal of high level nuclear waste. Many of the points made here are also applicable to the disposal of transuranic nuclear waste.

Objective of Nuclear Waste Disposal

- To isolate existing and future nuclear waste generated by defense and commercial activities from the biosphere so as to pose no threat to public health and safety.

Important Time Factor

- First 1000 years—This is generally accepted as the most critical period for high level waste disposal.
- Most of the intermediate-lived fission products will decay within that period.
- These are the fission products which contribute to the major radiation dose.
- The thermal effects—and the hazards—of the waste continue to decrease with time.

Multi-Barrier Approach

- Nuclear waste disposal relies on a multi-barrier approach to achieve the required level of isolation.
- Barrier No. 1: The waste form and its associated engineered barriers (sometimes called the waste package).
- Barrier No. 2: The disposal medium—a massive barrier between the waste and the biosphere.
- Barrier No. 3: The institutions of man, including adequate repository markers. It appears that U.S. regulations will limit consideration of institutional controls.

Each of these barriers will be discussed in detail in the following pages.

The Waste Form

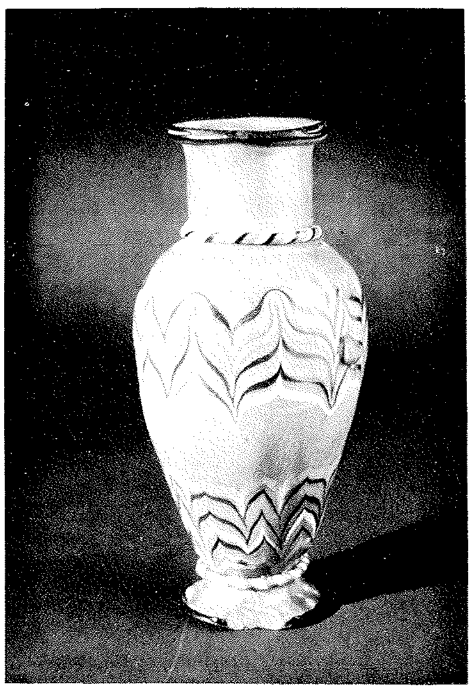
Glass was selected as the preferred waste form early in the U.S. program, as well as in several foreign programs. Some of the reasons for this choice are [35]:

- Insensitivity to waste composition.
- High resistance to radiation damage.
- Low leach rates and low solubility in water.
- Moderate temperature (~1000 °C) required for preparation.

Ancient Glasses

The samples of ancient glasses shown below are owned by the Corning Museum. Both of these glasses have survived the ravages of time, even though no specific precautions were taken to assure their safety. [35]

- The Egyptian glass was produced more than 3000 years ago.
- The Roman glass is about 2000 years old.
- Neither of these glasses was made to be durable. Rather they were created as decorative art.



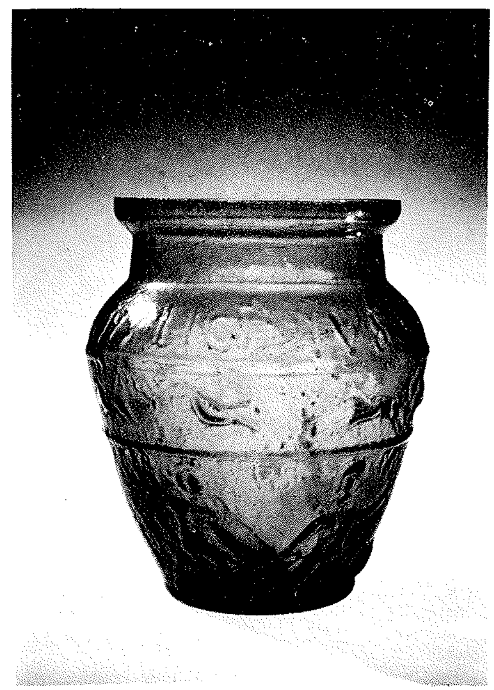
Egyptian Glass - 3000 Years Old

- Current technology permits the production of glasses several hundred times as durable.

Glass Development for Nuclear Waste

Incorporation of fission products in glass has been investigated in detail for the past 30 years.

- Borosilicate glass waste forms have been produced in the U.S. with leach rates measured in the laboratory of 10^{-6}g/cm^2/day in water.
- The leach rate of borosilicate glass is initially diffusion dependent, but after a short time ($\sim$1 year) becomes more dependent on the dissolution rate of the glass.



Roman Glass - 2000 Years Old

- Battelle Northwest has estimated that the leach time for a 1-ft. diameter x 10-ft. long glass monolith is approximately **150,000 years.** 36]
- Similar borosilicate glass waste forms have been produced in France with laboratory leach rates in the range of 10^{-7} to 10^{-8}g/ cm^2/day. This is an equivalent leach time of **1 million** to **10 million** years.
- As part of the U.S solidification program, radiation effects on waste glasses equivalent to 250,000 years of storage have been studied in detail and found to be minor. [3,35]
- These studies have emphasized the actinides, since their radioactive decay produces the alpha-recoil particles. These particles have the most potential for causing effects in waste glass.

Canadian Research and Testing

In Canada, nepheline syenite glass waste forms show a leach rate of about 10^{-10}g/ cm^2/day in groundwater after remaining in-situ for 20 years. The equivalent leach time for this easy-to-produce glass form is millions of years. [28]

- Canada is one of the few countries which has field tested the storage of nuclear waste in glass.
- In 1960 at Chalk River, 25 glass samples, each about 6 inches in diameter and containing 1100 curies of fission products, were placed in the ground.
- These were completely exposed to water flowing at 7 inches per day, without any barriers.
- The loadings in the Canadian experiment were kept low to eliminate the temperature as a significant variable (5×10^{-3}Ci/g of Sr 90).
- Measurements of Sr 90 concentration in the water have been carried out for 20 years.
- Measurements indicate that the long-term Sr 90 concentration is less than the maximum permissible concentrations in the Federal regulations (10CFR20).

Canadian Burial Test Site

Glass or Ceramic?

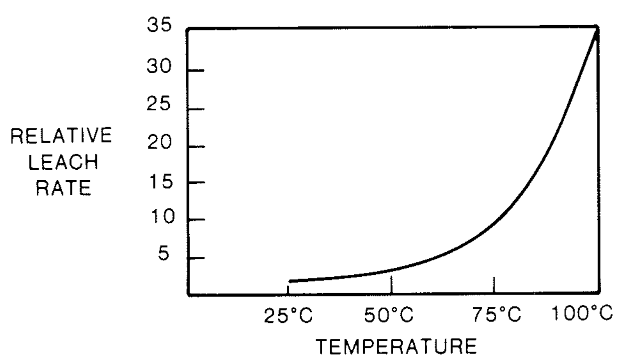
There is some controversy within the scientific community as to whether ceramic or glass is the optimum solid form for long-term high level waste storage.

- The National Academy of Sciences/National Research Council concluded that glass is an adequate solid waste form. [37]
- Some scientists, however, have criticized the selection of glass.
- They base their concerns on devitrification data and leach data at temperatures of 200 to 300° C.

Reduced Fission Products = Reduced Temperature

- Temperatures as high as 200-300 ° C will only be reached with the relatively high fission product concentration (~25%) being considered as an option in the U.S.

LEACH RATE OF GLASS vs. TEMPERATURE



- The proposed Swedish waste storage system will achieve a maximum temperature at the surface of the glass of 65° C.
- This is possible by reducing the fission product concentration to **9%** and allowing for 40 years' decay before implacement in the repository.
- A reduction of the U.S. waste from 25% to 5% will result in the same maximum temperature of 65° C at the glass surface after only 5 years' decay.
- Reduction of the fission concentrations in the glass is the key to its satisfactory performance.
- Reducing the fission product concentration results in significant increases in resistance to devitrification and significant decreases in leach rates, compared to higher temperatures. [26,29]

Natural Devitrification

- Devitrification is the rate at which glass crystallizes.
- Examples of the effect of temperature in glasses can be found in nature.
- For perlite, a natural glass, the rate of devitrification is 5000 times higher at 200° C than at 100° C. [38]
- Devitrification does not destroy the value of the glass solid waste forms as a barrier. A devitrified glass usually has a leach resistance only about 10 times worse than if it had remained a glass. [39]

Need for In-Situ Testing

- In-situ tests of the waste storage form in flowing groundwater in the geologic environment is an essential element of any program to demonstrate the adequacy of the nuclear waste storage system.
- Even though the sites for in-situ tests will require groundwater flow, an actual repository site will still be chosen to minimize flowing groundwater.
- Such tests will provide realistic data for use in fission product transport and dose analyses.

Solidification Experience

- Solidification of high-level liquid waste has been performed at the Government's Idaho National Engineering Laboratory since the early 1960s.
- The process for solidification of commercial high level waste has already been demonstrated at the Battelle Pacific Northwest Laboratories. [40]
- The French began to operate a pilot commercial solidification plant at Marcoule in July 1978. The plant, Atelier de Vitrification de Marcoule (AVM) was designed as the world's first continuous vitrification plant on a full commercial scale. AVM produces a 53-cubic-foot block of glass per day. [41,42]
- AVM produces about 1,940 cubic feet of borosilicate glass per year, the equivalent waste produced by thirty-three 500 megawatt gas-cooled reactors.
- Another such plant for La Hague, called AVH, is now being designed and is scheduled for completion in the early 1980s. This plant will have about double the capacity of AVM.
- The French process is presently being considered by Germany, Belgium and the United Kingdom for use with their planned reprocessing plants, even though many other processes for waste solidification have been developed and run on the pilot scale.
- Since the 1950s, international programs have tested different products for leachability, radiation damage, thermal effects, corrosion, erosion and other properties.
- All tests and demonstrations indicate that a vitrified form of waste solidification is a suitable waste form for disposal. [28,35,43]

Engineered Barriers

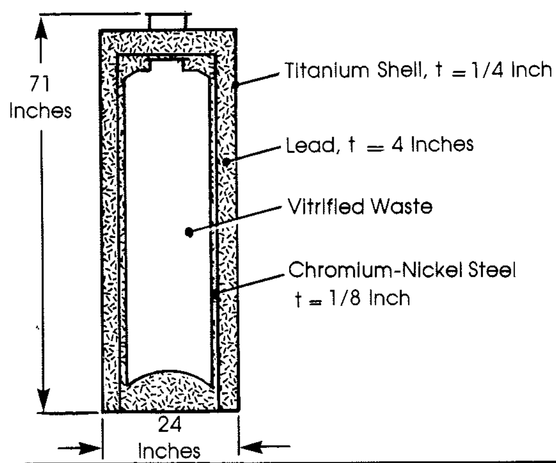
- In addition to the waste form and various geologic barriers, engineered barriers can also be provided, if required for a specific waste disposal system.
- These barriers can include the waste canister, which is required for the handling and transportation of the waste form.
- It can include the use of an overpack, which can be another canister or a buffer material, such as bentonite, between the waste canister and the geologic media. Detailed discussions of engineered barriers can be found in references [44,45,46] .

Disposal Medium

A wide variety of nuclear waste disposal concepts have been considered over the years. These include:

- Deep geologic disposal, using conventional mining techniques.
- Injection of liquid waste into wells (reverse well disposal).
- Disposal in very deep (5 miles) drilled holes.
- Rock melting concepts, where the hot liquid high level waste is injected into an underground cavity and the heat from the waste and ensuing waste/rock interaction produces a stable solid form.
- Disposal on offshore islands.
- Chemical partitioning of the waste, followed by synthesis of the waste products into very stable mineral forms prior to concentrated geologic disposal.

VITRIFIED HIGH LEVEL WASTE IN CANISTER OF LEAD AND TITANIUM

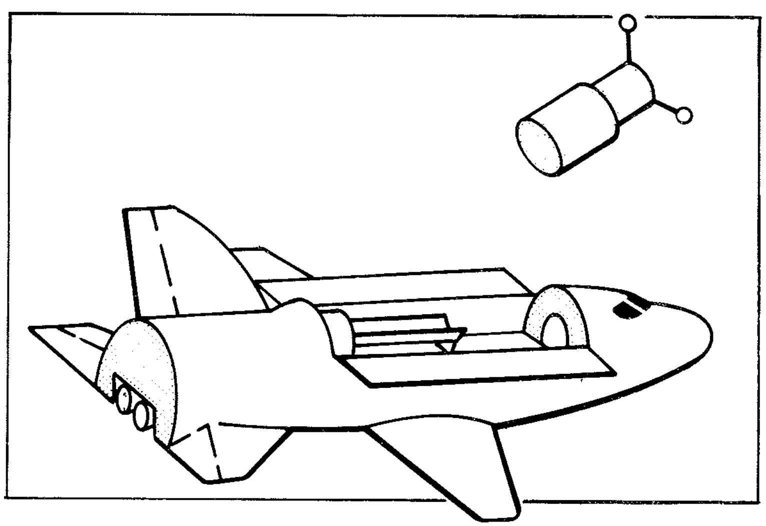


- Reduction in long-lived actinide (transuranium alpha emitter) content by more extensive chemical reprocessing and "burning up" the actinides in a breeder or fusion reactor.
- Rocket ejection into outer space.
- Burial in the antarctic ice-cap.
- Disposal in very stable areas of the sea-bed.

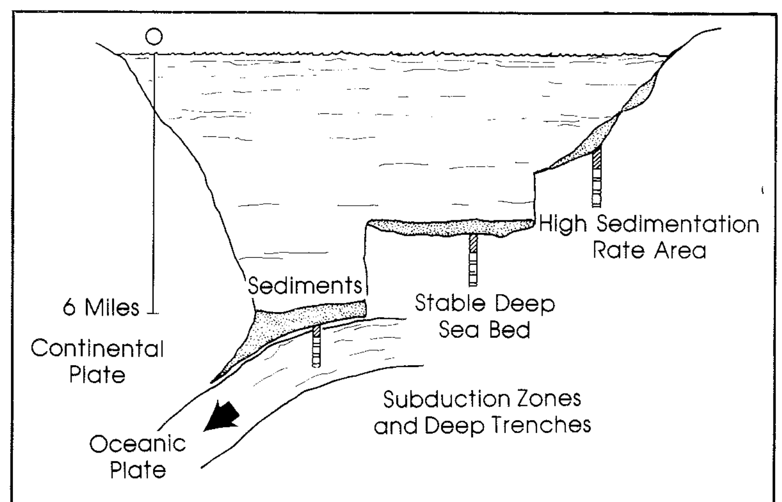
GEIS Report on Alternative Concepts

- The Government's recent Generic Environmental Impact Statement (GEIS) concerning management of commercially generated radioactive waste provides detailed discussions on the above disposal options.[46]
- GEIS indicates no major obstacles exist to the successful development of deep, geologic disposal in a safe, cost-effective and timely manner. Most experts consider disposal of high level waste in a stable geologic formation to be the most practical approach.[47]
- According to GEIS, the other alternative options are still in infant status of development, as follows:
- **Reverse Well and Rock Melting:** Lack of control over the waste immediately after it is placed in the geologic formations.
- **Very Deep Drilled Holes:** Requires both advances in drilling technology and development of methods to partition the waste further, so that only a very small residue of waste nuclides requires deep hole disposal.

- **Offshore Islands:** Not very different from conventional geologic disposal, except for location. The basic trade-off is that the dilution afforded by the water around the island, should water reach the waste, is offset by the need for sea transport of the waste. Island disposal is more applicable to countries such as Japan, which have only limited land areas.
- **Chemical Resynthesis & Actinide Recycle:** Both require advanced reprocessing technologies for more refined partitioning of the various waste nuclides. Not only is this advanced technology unavailable now, but care must be taken to avoid creating large quantities of LLW and TRU waste, which will also require disposal.
- **Outer Space:** Requires rocket technology that is reliable enough to provide assurance for public health and safety—a technology that does not yet exist.



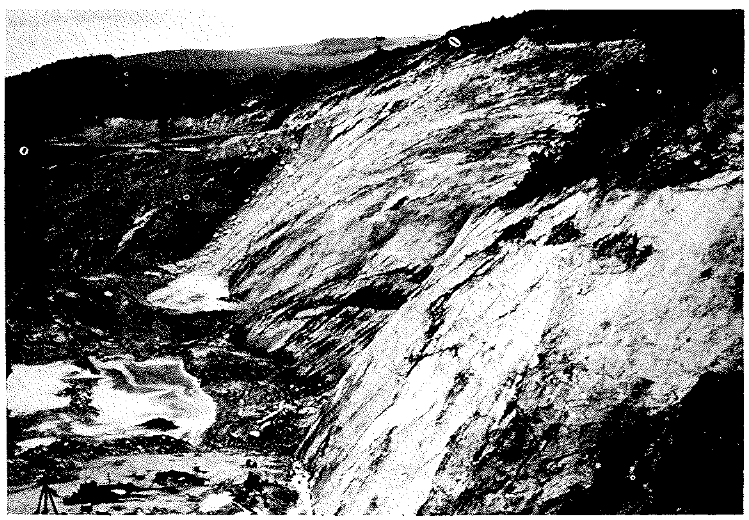
- **Antarctic Ice Cap:** Requires solving the problems of transportation over thousands of miles of ocean, the large number of unknowns concerning the movement of ice sheets, and existing international treaties restricting such activities.
- **Sea Bed:** Has some merit, but a great deal of additional research must be done.
- **Geologic Disposal/Conventional Mining Techniques:** While there are uncertainties in this method, all of the alternatives to geologic disposal either fail to give the same degree of protection to the public, involve greater uncertainties, or are not advanced enough to represent realistic disposal alternatives.



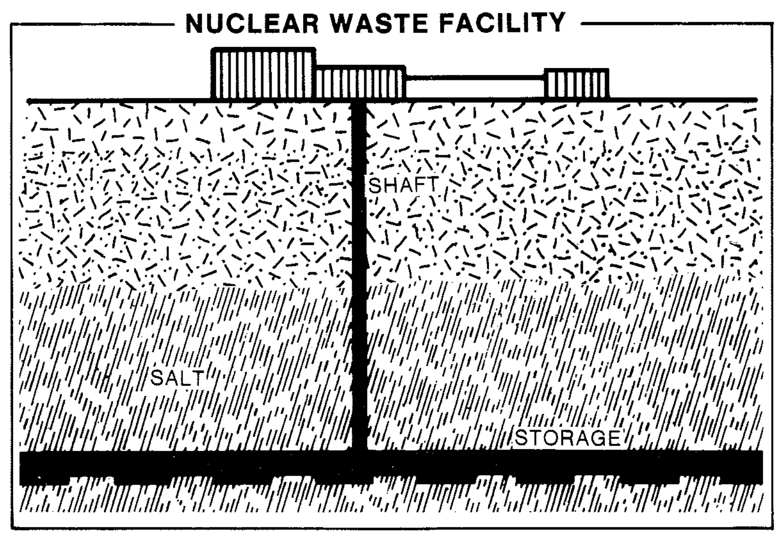
Sea Bed Disposal

Advantages of Geologic Disposal

- Stable geologic formations have existed in a relatively undisturbed state for hundreds of millions of years. This gives some confidence that waste can be safely disposed of, especially for 500 to 1000 years when the hazard is still higher than that of the ore used to produce the original nuclear fuel. [47]
- Geologic systems have long-term stability. An example of this stability is the Oklo phenomenon, where a natural nuclear reactor was created in a rich uranium deposit in what is now West Africa. The site was discovered in 1972, and since then the fission products and actinide isotopes in the vicinity have been studied exhaustively. After 2 billion years, all of the long-lived actinides, such as plutonium, have stayed at their point of origin. [48,49]
- Bedded salt, salt domes, clays, shales, granites and basalts are all being considered for the permanent disposal of nuclear waste. [46]
- By placing the waste several thousand feet below the surface of the earth, the geologic medium can provide highly effective barriers between the radioactivity in the waste and the public. [46]
- Geologic disposal of radioactive waste has been under development for the last twenty years, and the technology for doing it is available.



Oklo



Mined Geologic Disposal Sites

- While there are a number of approaches available for geological disposal, such as the use of deep drilled holes or rock melting concepts, the use of a mined repository is the best developed of these options and presents the fewest technological uncertainties. [46]
- Some scientists are concerned about the interaction of the geology with the waste at high temperatures.
- This uncertainty can be resolved by initially setting conservative thermal limits on the concentration of the waste in the solid waste form. This also improves the durability of the solid form.
- The number of canisters can also be limited within the repository.
- A number of geological media are under active investigation in the United States, including salt in New Mexico, the Gulf States and Utah, basalt in the State of Washington, and granite in Nevada. [25]

Waste Disposal in Salt

The first U.S. waste repository will probably be constructed in a salt geologic medium. Salt formations have been and continue to be the most investigated candidates for waste disposal facilities in the U.S.

Advantages of Salt [50,51]

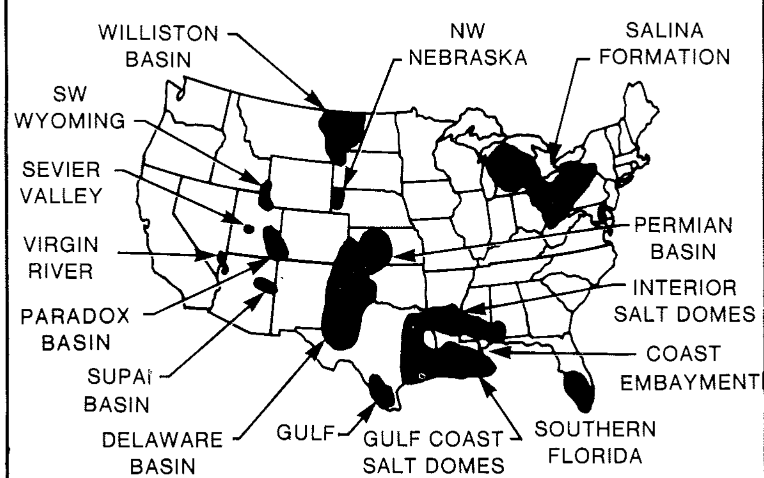
- Salt is relatively easy to mine and is found in great abundance in the U.S.
- Salt can be found in areas which are geologically very stable (very small probability of earthquakes).
- Salt can flow under pressure, and, thereby, "heal" any breaks in the deposit due to geological disturbances.
- Salt has a high thermal conductivity and a high resistance to radiation damage.
- Permian (200 million years old) salt deposits, by their very existence, demonstrated that these deposits have remained free of any significant amount of circulating groundwater for several hundred million years.

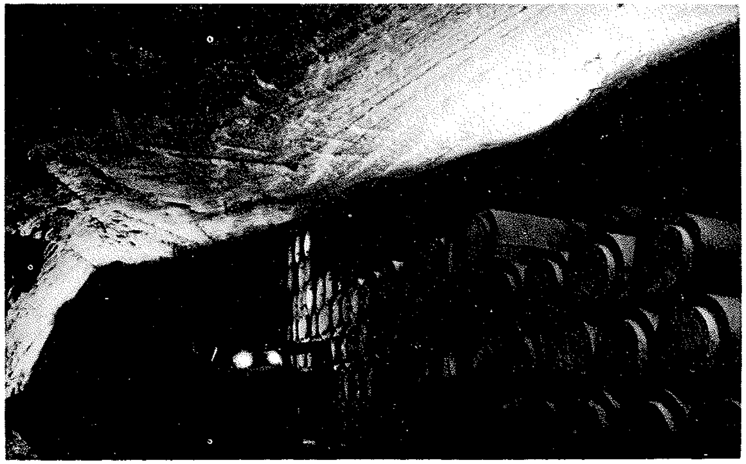
- Although salt can dissolve in water, salt deep underground is highly impermeable. It is also usually found with alternating beds of shale, which tend to keep the water out.
- Concerns expressed about salt as a disposal medium generally center on the corrosive nature of the brines. These are present even in very dry salt and migrate toward a source of heat. The use of conservative engineering practice, such as keeping the temperature of the waste below 100° C, can largely overcome these concerns.

Uses of Salt

- Salt is the best understood of the geologic media for nuclear waste disposal (based on 20 years of research). It is an appropriate medium which can be used for an early scale demonstration.
- The National Academy of Sciences/National Research Council recommended salt as a prime candidate for the geological disposal of radioactive waste as early as 1957. This position was reaffirmed in 1961, 1966 and 1970. [47]
- More recently, a Fuel Cycle Study Group of the American Physical Society, concluded in 1977 that salt is a satisfactory medium for the disposal of high level waste. [52]
- In West Germany, 80,000 drums of solidified low and medium level waste have been disposed of in the Asse Salt mine, which began operation in 1967. Present plans call for the start of field tests of solidified high level waste disposal in salt in the mid-1980s. [53]

ROCK SALT DEPOSITS





Asse Salt Mine

Foreign Programs for Geologic Disposal [19]

Some form of geologic disposal has emerged as the preferred waste disposal system in each of the major nuclear countries around the world.

- The West German program emphasizes geologic disposal in salt, as does the Netherlands.
- The programs in Sweden, the United Kingdom, France and Canada are concentrating on crystalline rocks, such as granite and basalt.
- The Italians and the Belgians are investigating clays, mudstone and shales.
- The work at the Asse Salt Mine in Germany plus the Swedish and Canadian efforts in crystalline rock all demonstrate that there are potentially suitable formations for waste disposal.
- Further studies in Denmark, France, the Federal Republic of Germany, the Netherlands, Sweden, Switzerland and the United Kingdom all concluded that deep geological burial is clearly feasible.
- There appears to be considerable technical consensus in these foreign programs that interim storage and subsequent disposal in deep geologic formations will provide the safest and most flexible approach.
- In several of these countries there is not only a technically acceptable method of waste disposal, but it is also politically acceptable to proceed.

The Institutions of Man

At the beginning of this section, a multi-barrier approach to high level nuclear waste disposal was presented. This included consideration of the solid waste form and the geological medium. Often overlooked is the potential barrier provided by the institutions of man. The dismissal of the potential benefit from human institutions likely results from a lack of historical perspective in a nation only 200 years old. In the rest of the world, there are examples of preservation by human activity.

For example:

- There is a wooden temple in Japan (see picture) 1300 years old. [54]

1300 Year Old Wooden Shrine

- There are many churches and monasteries in Europe still in daily use after more than 1000 years.
- The Ka'ba in Mecca has been the center of the Moslem world for over 1000 years.
- The dikes in the Netherlands have been maintained for about 1000 years in spite of changes in governments.
- The Great Wall of China dates initially from the third century B.C. and has been subject to improvements by human intervention to the present time.
- The pyramids of Egypt, the Roman roads, and the ganats (tunnels for water) of ancient Persia, works of man thousands of years old, as well as stone-age tools and paintings, which have been preserved for tens of thousands of years, have survived with minimal human intervention.

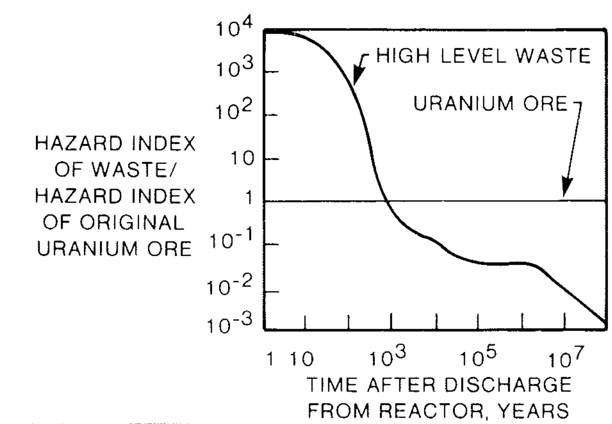
A prudent course of action is to design a waste disposal system which takes no credit for human institutions for the long-term isolation of nuclear waste. However, it would also be prudent to maintain some limited activities such as monitoring of regional groundwater and the placement of durable markers for the repository site.

4 Hazards

Numerous assessments have been made of the hazards associated with the long-term disposal of nuclear waste in geological formations:

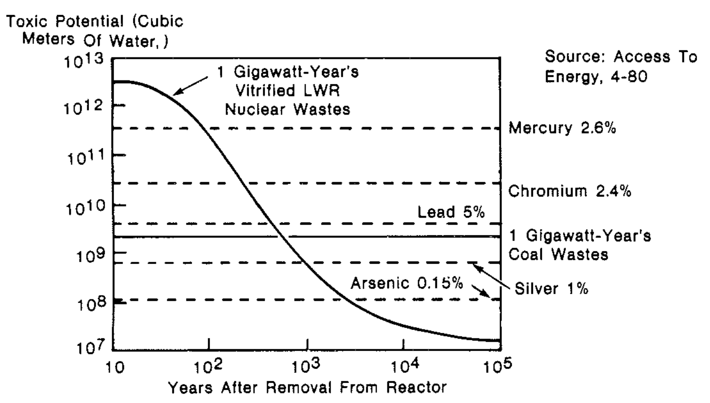
- Waste must be isolated for a minimum of ten half-lives of plutonium 239, or 240,000 years. This is an old rule-of-thumb, but we now know that half-life is not the most important factor from a radiological health standpoint.
- A better approach is to consider the water required to dilute radioactive materials to the maximum permissible concentrations (MPCs) allowed by federal regulations. Flowing water is the most likely mechanism for transport of the radioactivity in waste to man's environment.
- In less than 1000 years, reprocessed high level waste has a relative toxicity equal to that of the natural uranium ore from which it came. After the first 500 years, the strontium 90 and cesium 137 waste products have decayed to insignificant levels. This makes the waste significantly cooler, more stable, and, therefore, less hazardous. Some of the radioactive elements in the high level waste remain radioactive for hundreds of thousands of years, as in the natural uranium ore.
- The accompanying figure plots the toxicity index for the reprocessed high level waste derived from that quantity of natural uranium ore. (15, 54). The toxicity index compares an MPC relative to the MPC of natural uranium ore required to produce one ton of nuclear fuel. [55]
- If spent fuel is disposed of directly, it also drops in toxicity with time. However, its toxicity index does not reach that of natural uranium ore until about 10,000 years later. [55]
- After about 500 years, the reprocessed high level waste is also less hazardous than concentrations of many elements which are found in nature. These include mercury, cadmium, selenium, lead, silver and barium. [55]
- The risk from high level waste in a geologic repository after 100 years is much less than that from toxic nonradioactive chemicals now being handled routinely by society. These include barium, arsenic, chlorine, phosgene and ammonia. [46]
- The use of MPCs depends on standards selected by the Government. As such, they are subject to some changes. The use of MPCs does provide some perspective in the relative hazard potential of the waste compared to other substances.

URANIUM ORE vs. NUCLEAR WASTE

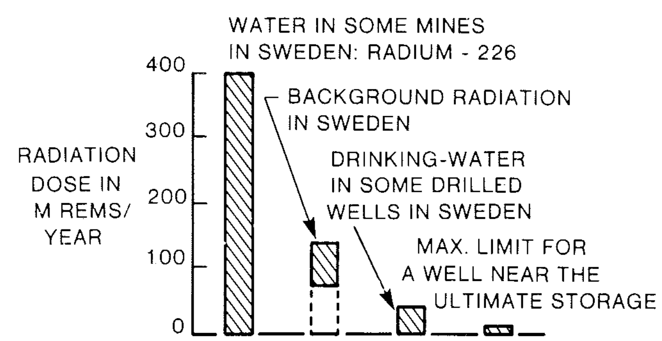


- More complete analysis must consider the actual solid form of the waste, the effect of any other engineered barriers, and the protection provided by placing the waste several thousand feet beneath the surface of the earth.
- Studies performed at the Battelle Pacific Northwest Laboratories indicate that using reasonable assumptions about solid form, engineered containment, and the pathways to man, the maximum annual dose to an individual in the vicinity of the repository is significantly below the annual dose this person would normally receive from natural background radiation. This statement includes consideration of the highly unlikely event that flowing water should enter the repository. [36]
- A Swedish study resulted in similar conclusions. An analysis of a proposed Swedish disposal system shows that even if the geologic barrier is penetrated by water, a person getting well water from the vicinity of the repository would get a maximum annual radiation dose from the waste equal to only about 10% of the annual dose received from natural background radiation. The disposal system studied consists of high leach resistant glass, a titanium and lead container, a packing of bentonite and quartz-sand to reduce water flow by a factor of 200, and the placing of the waste in granite 1600 feet below the surface. [29]

TOXIC SUBSTANCES



SWEDISH SAFETY ANALYSIS



35/52

5 U.S. Programs

The Federal Government has responsibility for storing spent fuel at away-from-reactor (AFR) sites and for the disposal of commercial high level and transuranic waste. The Government is also responsible for the disposal of defense generated nuclear waste.

The Department of Energy (DOE) has been assigned the responsibility for developing the required waste management technologies, and for building and operating the required AFR and disposal facilities.

- Government studies and development work on nuclear waste management have been underway for three decades.
- Substantial technical programs are in place under the Department of Energy. Current funding levels are about $600 million per year, an amount which has quadrupled between fiscal years 1976 and 1980. [25]
- Confidence has now increased to the point where the majority of informed technical opinion holds that the capability now exists to characterize and evaluate media in a number of geologic environments for use as repositories built with conventional mining technology. [2,52]
- The President's Interagency Review Group (IRG) on Nuclear Waste Management concluded that no scientific or technical reason is known that would prevent identifying a site that is suitable for a repository provided that a systems approach is utilized. This group included representatives from DOE, NRC, EPA and ten other executive branch departments. [2]
- The IRG final report made recommendations but did not resolve many key issues which will impact on the timing of the first defense and commercial repositories.
- Actions by the Administration and Congress are required to establish a focused, national plan for nuclear waste management. The key elements of this plan include:
  - Timely and realistic standards and regulations by NRC and EPA consistent with a specified DOE schedule to construct storage and disposal facilities.
  - AFR storage capacity provided as required to support continued reactor operations.
  - Scale demonstrations of nuclear waste disposal systems to help to provide early resolution to institutional (political and social) issues.
  - A step-wise progression to final repository operations.
  - Implementation of a State consultation and cooperation process, maintaining ultimate Federal pre-eminence.

DOE Waste Management Programs [25]

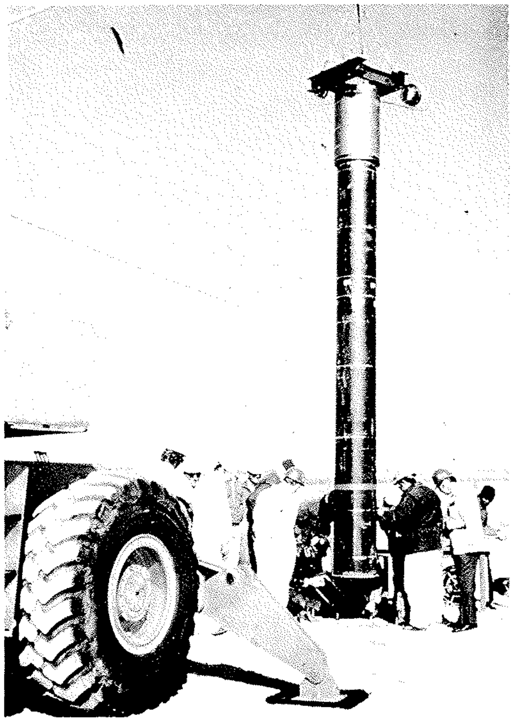
- The DOE Waste Management Program consists of Defense Waste Management, Commercial Waste Management and Spent Fuel Storage activities. The overall responsibility for these programs is assigned to DOE's Office of Nuclear Waste Management.
- The management of supporting technical and construction programs have been delegated to various lead DOE field offices and contractors.

Geologic Disposal

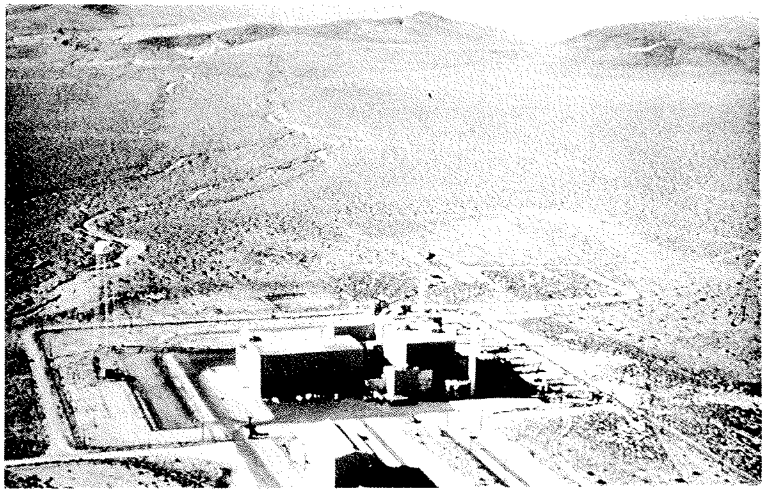
DOE has three major programs for the geologic disposal of commercial high level waste and one major program for the geologic disposal of defense waste. As presently scheduled, they could result in the first repository for commercial HLW to be operational in the mid-1990s. WIPP, the first repository for defense waste, could be operational by about 1986.

- **National Waste Terminal Storage Program:** The objective of this program is to locate, develop and operate repositories for disposal of commercial high level waste and transuranic waste. DOE has assigned program management to the Office of Nuclear Waste Isolation (ONWI) at Battelle Columbus. Regions being actively investigated include the bedded salt basins in Utah, New Mexico and Texas plus the salt domes in Mississippi, Louisiana and Texas. The ONWI program is being expanded to include crystalline formations in the U.S.

- **Hanford Basalt Waste Isolation Program:** This program will determine the feasibility and develop the technological capability for design, construction and operation of a repository in basalt on the DOE site at Hanford, Washington.
  - This repository would be used for disposal of commercial waste. Waste/rock interaction studies and borehole plugging studies, and geologic and hydrologic evaluations are currently in progress. Construction of the first phase of the Near Surface Test Facility (NSTF) will be completed in 1981. HLW demonstration in NSTF is planned to begin by 1982.
- **Nevada Terminal Waste Isolation Program:** This program evaluates the suitability of the Nevada Test Site (NTS) as a potential repository for commercial waste and conducts development work applicable to other sites. The geologic program is focusing on the tuff formations at NTS.
  - Technology development work is being conducted in support of ONWI generic programs. This includes operation of the Climax Spent Fuel Facility to test the behavior of granite with encapsulated spent fuel. Commercial waste and spent fuel packaging programs are being conducted at the E-MAD Facility. Dry storage technology programs are also underway at this NTS facility.

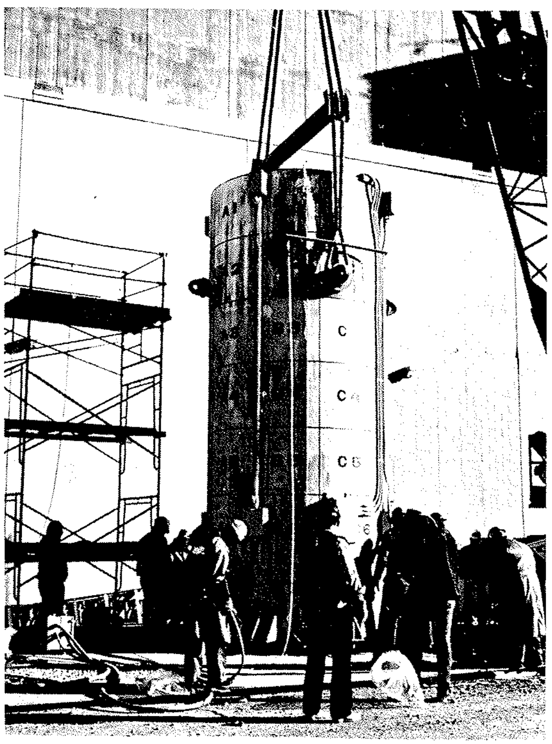


Dry Storage Test Location



E-MAD Facility

- **Waste Isolation Pilot Plant (WIPP)**: This DOE project is concerned with the disposal of defense, transuranic waste. The proposed site is located in southeast New Mexico.
  - The WIPP project has the earliest potential to address the outstanding institutional issues which require resolution in nuclear waste management (e.g., to establish an effective working relationship between the State and Federal Government, and to demonstrate the NEPA process, including meaningful public participation).
  - DOE is clearly much further along on repository design and site suitability work for WIPP than in any other location. Meaningful scale demonstrations at other candidate sites are many years behind WIPP.
  - In view of the extensive geological, environmental, and design investigations already completed, further development of the WIPP site and design will also provide early resolution of technical uncertainties related to the bedded-salt medium.



Storage Cask at E-MAD Facility

6 Conclusions

1. Spent fuel storage can be accomplished safely until reprocessing and waste disposal facilities become available.
2. To the maximum extent possible, spent fuel should be stored at reactor sites. However, some away-from-reactor storage capacity must be provided by the Government, as required to support reactor operations.
3. Waste disposal facilities must be provided regardless of the future growth of commercial nuclear power, since there will continue to be a growing inventory from existing defense and commercial activities.
4. Mined geologic disposal offers the most promising approach to waste disposal.
5. Adequate technology is available for waste disposal in geologic formations.
6. Facilities are needed to demonstrate disposal technology and to dispose of the waste that already exists.
7. Timely actions are needed to implement a focused national plan for nuclear waste management. Key elements of this plan include scale demonstrations of waste disposal systems, timely and realistic standards/regulations, and an effective State consultation and cooperation process.

[Note: For more detailed information on nuclear waste management, see Ref. 56 by Energy Research Group Inc.]

7 Glossary

- **Actinide Series**
  The series of elements beginning with actinium, Element No. 89, which together occupy one position in the Periodic Table. The series includes uranium, Element No. 92, and all the man-made transuranic elements. The group is also referred to as the "Actinides."

- **Activation**
  The process of making a material radioactive by bombardment with neutrons, protons, or other nuclear particles.

- **Alpha Particle**
  [Symbol α (alpha)] A positively charged particle emitted by certain radioactive materials. It is made up of two neutrons and two protons bound together; hence is identical with the nucleus of a helium atom. It is the least penetrating of the three common types of radiation (alpha, beta, gamma) emitted by radioactive material and can be stopped by a sheet of paper. It is not dangerous to plants, animals or man unless the alpha-emitting substance has entered the body.

- **Alpha Waste**
  See TRU waste.

- **Anhydrite**
  A mineral consisting of calcium sulfate: $CaSO_4$. It is gypsum free of water.

- **Atom**
  A particle of matter indivisible by chemical means. It is the fundamental building block of the chemical elements. The elements, such as iron, lead, and sulfur, differ from each other because they contain different kinds of atoms. There are about six sextillion (6 followed by 21 zeros, or 6×10^{21}) atoms in an ordinary drop of water. An atom contains a dense inner core (the nucleus) and a much less dense outer domain consisting of electons in motion around the nucleus.

- **Background Radiation**
  The radiation in man's natural environment, including cosmic rays and radiation from the naturally radioactive elements, both outside and inside the bodies of men and animals. It is also called natural radiation. The term may also mean radiation that is unrelated to a specific experiment.

- **Basalt**
  A dark, igneous rock, usually formed as lava flows.

- **Bedded Salt**
  Consolidated layered salt separated from other layers by distinguishable planes of separates.

- **Beta Particle**
  [Symbol β (beta)] An elementary particle emitted from a nucleus during radioactive decay, with a single electrical charge and a mass equal to 1/1837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is called a positron. Beta radiation at high doses may cause skin burns and beta-

emitters are harmful if they enter the body. Beta particles are easily stopped by a thin sheet of metal, however.

- **Biosphere**
  The part of the world in which life can exist.

- **Brine Inclusion**
  A small opening in a rock mass (salt) containing brine; also the brine included in such an opening. Some gas may also be present.

- **Burial Grounds**
  Areas designated for storage of containers of radioactive wastes by near-surface burial in surface soils.

- **Calcine**
  To heat to a high temperature without fusing to drive off volatile matter or affect other chemical changes. Also the product of calcination.

- **Commercial Reactors**
  Operate to produce heat for generating electricity. In this process some of the uranium is consumed and some is converted to plutonium.

- **Contact-Handled Waste**
  Waste that does not require shielding other than that provided by its container.

- **Containment**
  The retention of radioactivity within a system to the exclusion of its release to the biosphere in unacceptable quantities or concentrations.

- **Conversion and Enrichment**
  Fluoride form of uranium is produced which has a higher fraction of uranium 235 (i.e., 3-4%) than that contained in natural ore (i.e., 0.7%). The depleted uranium that results from this process, called "tailings," is predominately uranium 238.

- **Curie**
  The basic unit to describe the intensity of radioactivity in a sample of material. The curie is equal to 37 billion disintegrations per second, which is approximately the rate of decay of 1 gram of radium. A curie is also a quantity of any nuclide having 1 curie of radioactivity. Named for Marie and Pierre Curie, who discovered radium in 1898.

- **Daughter**
  A nuclide formed by the radioactive decay of another nuclide, which in this context is called the parent.

- **Decay, Radioactive**
  The spontaneous transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide. The process results in a decrease, with time, of the number of the original radioactive atoms in a sample. It involves the emission from the nucleus of alpha particles, beta particles (or

electrons), or gamma rays, or the nuclear capture or ejection of orbital electrons.

- **Devitrify**
  To change a glass to a crystalline form.

- **Dose (Radiation)**
  A general term indicating the amount of energy absorbed per unit mass from incident radiation.

- **Dose (Equivalent)**
  The product of absorbed dose and modifying factors that take into account the biological effect of the absorbed dose. While dose includes only physical factors, dose equivalent includes both physical and biological factors and provides a radiation-protection scale applicable to all types of radiation. Units are defined as rems for an individual.

- **Enrichment**
  See conversion and enrichment.

- **Fission**
  The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur spontaneously, but usually is caused by nuclear absorption of gamma rays, neutrons or other particles.

- **Fission Products**
  The nuclides (fission fragments) formed by the fission of heavy elements, plus the nuclides formed by the fission fragments' radioactive decay.

- **Food Chain**
  The pathways by which any material passes from the first absorbing organism through plants and animals to man.

- **Fuel Cycle**
  The series of steps involved in supplying fuel for nuclear power reactors. It includes mining, refining, and the original fabrication of fuel elements, their use in a reactor, chemical processing to recover the fissionable material remaining in the spent fuel, re-enrichment of the fuel material, refabrication into new fuel elements and disposal of waste.

- **Fuel Fabrication**
  The fluoride is converted to an oxide and forms the uranium oxide into small pellets, which are loaded into metal tubes (fuel rods) and the tubes are inserted into fuel assemblies for use in nuclear reactors.

- **Gamma Rays**
  [Symbol γ (gamma)] High energy, short-wavelength electromagnetic radiation. High energy gamma rays are very penetrating and are best stopped or shielded against by dense materials, such as lead or depleted uranium. Gamma rays are similar to light and radio waves, but are more energetic, and are nuclear in origin.

- **Half-Life**
  The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Half-lives vary from millionths of a second to billions of years.

- **High Level Waste (HLW)**
  The highly radioactive liquid waste from the reprocessing of spent fuel.

- **In-Situ**
  In the natural or original position. The phrase is used in this document to distinguish in-place experiments, rock properties, and so on, from those in the laboratory.

- **Irradiation**
  Exposure to radiation, as in a nuclear reactor.

- **Intermediate Level Waste (ILW)**
  This term is sometimes used to describe non-high level waste which requires shielding to limit personnel exposures to radiation during handling and transport. This term is not being used in the U.S.

- **Isotope**
  One of two or more atoms with the same atomic number (the same chemical element) but with different atomic weights. An equivalent statement is that the nuclei of isotopes have the same number of protons but different numbers of neutrons. Thus, $12C_6$, $13C_6$, and $14C_6$ are isotopes of the element carbon (the subscripts denoting their common atomic numbers; the superscripts denoting the differing mass numbers, or approximate atomic weight). Isotopes usually have very nearly the same chemical properties, but somewhat different physical properties.

- **Leaching**
  The process of extracting a soluble component from a solid by the percolation of a solvent (in this report, water) through the solid.

- **Lithostatic Pressure**
  Underground pressure due to the weight of overlying rock or soil.

- **Low Level Waste (LLW)**
  Any radioactive waste not classed as either high level or TRU waste and suitable for disposal in near-surface burial grounds rather than requiring, like high level waste, deep geologic disposal.

- **Maximum Permissible Concentration (MPC)**
  The amount of radioactive material in air, water, or food which might be expected to result in a maximum permissible dose to persons consuming them at a standard rate of intake for a lifetime.

- **Mining and Milling**
  Uranium ore is extracted from the earth and connected to a form called yellowcake.

- **Nano**
  A prefix that divides a basic unit by one billion (10^9). For example, a nano-curie is one billionth of a curie.

- **Nuclide**
  A general term applicable to all atomic forms of the elements. The term is often erroneously used as a synonym for "isotope," which properly has a more limited definition. Whereas isotopes are the various forms of a single element (hence, are a family of nuclides) and all have the same atomic number and number of protons, nuclides comprise all the isotopic forms of all the elements. Nuclides are distinguished by their atomic number, atomic mass, and energy state.

- **Overpack**
  A container put around another container. In the WIPP, overpacks will be used on damaged or otherwise contaminated drums, boxes, and canisters that it is not practical to decontaminate.

- **Parent**
  A radionuclide that upon radioactive decay or disintegration yields a specific nuclide (the daughter), either directly or as a later member of a radioactive series.

- **Population Dose**
  The sum of the radiation doses received by the individual members of a population.

- **Radiation**
  The emission and propagation of energy through matter or space by means of electomagnetic disturbances which display both wave-like and particle-like behavior; in this context the "particles" are known as photons. Also, the energy so propagated. The term has been extended to include streams of fast-moving particles (alpha and beta particles, free neutrons, cosmic radiation, etc.). Nuclear radiation is that emitted from atomic nuclei in various nuclear reactions, including alpha, beta and gamma radiation and neutrons.

- **Radioactivity**
  The spontaneous decay or disintegration of an unstable atomic nucleus, usually accompanied by the emission of ionizing radiation. (Often shortened to 'activity').

- **Remotely Handled Waste**
  Waste that requires shielding in addition to that provided by its container in order to protect people nearby.

- **Retrievable**
  Describes storage of radioactive waste in a manner designed for recovery without loss of control or release of radioactivity.

- **Sorption**
  The binding on a microscopic scale of one substance to another, such as by absorption or ion exchange. In the WIPP context, the word is especially used in the sorption of solutes onto aquifer solids.

- **Source Term**
  The kinds and amounts of radionuclides that make up the source of a potential release of radioactivity.

- **Spent Fuel**
  Nuclear reactor fuel that, through nuclear reactions, has been depleted of fissile material enough to require its removal from the reactor.

- **Storage**
  Temporary disposition in a repository. Use of the word storage implies keeping open the possibility of retrieving the waste for reprocessing, for moving it elsewhere, etc. Storage usually implies the need for continued surveillance.

- **Storage Pool, Spent Fuel**
  A water-filled and cooled basin in which spent fuel is stored prior to reprocessing or disposal.

- **Thermal Gradient**
  The rate of change of temperature in the direction of increasing temperature.

- **Transuranic Elements**
  Elements with mass number greater than 92. They include neptunium, plutonium, americium, and curium. See actinide series.

- **TRU Waste**
  Any waste material, other than high level waste, measured or assumed to contain more than a specified concentration. Since 1970 a level of 10 nanocuries of alpha emitters per gram of waste has been in effect. Geologic disposal of TRU waste will be required in the U.S.

- **Treatment**
  Operations intended to benefit safety or economy by changing the waste characteristics. Four basic treatment concepts are defined:

  — Volume reduction
  — Immobilization of radioactivity
  — Change of composition
  — Removal of radioactivity from the waste

- **Waste, Radioactive**
  Equipment and materials (from nuclear operations) which are radioactive and for which there is no further use.

8 References

References

1. U.S. Nuclear Regulatory Commission, Draft Code of Federal Regulations, 10 CFR Part 60, **"Disposal of High-Level Radioactive Waste in Geologic Repositories."** Draft dated September 1979.
2. Interagency Review Group, **"Report to the President by the Interagency Review Group on Nuclear Waste Management,"** TID-29442, March 1979.
3. U.S. Energy Research and Development Administration, **"Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle,"** ERDA 76-43, Vol. II, May 1976.
4. Dr. G. Oertel, **"The DOE Program in High Level Waste Immobilization,"** NUREG/CP-0005, December 1978.
5. **"Fact Sheet on the President's Program on Radioactive Waste Management,"** February 12, 1980.
6. National Environmental Studies Project, **"A Survey of Handling and Disposing of Solid Low-Level Nuclear Cycle Wastes,"** Atomic Industrial Forum, October 1976.
7. U.S. Nuclear Regulatory Commission, **"Review of the Federal/State Program for Regulation of Commercial Low-Level Waste Burial Grounds,"** NUREG-0217, March 1977.
8. U.S. Energy Research and Development Administration, **"Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle,"** ERDA 76-43, Vol. III, May 1976.
9. J. O. Blomeke, C. W. Kee and J. P. Nichols, **"Projections of Radioactive Wastes to be Generated by the U.S. Nuclear Power Industry,"** ORNL-TM-3965, 1974.
10. Ford, Bacon and Davis Utah Inc., **"Evaluation of Alternative Methods for the Disposal of Low Level Radioactive Waste,"** NUREG/CR-0680, July 1979.
11. U.S. Congress, 95th Congress, Public Law 94-604, **"The Uranium Mill Tailings Radiation Control Act of 1978."**
12. U.S. Nuclear Regulatory Commission, **"Code of Federal Regulations 10 CFR Parts 40 and 150,"** Federal Register, Vol. 44, No. 166, August 24, 1979.
13. U.S. Nuclear Regulatory Commission, **"Draft Generic Environmental Impact Statement on Uranium Milling,"** NUREG-0511, April 1979.
14. General Accounting Office, **"How to Dispose of Hazardous Waste — A Serious Question that Needs to be Resolved,"** CED-79-1B, December 19, 1978.
15. Dau, G. J. and Williams, R. F., **"Status of Commercial Nuclear High-Level Waste Disposal,"** NP-44-SR, Electric Power Research Institute, Palo Alto, California (September 1976).
16. Energy Research Group, Inc., **"Assessment of the Status of Commercial Nuclear Waste Storage Technology,"** In preparation.
17. U.S. Nuclear Regulatory Commission, **"Final Generic Environmental Impact Statement on Handling and Storage of Spent Light Water Reactor Fuel,"** NUREG-0575, September 1979.

18. D. C. Lelland, et. al., "**A Review of European High-Level Waste Solidification Technology,**" International Symposium on the Management of Wastes from the LWR Fuel Cycle, Denver, Colorado, U.S.A. (1976).

19. "**International Symposium on the Underground Disposal of Radioactive Wastes,**" Helsinki, Finland (2-6 July 1979).

20. Boulton, J. (ed.), "**First Annual Report of the Canadian Nuclear Fuel Waste Management Program,**" AECL-6443, Atomic Energy of Canada Limited (December 1979).

21. "**Marcoule Vitrification Plant Start-Up Announced,**" Nuclear Engineering International Vol. 23, No.10 (1978 March).

22. "**Inquiry Report Supports BNFL Reprocessing Plant,**" Nuclear Energy International, Vol. 15, No. 5 (May 1979).

23. "**BNFL Gets Going Again on Thorp,**" Nuclear Engineering International, Vol. 23, No. 274 (July 1978).

24. Nuclear News, Page 20, Vol. 20, No. 10 (August 1978).

25. U.S. Department of Energy, "**Nuclear Waste Management Program Summary Document,**" DOE/ET-0094, April 1979.

26. Panel on Hanford Wastes, "**Radioactive Waste at the Hanford Reservation—A Technical Review,**" National Academy of Sciences, Washington, D.C., 1978.

27. J. W. Langhaar, "**Transport Experience with Radioactive Materials,**" Proceedings of the International Symposium on the Management of Waste from the LWR Fuel Cycle, CONF-76-0701, Denver, CO. (1976).

28. Boulton, J. (ed.), "**Management of Radioactive Fuel Wastes: The Canadian Disposal Program,**" AECL-6314, Atomic Energy of Canada Limited (October 1978).

29. "**Safe Handling and Storage of High Level Radioactive Waste: A Condensed Version of the Proposals of the Swedish KBS Project Regarding Reprocessing Waste and Spent Fuel,**" Karn-Brahsle-Sakerhet, Box 5864, S-102, 48 Stockholm. Sweden (1979).

30. Franklin, N. L., "**Irradiation Fuel Cycle,**" British Nuclear Fuels Limited, paper first presented at the European Nuclear Conference, Nuclear Energy Maturity, Paris, 21-25 April 1975.

31. U.S. Nuclear Regulatory Commission, "**Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Means,**" NUREG-0170, December 1977.

32. Code of Federal Regulations, 10CFR71, Appendix B.

33. U.S. Nuclear Regulatory Commission, Regulatory Guide 73, May 1975.

34. Atomic Energy Clearinghouse, March 28, 1977.

35. J. E. Mendel, "**The Storage and Disposal of Radioactive Waste as Glass Canisters,**" PML-2764, December 1978.

36. H. C. Burkholder, et. al., "**Incentives for Partitioning High-Level Waste,**" Nuclear Technology, November 1976.

37. National Academy of Sciences/National Research Council, "**Solidification of High-Level Wastes,**" Report of the Panel on Waste Solidification, December 1978.

38. R. R. Marshall, "**Devitrification of Natural Glass,**" Geological Society of America Bulletin, Vol. 72, October 1961.

39. Chemical Technology Division of Oak Ridge National Laboratory "**Annual Progress Report for Period Ending March 31, 1975,**" ORNL-5050, October 1975.

40. J. E. Mendel, "**Nuclear Waste Disposal,**" Testimony prepared for the Subcommittee on Energy, Nuclear Proliferation and Federal Services of the U.S. Senate, March 13, 1979.

41. "**French See Radwaste Process as 'Another Technical Triumph',**" The Energy Daily, Vol. 6, No. 213 (November 3, 1978).

42. Gauvenet, A., et. al., "**High Level Waste Management,**" Proceedings of the International Conference on World Nuclear Energy — A Status Report, Washington, D.C., November 14-19, 1976, published by American Nuclear Society (1977).

43. Testimony of Professor Gregory J. McCarthy on Nuclear Waste Forms Before the Senate Subcommittee on Energy Nuclear Proliferation and Federal Services (Glenn) of the Committee on Governmental Affairs (March 13, 1979).

44. Ingvar Wivstad, "**Swedish Utilities Design Completely Safe Disposal Route,**" Nuclear Engineering International, January 1978.

45. M. A. Clynne and R. W. Potter, II, "**P-T-X Relationships of Anhydrite and Brine and Their Implications for the Suitability of Anhydrite as a Nuclear Waste Repository Medium,**" Annual Meeting of the Materials Research Society, Boston, Massachusetts, November 28 - December 2, 1978.

46. U.S. Department of Energy "**Draft Generic Environmental Impact Statement — Management of Commercially Generated Radioactive Waste,**" DOE/EIS-0046-17, April 1979.

47. National Academy of Sciences, "**Risks Associated with Nuclear Power: A Critical Review of the Literature,**"April 1979.

48. G. A. Coman, "**A Natural Fission Reactor,**" Scientific American, July 1976.

49. R. D. Walton and G. A. Coman, "**The Relevance of Nuclide Migration at Oklo to the Problem of Geologic Storage of Radioactive Waste,**" IAEA-SM-204/1, June 1975.

50. J. O. Blomeke, et. al., "**Managing Radioactive Waste,**" Physics Today, August 1973.

51. Project Salt Vault, "**A Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines,**" R. L. Bradshaw and W. C. McClain," Eds., ORNL-4555, Oak Ridge National Laboratory, April 1971.

52. APS Study Group, "**Report to the American Physical Society by the Study Group of Nuclear Fuel Cycles and Waste Management,**" Review of Modern Physics, January 1978.

53. R. P. Raull, "**Waste Management in the Federal Republic of Germany—A Survey of Policy and R&D,**" IAED-CN-36/98, Salzburg, Austria, May 1977.

54. Japanese Temple.

55. J. J. Cohen and K. A. Tonnessen, "**Survey of Naturally Occurring Hazardous Materials In Deep Geology Formations: A Perspective on the Relative Hazard of Deep Burial of Nuclear Wastes,**" UCRL-52199, January 1, 1977.

56. I. A. Forbes et. al., "**Assessment of the Status of Commercial Nuclear Waste Storage Technology,**" Energy Research Group, Inc., July 1980.

For more information, contact:

Advanced Energy Systems Division P.O. Box 10864 Pittsburgh, PA 15236
(412) 892-5600 (Ext 6501)

PRINTED IN THE U.S.A.