Radioactive Waste

ISSUES AND ANSWERS

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Foreword

The American Institute of Professional Geologists is a nationwide organization of about 5,000 members representing all areas of specialization in the professional practice of geology. The Institute serves both the profession and the public through its certification program and its involvement in public affairs. One form of AIPG involvement in public concerns is publication of "issue papers" such as this one, dealing with current specific matters in which geology is significant to formulating prudent public policy, legislation, or governmental regulation.

The disposal of radioactive waste is currently a focus of public interest. Prudent public policy concerning disposal of radioactive waste requires a good understanding of the scientific, technical, and social issues involved. The purpose of this booklet is to provide policy-makers, legislators, and the general public with information to better understand the issues, particularly geological considerations.

We hope this booklet serves that purpose. If you have questions or comments, or if you would like additional copies, please contact:

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Material in this booklet was submitted by an AIPG ad hoc committee of experts on radioactive-waste disposal chaired by A. M. La Sala, Jr., and including A. F. Agnew, R. C. Benson, G. D. DeBuchananne, S. Gonzales, K. B. Krauskopf, B. M. Wilmoth, and R. M. Winar.

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Important note--This booklet furnishes general information in the spirit of developing enlightened management policy. This material is introductory, and not intended to provide detailed information or professional advice. Because each situation is unique, this booklet cannot be used in solving specific problems. The direct advice of professionals in the discipline is essential. (A Directory of Certified Professional Geological Scientists, giving names, addresses, and specialties, is available without charge from AIPG.)

TRU Wastes USDOE

Contents

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Understanding Radioactivity

Radioactivity. Nuclear Power. Atomic Weapons. Half-life. Plutonium. How familiar are the words, and yet how rarely they are understood. Since this booklet's purpose is to clearly explain the radioactive-waste disposal problem, we must first explain radioactivity, and why it is so dangerous.

Radioactivity is a natural process. Atoms of most substances are internally balanced, or "stable". They have no tendency to change, or break up into simpler atoms. But some complex atoms, like uranium, are unstable. They regain stability by expelling particles or bursts of energy, a process we call radiation-activity, or **radioactivity.** The phenomenon was discovered less than a century ago, in 1896.

Radioactivity is hazardous. The particles and energy emitted are invisible, odorless, tasteless, soundless--our senses cannot warn of their presence. But even modest amounts of radiation can cause sickness, cancer, and birth defects.

The troublesome particles and energy bursts are--

- **alpha particle** (actually two protons and two neutrons expelled from an atom's nucleus).
- **beta particle** (an electron expelled from an atom).
- **gamma radiation or "ray"** (a burst of wave energy like an x-ray).

Radiation is a health hazard because it can penetrate human tissue and "ionize" the atoms in living cells. The ionized atoms possess altered electrical charges, and therefore a different chemical behavior, which can upset normal body chemistry. If the radiation dose is severe enough, the result is **radiation sickness.**

Natural alchemy. Each time an unstable atom expels a particle of energy, the atom readjusts internally and becomes a different chemical element. For example, a uranium atom discharges an alpha particle and a gamma ray, and becomes a thorium atom. The thorium atom, also unstable, is radioactive; it expels an electron and gamma ray, and becomes a protactinium atom. This process continues (see Decay Chain) until the atom finally becomes a stable form of lead, and radiates no more.

This "natural alchemy" is extremely important. Going down the decay chain, the different elements have diverse characteristics. Some are more soluble in water, posing a hazard to ground-water supplies. One is a gas (radon), which is a breathable, airborne radioactive hazard. And each element has its own combination of alpha, beta, and gamma radiation, so that the risk related to each element varies.

Half-life is the time required for half of a radioactive element to decay into the next element in the decay chain. If you start with one pound of uranium, after 4.5 billion years pass, radioactive decay will have transmutted one-half of it into thorium, leaving 8 ounces of uranium. After another 4.5 billion years, half of the remaining 8 ounces will have decayed to thorium, leaving 4 ounces of uranium. And so on. Thus 4.5 billion years is the *half-life* of uranium.

The thorium is also radioactive, with a half-life of 24.1 days. In the first 24.1 days, half the thorium transmutes into protactinium; during the second 24.1 days half of the remaining half decays, etc. Note that different elements have widely different half-lives, from under one second to billions of years. Half-lives, like the speed of light, are fixed and can be neither accelerated nor slowed.

Radioactivity is measured by the *curie,* defined as 37 billion disintegrations (expulsions of particles or rays) per second. Most uranium has low radioactivity--only 0.0000003 curie per gram (11,000 disintegrations per second), and therefore a protracted half-life of 4.5 billion years. Strontium-90 is highly radioactive--140 curies per gram (5,180,000,000,000 disintegrations per second), with a briefer half-life of 28.1 years.

Nuclear reactions. Natural radioactivity comes from normal decay of unstable elements in rock, soil, and from space. But man-induced radioactivity is the product of two types of *nuclear reactions in uranium: fission* and *neutron-absorption.* Each requires a particular kind of uranium.

Uranium has several *nuclides* ("species" having different physical properties such as weight). Two nuclides are very important: *uranium-235* is essential in the *fission* reaction, and *uranium-238* is essential in the *neutron-absorption* reaction.

Fission of uranium-235. In 1938 German chemists found that bombarding uranium-235 atoms with neutrons caused the atoms to fission (split) into simpler ones, concurrently releasing a stunning volume of energy. Just one pound--a cubic inch--of fissioning uranium could yield the energy of 1,500 tons of coal, or nearly 10,000,000 kilowatt-hours of electricity. Fission also produces additional neutrons, which split more atoms, creating a *chain reaction.* If *controlled,* heat from the fission chain reaction could run steam turbines to generate electrical power. If *uncontrolled,* the abrupt release of energy would be a bomb.

THE URANIUM—238 DECAY CHAIN*

Radiation Emitted			Radioactive Elements	Half-life		
Alpha	Beta	Gamma		Minutes	Days	Years
☢		☢	Uranium-238			4.5 BILL
	☢	☢	Thorium-234		24.1	
	☢	☢	Protactinium-234	1.2		
☢		☢	Uranium-234			247,000
☢		☢	Thorium-230			80,000
☢		☢	Radium-226			1,622
☢			Radon-222		3.8	
☢	☢		Polonium-218	3.0		
	☢	☢	Lead-214	26.8		
☢	☢	☢	Bismuth-214	19.7		
☢			Polonium-214	(0.00016 second)		
	☢	☢	Lead-210			22
☢	☢		Bismuth-210		5.0	
☢		☢	Polonium-210		138.3	
	NONE		Lead-206		STABLE	

*Simplified; data from Lipschutz 1980. Three other decay chains exist.

Neutron-absorption of uranium-238. Uranium-238 behaves differently. When bombarded with neutrons, it does not fission like U-235. Instead, it absorbs neutrons and changes into *transuranic* elements ("beyond uranium" in weight). An example is plutonium, which happens to be like U-235: it fissions readily.

During World War II, the Manhattan Project successfully employed both reactions: uranium-235 fissioned over Hiroshima, and plutonium (created by neutron absorption) fissioned over Nagasaki.

Thus we first exploited the astonishing energy available in atoms. Since then, we have learned to use this energy in generating power, and to use radioactivity in medicine, instruments, geologic dating, and research.

This brings us to the focus of this booklet: all of these activities have generated hazardous nuclear waste which must be safely, permanently disposed of.

References: Murray 1982, Lipschutz 1980, Van Nostrand 1976, Encyclopedia Britannica 1977, NRC/NAS 1980, USDOE 1980.

The Goal: Protecting People From Radiation

How Much is Too Much?-- There are different types of radiation, and they have different abilities to do bodily harm. Also, body tissues differ in their resistance to radiation. To take these differences into account, radiation doses are measured in the unit called "rem" (Roentgen Equivalent Man*). Doses well over 10 rems can cause weakness, reddened skin, and reduced blood cell counts. A dose of 500 rems will kill half the people exposed.

In radioactive waste, our concern is with very small releases that could reach the public. Doses from such occurrences are tiny, and are measured in "millirems" (thousandths of a rem).

How significant are such doses? Their effects have been studied, using people who are occupationally exposed, such as nuclear workers and radiologists. These studies show that cumulative exposure does increase health risk. (The effects of *very* low exposure have not been determined, as they are overshadowed by health effects from other causes.)

But it is best to be on the safe side. Our view of radioactivity has been conservative and a health risk is presumed to exist from *any* exposure. Exposure of the general public must be kept to a minimum.

Protecting People from Radioactive Waste-- Everyone is exposed daily to small amounts of natural radiation, which apparently cause no harm. But when man's activities expose people to concentrated radiation, or to minor radiation for long periods, a hazard can exist. This is the reason for controlling the storage of radioactive waste, and regulating its disposal.

Federal, state, and local laws permit only extremely low exposure levels for the public. Since large-scale production of nuclear materials began during World War II, safety requirements have been continually tightened, so much that present standards allow general public exposure to man-caused radiation at only a fraction of the natural level.

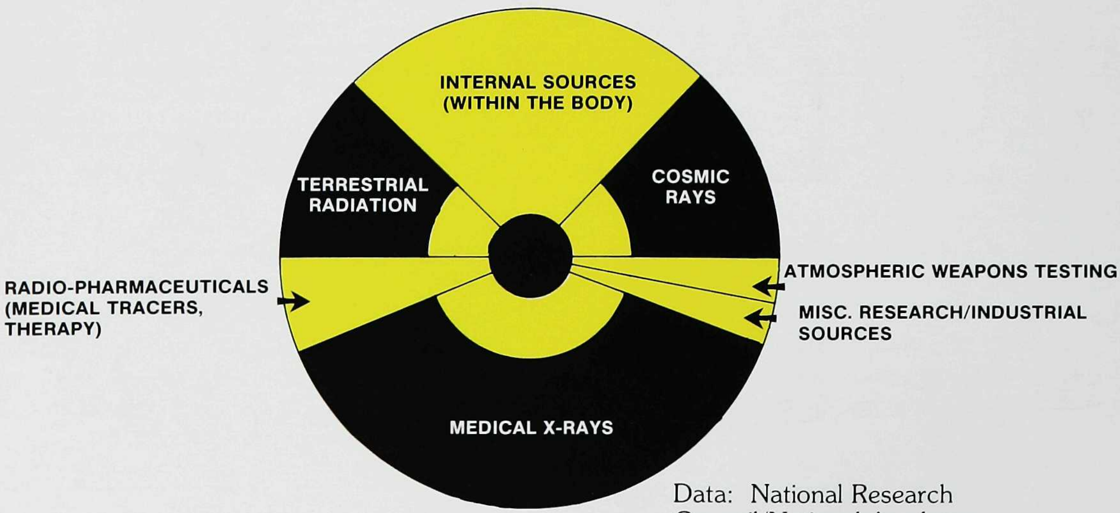
Unfortunately, these standards have also made nuclear-waste management difficult and expensive. The challenges of radioactive-waste management are:

- Disposing of large volumes of nuclear waste, within present stringent requirements.
- Raising to modern safety standards the older waste-management facilities, decommissioned nuclear operations, and uranium mill tailings.

References: NRC/NAS 1980; USDOE 1980.

*A roentgen is a unit of measure of the ionizing effects of radiation. Such technical terms are defined in the Glossary.

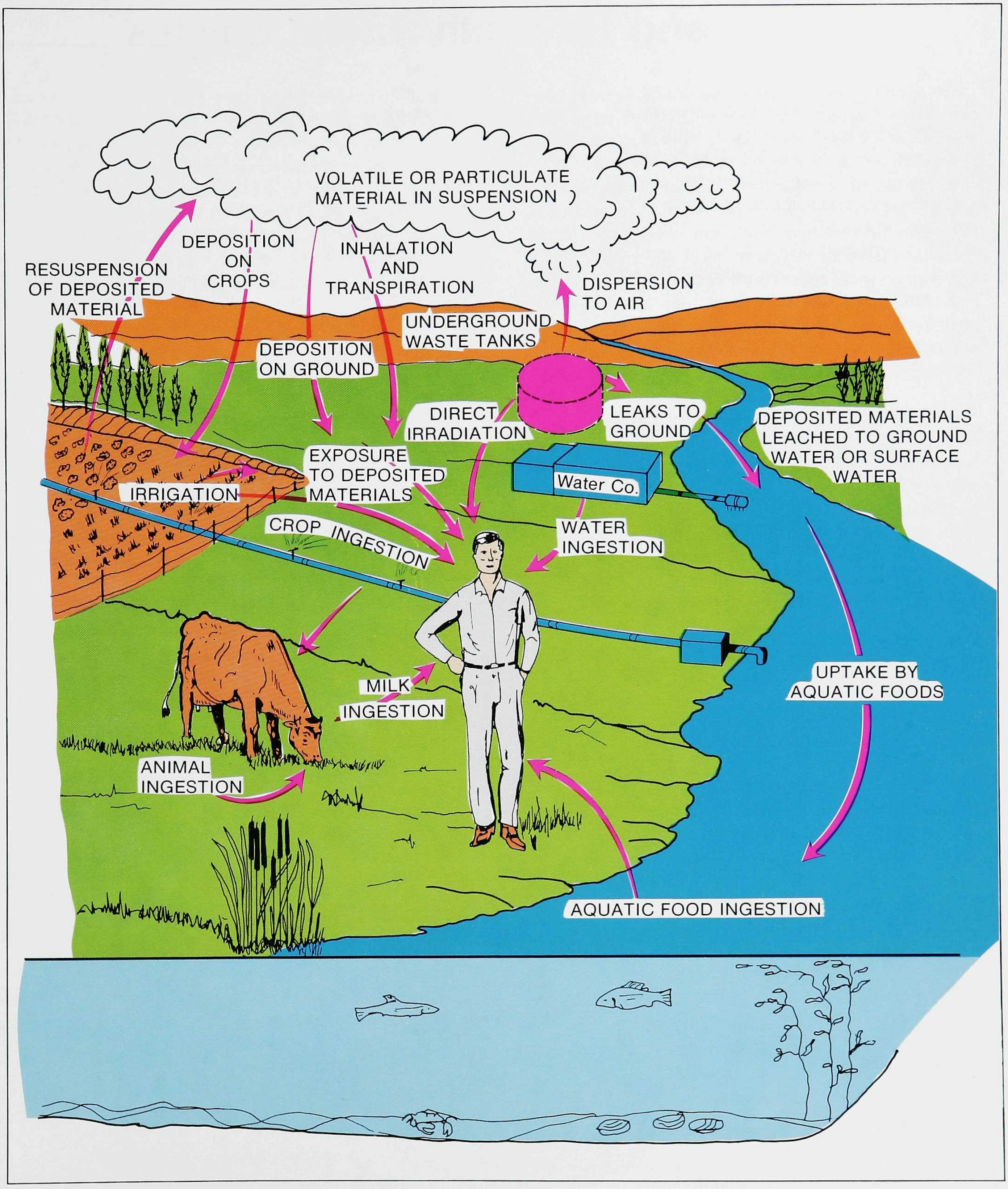
THE TYPICAL AMERICAN RECEIVES 208 MILLIREMS A YEAR FROM—



Data: National Research Council/National Academy of Sciences, Committee on Biological Effects of Ionizing Rac

Proportions of annual whole-body dose, by source. Doses to some medical, research, and industrial workers considerably exceed the 208 millirem average.

HOW RADIOACTIVE SUBSTANCES REACH PEOPLE



Courtesy of Pacific Northwest Laboratory

The Nuclear Fuel Cycle— and its Radioactive Wastes

The **nuclear fuel cycle** is the cradle-to-grave processing of uranium, from mining through permanent disposal of wastes. Every step in the fuel cycle creates radioactive wastes of varying volume and toxicity:

1. Mining of uranium ore-- about 20,000 tons of uranium ore is mined daily in the United States (mostly in Colorado, New Mexico, Utah, and Wyoming). Mining operations generate radioactive dust and release radon gas, a lung-cancer hazard principally to uranium miners.

2. Milling of uranium ore-- ore is ground and chemically concentrated into "yellowcake". Since only about 0.2% of the ore is the desired uranium, 99.8% of the ore becomes "mill tailings", a slightly radioactive sand.

3. Conversion and enrichment-- yellowcake contains both uranium nuclides, U-235 and U-238. U-235 is the one needed for fission reactions, but it comprises only 0.7% of yellowcake. Thus the goal is to "enrich" the percentage of U-235 to the 3-4% needed by reactors. The most-used method converts yellowcake to a gas and forces it against a porous barrier. The slightly-lighter U-235 passes through the barrier easier than U-238. Repeated thousands of times, this "gaseous diffusion" process gradually concentrates (enriches) the U-235 to 3-4%. Substantial low-level radioactive wastes are generated by this process.

4. Nuclear-fuel fabrication-- the enriched gas is converted to solid, fingertip-size pellets of uranium dioxide and loaded into long tubes *(fuel rods)* which are bracketed together into *fuel assemblies.* The operation produces low-level radioactive wastes.

5. Nuclear fuel in the reactor-- when the chain reaction is started, some remarkable physics ensues: (a) U-235 atoms fission into about 30 simpler elements, many radioactive; (b) copious heat energy is released, and is usually used to generate steam; (c) nonfissioning U-238 (comprising 96-97% of the fuel) absorbs neutrons to form several transuranic elements, including plutonium; and, (d) the plutonium itself fissions (by the time a fuel rod is "spent," nearly a third of its energy is from fissioning plutonium). Each year, one-third of the fuel rods are considered "spent" and become waste. Overall, reactors produce the most significant radioactive wastes in the fuel cycle.

6. Reprocessing of spent fuel is possible to recover residual U-235 and plutonium, for making new fuel rods or weapons. At present, reprocessing for weapons is conducted by the U. S. Department of Energy, but reprocessing of power-plant fuel rods has been halted indefinitely. Substantial high-level radioactive waste is produced in reprocessing.

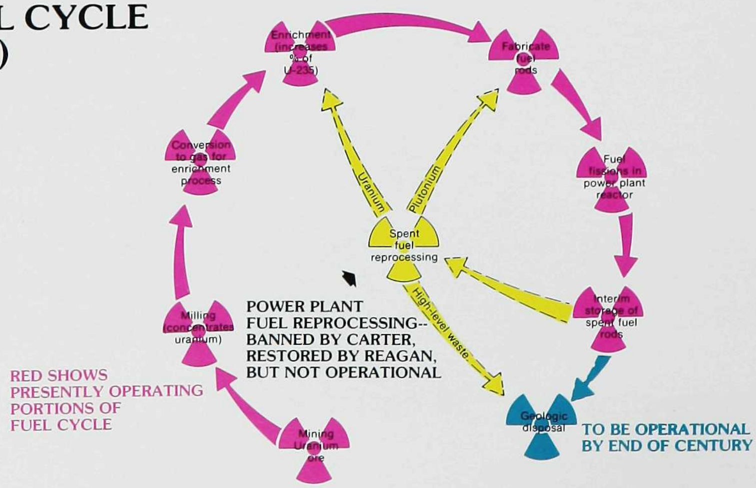
7. Spent-fuel storage-- spent-fuel rods are stored in cooling pools near the reactors. The amount of this extremely radioactive waste grows yearly from the approximately 80 power-plant reactors in the U. S., and it awaits permanent disposal.

8. Permanent disposal-- ultimately, all of these wastes--tailings, high-level, low-level, transuranic, and spent-fuel--must be permanently disposed of. Each type of waste poses special problems (intensity or radiation, its longevity, its volume, or a combination).

In the following pages, we examine each type of waste and disposal methods in greater detail.

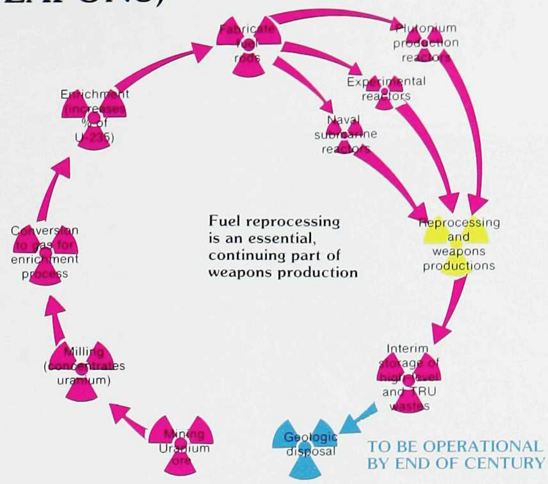
References: Lipschutz 1980, Murray 1982, USDOE 1980, Van Nostrand 1976, Encyclopedia Britannica 1977.

NUCLEAR FUEL CYCLE (COMMERCIAL)



Every step generates radioactive waste.

NUCLEAR FUEL CYCLE (WEAPONS)



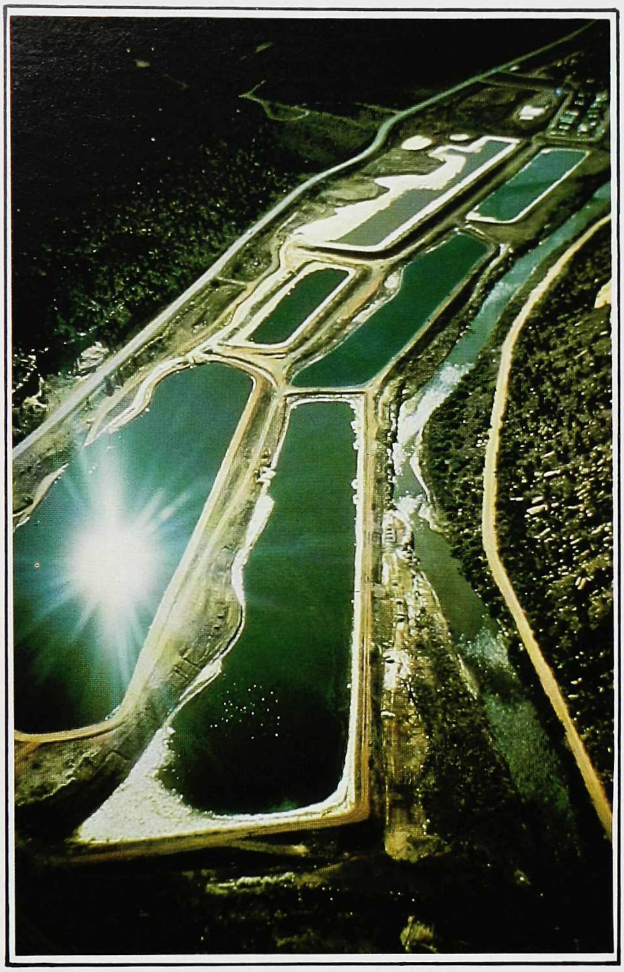
Every step generates radioactive waste

Source: USDOE

Nuclear Fuel Cycle Wastes

WASTE	MANAGEMENT TECHNIQUE
Mill tailings--wastes from the refining of uranium ore are a moderate radioactivity hazard due to soluble radium and radon gas. (The most plentiful type of radioactive waste.)	Secured against erosion; isolated from inhabited areas.
Spent fuel rods from commercial reactors-- very highly radioactive.	Stored in water-filled pools at reactor sites (a small amount is pooled at two unused commercial fuel-reprocessing plants). Underwater storage is long-term but temporary, until permanent disposal can be achieved.
High-level liquid wastes from nuclear reprocessing-- very highly radioactive.	Often reduced to a slurry or solidified. Stored in tanks, a long-term but temporary measure, until permanent disposal can be achieved.
Transuranic wastes-- mostly assorted laboratory refuse (equipment, supplies) contaminated with traces of the TRU elements plutonium, neptunium, americium, etc. Most TRU wastes have fairly low radioactivity, but are generated in large quantities and have long half-lives.	Formerly disposed of by shallow land-burial. But due to long-term hazard, they are now carefully packaged and buried for retrieval when permanent disposal can be achieved.
Low-level wastes-- highly varied, some solid, some liquid. Much of it is so low in radioactivity that it can be contact-handled.	Buried in shallow landfills, with barriers to ground water, and guarded from human intrusion.

Uranium Mill Tailings—the Insidious Waste



Mill tailings USDOE

Mill tailings are the sand-like residue and slimes that remain after uranium ore is finely ground and chemically treated to extract the uranium. Over 99% of the original processed ore becomes tailings, and their total volume is nearly 20 times that of all other forms of radioactive waste. However, tailings are the least radioactive of nuclear wastes.

Although tailings radiation is modest, it is insidious. As the residual uranium decays (see decay chain, p. 3), it changes to a gas, radon. The radon is inhaled, and soon (half-life only 4 days) changes back into metallic radionuclides of lead, bismuth, and polonium which lodge in the lungs, radiating into tissues for years. In this Machiavellian fashion, lung cancer has resulted in uranium miners. People living near tailings are under risk.

Decaying uranium also produces radium, which is readily leached out of tailings by rain and ground water, and thus dispersed into the human environment.

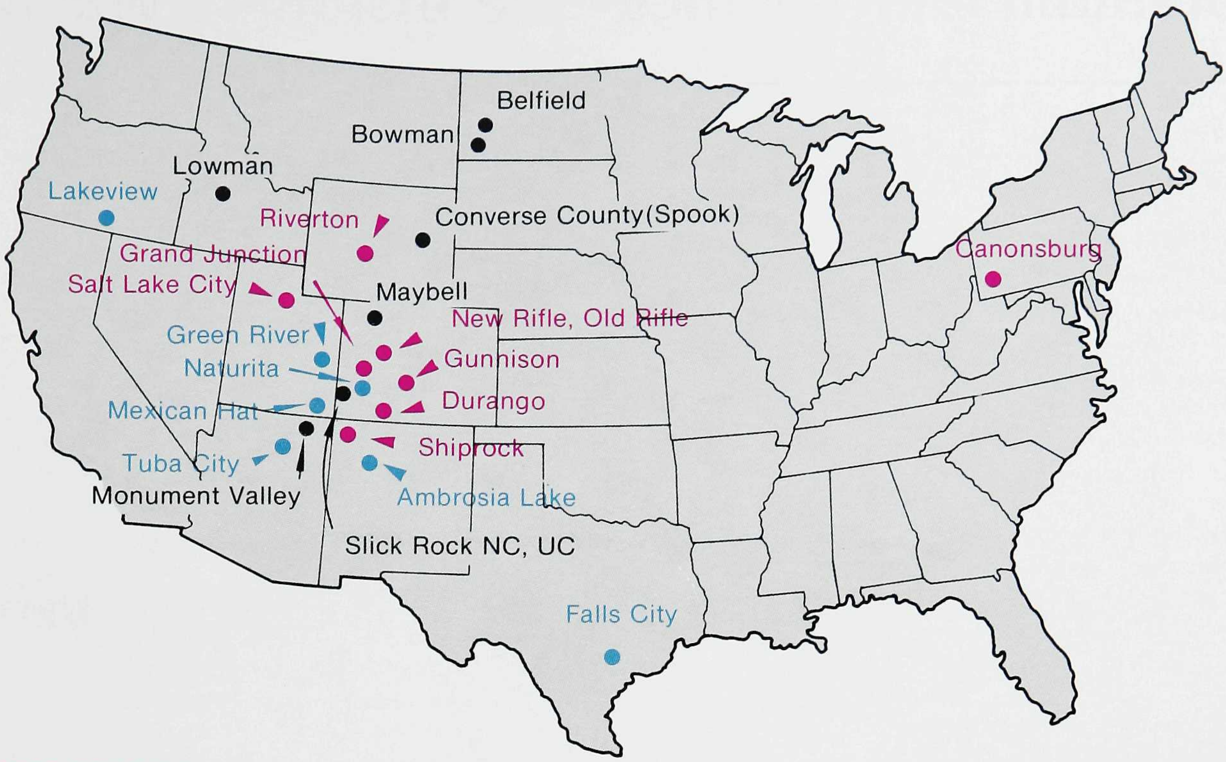
Because most uranium has a half-life of 4.5 billion years (about half the age of Earth), it will continue to spawn radon gas and radium almost forever. Thus the containment of tailings in perpetuity is critical.

Disposal. In the past, uranium tailings have been disposed of in various ways--onto flat ground, into basins, into abandoned mines, into streams and oceans, but mostly behind embankments. Historically, the uranium mining/milling industry has sometimes handled tailings unsafely, and some containments have failed. And, until the early 1970s, radioactive tailings were even used as fill around thousands of buildings and private homes in some parts of the West.

The main problems are at 24 inactive milling sites (see map) that operated prior to government regulation. There are 25 million tons of tailings at these sites. At the *surface*, runoff can transport into nearby streams long-lived radionuclides, such as radium (half-life 1,622 years). *Underground*, water can leach radionuclides from tailings, and transport them either to the surface or off-site.

References: USDOE March 1980, USNRC 1979, Lipschutz 1980.

INACTIVE URANIUM MILL SITES SCHEDULED FOR IMPROVEMENTS



HIGH PRIORTIY

Cleanup to start

Canonsburg, PA	Oct 1983
Durango, CO	Apr 1985
Grand Junction, CO	Oct 1986
Gunnison, CO	Apr 1986
New Rifle, CO	Oct 1986
Old Rifle, CO	Oct 1986
Riverton, WY	Apr 1985
Salt Lake City, UT	Apr 1984
Shiprock, NM	Oct 1984

MEDIUM PRIORITY

Cleanup to start

Ambrosia Lake, NM	Apr 1987
Falls City, TX	Jul 1988
Green River, UT	Jul 1988
Lakeview, OR	Jul 1986
Mexican Hat, UT	Apr 1986
Tuba City, AZ	Oct 1985
Naturita, CO	Jul 1987

LOW PRIORITY

Cleanup to start

Converse County, WY	Jul 1989
Lowman, ID	Jul 1989
Maybell, CO	Jul 1987
Monument Valley, AZ	Jul 1987
Slick Rock, CO (NC)	Jul 1988
Slick Rock, CO (UC)	Jun 1988
Belfield, ND	Apr 1989
Bowman, ND	Apr 1989

USDOE, Sept. 1983

What is being done? The U.S. Department of Energy is correcting the 24 sites (see list below map) by stabilizing tailings piles with retaining structures and compacted soil covers. Tailings are also being removed from some locations where they pose an immediate hazard.

Uranium mining/milling is now controlled by the U.S. Nuclear Regulatory Commission, or by states having agreements with NRC. NRC's regulations establish safe handling practices for tailings.

The proper way. Careful site selection by geologists, and well-engineered containments, reduce the need for monitoring, and reduce maintenance following site closure and reclamation. The basic requirements for tailings disposal are:

- Tailings must be stored in areas remote from people.
- Containments must be designed to prevent dispersion by wind, rain, floods, etc.
- Containments must prevent seepage of toxics into ground water.
- Containments must prevent movement of tailings off-site, by either human or natural forces
- Containments must limit emission of radon gas and gamma rays.
- Impoundment design must consider the geology and hydrology of sites.

Nuclear Power Plants: Spent-Fuel Storage is Nearly Full

Nuclear power-plant fuel consists of pellets of enriched uranium dioxide, encased in 12-foot-long metal tubes. These *fuel rods* are bundled to form *fuel assemblies*. In use, the rods gradually lose efficiency, and one-third of the rods are removed annually from a typical reactor.

Spent-fuel rods are stored in water-filled pools at the reactor sites. The intent was to use the pools only as temporary storage, until the rods cooled enough to be shipped to a reprocessing plant for recovery of the unused enriched uranium and plutonium. However, little spent fuel has ever been reprocessed.

A commerical reprocessing plant at West Valley, New York, closed after seven years because of problems in expanding the plant. Another reprocessing plant in Morris, Illinois, never became operational due to design problems. In 1977 President Carter deferred commercial reprocessing as part of his nuclear-nonproliferation policy.

President Reagan lifted the restrictions on reprocessing, but no such facility is presently operating in the United States. A commercial plant built at Barnwell, South Carolina, near the DOE's Savannah River Plant, was never licensed and closed in 1983. Thus the commercial feasibility of reprocessing under present conditions remains unproven.

The total spent fuel stored in powerplant pools at the close of 1980 was about 27,000 fuel assemblies, weighing 7,720 tons, having the volume of a cube 45 feet on each side, and 2 billion curies of radioactivity.

Of the approximately 80 operating reactors in the U.S., three-fourths are "pressurized water reactors" (PWRs). About 30% of the fuel from a PWR is removed each year. (The remaining 70% is redistributed in the reactor, and fresh fuel rods are added.) The fuel removed from each reactor, every year, weighs about 66,000 pounds which, because of its great density is only the size of a small car.

Despite delays and cancelled construction, the number of operating reactors is gradually increasing, and therefore spent fuel is accumulating faster. By 1995, accumulated spent fuel is projected to be 64,000 metric tons, the volume of a cube 95 feet on each side.

It is general practice to leave room in a reactor's storage pool for *all* the fuel in the reactor, in case of an emergency. This is called "full core reserve" room (FCR). But storage pools are filling up fast. By 1985, 34 reactor pools will be full, allowing only FCR room (see chart). As storage pools have filled, operators have close-packed the fuel assemblies or shipped them to other sites with more space.

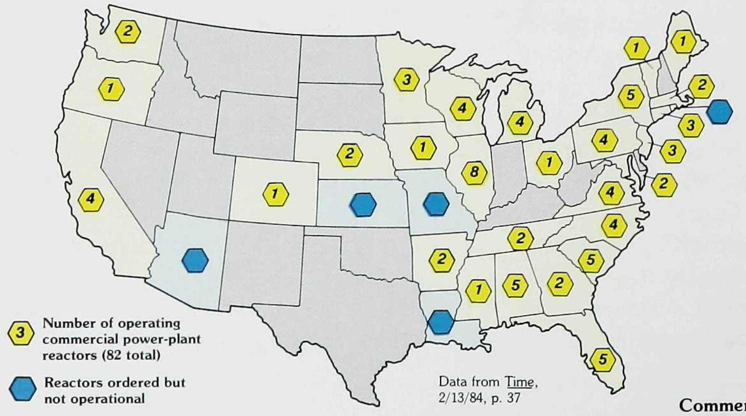
About 10% of U.S. spent fuel is stored at the shutdown reprocessing plants in West Valley, NY, and Morris, IL, as these plants were equipped to handle high level waste. However, a court recently ordered West Valley's spent fuel returned to the utilities.

Two serious concerns about pool storage are that an inadvertent nuclear reaction could start in the pool, and that fuel pellets and rods may deteriorate. But boron shields between fuel assemblies prevent a reaction, and deterioration appears negligible. So, DOE concludes that spent fuel can be safely stored under water for many years.

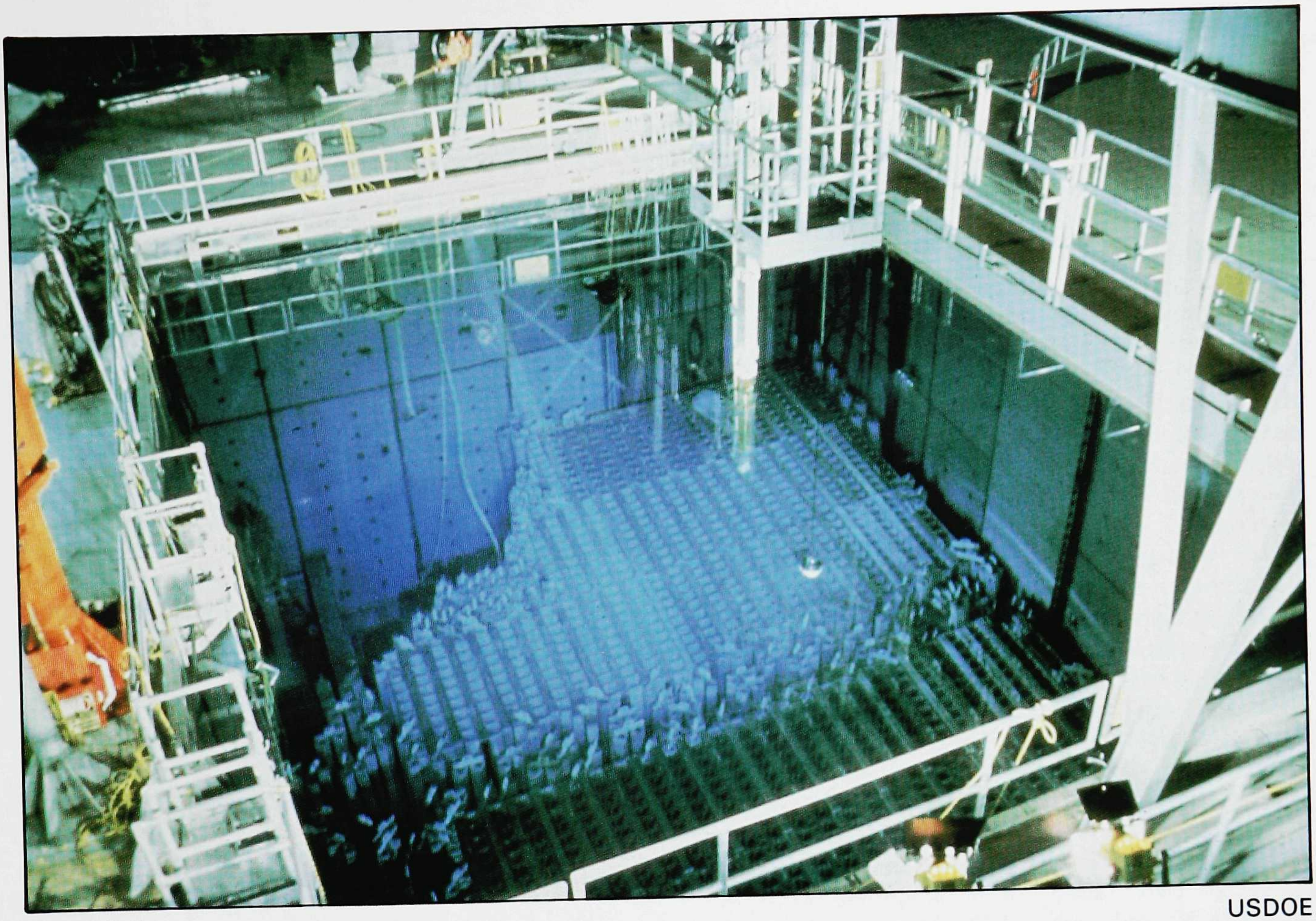
But not forever. The Nuclear Waste Policy Act of 1982 requires DOE to accept spent fuel for *permanent* disposal in deep underground "geologic"repositories. There are no such repositories yet, but DOE is evaluating sites (see p. 22).

References: USDOE April 1980, January 1981; Van Nostrand 1976; Stoler 1984.

POWER-PLANT REACTORS AS OF FEBRUARY 1984



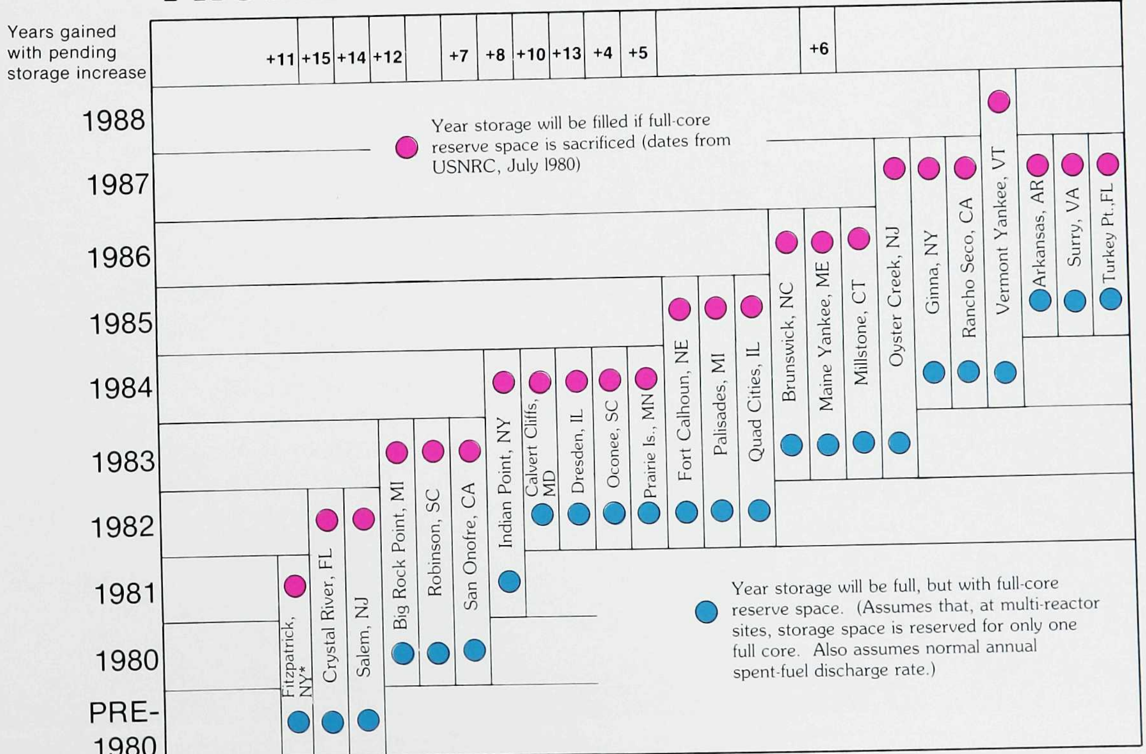
Commercial nuclear power plants povide about 13% of our electricity, and are projected to supply nearly 20% by the 1990s. Spent Fuel is stored at all operating sites.



USDOE

Spent fuel storage

THE SPENT-FUEL STORAGE PROBLEM IS CRITICAL



USDOE, Jan. 1981

Nuclear-Fuel Reprocessing Produces High-Level Radioactive Wastes

Spent reactor fuel can be *reprocessed* to recover unused (unfissioned) uranium-235 and plutonium-239 for making new fuel, and for weapons production. In 1977, President Carter indefinitely banned *commercial* reprocessing of power-plant fuel, to restrict the plutonium supply and thereby inhibit nuclear weapons proliferation. President Reagan lifted the ban, but no commercial fuel is yet being reprocessed. However, *defense* reprocessing continues under Department of Energy supervision, and this is the major source of high-level waste.

Reprocessed wastes are indeed high-level, some with radioactivities of several thousand curies per gallon, which means that trillions of particles and rays are given off every second by each gallon. Most of this energy is converted to heat in the waste storage tanks, and the liquid wastes can become hot enough to boil. The wastes will remain highly radioactive for centuries.

Reprocessing involves chopping up the spent fuel rods, dissolving them in nitric acid, and chemically separating the desired uranium-235 and plutonium. The remaining waste includes over 50 radionuclides that are significant (very radioactive or long-lived), such as strontium-90 and cesium-137. There is about 11 million cubic feet of such waste (it would fill a football field piled 228 feet deep), stored at four U.S. sites:

- **Hanford Reservation,** a federally-owned area straddling the Columbia River in south-central Washington (reprocessing of fuel from plutonium-production defense reactors)
- **Savannah River Plant,** South Carolina, a federally-owned area bordering Georgia (reprocessing of fuel from plutonium-production defense reactors)
- **Idaho National Engineering Laboratory** (INEL), a federally-owned area west of Idaho Falls (reprocessing of fuels from nuclear submarine reactors and experimental reactors)
- **West Valley,** New York, 35 miles south of Buffalo, privately-owned, and the only U.S. plant to have reprocessed commercial power-plant fuel.

The first reprocessing was done at Hanford Reservation as part of the World War II effort to develop an atomic bomb. That and subsequent production generated tons of plutonium for weapons, and millions of gallons of high-level liquid wastes.

Hanford's wastes were stored underground in large, single-walled steel tanks. The hot, acid wastes corroded the tanks, so the wastes were neutralized and diluted, and returned to the same tanks. Leaks appeared, and hot spots in the waste caused spontaneous boiling.

Extensive efforts have improved waste storage at Hanford, and at the Savannah River Plant. New tanks have double shells and leak-detection systems. Some tanks have stirrers to eliminate hot spots; others use cooling coils.

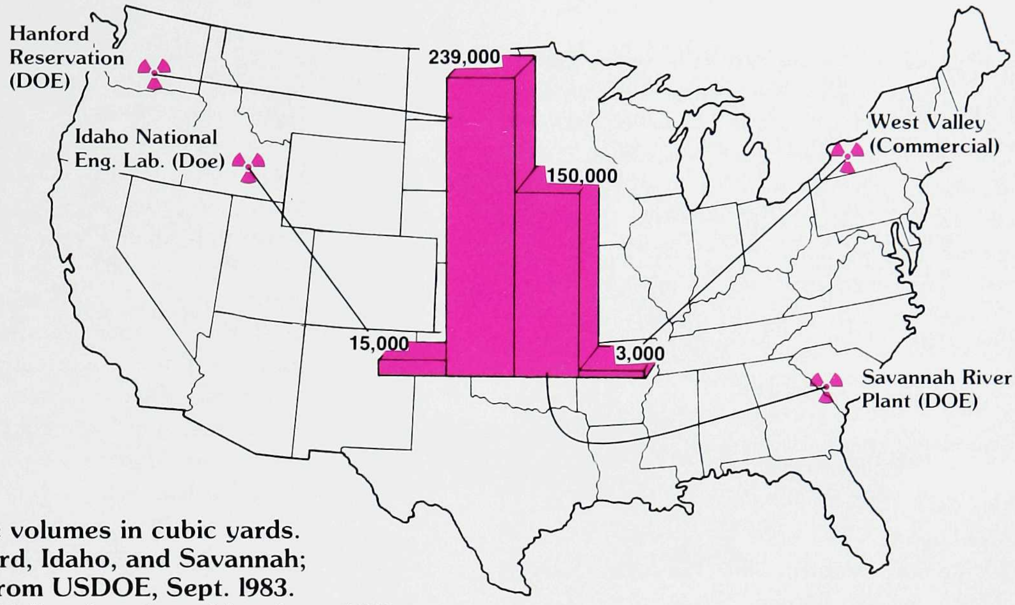
Waste liquids have been partly solidified to "salt cake", reducing the volume by two-thirds, and limiting waste mobility in case of leaks. Another step at Hanford was to lower the waste temperature by removing troublesome strontium-90 and cesium-137 from the salt cake, and storing them seperately in submerged metal capsules.

At the Idaho facility, liquid wastes are "calcined" (sprayed through an atomizer and heat-dried) to form a granular solid, which is stored in bins.

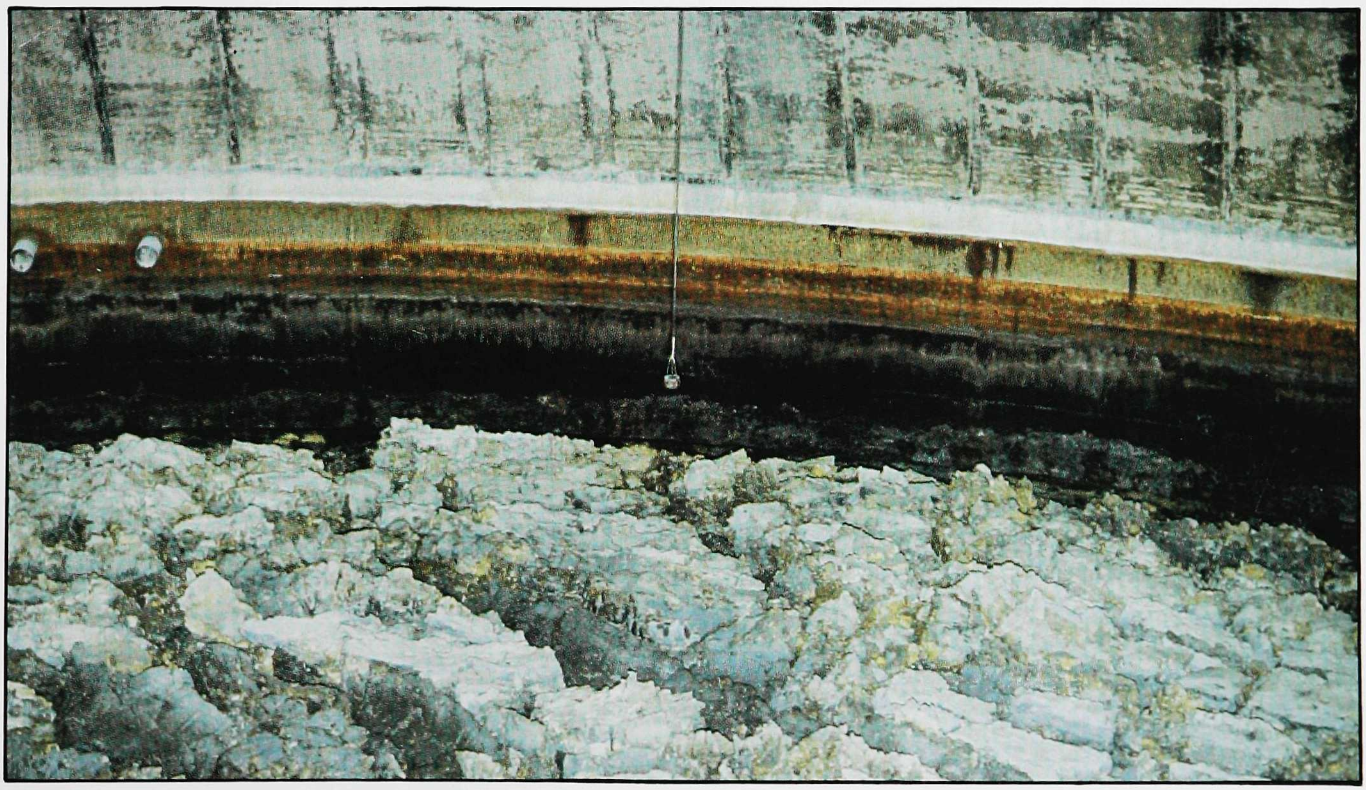
At present, all high-level wastes are in temporary storage. The Department of Energy plans conversion of the wastes to a solid form (probably encased in borosilicate glass), and permanent disposal in geologic repositories at least 1,000 feet deep to isolate the wastes from the environment, hopefully forever (see p. 22).

References: USDOE Nov. 1979, 1980, Sept. 1983; Lipschutz 1980

HIGH-LEVEL WASTE STORAGE IN THE U.S.



Waste volumes in cubic yards.
Hanford, Idaho, and Savannah;
data from USDOE, Sept. 1983.
West Valley data from Lipschutz, 1980.



Solidified high-level waste in tank at Hanford, Washington USDOE

Transuranic (TRU) Wastes: Long-Term Hazard

The form of uranium that fissions in a reactor (splits into simpler atoms) is U-235. But reactor fuel contains only 3-4% U-235. The fuel is mostly U-238, which does not fission. Instead of splitting when struck by neutrons, U-238 *absorbs* neutrons, growing heavier, and changing character into various "transuranic" elements (so called because they are "beyond uranium" in weight).

Transuranic (TRU) elements* are all artificial, being man-made in reactors, and comprise a small portion of spent fuel. They are unstable and therefore radioactive. Because of the great complexity of their atoms, they require a long time to decay, and thus have long half-lives (tens of thousands of years for some), and therein lies the problem.

TRU wastes vary widely in radioactivity. Some can be contact handled, while some must be remotely handled for safety. But the main problem with TRU wastes is their *longevity*. These wastes require secure disposal for millennia, far longer than any civilization has survived.

Most TRU wastes result from fabricating plutonium into weapons. Smaller quantities come from submarine reactors, test reactors, commercial power plants, and the decontamination/decommissioning of nuclear facilities.

At first TRU wastes were disposed of by shallow burial, along with low-level wastes. But as the potential hazard to the public of long-term exposure became recognized, disposal requirements were tightened. In 1970 the U.S. Atomic Energy Commission required TRU waste to be segregated from other radioactive waste, and to be packaged and stored for retrievability within 20 years (for later geologic disposal).

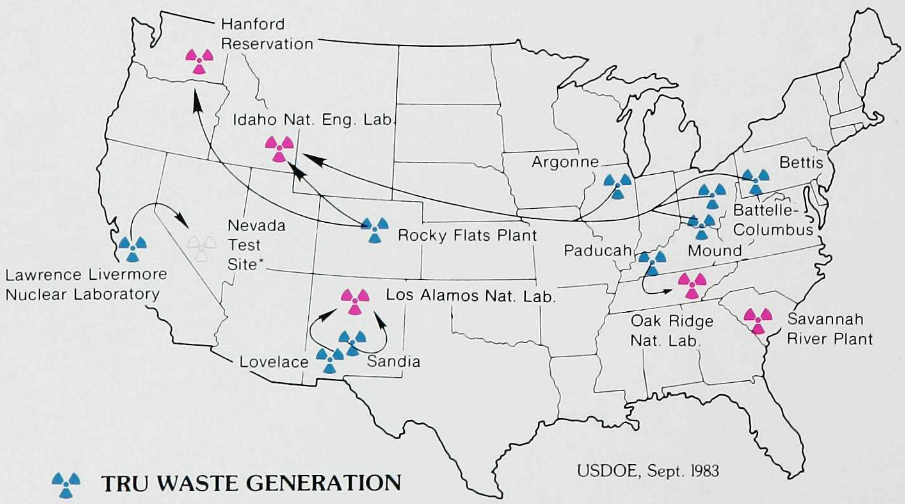
Six DOE sites currently accept TRU waste for storage. The largest volume is at Hanford, Washington, where part is in low-level waste-burial grounds, and part is stored for retrieval. Since 1980, power plants have stored their own TRU wastes, and cannot send them to commercial disposers.

DOE's plan is to ultimately place TRU wastes in a geologic repository, when one becomes operational. The Waste Isolation Pilot Plant (WIPP) in New Mexico is being considered (p. 18).

References: USDOE Jan. 1981; Lipschutz 1980.

*Neptunium, Plutonium, Americium, Curium, Berkelium, Californium, Einsteinium, Fermium, Mendelevium, Nobelium, Lawrencium.

WHERE TRANSURANIC WASTE IS GENERATED AND STORED



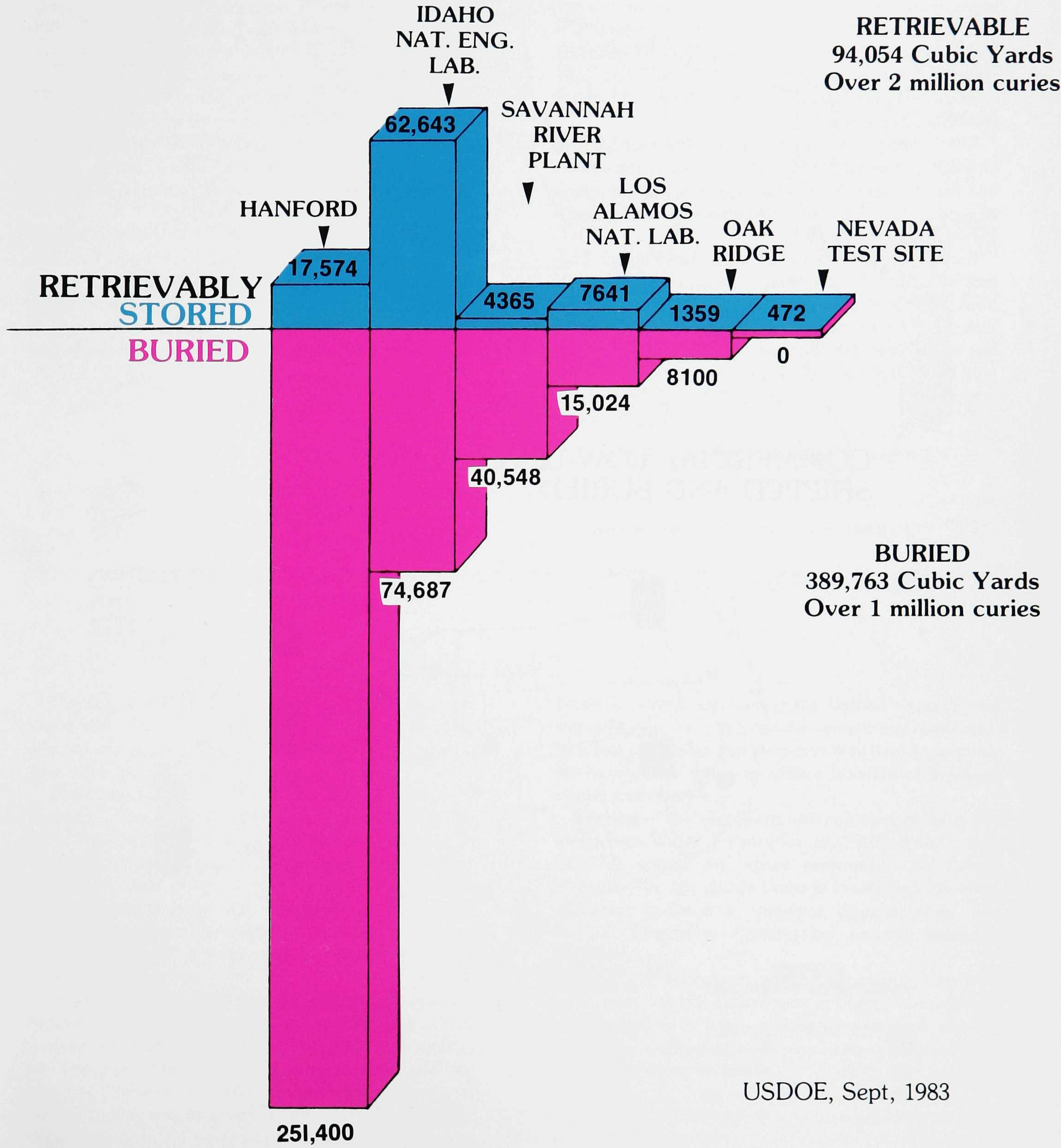
TRU WASTE GENERATION

TRU WASTE GENERATION AND STORAGE

* STORAGE ONLY

→ WASTE SHIPMENTS

HOW MUCH TRU WASTE IS IN STORAGE?



USDOE, Sept, 1983

Low-Level Radioactive Wastes

Low-level radioactive wastes are those that do not fall within the previously-described categories of high-level waste, spent fuel, transuranic waste, or uranium mill tailings. About half of all low-level wastes are generated in nuclear power plants, and the other half by hospitals, research laboratories, and industry. Such waste commonly includes contaminated gloves, clothing, machinery, tools, and paper.

These wastes have comparatively little radioactivity (averaging under one curie per cubic foot), and contain less than 10 billionths of a curie per gram of transuranic elements. Most of this waste requires no shielding and is buried in shallow landfills.

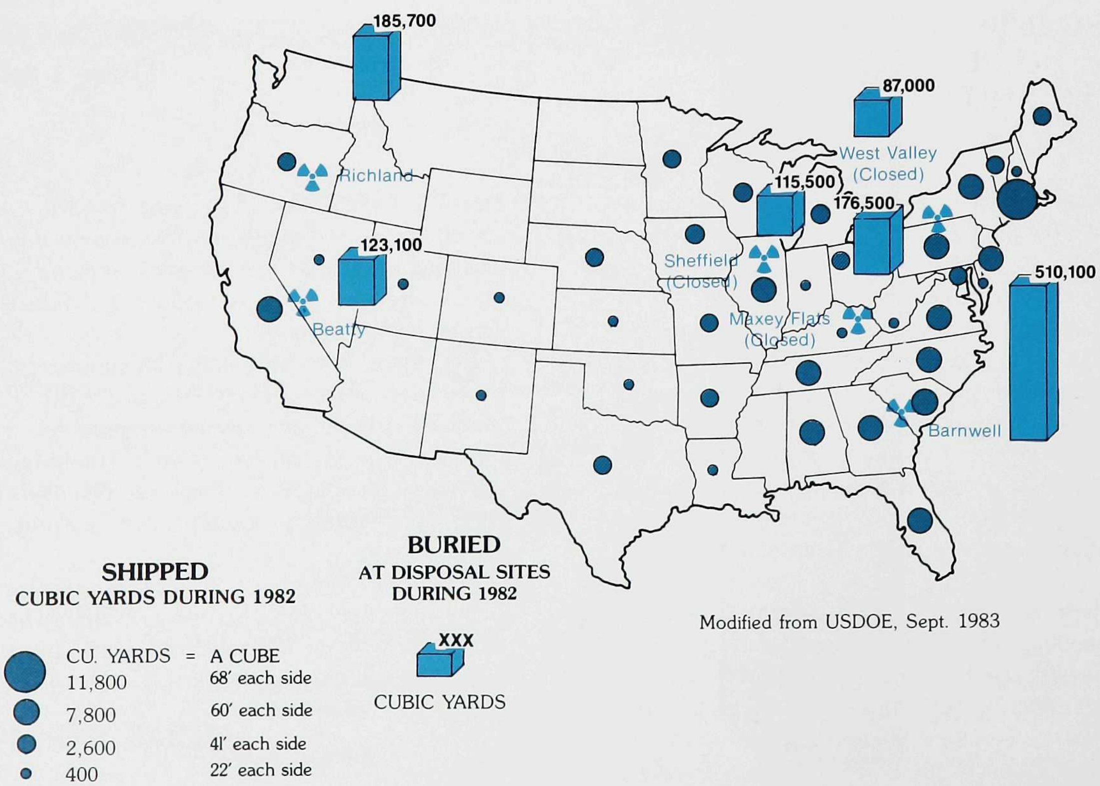
But low-level wastes are not to be treated lightly. They lack the toxicity of high-level waste and the longevity of transuranic waste, but they are still hazardous, for two reasons: (1) their huge volume (1,000,000,000 cubic feet by the year 2,000 according to U.S. EPA); and, (2) long-term exposure to even low-level radiation is cumulative.

Shallow land burial has been the preferred disposal method since the early 1940s. However, for a quarter century (1946-1970), ocean-dumping was also used. The Pacific Ocean near San Francisco received 47,000 drums (55-gallon) of military and commercial low-level waste. The Atlantic swallowed 28,000 drums off Delaware and Boston. But this practice ceased in 1970, and all low-level waste is now buried in shallow trenches.

Low-level wastes are interred at 20 sites in the U.S. Six contain "commercial"waste from power plants, hospitals, and laboratories, and the other 14 hold waste from defense and government research.

The six commercial sites are on state-controlled land in Illinois, Kentucky, Nevada, New York, South Carolina, and Washington. Three of them--Sheffield, IL, Maxey Flats, KY, and West Valley, NY --were closed in the 1970s. Collectively, the six sites held 1,197,900 cubic yards of waste as of 1982 (equal to a football field piled 674 feet deep).

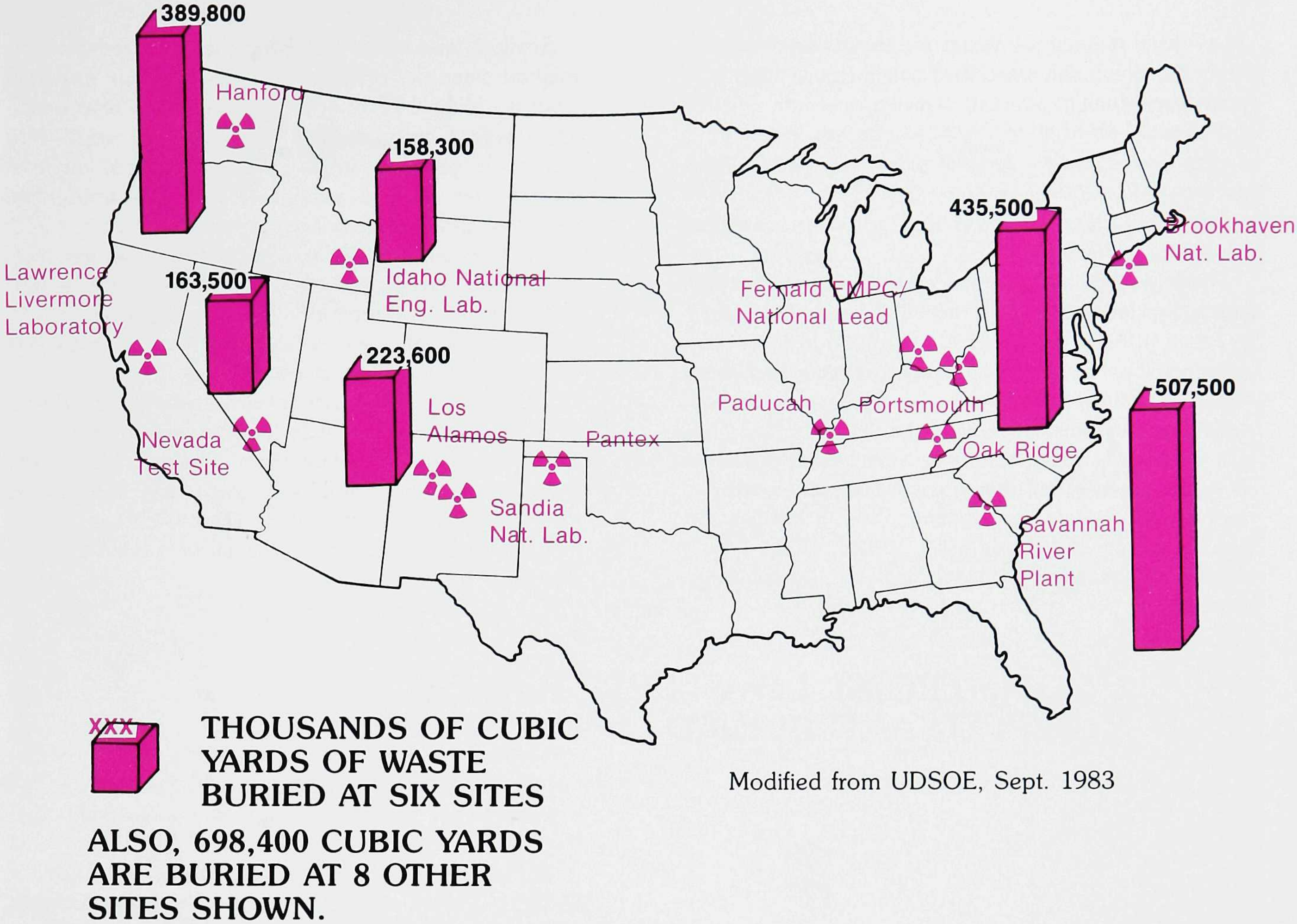
COMMERCIAL LOW-LEVEL WASTE SHIPPED AND BURIED



Modified from USDOE, Sept. 1983

DEFENSE LOW-LEVEL WASTE BURIALS

(2,576,600 CUBIC YARDS TOTAL)



Modified from UDSOE, Sept. 1983

The U.S. Department of Energy runs the 14 defense-waste sites. These hold 2,576,600 cubic yards of waste (the volume of three football fields piled 483 feet deep), over twice the commercial volume.

Burial trenches are usually 40 feet wide at the top, 25 feet wide at the bottom, 25 feet deep, and 100 to 600 feet long. After waste containers are emplaced, 2 to 6 feet of clay-rich soil is placed on top as a water-resistant cap. Permanent stone or metal markers locate the trenches and show the volume and radioactivity of the buried waste. Depending on terrain, trenches are tightly spaced (25 feet apart), with a buffer zone surrounding the trench area.

Present low-level waste sites were apparently selected by land availability, rather than by sound geology. Thus, problems related to geology and hydrology have emerged. The main difficulty is infiltration of water into the trenches. The water becomes leachate contaminated with radionuclides, and migrates to the surface, or travels underground. In no case, however, has this proven to create a hazard. Dewatering the flooded trenches and strengthening the clay caps has greatly improved matters. But, these stop-gap measures may have to continue for hundreds of years to ensure isolation of low-level wastes from people.

Because of such problems with commercial burial, the Low-Level Waste Policy Act of 1980 (Public Law 96-573) makes the *states* responsible for proper disposal. The law allows states to create regional compacts for cooperative, interstate disposal sites. The Nuclear Regulatory Commission permits states to license sites.

Based on hydrologic studies of existing low-level waste sites, the U.S. Department of Energy has prepared rational criteria for site-selection. These criteria, plus the 1980 law, are important steps toward solving low-level waste disposal problems.

References: Cahill 1982; Dyer 1976; Falconer and others 1982; Conservation Foundation 1981; USDOE July 1982; Lipschutz 1980.

Permanent Disposal of Radioactive Wastes

We have examined the types of radioactive waste, and the special problems of each. Now, let's look at the major goals of radioactive-waste management:

1. Permanent disposal of high-level wastes and spent fuel (intense radioactivity).

2. Permanent disposal of transuranic wastes (extremely long-lived).

3. Permanent disposal of low-level commercial wastes (large volumes).

The last of the three, low-level waste, is the easiest to handle; low-level wastes are being successfully **buried in shallow landfills** (see p. 20).

But the United States has yet to "permanently" dispose of any high-level or transuranic wastes. **Geologic disposal** in deep, stable rock layers is the most feasible solution proposed so far, for isolating high-level and transuranic waste. After much research and debate, it is the approach to which the U.S. is now committed.

The **geologic respository** (see picture) will be a large room-and-pillar mine (perhaps 4 square miles in area), 1,000-3,000 feet deep to fully isolate it from people. The repository will have above-ground areas for receiving wastes, packaging them, and lowering them into the mined area. High-durability containers for high-level waste and spent fuel will be carefully distributed underground to prevent any area from overheating.

Selection of the geologic disposal method, and specifying its requirements, has not been simple. Experts in science, engineering, government, politics, health, and environment have studied the problem for years. Among the principal organizations have been:

U.S. Department of Energy (waste management and disposal),

U.S. Nuclear Regulatory Commission (regulation),

U.S. Environmental Protection Agency (standards for public protection),

U.S. Geological Survey (independent geologic and hydrologic studies),

National Academy of Sciences (independent geologic and hydrologic studies; long-term safety studies), and

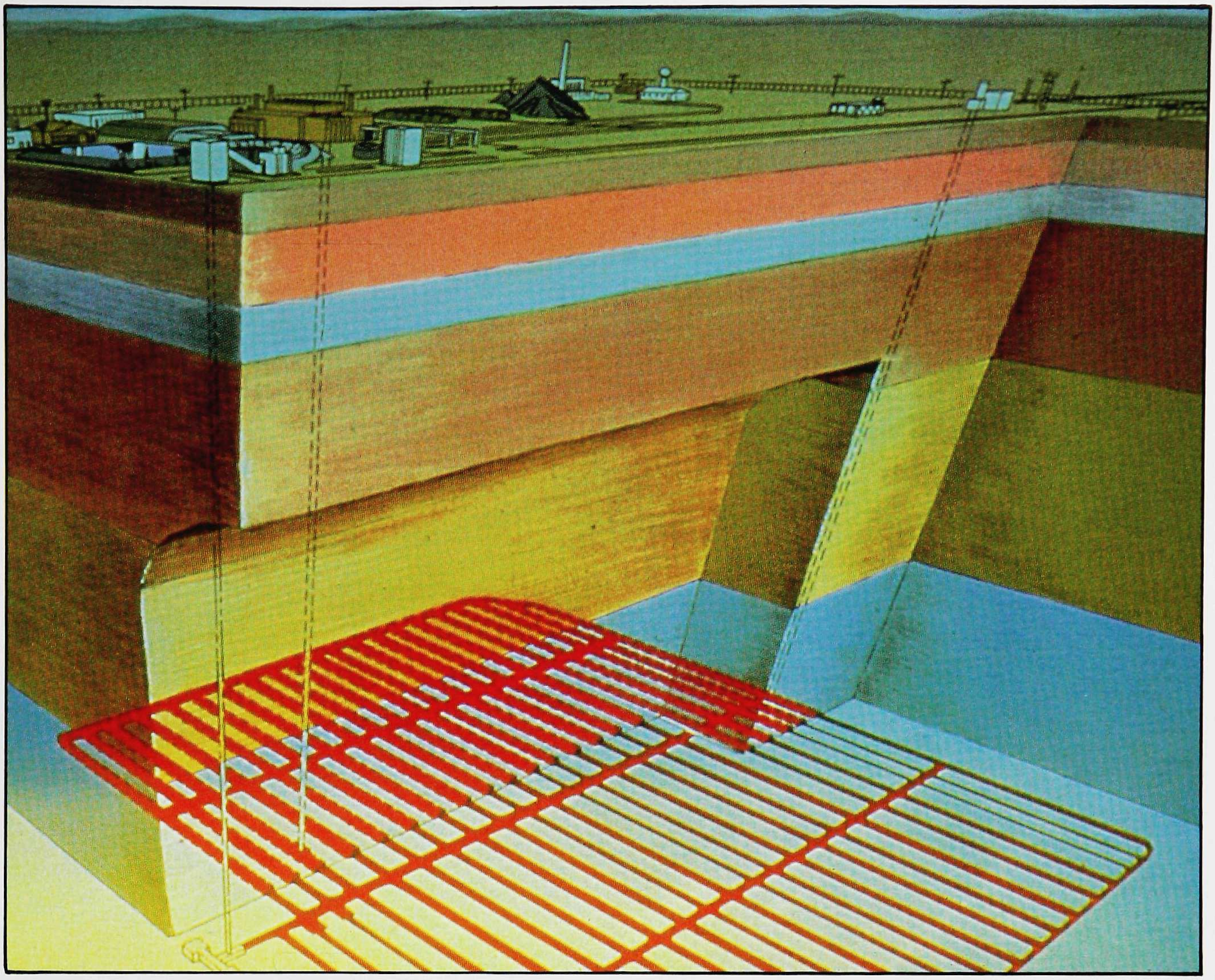
Professional geological organizations (recommendations from the geological viewpoint).

Of the many possibilities examined--including surface storage, seabed disposal, polar ice cap disposal, transmutation, and rocketing wastes into space--geologic disposal is the most feasible with present technology. The DOE has endorsed this method to assure long-term (thousands of years) isolation of wastes from the human environment.

DOE's particular focus is upon: (1) providing a respository for high-level waste, spent fuel, and defense transuranic waste; (2) helping the states create regional low-level waste sites; (3) recovering cost from commercial users of high-level waste-disposal services; and, (4) compliance with the National Environmental Policy Act.

Congress has passed laws regarding most of these concerns. Recent legislation provides:

- **The WIPP (Waste Isolation Pilot Plant)** near Carlsbad, NM, will dispose of transuranic waste, and will temporarily, experimentally, use small amounts of high-level waste. (DOE Defense Authorization Act).



Repository concept USDOE

• **The states must handle low-level waste disposal**, and may set up joint, interstate facilities (National Low-Level Radioactive Waste Policy Act, 1980).

• **DOE must construct permanent geologic repositories** for spent power-plant fuel and high-level waste. The steps are to nominate five sites by 1985, recommend three for detailed study, pick the best one, obtain an NRC license to build and operate, have the respository operational by 1998, and then repeat the procedure for a second site. DOE must also temporarily store spent fuel. Consumers of nuclear-generated electricity will pay users fees to fund commercial waste disposal (Nuclear Waste Policy Act, 1982).

Cooperation is the key. Cooperation--among Federal agencies, states, local government, the public, and special-interest groups--is critical to solving our radioactive-waste problems. President Carter made concurrence of the states integral to decision-making, and President Reagan has followed a policy of "consultation and cooperation" with the states.

Congress affirmed a Federal-state partnership in the National Low-Level Radioactive Waste Policy Act, which requires Congressional approval of regional interstate compacts. Federal-state partnership is also part of the Nuclear Waste Policy Act, under which an affected state may veto a DOE repository site (only a counter-veto by both Senate and House can overcome the state's objection).

However, serious differences have arisen between DOE and some states over the adequacy of DOE studies of geology and hydrology at repository sites. Public-interest groups have also criticized DOE.

Patient efforts by all to improve communication are essential. Honest, diligent effort is needed to resolve needless misunderstandings, and to allow states their voice.

References: Carter 1983; NAS/NRC 1983; Peterson 1982; Lipschutz 1980.

Shallow Land-Burial of Low-Level Wastes

The National Low-Level Radioactive Waste Policy Act (1980) requires each state to dispose of all non-defense low-level waste generated within its borders. The Act also encourages states to enter compacts for regional interstate disposal grounds. Each such compact must be approved by Congress (and Congress may withdraw consent every five years). After 1/1/86, a compact may restrict its facilities to waste generated only within its region.

Based partly on U. S. Geological Survey studies, the Nuclear Regulatory Commission has set standards for licensing burial grounds. They cover geologic and hydrologic characteristics of the site, types of wastes, site operation, and site treatment after closure. The point of these standards is to ensure safe, unrestricted human use of the land and water outside a buffer zone around the burial ground.

Wastes which can undergo shallow burial are those that will decay to the nonhazardous level within 100 years. Longer-lived wastes, that will remain hazardous for 500 or more years, must be buried deeper. If the geology is not suitable for deeper burial, physical barriers such as concrete covers could be used.

NRC's geologic/hydrologic criteria are general, to allow for varied conditions around the Nation. But the geologic/hydrologic evaluation required for each site under NRC's rules is elaborate. DOE is helping the states technically via guidelines for geologic/hydrologic evaluation of sites.

Above all, each site must meet one performance objective: **safety.**

Reference: USNRC 1981.

Low-level waste site, Beatty, Nevada USGS

Cut-off wall to prevent ground-water dispersal of low-level waste USGS

NRC Criteria for Low-Level Waste Sites--Hydrology and Geology (Simplified from **Code of Federal Regulations,** Chapter 10, Part 61):

- Site must be capable of being scientifically described, modeled, analyzed, and monitored.
- Site must not have significant economic resources which, if exploited, might expose humans to radiation.
- Site must be well-drained, free from flooding or frequent ponding, and not be in a 100-year flood plain, wetland, or coastal high-hazard area.
- Upstream drainage must be minimized to decrease water runoff that might erode or inundate the site.
- The water table must be deep enough beneath the site so that ground water can't reach the waste (with some exceptions).
- Springs must not emanate from the rock layers in which wastes are disposed.
- Areas prone to earthquakes, volcanoes, or rock folding/faulting must be avoided.
- Areas prone to landslides and erosion must be avoided.
- Site must not be susceptible to disturbance by nearby facilities or activities.
- Site covers (usually clay caps) must prevent water infiltration, divert surface water, and resist erosion.
- Site must prevent water from contacting the waste during storage, disposal, and after disposal.

The Geologic Repository

The Nuclear Waste Policy Act of 1982 authorizes DOE to construct permanent geologic repositories for spent power-plant fuel and high-level waste. But this raises difficult questions:

Can geologic repositories safely isolate nuclear wastes from the biosphere for millennia? Will repositories really protect future generations?

Can we find rock formations 1,000-3,000 feet deep that will be impervious to geologic catastrophe (such as an earthquake), and that will not be disturbed by mining or drilling for tens of thousands of years?

If the waste canisters in the repository are damaged, how can we assure that radioactive substances won't escape to the surface or into ground water?

Can we predict ground-water movement around and through a repository for 10,000 to 50,000 years? If ground water should contact the wastes, can we predict how much will reach our environment, and when?

These questions have been hotly debated for years. But since every ounce of nuclear waste ever generated remains in (or near) the biosphere*, action is long overdue, and the geologic repository is the choice.

How could it fail? The geologic repository must isolate high-level waste from humans for thousands of years, outlasting institutions, governments, nations, and perhaps even some species. This extraordinary requirement demands exhaustive study of how the repository might fail--how could radioactive material escape?

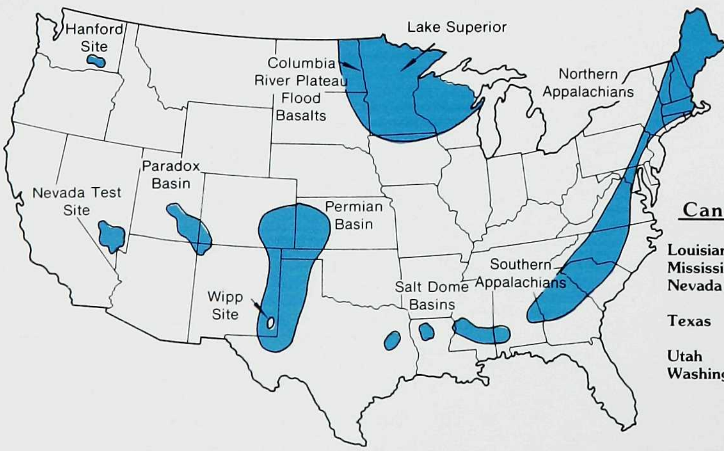
The most likely mode is *transport in ground water.* In fact, ground water is the major consideration in waste burial, for it can launch radionuclides from the waste, and return them to the surface.

At Nevada's Yucca Mountain site, the water table (upper limit of ground water) is 1,900 feet below land surface, allowing construction of a repository entirely above ground water. By contrast, at the other candidate sites, the water table is nearer to the surface, and a repository would be below the water table.

Salt. Most proposed sites would entomb nuclear wastes in rock salt. Salt is attractive because it is relatively dry and impermeable to water, and thus would prevent circulating ground water from contacting the wastes. The search has been for sites where salt is structurally stable and is not being dissolved by ground water fast enough for the repository to be breached during the long isolation period required for the wastes. The Waste Isolation Pilot Plant site in New Mexico is in a salt bed 2,400 feet deep. Tests are underway to assess WIPP's suitability for transuranic waste.

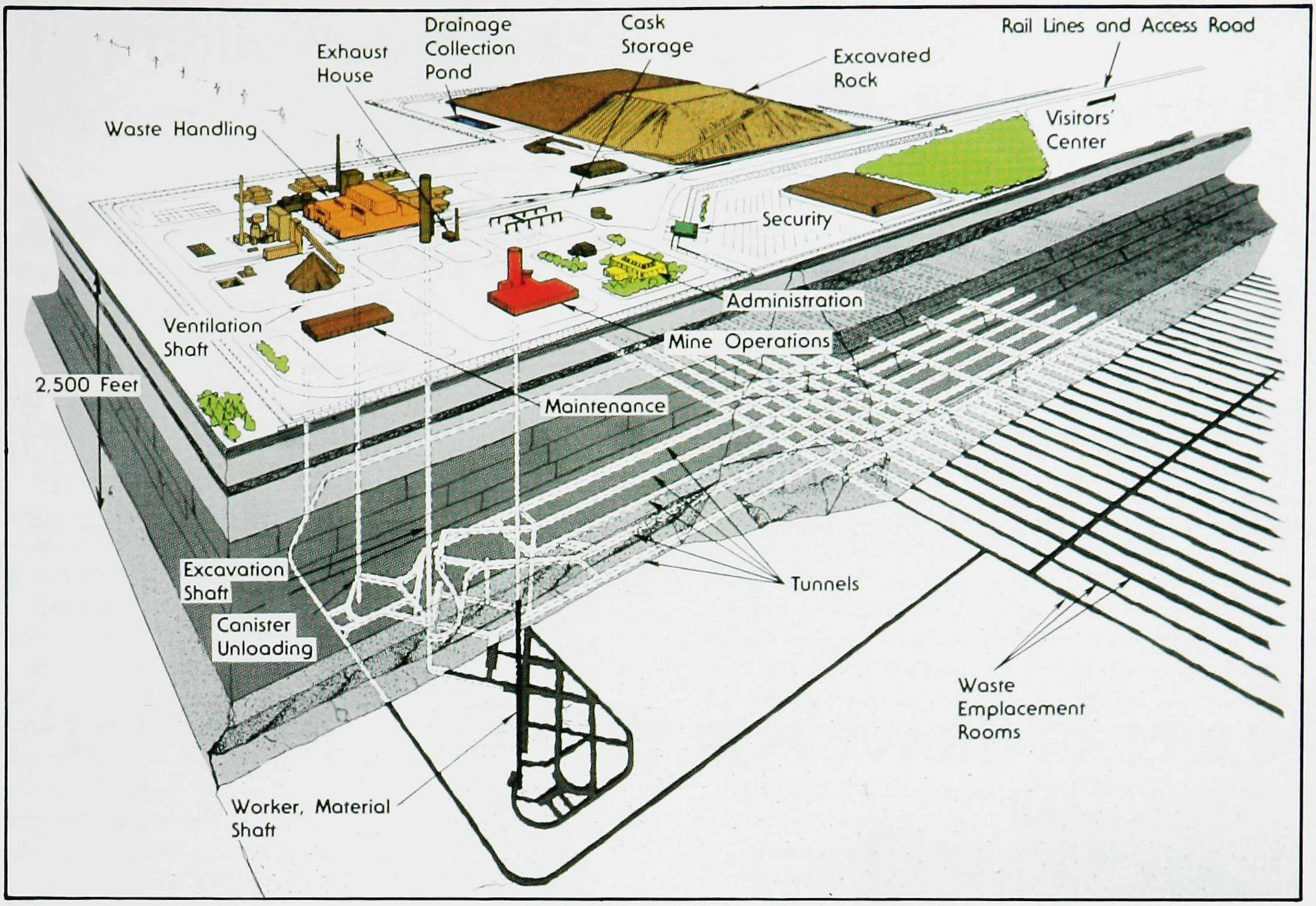
*Except for what has naturally decayed through half-lives to the stable, nonradioactive state.

POTENTIAL REGIONS AND SITES FOR GEOLOGIC REPOSITORIES



U.S. Department of Energy Candidate Sites for First Repository

Louisiana	Vacherie Salt Dome
Mississippi	Richton and Cypress Creek Salt Domes
Nevada	Nevada Test Site - tuff (volcanic ash) underlying Yucca Mountain
Texas	Deaf Smith and Swisher Counties, bedded salt deposits
Utah	Gibson Dome (bedded salt deposit)
Washington	Hanford basalt (hard, dense volcanic rock)



Waste Isolation Facility Concept USDOE

Site requirements. The feasibility of constructing a repository at a given site rests upon:

- Confidence that radioactive ground water will take millennia to reach the biosphere.
- Thorough understanding of the geochemistry of rocks, ground water, and barrier materials at the site.
- Packaging that will prevent waste dissolving in ground water, at least through its thermally "hot" period (about 300 years).
- Shafts that can be permanently sealed against leakage.
- Confidence that the rock media, through which any radioactive leachate may migrate, will sorb the waste.
- Knowledge of how rocks and ground water at the site will react to stresses from mining, and heat from radioactive decay. Will the rocks fracture? Will they flow plastically? Will heat force contaminated water up to the surface?
- Knowledge of the site's climate. Could it change from arid to moist, elevating the water table?
- Knowledge of rock stability--are they prone to being folded or faulted (cracked), encouraging ground water flow?
- Confidence that geologic uplift or subsidence is unlikely.

To address these concerns, DOE is designing for multiple barriers to water flow: low-permeable rocks; deep host rock that is physically stable and chemically sorptive; long-lasting tunnel/shaft seals and canisters; arid environment. The strategy is that each part of the system will back up the others.

The geologist's role. Each site has unique characteristics--superior climate, host rock, or overburden, or ground-water conditions. Geologists and hydrologists are essential in evaluating each site.

References: USDOE April 1980, Winograd 1981, Bredehoeft and others 1978; Bredehoeft and Maini 1981; Lipschutz 1980; Lindblom and Gnirk 1982.

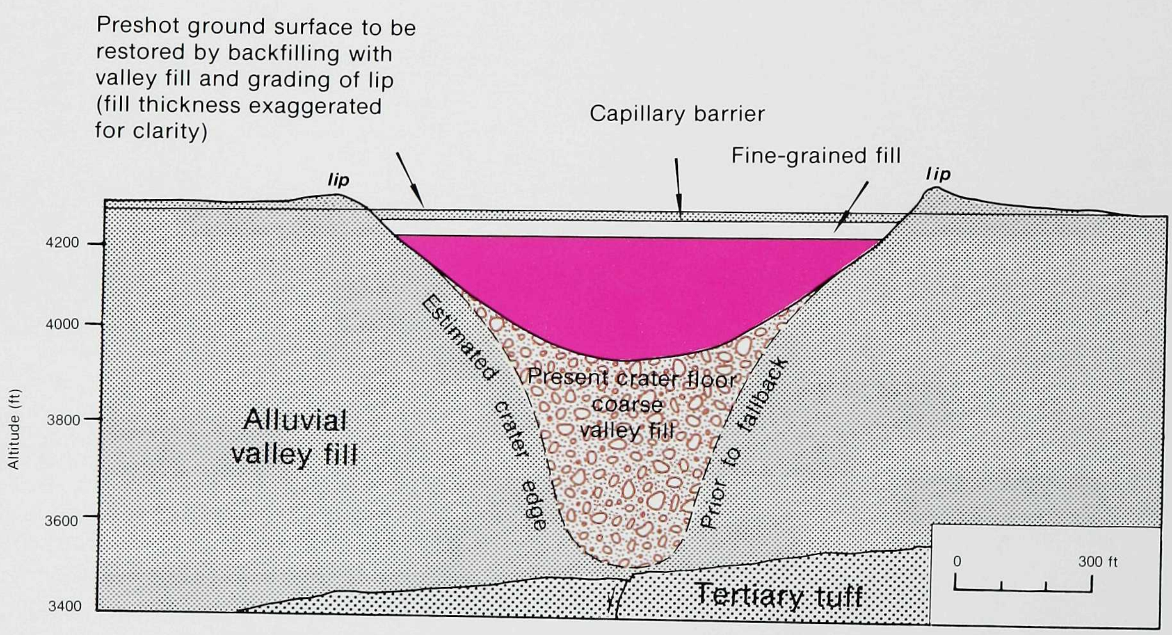
An Interesting Alternative

An interesting alternative for geologic disposal of modestly-radioactive but long-lived transuranic waste has been proposed by researcher I. J. Winograd. At the Nevada Test Site, the Sedan Crater (a man-made nuclear-explosion crater) is large enough to hold all transuranic wastes generated in the U.S. through the year 2,000.

Because the site's climate is arid (annual precipitation less than five inches), the scant soil water is unlikely to leach and transport transuranic elements from the waste. The rate of water movement is only about 1/16 inch per year. Climatic evidence over the past two million years indicates continued aridity. But, should this prediction be wrong, the site has back-up barriers:

- The valley fill and underlying tuff are sorptive and will retard radionuclide migration.
- Any radionuclides that might reach the aquifer beneath the tuff would be diluted.
- Overlaying the coarse-grained (sand-size) fill with fine-grained material (clay/silt-sized particles) creates a barrier to water movement.
- The wastes are not very soluble to begin with.

A NUCLEAR GRAVE FOR TRANSURANIC WASTE



After I. J. Winograd in Science, © 1981 by Amer. Assoc. for the Advancement of Science. Used with permission.

Public Policy and the Geological Profession

Involving everyone. We must have public participation in nuclear-waste disposal decisions, not only because this is the fairest way, but because the law requires it (Atomic Energy Act; DOE's Organization Act; NEPA guidelines). Public participation enables individuals to air their concerns, beliefs, and feelings. In so doing, they remind policical leaders and government workers that, in our democracy, all concerns of a varied populace must be considered.

Sadly, public response to nuclear waste disposal is often emotional and poorly-informed. This state of affairs cries out for better public information, so individuals can deal knowledgeably and reasonably with the problem.

Communication. Radioactive waste disposal is an arcane subject, and is not widely understood outside of the scientific community. This adds a special burden upon geologists--*communication.* Professional geologists must work dilligently to explain to the public, the legislators, and the courts the complex problems of nuclear waste. Geologists must also apply their geologic/hydrologic knowledge to the intelligent siting of disposal facilities, and prediction of events.

The communication problem is actually much larger than merely understanding a difficult technical subject. There is a fundamental clash of method between the geological and legal professions:

— The geologist studies a problem, and then makes a professional judgement in the context of his education and experience. This is the scientific method--proposing a hypothesis, collecting information, analyzing it, testing it, refining it

— But in law, to resolve a problem, one must identify opposing views (the adversarial system), and develop evidence that results in one view being declared correct.

So, when acknowledged experts from two professions (geologists and attorneys) cannot even agree on how to approach the problem (let alone on how to solve it), is it any wonder that the public is confused and suspicious?

Even though the siting and design of disposal facilities is an enormous challenge to the geologist, hydrologist, and engineer, perhaps an even greater task is to gain the public's confidence in geologic methods and conclusions.

This huge challenge is actually a golden opportunity for geologists and the public to share the responsibility, and to reach wise decisions affecting countless future generations.

Some Thoughts on Public Understanding

"Each disposal site should be selected and developed cooperatively by government entities, private industry and academic researchers. Full and open disclosure must be an integral part of the entire process to assure the protection of the health, welfare and safety of the public. The selection process should proceed with all deliberate speed."

--Association of Engineering Geologists, Policy Statement on Disposal of High-Level Radioactive Waste, June 27, 1980.

"The greatest single obstacle that a successful waste-management program must overcome is the severe erosion of public confidence in the Federal Government that past problems have created, based on:

1) Whether the Federal Government will stick to any waste policy through changes of administration;

2) Whether it has the institutional capacity to carry out a technically complex and politically sensitive program over a period of decades; and,

3) Whether it can be trusted to respond adequately to the concerns of States and others who will be affected."

--Office of Technology Assessment, Managing Commercial High-Level Radioactive Waste, May 1982.

"'Radioactive waste disposal is a political but not a technical problem' is a cliche that continues to be heard. It reflects a misapprehension of the realities of geologic disposal which is obviously quite widely held in Congress as well as in nuclear industry circles."

--Luther J. Carter, The Radwaste Paradox: Science, 1/7/83, p. 36.

"Scientists and engineers make value judgements, in choosing among alternatives; their tasks require answers in social/political, as well as in technical, terms."

--Brian J. Skinner and C. A. Walker, Radioactive Wastes; American Scientist, March-April 1982, p. 180.

"If the siting decision process is to [fairly treat future generations and deal with] aesthetics and wilderness values, it is essential that members of the public be given a genuine opportunity to develop and defend different points of view. There is no societal consensus on these "higher" values; the decision process itself may assist in formulating and articulating them."

--Hill and others, 1982, p. 863.

Glossary

Radioactive waste has its own special terminology, and an understanding of these terms is essential. The definitions below are in part adapted from Lipschutz 1980 and Van Nostrand 1976.

Alpha particle--Positively-charged assembly of two protons and two neutrons, given off during decay of some radioactive elements. The least-penetrating form of radiation; can be stopped by a few sheets of paper.

Atom--the smallest particle into which an element can be divided, and still retain its chemical properties. Each of the more than 100 elements has a different number of electrons, protons, and neutrons.

Beta particle--negatively-charged electron given off during decay of some radioactive elements. A more-penetrating form of radiation than alpha particle; can be stopped by thin metal.

Cesium-137--highly radioactive element from nuclear reactors, very mobile in the environment.

Chain reaction--the continuing fission (splitting) of atoms; one atom splits, releasing neutrons that split other atoms, etc.

Curie--unit of measure of radioactivity; the radiation from one gram of radium during one second; about 37 billion disintegrations per second.

Daughter--in a decay chain, the element formed when its "parent" decays.

Decay--the expulsion of radiation by an unstable element, resulting in formation of a new element.

Decay chain--the series of elements that form sequentially as radioactive decay progresses.

Disposal--permanently confining radioactive waste from the human environment.

Electron--negatively-charged particle that orbits an atom's nucleus (see beta particle).

Enrichment--increasing the proportion of uranium-235 to 3-4% for use in nuclear reactors.

Fission--splitting of a complex atom into two simpler atoms, triggered by impact of a neutron, releasing much energy.

Fuel cycle--the cradle-to-grave processing of uranium ore from mining through disposal.

Gamma ray--high-energy, short-wavelength electromagnetic radiation given off during decay of some radioactive elements. The most penetrating form of radiation; can be stopped by thick metal.

Gaseous diffusion--method used to enrich uranium-235 content of raw uranium.

Geologic isolation--entombment of radioactive wastes deep underground in stable rock layers.

Half-life--time required for half of a radioactive element to decay into the next element in the decay chain.

High-level waste--waste from reprocessing of spent reactor fuel; contains thousands of curies per gallon.

Interim storage--temporary secure storage of radioactive wastes, pending final disposal.

Ionizing radiation--radiation (alpha, beta, gamma) that alters electrical charge on atoms, thus changing chemical behavior; may cause human-tissue damage.

Low-level waste--low-radioactivity waste such as contaminated clothing.

Mill tailings--radioactive sandy refuse from refining uranium ore.

Neutron--chargeless particle in an atom's nucleus that can cause fission in uranium-235 and plutonium upon impact.

Neutron absorption--nuclear reaction in which uranium atoms absorb neutrons and transmute into heavier transuranic elements, such as plutonium.

Nuclide--species of atom having a specific atomic number, mass, radioactivity--e.g., uranium-235, strontium-90.

Parent--in a decay chain, the element which decays to produce a "daughter."

Plutonium--man-made transuranic heavy element which can be made to fission; highly toxic.

Proton--positively-charged particle in an atom's nucleus.

Radioactive waste--wastes from the nuclear fuel cycle and other activities using radioactive material (medical, industrial).

Radioactivity--spontaneous release of alpha or beta particles, or gamma rays, by an unstable atom seeking stability.

Rem--"roentgen equivalent man"--unit of measure of radiation dose; equivalent biological effect of one roentgen of x-rays.

Reprocessing--chemical recovery of uranium-235 and plutonium from reactor fuel rods.

Spent fuel--"worn out" reactor fuel rods having less than 1% uranium-235 remaining.

Strontium-90--radioactive element from nuclear reactors; chemically like calcium, and prone to accumulate in bone.

Transmutation--conversion of one element to another by radioactive decay, or by neutron-absorption.

Transuranic waste--waste including heavier-than-uranium radioactive elements.

Uranium--fittingly, "father of the titans" in Greek--natural radioactive element occurring in two main forms: U-235 and U-238.

WIPP--DOE's Waste Isolation Pilot Plant in a New Mexico salt bed.

Yellowcake--partially refined uranium ore.

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