Disposal of Liquid Radioactive Wastes Through Wells or Shafts

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DISPOSAL OF LIQUID RADIOACTIVE WASTES THROUGH WELLS OR SHAFTS

by

B. L. Perkins

ABSTRACT

This report describes disposal of liquids and, in some cases, suitable solids and/or entrapped gases, through (1) well injection into deep permeable strata, bounded by impermeable layers, (2) grout injection into an impermeable host rock, forming fractures in which the waste solidifies, and (3) slurring into excavated subsurface cavities.

Radioactive materials are presently being disposed of worldwide using all three techniques. However, it would appear that if the techniques were verified as posing minimum hazards to the environment and suitable site-specific host rock were identified, these disposal techniques could be more widely used.

I. FLUID INJECTION WITHOUT FRACTURING

A. Description

Fluid injection without fracturing involves disposing of liquid wastes via a disposal well, which is drilled into a permeable host rock. Depending on the properties of the host and the injection depth, gravity flow may be used, or the injection may require auxiliary pumping at pressures that do not result in fracturing the rock. Liquid treatment before injection is sometimes necessary in order to maintain flow into the desired host rock.

B. Site

1. Criteria

There are several necessary criteria that must be met before a disposal is well drilled. These include:

- The disposal formation (a) must be porous and permeable in order that the liquid can be injected without causing fracturing, and (b) must have sufficient thickness

and lateral extent that several million cubic meters of liquid can be injected. As the injected fluid moves into the disposal formation, the reservoir pressure is increased. Therefore, in a confined disposal formation, the life of the disposal system will depend on the amount of space that can be made available for waste storage by compression of the interstitial fluids (gas and brine) and expansion of the rock matrix. The reservoir pressure will gradually increase to a point where continued injection will be inadvisable because of the possibility of fracturing the confining strata. If the aquifer is not tightly confined in a small area, the original interstitial fluids will move outward, in turn increasing pressure in that region of the reservoir. The outward movement and increased pressure will continue until a discharge point, such as a spring or major fracture area, is encountered (Donaldson, 1974).

- The host rock should not be a fresh water aquifer. In general, as drilling becomes deeper, the water becomes more saline. Thus, it is usually necessary to go to depths of a kilometer or more and out of the region of circulating groundwater before saline waters are encoun-

tered in permeable rock formations (Piper, 1969). A general description of zones of circulation vs their potential for injection of waste is found in Piper, 1969.

- After a suitable injection zone has been identified, it is necessary that the permeable injection target host rock be bounded above and below by impermeable strata. In addition, fractures and faults or any other permeable zones should not penetrate through the impermeable strata. Any wells through these zones should be completely plugged to prevent interaquifer connection through the well. In addition, the area should be free of mineral potential so that future development of wells or mine shafts through these formations is unlikely (Donaldson, 1974).

- Because the integrity of the reservoir could be lost, there must also be minimal earthquake activity. It appears that, in very limited areas, the injection itself may trigger an earthquake (Raleigh, 1976). Trevorrow et al. have suggested, "Depending on the individual situation, it might be recommended that the distance from the well bore to the nearest known fault be greater than the radius of pressure influence of the well." (Trevorrow, 1977).

2. Selection Studies

The selection of a site requires a detailed knowledge of the geology and hydrology of the region. The US Geological Survey (USGS) has completed many preliminary feasibility studies for underground disposal for various regions of the United States (Clebsch, 1967). These studies include:

a. Summary of geology of sedimentary basins in the United States

- J. D. Love and H. Lynn, "A Summary of the Geology of Sedimentary Basins of the United States, with Reference to the Disposal of Radioactive Wastes," AEC TEI 768 (open), 1960, 92 pp.

- American Association of Petroleum Geologists, "Radioactive Waste-Disposal Potentials in Selected Geologic Basins—A Reconnaissance Study," US Atomic Energy Comm. report. San-413-2, 26 June 1964, 31 pp.

- J. E. Galley, "Geologic Basin Studies as Related to Deep-Well Disposal," US Atomic Energy Comm. report. TID-7628, Book 2, 1962, pp. 347-355.

b. Appalachian Basin

- G. W. Colton, "Geologic Summary of the Appalachian Basin, with Reference to the Subsurface Disposal of Radioactive Waste," US Atomic Energy Commission report TEI-791, 1961, 121 pp.

- J. E. Hardaway, "Possibilities for Subsurface Waste Disposal in a Structural Syncline in Pennsylvania," American Association of Petroleum Geologists Memoir 10, 1968, pp. 93-127.

- T. P. McCann, N. C. Privrasky, F. L. Stead, and J. E. Wilson, "Possibilities for Disposal of Industrial Wastes in Subsurface Rocks on the North Flank of Appalachian Basin in New York," American Association of Petroleum Geologists Memoir 10, 1968, pp. 43-92.

- W. L. Kreidler, "Preliminary Study of Underground Disposal of Industrial Liquid Waste in New York State," Subsurface Disposal of Industrial Wastes, Oklahoma City, Interstate Oil Compact Commission, 1968, pp. 100-108.

c. Michigan Basin

- L. I. Briggs, Jr., "Geology of Subsurface Waste Disposal in Michigan Basin," American Association of Petroleum Geologists Memoir 10, 1968, pp. 128-153.

- W. DeWitt, Jr., "Geology of the Michigan Basin with Reference to Subsurface Disposal of Radioactive Wastes," US Atomic Energy Commission report TEI-771, 1960, 100 pp.

d. Salina Basin

- R. W. Edmund and E. D. Goebel, "Subsurface Waste-Disposal Potential in Salina Basin of Kansas," American Association of Petroleum Geologists Memoir 10, 1968, pp. 154-164.

e. Denver Basin

- S. Gabarini and H. K. Veal, "Potential of Denver Basin for Disposal of Liquid Wastes," American Association of Petroleum Geologists Memoir 10, 1968, pp. 165-168.

f. San Juan Basin

- J. A. Peterson, A. J. Loleit, C. W. Spencer and R. A. Ullrich, "Sedimentary History and Economic Geology of San Juan Basin, New Mexico and Colorado" American Association of Petroleum Geologists Memoir 10, 1968, pp. 186-229.
- C. A. Repenning, "Geologic Summary of the San Juan Basin, New Mexico, with Reference to Disposal of Liquid Radioactive Waste," US Geol. Survey report TEI-603, 1959, 57 pp.

g. Powder River Basin

- H. M. Beikman, "Geology of the Powder River Basin, Wyoming and Montana, with Reference to Subsurface Disposal of Radioactive Wastes," US Geol Survey report TEI-823, February 1962, 84 pp.

h. Williston Basin

- C. A. Sandberg, "Geology of the Williston Basin, North Dakota, Montana, and South Dakota, with Reference to Subsurface Disposal of Radioactive Waste," US Atomic Energy Commission Trace Elements Inv. report 809 (open file) 1962, 148 pp.

i. Atlantic and Gulf Coastal Plains

- H. E. LeGrande, "Geology and Ground-Water Hydrology of the Atlantic and Gulf Coastal Plain as Related to Disposal of Radioactive Wastes," US Atomic Energy Commission Trace Elements, Inv. report 805, January 1962, 169 pp.
- Philip M. Brown and Majorie Reid, "Geologic Evaluation of Waste-Storage Potential in Selected Segments of the Mesozoic Aquifer System Below the Zone of Fresh Water, Atlantic Coastal Plain, North Carolina through New Jersey," Geological Survey Professional Paper 881, Washington, DC, 1976, 47 pp.

j. Central Valley of California

- C. A. Repenning, "Geologic Summary of the Central Valley of California, with Reference to Disposal of Liquid Radioactive Waste," US Atomic Energy Commission report TEI-769, June 1960, 69 pp.

k. Anadarko Basin

- M. E. MacLachlan, "The Anadarko Basin (of parts of Oklahoma, Texas, and Colorado)," US Atomic Energy Commission Trace Elements Inv. report 831, March 1964, 75 pp.

l. Glorieta and Ogallala in the Oklahoma Panhandle

- J. H. Irwin and R. B. Morton, "Hydrogeologic Information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and Adjoining Areas as Related to Underground Waste Disposal," US Geol. Survey Circ. 630, 1969, 26 pp.

m. Other specific areas

- R. M. Alverson, "Deep Well Disposal Study for Baldwin, Excambia, and Mobile Counties, Ala.," Alabama Geol. Survey Cir. 58, 1970, 49 pp.
- J. T. Barraclough, "Waste Injection Into a Deep Limestone in Northwestern Florida," Ground Water, Vol. 4, No. 1, 1966, pp. 22-25.
- R. E. Bergstrom, "Feasibility of Subsurface Disposal of Industrial Wastes in Illinois," Illinois Geol. Survey Circ. 426, 1968, 18 pp.
- C. D. Hartman, "Deep-Well Disposal of Steel-Mill Wastes," J. Water Pollution Control Fed., Vol. 40, No. 1, January 1968, pp. 95-100.

These studies indicate that there are probably suitable liquid waste disposal zones in almost every region of the US. They also indicate the regions and formations that are the most promising. However, when the regional survey is completed, very specific site studies will be needed to verify the site selected (for example, see Trevorrow, 1977, for details on site selection).

C. Procedures

1. Well Construction

The disposal well must be properly drilled and cased in order that fluid is delivered only to the desired host reservoir. Techniques for proper well construction are usually tightly regulated by the states in which the wells

are drilled. General outlines for proper well completion are covered in Trevorrow, 1977; Donaldson, 1964, 1972, 1974; and Selm, 1959.

After an injection well has been drilled and possible injection zones identified, injection tests are usually run (Trevorrow, 1977).

2. Operation

Operating parameters vary according to formation, completion, etc. Data taken from Piper, 1969 on representative waste injection wells are in Table I.

To prevent corrosion of the injection equipment and plugging of the well and receiving formation, the liquid waste must often receive specific treatment, such as filtering and the addition of chemicals; treatment to eliminate bacteria is often necessary. Preinjection treatment procedures are outlined in Trevorrow 1977; Selm, 1959; and Donaldson, 1964, 1972, 1974.

It is also necessary to limit injection pressures to ensure that fracturing of the formation and confining layer (and hence loss of containment) does not occur (Clebsch, 1967).

3. Monitoring

A monitoring program is necessary, particularly at the injection well itself. Volume of injected fluid, temperature, water quality, injection pressure, and pressure in the casing-tubing annulus are usually determined throughout the lifetime of the injection program. Other monitoring (including monitoring of wells completed into the receiving aquifer and/or the regions above) may also be undertaken, depending on the type of fluid, well completion, etc. (Trevorrow, 1977).

TABLE I

REPRESENTATIVE INJECTION WELLS

	Maximum	Minimum	Median
Depth Drilled (m)	3886	90	811
Injection Zone			
Depth to top (m)	3650	61	625
Thickness (m)	640	1.5	56
Injection Rate (l/sec)	271 *	0.01	8

*Two wells jointly.

4. Liquefaction

Presently, only wastes that were originally liquid are being injected. It has been suggested that various solid low level wastes could be converted to a liquid (for example, by using acid digestion) and injected into the disposal formation (Gilbert/Commonwealth, 1980). However, liquefaction will cost additional money and may face many technical problems (Gilbert/Commonwealth, 1980).

D. Operating Experience

1. Non-Radioactive Liquid Waste

By the late 1960s, approximately 12.33×10^6 m³ yearly of unwanted oil field brines were being disposed of in the US in deep underground injection wells (Piper, 1969). Presently, in New Mexico alone, there are approximately 260 brine injection wells.* Between 1950 and 1960, a few chemical companies began to apply fluid injection to the disposal of chemical manufacturing wastes and by 1960 there were about 30 such wells in the US. The operation grew to 246 such disposal wells by 1972 (Donaldson, 1974; Warner, 1973). Surveys of disposal wells have been undertaken by the US Environmental Protection Agency (USEPA) (US Environmental Protection Agency, 1974), and by the Interstate Oil Compact Commission (IOCC and IOCC Suppl. 1). Well injection of non-radioactive liquids, and in some cases the problems encountered during operation, are described in Donaldson, 1964, 1972, 1974; Bayazeed, 1973; Healy, 1968; Ehrlich, 1979; and Warner, 1973. Failure of wells was mainly caused by unsuitable geologic conditions or faulty construction. Overall, there has been a high success rate (Warner, 1973).

2. Radioactive Liquid Waste

While there has been extensive experience with deep well injection of chemical wastes and oil field brines in the US, experience with radioactive wastes has been limited.

a. Anaconda. From 1960 through 1977, the Anaconda Company operated a deep injection well to dispose of decantate from their uranium mill tailings

*Mike Holland, Oil Conservation Commission, State of New Mexico, personal communication (October 1980).

pond at Bluewater, New Mexico. Concentrations of iron and manganese were persistently high in the injected fluid and would probably have caused plugging if the formation had not been fractured and conditioned with acid (West, 1972). Further details on injected liquid are available in West, 1972.

The well was initially drilled through several zones of sandstone to test each for injection development. (These sandstones have dense beds of mudstone, siltstone, and anhydrite above and between the beds.) The sandstones were fractured and tested, and the most favorable injection zones were selected (Clebsch, 1967). The well bore and the initial injection fluid were treated with citric acid to prevent precipitation of iron. Details of the well completion are given in West, 1972.

The injected liquid was decanted from the mill tailings pond and forced from the sump alternately through one of two circular leaf filters. The filtrate was run into a sump and then, during injection, through 2252.6 m (1.4 miles) of pipeline to the wellhead. The liquid entered the well by gravity flow through a sealed pipeline-wellhead connection. All equipment from the sump pump to the lower end of the injection pipe was rubber lined or stainless steel. Copper sulfate was added for control of bacteria and fungi, and calcium sulfate to retard precipitation. High turbidity in the supply pond was the most frequent reason for shutdowns. A few times, the well overflowed. Injection rates varied from ~ 0.0277 m³/s (440 gpm) to <0.0158 m³/s (250 gpm) (West, 1972).

By the end of December 1965, 1.89 million m³ (500 million gal) of liquid had been injected containing 13.89 curies of uranium, 312.6 curies of ²³⁰Th, and 0.612 curies of ²²⁶Ra (West, 1972).

A monitoring well completed into a formation above those being used for injection and some other nearby wells showed increased concentrations of uranium and chloride (Kaufman, 1975). However, it is difficult to tag the source of the contaminants because the tailings pile of the Anaconda mill is in the same region as the injection well and any seepage from the tailings could influence the water quality in the region.

The predicted head increase did not occur as injection continued. West states, "The fact that the head did not increase as predicted indicates that 1) the hydraulic characteristics of the aquifer were not evaluated correctly, 2) water leaks to other formations, 3) the characteristics of the reservoir rock have been changed by solution, or 4) aquifer damage near the well bore was not adequately evaluated." He also states, "The insignificant

rise of water level in the injection well suggests that water is leaking from the Yesso formation into the Glorieta and San Andres" (West, 1972).

b. Idaho Chemical. Another case of liquid radioactive waste injection in the United States is the disposal of liquid wastes from Idaho Chemical Processing Plant (ICPP). The Idaho well, however, is only 179.8 m (590 ft) deep, with the perforated zone from 106.7 to 179.8 m (350 to 590 ft). Injection is into a non-confined fresh water aquifer (Snake River Plain), with the water table about 137 m (449 ft) below the land surface.

From 1953 to 1970, about 1.135 million m³ (300 million gal) per year of waste water was discharged (Trevorrow, 1977; Robertson, 1973). This level of discharge has continued through the present time.* Nearly all radioactive wastes discharged down the ICPP well are fission and activation products originating from spent fuel elements processed at the plant and some water from laboratory sink drains. Most of the liquid is evaporator condensate. The effluent passes through an ion exchange system to remove most of the cationic ions (Trevorrow, 1977). Average concentrations of radioisotopes during the early 1970s are shown in Table II. At the present time, the concentrations of radioisotopes are slightly lower.*

The water moves from the injection well into the unconfined aquifer. In the general direction of flow of the aquifer, the USGS monitor well has indicated present ⁹⁰Sr levels of 0.005 pCi/m^l 1609 m (1 mile) from the injection site. Near the well, USGS measurements indicate present levels of ⁹⁰Sr as 0.15 pCi/m^l. For tritium, 4827 m (3 miles) from the injection well in the direction of the aquifer flow, present levels are 50 pCi/m^l, and at 8045 m (5 miles), 2 pCi/m^l. The Cl and Na ions are not sorbed well and are also detected in the USGS monitor wells. Attention is being given to ¹²⁹I levels at the injection site.* Alternatives to well injection are being considered for disposal of the waste.*

There have been several problems at the ICPP. In 1970, it was discovered that the waste water had corroded the steel casing until it collapsed. The well was plugged to a depth of 68.9 m (226 ft), and injection was occurring into the unsaturated zone above this level. The well was redrilled and relined (Trevorrow, 1977).

At another time, an upset in the process allowed low pH fluid to pass into the ion exchange facility. This pH

*George Lohse, Idaho Chemical Programs, Operations Office, Idaho Falls, personal communication (November 1980).

TABLE II
AVERAGE CONCENTRATIONS OF
RADIONUCLIDES IN THE ICPP
DISPOSAL WELL DISCHARGE

Isotope	Concentration (pCi/m ³)	Soluble Radiation Concentration ^a (pCi/m ³)
Cerium-144	4.5	10
Cesium-137	2.4	20
Tritium	526	3000
Ruthenium-106	1.1	10
Strontium-89	0.39	3
Strontium-90	2.4	0.3
Zirconium-95	3	60

^aFor unrestricted area, as given in Chapter 0524, as of 3/30/77 in *Standards for Radiation Protection*.

Source: Trevorrow 1977.

change eluded Sr collected on the resins and allowed higher than normal levels of Sr in the injection well fluid. Safety devices have now been installed to prevent a recurrence.*

c. *Texas in situ uranium recovery.* Another application of deep well injection of radioactive fluids is injection of liquid waste streams from *in situ* uranium recovery operations. Table III indicates the projects that have received injection permits.** The liquid is produced in two ways: (1) as a bleed stream during actual operations in which the uranium is being leached in the *in situ* process by a liquid (containing suitable oxidizing and reaction chemicals) moving through the leaching zone; the liquid is produced, treated, and then reinjected except for the bleed stream, and (2) as a "cleanup" stream resulting from pumping aquifer water into and through the leached zone to remove contaminants, and then pumping it to the surface for injection in the deep disposal well (Cowan, 1980). Water quality for the bleed stream is indicated in Table IV, and water quality for the expected "cleanup" liquid for one lixiviant system is given in Table V.

While the permitted injection rate varies from 283 to 1323 l/min (75 to 350 gpm),** the actual injection rate has been reported as 19 to 757 l/min (5 to 200 gpm), with total volumes ranging from 7 570 000 to 34 065 000 l (2 000 000 to 9 000 000 gal) per month (Cowan, 1980). Actual injection rates may increase as more companies begin full-scale aquifer restoration and the "cleanup" streams are produced.

Permitted injection pressures range from 6 550 000 to 8 280 000 Pa (950 to 1200 psi) (Cowan, 1980), whereas operating pressures are usually 27 600 to 5 516 000 Pa (4 to 800 psi) at the surface.**

Before an injection well can receive a permit in Texas, such as in the case of the uranium *in situ* injection wells, it must be demonstrated that there are no artificial unplugged penetrations near the area and that the formation is free of faults, etc. that might allow inter-aquifer connection.** The injection well casing is tested before operation by electric log and by a pressure test. The well pressure is monitored during operation, and monitor wells are used to detect seepage into non-target formation zones.**

d. *Soviet Union.* Underground injection of radioactive liquid waste in deep-lying aquifers has been studied in detail on the experimental and pilot scale for more than 13 years in the Soviet Union. It is reported that the host rock meets the qualifications of (1) confined, but adequately thick porous, permeable disposal formation, (2) beyond the limits of tectonically active regions, and (3) saline waters in a region containing no useful minerals (Spitsyn, 1967, 1972, 1978).

The injection systems are closed systems with safety backups. When the injection is complete, the wells are plugged, using cement and other suitable reagents to ensure integrity. Monitoring wells are located to detect any excursions (Yudin, 1968). The wastes are treated to make them compatible with the waters in the host rock; neutralization and clarification, at least, are usually required (Spitsyn, 1978). Initial pilot tests in Russia were carried out near the Nuclear Reactor Research Institute (NIIR). The pilot plant began operations in April 1966 (Kolychex, 1967). The injected liquids (specific activity of 1×10^{-4} to 1×10^{-6} Ci/l) contained surfactants and had a saline content of up to 9 g/l with a pH of 6 to 11. These were injected to a depth of 1550 m (5082 ft) into a formation having a saline content of 230 to 250 g/l.

*George Lohse, Idaho Chemical Programs, Operations Office, Idaho Falls, November 1980, personal communication.

**Bill Klemt, Texas Department of Water Resources, December 1980, personal communication.

TABLE III

**DEEP INJECTION WELL PERMITS IN TEXAS FOR INJECTION OF WASTE
PROCESS WATER FROM URANIUM *IN SITU* LEACHING PROJECTS**

Permit Number	GPM	m ³ /s	Company	Formation
WDW-123, 124	200	0.0126	US Steel	Yegua
WDW-130	350	0.221	US Steel	Yegua
WDW-134	200	0.0126	Union Carbide	Yegua
WDW-140	200	0.0126	US Steel	Yegua
WDW-141	200	0.0126	US Steel	Yegua
WDW-150	300	0.0189	Mobil	Yegua, Queen City
WDW-151	300	0.0189	Mobil	Yegua
WDW-156	200	0.0126	Wyoming Minerals	Wilcox
WDW-159	75	0.0047	IEC	Yegua
WDW-168	160	0.0101	Everest	Wilcox
WDW-170	225	0.0142	Wyoming Minerals	Yegua
WDW-174	200	0.0126	US Steel	Yegua
WDW-177	300	0.0189	Mobil	Queen City
WDW-178	300	0.0189	Mobil	Queen City
WDW-181	150	0.0095	Mobil	Wilcox
WDW-182	150	0.0095	Mobil	Wilcox
WDW-183 (pending)				
WDW-185	200	0.0126	Caithness Mining Corp.	Yegua
WDW-187	200	0.0126	Everest Minerals Corp.	Yegua

Source: Bill Klemt 1980.

Injection pressure was 36 to 42 atm ($36 \text{ to } 42 \times 10^5 \text{ Pa}$) in order to achieve a flow rate of $10 \text{ m}^3/\text{hr}$ (Zakharov, 1967). The wastes were usually injected for a period of about 30 days, and then no injection took place for the next 10 to 20 days (Kolychex, 1967). Gases that had to be vented underwent purification before release to the ambient atmosphere.

From April 1966 to January 1967, $40\,000 \text{ m}^3$ of effluents with a total activity of 360 Ci were injected (Zakharov, 1967). From 1966 to 1970, $320\,000 \text{ m}^3$ ($84.544 \times 10^6 \text{ gal}$) containing 3500 Ci of beta activity had been injected (Sedov, 1970). It is reported that by 1976, a total of $750\,000 \text{ m}^3$ ($198.150 \times 10^6 \text{ gal}$) of low-level liquid had been injected in the pilot plant at NIIAR.

In addition, approximately $2\,000\,000 \text{ m}^3$ ($528.4 \times 10^6 \text{ gal}$) of intermediate level waste with an activity of 95 000 Ci at the time of injection have also been disposed of via deep well injection. Trial injections of 1500 m^3 (396

$\times 10^3 \text{ gal}$) of high-activity waste have also occurred. It has been stated that gamma monitoring indicates localization of the waste in the disposal host rock (Spitsyn, 1978).

It is reported, "Throughout the entire period of injection no emergency situations have been detected." It is also stated, "Restorative measures have not been required" (Spitsyn, 1978). Where suitable geological formations are available at depths of 350 to 1500 m (1151 to 4918 ft), deep well disposal of radioactive liquid wastes from nuclear power plants is continuing (Kon-drat'ev, 1979).

e. Czechoslovak Socialist Republic. In the Czechoslovak Socialist Republic, liquid injection, including sludges, has been reported (Radioactive Waste Disposal into the Ground—IAEA, 1965).

TABLE IV

**WATER QUALITY OF BLEED STREAMS FROM
AMMONIUM CARBONATE/BICARBONATE
LEACH PROJECTS**

Constituent	Concentration (mg/l)
Ca	78 – 2040
Mg	18 – 400
Na	100 – 3400
HCO ₃	300 – 3600
SO ₄	400 – 4700
Cl	350 – 44 000
NH ₄	50 – 23 000
Mo	0 – 100
V	0 – 25
As	0 – 75
K	25 – 600
U ₃ O ₈	1 – 30
pH	4.0 – 9.5
Gross α	1000 – 15 700 pCi/l
Gross β	4550 – 6060 pCi/l
Radium-226	600 – 2500 pCi/l

Source: Obtained from permit applications to the Texas Water Commission and published in "Some Implications of *In Situ* Uranium Mining Technology Development," PNL-3439 (Cowan 1980).

TABLE V

**ESTIMATED RESTORATION WASTE WATER
STREAM FOR AMMONIUM-BICARBONATE
LEACH SYSTEMS FROM VARIOUS STAGES OF
THE RESTORATION PROCESS**

Constituent	Concentration (mg/l)
Ca	21 – 400
Mg	54 – 200
Na	210 – 8650
K	3 – 135
HCO ₃	105 – 14 320
SO ₄	110 – 15 620
Cl	230 – 12 750
F	0.3 – 14
NO ₃	1 – 19
TDS	710 – 54 100
NH ₄	2 – 9500
Mo	0.42 – 377
V	<0.05 – 0.21
U ₃ O ₈	3.5 – 403
Radium-226	370 – 4100 pCi/l
pH	4.5 – 8.5 standard units

Source: "Some Implications of *In Situ* Uranium Mining Technology Development," PNL-3439 (Cowan 1980).

E. Proposals for Injection of Liquid Radioactive Wastes

1. Federal Republic of Germany

There have been several proposals for deep underground injection of liquid radioactive wastes. For example, at Karlsruhe Nuclear Research Center, injection of tritium-containing effluents into an isolated depleted ore horizon using an inactive oil well was considered as early as 1972 (Hild, 1972). During the 1979 IAEA meeting held in Finland, it was reported that preparations for injection of tritium were being made under the direction of the Jülich Nuclear Research Center (Kühn, 1979).

2. France

In France, a survey was undertaken of the geological structures that might prove suitable for liquid injection (Barbreau, 1967).

3. United States

Kerr-McGee, at their UF₆ Sequoyah facility, proposed to inject waste containing some U, ²³⁴Th, ²³⁰Th, and ²²⁶Ra into a deep well located at the site. A well was drilled and tested. The Atomic Safety and Licensing Board rejected Kerr-McGee's application. It is reported, "The principal difficulties in this case were related to the fairly complex nature of the geology and subsurface hydrology, which made it difficult, if not impossible for Kerr-McGee to prove to the Board's satisfaction that no health and safety hazard was involved." (Trevorrow, 1977).

A disposal well was also considered for the Nuclear Fuel Services' West Valley New York facility. Specifications for the well were filed with the US Atomic Energy Commission (USAEC) Division of Materials Licensing in 1969. This well was to have disposed of low level

wastes generated during reprocessing and initially discharged to the surface streams (Trevorrow, 1977). Preliminary discussions were held with the AEC, USGS, New York officials, and consultants and staff of Nuclear Fuel Services. It is reported that the proposal "was not actively pursued after the initial phases" (Trevorrow, 1977).

In the mid-1970s, a preliminary study of possible ways to dispose of very low level, short half-life wastes generated at various facilities at the Los Alamos Scientific Laboratory was undertaken by Group H-7. Although well injection was considered for these liquids, the technique was rejected because (1) knowledge of the local geology was incomplete and there did not appear to be any extremely suitable injection zone, (2) EPA and NRC policy did not appear favorable toward well disposal without extensive documentation of safety, and (3) other disposal techniques were available.*

Gulf Mineral Resources recently drilled a test well near Mt. Taylor, San Juan Basin, New Mexico in order to test the feasibility of injecting radioactive decant from the tailings pond of a proposed uranium mill. Although the well is several kilometers deep, no formation was found that would accept fluids at reasonable injection rates and pressures.**

Two uranium companies, which have proposed *in situ* uranium recovery projects in New Mexico, have indicated that they are studying the feasibility of deep well injection of the waste fluids produced in the *in situ* process. These wells would also be located in the San Juan Basin.†

A generic study for disposal of tritium-bearing low-level liquid wastes by injection wells into deep formations was published in 1977. The study covers fluid characteristics, injection well siting, completion and operation, legal and regulatory controls, environmental impacts, and decommissioning (Trevorrow, 1977).

F. Technical Considerations

There are several technical limitations in deep well injection disposal.

- Equipment to withstand the corrosion and erosion of the injected liquid must be used.

- Suitable host formations must be available. These formations are probably quite large in volume and extent, however, they are finite, and because they cannot be replaced (unless liquids are withdrawn) once they become "full," this resource should not be used unnecessarily (Piper, 1965).
- The liquid cannot contain more heat generating radioactivity than can be safely conducted by the host rock and fluid movement away from the injection zone (Skibitzke, 1961). Depending on the host rock, if the waste contains enough activity to increase reservoir temperature by a significant amount, adverse geochemical and mineralogical changes may occur. More information on this aspect is contained in Chapman, 1979.
- The fluid to be injected must be compatible with the fluid and host rock in the injection zone so that clogging does not occur in the formation. Scaling in the injection equipment must also be minimized through waste treatment (Donaldson, 1974).

G. Environmental and Safety Concerns

Some of the primary safety and environmental concerns are (1) proper completion and maintenance of wells so that fluid flows only into the desired host rock, (2) lack of fractures and faults or other permeable zone and/or improperly plugged wells, which would permit interaquifer contamination, (3) surface sumps and other safety devices to catch the fluid in event of well plugging or pipe or tank failures, etc. at the surface facilities, (4) proper shielding for radiation at surface facilities, and (5) suitable decommissioning of surface facilities and well plugging upon completion of the injection program.

In the EIS for management of commercially generated radioactive waste, the concern for long-term integrity of liquid injected into deep wells was expressed as follows: "The waste is expected to remain in liquid form and may thus progressively disperse and diffuse throughout the host rock. Unless limits of movement are well defined, this mobility within the porous host media formation would be of concern regarding eventual release to the biosphere." (DOE/EIS-0046F).

*L. A. Emelity, H-7, Los Alamos Scientific Laboratory, November 1980, personal communication.

**On site visit, November 1980.

†Water Pollution Control Bureau Staff, EIL, New Mexico Health and Environment Department, December 1980.

In addition, there is limited knowledge of the possible reaction of waste constituents with subsurface environments; therefore, it is impossible to model the actual fluid and contaminant movement (Donaldson, 1972). Monitoring wells may not detect fluid movement if the movement is not uniform surrounding the injection site. Detailed knowledge of subsurface faults and fractures and other permeable zones is often difficult to obtain; hence it may be difficult to predict containment. Erle Donaldson has mentioned that from experience with deep underground oil wells, it may be impossible to know if wells completed into the same formation are connected hydrologically.* As the experience at Anaconda indicates, it is sometimes hard to determine what actually is happening with the injection and where initial pre-injection fluids and contaminated injection fluids are moving.

Injection of fluids may also cause earthquakes. This was first suggested in relation to the waste injection program at the Hollister Rocky Mountain Arsenal and earthquakes near Denver (Healy, 1968). Further experiments at the Rangely, Colorado oil field would also indicate that injection may trigger earthquakes under certain conditions in the subsurface region (Raleigh, 1976).

H. Cost Factors

Cost of the injection facility will vary greatly depending on (1) necessary pretreatment, (2) depth to desired formation, (3) number and completion depth of any monitoring wells, and (4) type of flow (gravity, pressure) into the injection formation. Erle Donaldson has indicated that today monitoring wells completed to depths of a few thousand meters cost between \$500 000 and \$1 000 000.*

II. FLUID INJECTION WITH FRACTURING

A. Description

For the technique of hydrofracture/injection, the liquid waste, mixed with suitable grout, is injected into the desired impermeable host rock at such pressure that horizontal fractures that were initially induced in the strata are further extended, thereby allowing fluid flow into the strata. The waste/grout mixture solidifies, forming a solid sheet with the host rock.

B. Site

1. Criteria

There are several criteria that must be met before an injection well is drilled. These include (Sun, 1977, 1980):

- Well-bedded shale or similar structure at least several hundreds of meters thick, with nearly horizontal bedding planes, without known faults and/or major interconnected joints and fractures.
- The direction of least principal stress oriented normal to the nearly horizontal bedding planes so that fractures are induced horizontally by the hydraulic fracturing. (This requirement is usually met only at depths of less than 600 to 1000 m and only at particular locations and in certain host rocks.)
- An area of seismic stability.
- An area isolated from surface or ground water flow.
- An area free of any known mineral resources.

2. Host Rock

Sun (1980) has reported the possibilities of using sandstone and limestone or crystalline igneous and metamorphic rocks and concluded that, in general, these are not as favorable candidates as shale. He found that shale typically provides the following properties favorable for radioactive waste disposal by hydraulic fracturing:

- susceptibility to the induction of nearly horizontal bedding plane fractures,
- bedding planes that probably inhibit the extension of existing vertical fractures and joints,
- extremely slow ground water movement, and
- further retardation by clay minerals of most radionuclides leached from the grout (Sun, 1980).

On the other hand, because of possible phase transitions in components in the shale and interaction of hot fluids with the shale host rock, Sun (1980) qualifies the recommendation for shale fracturing disposal, stating "Limited by present knowledge, radioactive waste whose cumulative decay temperature plus existing ground water temperature are above 100°C at the disposal depth, is

*Erle Donaldson, Bureau of Mines, Bartlesville, Oklahoma, October 1980, personal communication.

not recommended for disposal in shale or other rocks by grout injection and hydraulic fracturing without further studies."

3. Possible Sites in the US

It has been suggested by Shaffer and Blomeke (1979) that suitable shale injection-fracture host rocks are located in the Appalachian, Illinois, and Michigan basins. In addition, they have indicated that many of the Gulf Coast shales, and the Pierre and Mancos shales of Colorado and adjacent areas, may be suitable.

4. Investigation

Once a suitable site is located, extensive studies are necessary to determine in detail that the site has the necessary criteria for hydraulic fracture-disposal. Specific studies include test drilling, with suitable logging and core analyses and hydraulic fracture tests. Further details on these studies may be obtained from Sun, 1980 and Sun, 1973.

C. Operation

If the final site investigation indicates a suitable area, additional monitor wells can be installed. Finally, the actual initial fracture and injection of radioactive-containing grout can be started through the well casing, perforated at the desired depth, using high pressure oil well equipment. After several injections are made, the well can be cemented to close off that horizon and a new fracture-injection horizon developed above the former area. This can be continued until there are no longer any upper shales available for fracturing.

D. Operating Experience

This injection procedure can probably be best understood by referring to the experience at Oak Ridge National Laboratory (ORNL). The Laboratory is located in eastern Tennessee and is underlain by the Conasauga Group, 400 m thick at the injection site (Fig. 1); there is no known movement of groundwater below 100 m and no known active faults are located at the ORNL Site.

A trial grout injection was made in 1959 at a shallow depth of 90 m, and bedding-plane fractures were induced. In 1960, a second experimental well was tested with injections on two shale horizons, and again grout sheets were found to conform to bedding planes. A third well was drilled into shale at a depth of 329 m, and from 1964 to 1965, eight experimental injections composed of actual radioactive wastes produced at ORNL were completed. Operational injections in this well began in 1966. From 1964 to 1978, a total volume of 6400 m³ of intermediate radioactive waste ($<5.3 \times 10^2$ $\mu\text{Ci}/\text{m}^3$) containing a total activity of approximately 641 300 curies (mainly ¹³⁷Cs and ⁹⁰Sr) has been disposed of (Sun, 1980).

Each grout sheet is approximately 1 cm thick and up to 200 m wide, as determined by gamma surveys in the monitor wells. Figure 2 indicates the general pattern of fractures (Energy Research and Development Agency, 1977). After about four injections, the bottom of the well was plugged and a new slot cut in the casing about 3 to 5 m above the old slot. The surrounding shale formation was fractured at this new depth by water-pressurizing the well until a sudden drop in pressure signals the creation of a fracture (Weeren, 1979). Approximately 567.75 m³ (150 000 gal) of grout could be injected each time at a

Fig. 1. Subsurface geology at shale fracturing site (ERDA 1553).

Fig. 2. General pattern of fractures—north-south section (ERDA-1553).

rate of $0.0126 \text{ m}^3/\text{sec}$ (200 gpm). The last injection was in May 1979. At the present time, the liquid waste is in storage until a new facility is completed.*

Radioactive wastes produced by operations at ORNL are first neutralized with sodium hydroxide and stored in underground stainless steel tanks until decanting into concrete storage tanks. The decantate from the concrete tanks then goes to an evaporator for concentration by a factor of 20 to 30, and finally is stored until disposal. The circuit from the storage tanks is shown in Fig. 3 (Sun, 1980).

The ratio of injected slurry to original waste liquid is approximately 1.5:1.0. The clay cement mix added to the liquid waste must form a grout that (1) is compatible with the liquid waste, (2) is pumpable for periods of at least 24 h, (3) retains most of the associated water when it sets, and (4) has a relatively low leach rate.

The blend of solids that, when mixed with ORNL waste solutions, has been found to produce grouts with these properties contains cement, a retardant to delay setting of the grout, attapulgite clay to retain excess water, a second clay to retain cesium, and fly ash to retain strontium. The proportions of the different ingredients can be adjusted to allow for considerable variation in the composition or concentration of the waste solution being injected. A typical composition for ORNL wastes is shown in Table VI.

This dry solids mix is usually blended with liquid waste solution at a solids to liquid ratio of 720 to 1079 g/l (6 and 9 lb/gal). The grout produced has a density of about 1430 g/l (12 lb/gal) and an apparent viscosity of about $0.04 \text{ Pa}\cdot\text{s}$ (40 centipoise).

A new facility is being built at ORNL, 245 m from the present disposal site. A test hole was cored to determine

*H. O. Weeren, personal communication, November 1980.

Fig. 3. Flow diagram of new shale fracturing facility (ERDA-1553).

TABLE VI
COMPOSITION FOR ORNL
DRY SOLIDS MIXTURE

<u>Ingredient</u>	<u>Wt%</u>
Cement (Type I)	38.5
Fly Ash	38.5
Attapulgate	15.4
Pottery Clay	7.7
Retardant	0.05

Source: ERDA 1553.

rock properties at the site. This well was converted to an observation well, and three more observation wells were completed. The injection well has been drilled and completed similar to the former injection well, but about 60 m deeper, with the host rock comprising the Pumpkin Valley shale of the Conasauga Group. A test grout injection was made, followed by a water test injection (Sun, 1980).

The new facility will be designed to handle higher activity wastes (up to 8 Ci/t) and the sludges that have accumulated at ORNL in the waste storage tanks over the past 35 years (which will have ^{90}Sr as the main contaminant) (Sun, 1980; Weeren, 1979; * ERDA-1553).

E. Proposed Facilities

In addition to the ongoing program at ORNL, it has also been proposed to dispose of wastes at West Valley, New York through a program of grout injection. Experimental studies were made jointly by ORNL and USGS from 1969 to 1971 at that site. An injection well (463 m) and monitoring wells were drilled into the shale below the site. Five water and one water and grout injections (at depths of 150 and 435 m) determined that bedding-plane fractures could be induced (Sun, 1980; Sun, 1973). More data on this study are given in Sun, 1973.

A feasibility study for disposal, by hydraulic fracturing, of high level wastes at West Valley, composed of 2271 m³ (600 000 gal) of neutralized Purex waste and

45.4 m³ (12 000 gal) of acidic Thorex waste, was completed by Acres American Incorporated in 1978. Although this study concluded that the technique was feasible, a program of further research and development to verify this technique was outlined in the study (Acres American, Inc. et al., 1978). This program included laboratory tests to develop a grout mix suitable for the West Valley waste.

It has also been proposed that tritiated water could be included in the slurry during grout injection for any facility needing to dispose of tritium (Shaffer, 1979).

F. Technical Limitations

This process has the limitation that fracturing must be in the horizontal plane, as described earlier, in practice limiting the operation to bedded shales at a fairly shallow depth. In addition, grout mixtures must be tailored to meet the needs of each type of waste (Sun, 1980; Energy Research and Development Agency, 1977). The site must be selected so that a minimum of human interference from resource recovery will occur in future years (though shafts with thick casings could pass through the implanted grout).

Once the grout is emplaced in the well region, no future disposal will be possible; thus, this technique should be used in such a way as to maximize the amount of material injected into a given region. For example, it is hoped that injection layers can be made closer to each other in the new facility at ORNL.

Occasional operational problems have been experienced at ORNL, and are described in Weeren, 1979. The new facility at ORNL will use thicker walls for better shielding, and the cells will have stainless steel liners. Thus, with proper construction procedures, fairly high level beta-gamma wastes can be handled.*

G. Environmental and Safety Concerns

A number of questions concerning the safety of this method have been raised (Sun, 1980). They are

- the possibility that liquid waste might separate from the grout during and after injection and migrate through existing fractures or joints,
- whether waste can be leached out of a grout sheet by ground water,

*H. O. Weeren, Oak Ridge National Laboratory, personal communication (November 1980).

- reliability of methods of determining with certainty that orientation of the induced fractures is horizontal, or nearly so,
- whether grout injection and hydraulic fracturing has potential for triggering earthquakes, and
- safe isolation time required for the disposed waste.

At ORNL, careful mixing and grout composition minimizes separation of grout-liquid. However, there is always liquid separation after grout solidification, and, under pressure, the unbound water could leak through fractures into shale pores. At ORNL, bleedback of unbound water to the surface from the injection well after the grout has solidified is used to reduce the free water (about 4% of the total injection volume). This bleed is stored until the next injection (Energy Research and Development Agency, 1977). Free water was intersected in an observation well at ORNL, indicating that all free liquid may not be recovered as bleedback. Although it is believed that the free liquid is minimal and that sorption of contaminants will occur, a series of observation wells is necessary (Sun, 1980).

Tests at ORNL indicate low leach rates for the grout material (Weeren, 1979; Sun, 1980). Thus, if ground water contacts the grout sheet, there should be little mobilization of the radionuclides in the grout.

Monitoring techniques can be used to determine to some extent the orientation of the grout sheet and thus ensure that only horizontal flow has occurred. There are two types of monitoring wells: (1) wells for determination of the orientation of the grout sheet, and (2) wells for verification of the continued low permeability of the shale above the grout sheet. Six to eight wells can be used in a suitable host rock to determine grout sheet position. It is anticipated that wells completed above the injection region can detect any induced vertical fractures. In addition, during injection, the wellhead pressure is monitored to detect any pressure drop that might mean the opening of a vertical fracture. The rise in surface caused by the grout sheets can also be monitored (Sun, 1980). For example, at ORNL, after 5677 m³ (1 500 000 gal) of liquid had been injected, the maximum measured ground rise was 0.06 m (0.2 ft).

At some locations, it might be possible for grout injection to trigger earthquakes. The potential for this at the ORNL site is discussed in Sun, 1977 and Energy Research and Development Agency, 1977. The grout method may be less apt to generate earthquakes than

deep well liquid injection, as the grout technique does not produce an increase in pore pressure.

The shale-grout layers would appear to minimize possible migration of radionuclides from the grout because sorption should occur in many cases in the clays in the shale if radionuclides were leached from the shale. Careful site selection will further minimize the likelihood of migration.

In the surface operation, radionuclides in off-gas discharges from surface holding and processing tanks can be held to a minimum by using filters on the release vents. Radiation levels above background around holding tanks, processing equipment, and injection equipment can be minimized by shielding in these areas. Leaks developing in the processing area, holding tanks, and piping will require catchment basins and other secondary containment systems. An emergency waste pit can be constructed to contain grout in the event of a wellhead rupture.

H. Decommissioning

Once the upper part of the formation has been reached, the contaminated above-surface equipment must be removed. At ORNL, it has been found that the injection piping has a radiation field of approximately 100 mR/h near the top of the well.* Thus, special care is necessary in decommissioning the more contaminated pieces of equipment. The surface equipment can be used in another injection facility or can be sent to a solid waste burial site if washdown does not remove the contamination. The injection and monitoring wells should be plugged (Shaffer, 1979).

I. Cost and Other Factors

When ORNL was determining the best technique for management of the intermediate level radioactive waste, several processes were evaluated. These included

- mixing the solution or sludge with a cement-solids blend and solidifying in drums, with interim and then final drum storage,
- fixation of the waste in glass with glass storage,
- shale fracturing similar to that already in use, and

*H. O. Weeren, Oak Ridge National Laboratory, personal communication (November 1980).

- using an ion exchange facility to remove radionuclides.

Table VII summarizes volumes, discharge, operator exposure, cost, etc., for the ORNL treatment of waste (302 m³/yr; 80 000 gal/yr), and as noted, 37.8 m³/yr (10 000 gal/yr) of sludge with 1514 m³ (400 000 gal) of sludge in storage (Energy Research and Development Agency, 1977).

III. BEDROCK CAVITIES/TUNNELS

A. Description

This method involves slurring a waste/grout mixture into a specially constructed cavity.

B. Site

1. Criteria

The host rock must be competent and free of fractures and seams, have sufficient formation thickness, have low permeability and be isolated from groundwater, be located in a seismically stable area, and be located at suitable depth (Wacks, 1980).

2. Unsuitable Regions

Primary causes of concern are thin interbeds providing anomalously high groundwater flow, transecting fault or shear zones, faulted or pinched-out beds, variations in lithology, breccia pipes, caverns and abandoned excavations, gas or brine pockets, and high density of fractures and seams (Wacks, 1980).

TABLE VII
SUMMARY COMPARISON OF FIXATION PROCESSES

	Shale Cement	Glass	Shale Fracture	Cesium Strip
Solidified Waste Volume, m ³ /yr	362	145	1326	242
Solidified Waste Volume, gal/yr	95 700	38 300	350 000	63 800 ^a
Stored Waste Volume, m ³ (5 yr storage)	1814	726	none	1209
Stored Waste Volume, gal (5 yr storage)	478 500	191 500	none	319 000
Processing Temperature, °C	25	950	25	25
Operators Required, average man—day/wk	65	323	1.4	131
Shipping Volume, carrier loads/yr	204	123	none	129
Startup Date	1982	1985	1980	1983
Completion of Sludge Removal	1989	1992	1982	1990
Estimated Facility Cost (\$10 ⁶)	46	74	5.4	55
Estimated Annual Operating Cost (\$10 ⁶)	2.1 — 6.8 ^c	4.6 — 6.2 ^c	0.1 ^b	2.1 — 4.1 ^c
Operator Exposure, man—rem/yr	16	55	3	31
Radionuclide Discharge with Off—Gas, Ci/yr	0.001 — 0.4	0.01 — 0.6	0.0002	0.001 — 0.4
Radionuclide Discharge with Solid Waste, Ci/yr	1 — 5	100 — 500	<1	3 — 10
Estimated R&D, man years	14	35	6	26

^aDoes not include 102 m³ (27 000 gal) of low level waste generated by the process.

^bFor currently generated LLW only; disposal of accumulated sludge from past operations will require \$2 × 10⁶ over a 2 yr period.

^cRange reflects uncertainty in terminal storage charges.

Source: ERDA 1553.

Any of these conditions would provide the waste with a potential path of egress to the surface, and would thus render a site unusable. Therefore, it would clearly be economically advantageous to discover the presence of any of the above before the actual design and excavation of a storage tunnel, despite the generally high cost of the exploration techniques involved (Wacks, 1980).

3. Types of Host Rock

Rock types that appear to be good candidates for host rocks for cavern excavations include granite and granitic gneiss, basalt, tuff, and shale (Wacks, 1980). In cases of grout injection, the Germans are considering salt caverns (Köster, 1979).

C. Configuration

Several types of mine configurations have been proposed. One proposal envisions a central access shaft of 3 to 4 m i.d., and tunnels with service shafts (about 1 m i.d.) (Proctor, 1965). The tunnels would be approximately 10 by 6 m and isolated from the central access shaft with concrete bulkheads (Proctor, 1965; Trevorrow, 1977). This concept is illustrated in Fig. 4. Another concept would be to replace the storage tunnels with

egg-shaped caverns as illustrated in Fig. 5 (Köster, 1979) or with just a central cavern (Topp, 1979).

D. Development

The main mine shaft could be developed either through the traditional blast and muck technique or, in suitable formations, by drilling. At the present time, shafts up to the suggested 3- to 4-m-diam have been completed, using a special drilling rig, down to ~700 m.* There should be no problem in drilling service shafts, as shafts of these diameters are frequently drilled. Techniques for completion of the tunnels or cavities are dependent upon the host rock type, but again the technology is available for this type of construction.** In Germany, because salt is envisioned as the host rock, solution mining the cavity is being considered (Köster, 1979). This is also a well developed technique (Davis, 1981).

*On-site visits to Crownpoint, New Mexico, Conoco's shafts drilling project, June and November 1980.

**On-site visits to hard rock mines, 1977 to 1980.

Fig. 4. Storage value for radioactive wastes (Proctor 1965).

Fig. 5. Reference system for the container-free disposal of liquid MLW/LLW in a salt cavern (Köster 1979).

If the shafts pass through aquifers and cannot be sealed, water rings will have to be located around the shaft to convey the water leaking into the shaft into a central sump for pumping to the surface (Wacks, 1979).*

E. Operating Experience

There has been extensive experience with the storage of hydrocarbons in cavities. Such storage is particularly common in solution-mined salt cavities (Davis, 1981).

For a number of years, radioactive mill tailings sands have been placed in mined-out stopes of uranium mines. The usual procedure is to construct a bulkhead containing drainage holes in front of the area to be filled (Perkins, 1979). The sand is mixed with water on the surface and is carried by pipe down to the designated

area and sprayed into the bulkheaded room until the material nearly reaches the roof. The water drains from the sands into suitable sumps and is pumped to the surface, leaving the stable sand-filled region to aid in ground control (Goad, 1980). More information can be obtained from Goad, 1980 and Perkins, 1979.

In New Mexico, United Nuclear Corporation's Northeast Church Rock, Kerr-McGee's Sec. 35 and 36, and Rancher's Johnny M mines are all having mill tailings sands emplaced in mined-out areas. Section 35 is receiving approximately 725 600 kg/d (800 tons/d), Section 36 about 362 800 to 453 500 kg/d (400 to 500 tons/d), and Johnny M 5 442 000 to 5 895 500 kg/month (6000 to 6500 tons/month).* The sand emplacement at Northeast Church Rock varies greatly day to day, but can be as much as approximately

*On-site visits to hard rock mines, 1977 to 1980.

*On-site visits, November 1980.

1 360 500 kg/d (1500 tons/d) (United Nuclear Corporation, 1980). For several mines now undergoing development, there are plans for returning tailings sands to mined-out areas.* While the emplaced sands are draining, an increase in SO_4^{2-} has been measured in the water pumped from the mine (Goad, 1980). Further data are needed to determine whether leaching of radionuclides from the emplaced sands is occurring, and if so, what the rate of migration of these leached radionuclides is.

F. Proposed Facilities

1. United States

Slurrying wastes from the existing tanks into a bedrock excavation has been proposed for the wastes at Savannah River. In 1962, 1969, and 1972, several exploratory holes were drilled at Savannah River to determine the hydrology and rock structure. Gravity, magnetic, and reflection surveys also were undertaken (Proctor, 1965; Marine, 1973). The procedure of isolation in a cavern was later considered in a waste management survey for wastes from the Savannah River site (Topp, 1979).

The initial proposal was to slurry the liquid waste, which has a pH of approximately 9, into the cavern without treatment. Later, the idea of adding solids to form a grout was considered; however, no experimental work was done to determine suitable grout mixtures. The cavity was to be excavated in the Triassic mudstone (approximately 1615.4 m thick) located approximately 5000 m below the Savannah River site (Topp, 1979; Marine, 1973). The mudstone is well below the unconfined water table and about 200 m below the Tuscaloosa aquifer. The first step in augmenting this plan was envisioned as constructing test tunnels in the mudstone. However, this disposal treatment technique has been dropped and solidification (multiple barrier concept) processes are being studied.**

2. Federal Republic of Germany

In Germany, the concept of injection into a cavity in order to dispose of liquid MLW/LLW waste produced at the projected German nuclear fuel cycle back end center

is undergoing study. The main features of the concept under study are (Köster, 1979)

- "1) prefabrication of granules (diameter ca. 10 mm) with the aqueous MLW/LLW and inorganic binders above ground.
- 2) transportation of the granules in cementitious grout via vertical pipeline into a 75,000 m³ cavern, located ca. 1000 m below ground. The grout may consist of tritiated water.
- 3) *in situ* solidification of the concrete-like waste product forming layers which represent subsequent batches."

The wastes, as outlined in Table VIII, are granulated above ground by adding inorganic binder with the help of special technical equipment. Prefabricated pellets are mixed with a cement grout using either inactive water or tritium-enriched water as generated at the HLW concentration and vitrification facility. This mixture is transported by gravity through a vertical pipe directly into a big cavern with a capacity of 75 000 m³ located 800 to 1000 m underground. The velocity of the mixture in the vertical pipe is controlled by the wall friction and the pipe diameter. Figures 5 and 6 indicate the general concept for the process.

The advantages outlined by Köster, 1979 for this technique are

- "1) large quantities of waste can be handled easily;
- 2) a small number of processing steps, lack of container, and a simplified handling will lead to a reduction of radiation doses for the staff;
- 3) this concept is considered to achieve a complete filling of the caverns, resulting in a final state of the salt formation which is very close to its original state;
- 4) the formation of a quasi-monolithic block with a small surface-to-volume ratio is of advantage in case of a brine intrusion;
- 5) the utilization of the cavern volume is ~10 times better than in case of using containers with lost concrete shielding; thus, relatively low costs may be achieved. Preliminary cost estimations have shown

*On-site visits, November 1980.

**S. V. Topp, Savannah River Laboratory, personal communication (December 1980).

TABLE VIII
CHARACTERISTICS OF SOLIDIFIED LIQUID MLW AND LLW WITH CEMENT

<u>Waste Type</u>	<u>Waste Category</u>	<u>Final Product (m³/yr)</u>	<u>Mean β/γ Activity (Ci/m³)</u>
Used as filling material	Distillates containing HTO	5550 (water/cement ratio = 0.4)	130
	Aqueous low level waste	2700 ^a	8×10^{-2}
Used for pellet production ^b	Aqueous medium level	5300 ^a	260
	Ashes	140	1
	Bead resins	750	25
	Powder resins plus evaporator concentrates	820	80

^a10% salt content.

^bAverage α -activity = 10^{-3} Ci/m³.

Source: Köster 1979.

that the proposed concept decreases specific costs by a factor of 5 compared with the conventional concept."

G. Decommissioning

Once the caverns are full, the shafts and tunnels must be suitably sealed to prevent water from aquifers penetrated by the shafts from moving into the waste zone. This will require the use of special seals, perhaps similar to those being developed for HLW storage facilities (D'Appolonia, 1980).

H. Technical Limitations

Technical limitations include available suitable host rock and need for the liquid or slurry to originate close to the disposal site to avoid transporting the radioactive liquids long distances.

I. Environmental and Safety Concerns

Concern about loss of shaft integrity during slurring operations has been expressed. "Tightness" of the host rock and upward leakage through the shaft or fractures after completion of disposal will require careful study on a site-by-site basis (Proctor, 1965; Topp, 1979; D'Appolonia, 1980).

In order to achieve maximum safety and a minimum of exposure, it will be necessary to

- equip all gas discharge points with filters and other devices as necessary to minimize radioactive emissions to the atmosphere,
- design the surface handling and injection equipment to withstand erosion and corrosion,
- design the surface handling equipment (particularly if the German concept is used) to avoid plugging,
- have standby pumps and emergency power available if the shaft has water entering it,
- install suitable shielding at surface facilities,
- have emergency drains and sumps to catch the liquid if breaks in piping or other equipment occur,
- dilute all wastes to levels of activity low enough to prevent excessive temperature increase (the temperature of the solidified waste and cavern will be dependent upon contributions of the heat of hydration, decay heat of radionuclides, and initial temperature of the host rock) and allow time between injections for the heat of hydration to be dissipated,
- pump back for reuse any free water resulting from the hardening of the grout mixture,

Fig. 6. Scheme of three caverns in different states- construction, operation, decommissioning (Köster, 1979).

- install monitor wells,
- monitor flow rate and pressure during slurring to ensure that unexpected plugging or leaks have not occurred, and
- monitor emplacement level in the cavity and compare with expected level.

Because the volume-to-surface ratio of the waste in the cavity is large, it would be expected that if the waste forms an impervious mixture, there would be minimum leaching by any groundwater moving in the host rock.

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