FINAL VERSION

CONF-770512--13

WASTE DISPOSAL BY SHALE FRACTURING AT ORNL*

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*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

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Abstract--The shale fracturing process is a method of waste disposal currently in use at the Oak Ridge National Laboratory (ORNL) for the permanent disposal of certain locally generated radioactive waste solutions. In this process, the waste solution is mixed with a solids blend of cement and other additives; the resulting grout is injected into an impermeable shale formation at a depth of 700 to 1000 ft (200 to 300 m). A few hours after completion of the injection, the grout sets, fixing the radioactive waste in the shale formation. The operational experience with this process since 1966, the monitoring techniques that have been developed, and some considerations of the impact on the environment are discussed.

INTRODUCTION

The shale fracturing process is a waste disposal process currently in use at the Oak Ridge National Laboratory (ORNL) for the permanent disposal of locally generated intermediate-level waste solutions. In this process, the waste solution is mixed with a solids blend of cement and other additives; the resulting grout is injected into an impermeable shale formation at a depth of 700 to 1000 ft (200 to 300 m)--well below the level at which ground water is encountered. During the course of the injection, the injected grout forms a thin, approximately horizontal grout sheet that measures several hundred feet across. A few hours after completion of the injection, the grout sets, thereby permanently fixing the radioactive waste in the shale formation.

The process was developed in a series of experiments between 1959 and 1965. The geology of the site was investigated, a cement base mix was developed, and several experimental, large-scale injections were made to evaluate the process and the equipment. The experimental facility was modified in 1966 for the routine disposal of intermediate-level waste solutions generated at ORNL. Since this date, this facility has been used to inject 1.8 million gal (8.6 million ℓ.) of waste grout containing 550,000 Ci of radionuclides. The results have been quite good.

I plan to discuss the operational experience with this method of waste disposal, the monitoring techniques that have been developed, and some considerations of the impact on the environment.

FACILITY DESCRIPTION

The shale fracturing facility consists of the injection well, a network of monitoring wells, storage tanks for the waste solution, storage bins for the dry solids mix, a mixer, a surge tank, and an injection pump and associated high-pressure piping. A standby injection pump is rented for each injection; its function is to clear grout from the injection well and other high-pressure piping in the event of failure of the main injection pump. An isometric view of the facility is shown in Fig. 1.

Three types of wells have been used at the shale fracturing facility: (1) an injection well for the injection of waste grout, (2) a network of observation wells for the determination of the orientation of the grout sheet, and (3) a network of rock-cover monitoring wells for verification of the continued impermeability of the shale above the grout sheets. A sketch of these well-types is given in Fig. 2. All waste injections are made through slots cut in the casing and the surrounding cement of the injection well. As the grout sheet spreads out from the injection well, it intersects the cemented casing of one or more observation wells. A gamma-sensitive probe in the observation well then detects the presence

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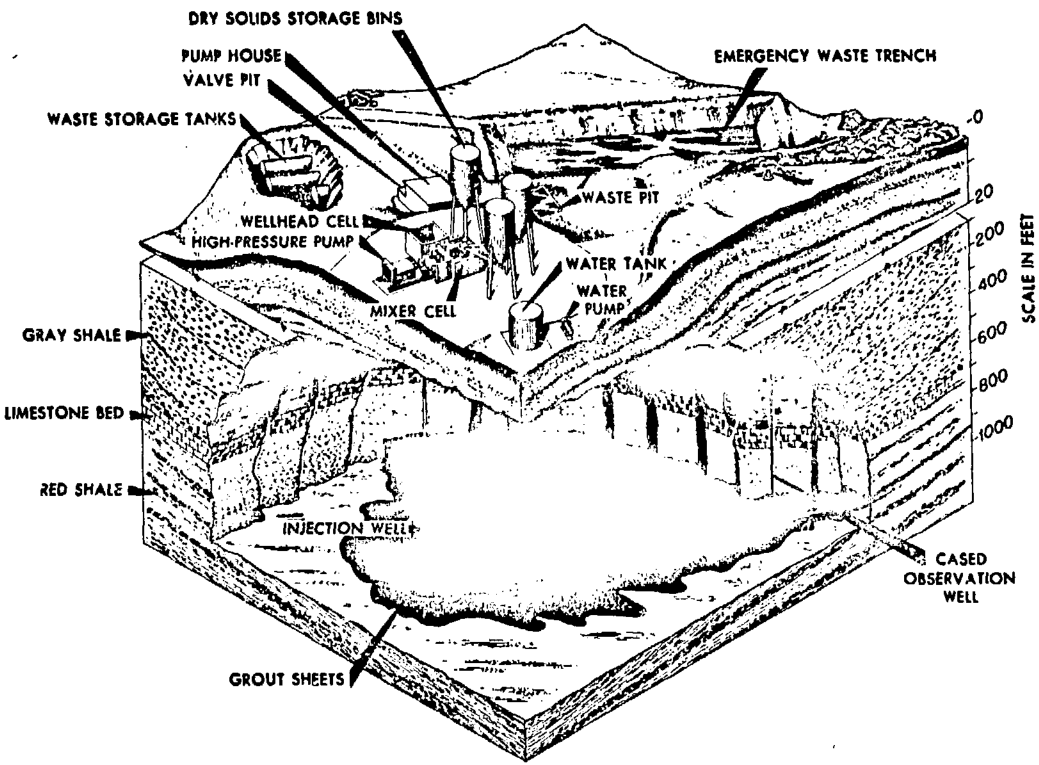

Fig. 1. The Shale Fracturing Disposal Plant at ORNL.

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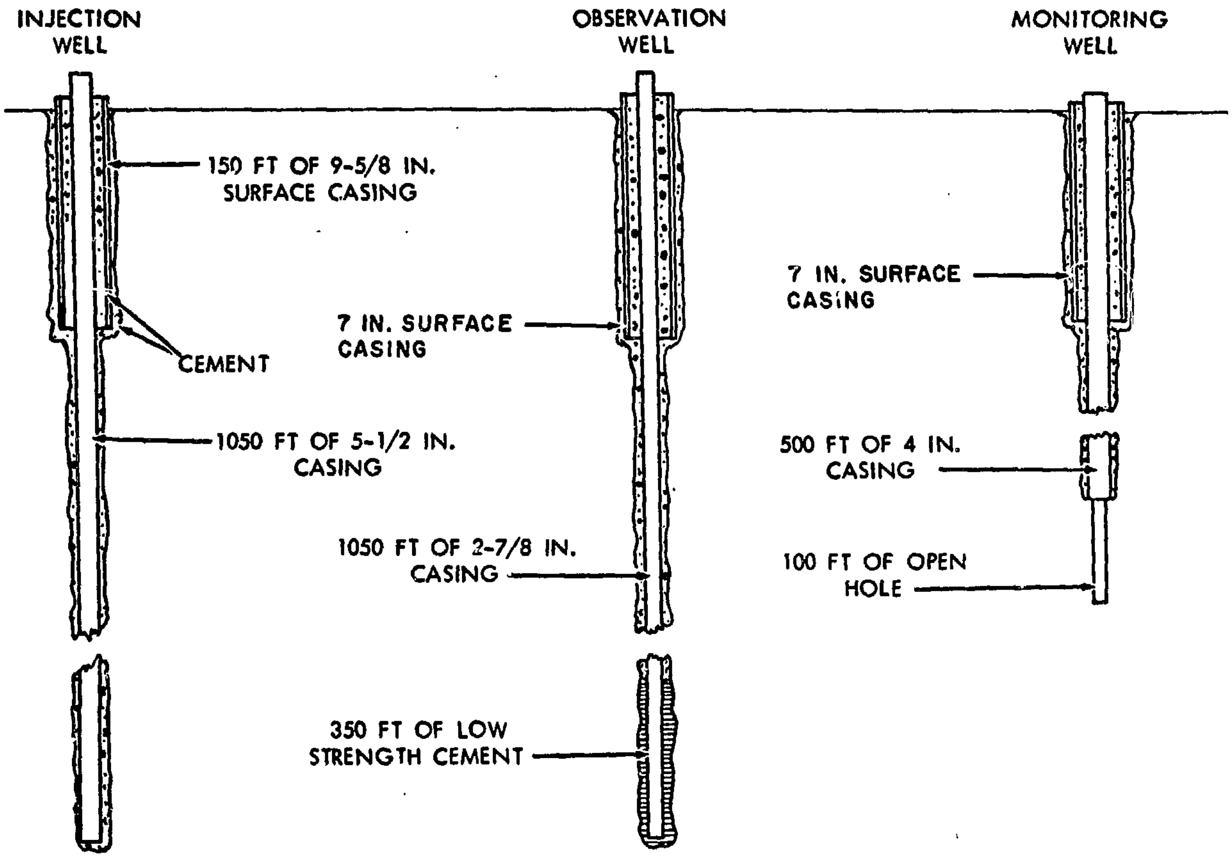

Fig. 2. Sketch of Wells for Fracturing Facility.

of the grout sheet, thereby establishing the depth of the grout sheet at that point. A network of six to eight observation wells is used to verify the horizontal orientation of the grout sheet. The lower section of most of the observation wells is cemented with a low-strength grout so that the well casing will not be pulled apart by the stresses generated by the grout sheet lifting the overburden. Instead, the low-strength grout will yield and permit the casing to rise with the overburden and relieve the stress. The rock-cover monitoring wells are used to determine periodically the permeability of the shale cover rock at a depth of 600 ft (180 m). The procedure confirms that accumulated stresses generated by repeated injections have not fractured the shale zone above the disposal zone and, thereby, endangered the isolation of the disposal zone.

The mix used in the shale fracturing process should meet the following requirements: (1) inexpensive, (2) pumpable for at least 8 hrs, (3) retain virtually all of the associated water when it sets, and (4) be as leach resistant as possible. The mix developed for the experimental program and still in use consists of Portland cement (38.5 wt %), fly ash (38.5%), Attapulgite drilling clay (15.4 wt %), clay (7.7 wt %), and a retarder (0.05 wt %). The cost of this mix is about 10 cents per gallon (2.6 ¢/ℓ.) of waste and the leach resistance is roughly equivalent to that of a good borosilicate glass, as observed by Moore et al. (Mo 75).

OPERATIONAL PROCEDURE

Prior to an injection, 80,000 to 90,000 gal (300,000 to 340,000 ℓ.) of waste solution is pumped to the waste storage tanks at the injection site. The cement, fly ash, and other dry solids are blended and stored in bins at the injection facility.

At every fourth injection, the slot in the casing of the injection well through which the previous injections were made is plugged with a small volume of cement; a new slot is then cut in the casing at a depth 10 ft (3 m) higher in the well. This is done by directing a high-velocity stream of sand and water slurry against the casing at the desired level until the casing and the surrounding formation is cut away.

During an injection, the waste solution is pumped to the mixer, continuously mixed with the preblended solids, and then discharged into the surge tank. From the surge tank, the grout is pumped down the tubing string in the formation well and out into the shale formation. The solids-to-liquid mix ratio is controlled to ensure that the grout has the desired properties. This control of the mix ratio is achieved by (1) determining the waste flow rate with a fluid flowmeter, (2) obtaining the solids flow rate with a 'mass flowmeter' (a device that continuously weighs the flow of solids through it), and (3) integrating these signals to provide a continuous readout of the mix ratio. An operator continuously adjusts the flow of solids to the mixer to maintain this ratio at the desired value. A second operator adjusts the speed of the injection pump to maintain a near-constant grout level in the surge tank.

The normal flow rate of waste solution is about 180 gal/min (680 ℓ./min); the normal mix ratio is about 7.5 lb of solids per gallon of waste (0.9 kg/ℓ.), and the normal grout injection rate is about 250 gal/min (950 ℓ./min). An injection requires about 8 hr to complete. At the end of the injection, the well is flushed with water. A small excess of water (about 100 gal) is used so that the slot in the injection well will be free of grout and can be re-used for the next injection. The well is shut in under pressure to permit the grout to set, and the grout residues are washed from the equipment in the facility.

A few weeks after an injection has been completed, the well is opened and any free water that has separated from the grout is allowed to flow back up the well. At this point, the waste is collected and fed to the Laboratory waste-collection system. This operation removes from the disposal formation the very small fraction of radionuclides that are associated with the potentially mobile free water and leaves the bulk of the radionuclides fixed in the grout. The bleed-back water usually contains <0.1% of the injected radionuclides.

INJECTION MONITORING

The injection pressure and the radiation exposure of the operating crew are regularly monitored during each injection. A few days after the injection,the orientation of the grout sheet is determined by logging the observation wells. After several injections have been completed, the cumulative surface uplift around the injection well is determined, and the continued impermeability of the shale overlying the disposal zone is verified. Other monitoring techniques have been investigated at various times, but their usefulness is unproven. A representative series of gamma-ray logs is shown in Fig. 3.

A series of surface uplift measurements is shown in Fig. 4.

A fragement of core containing a grout sheet is shown in Fig. 5.

OPERATIONAL HISTORY

The existing disposal facility was built in 1963, and a series of experimental waste injections was made in 1964 and 1965 to demonstrate the feasibility of the process. An account of this procedure was given

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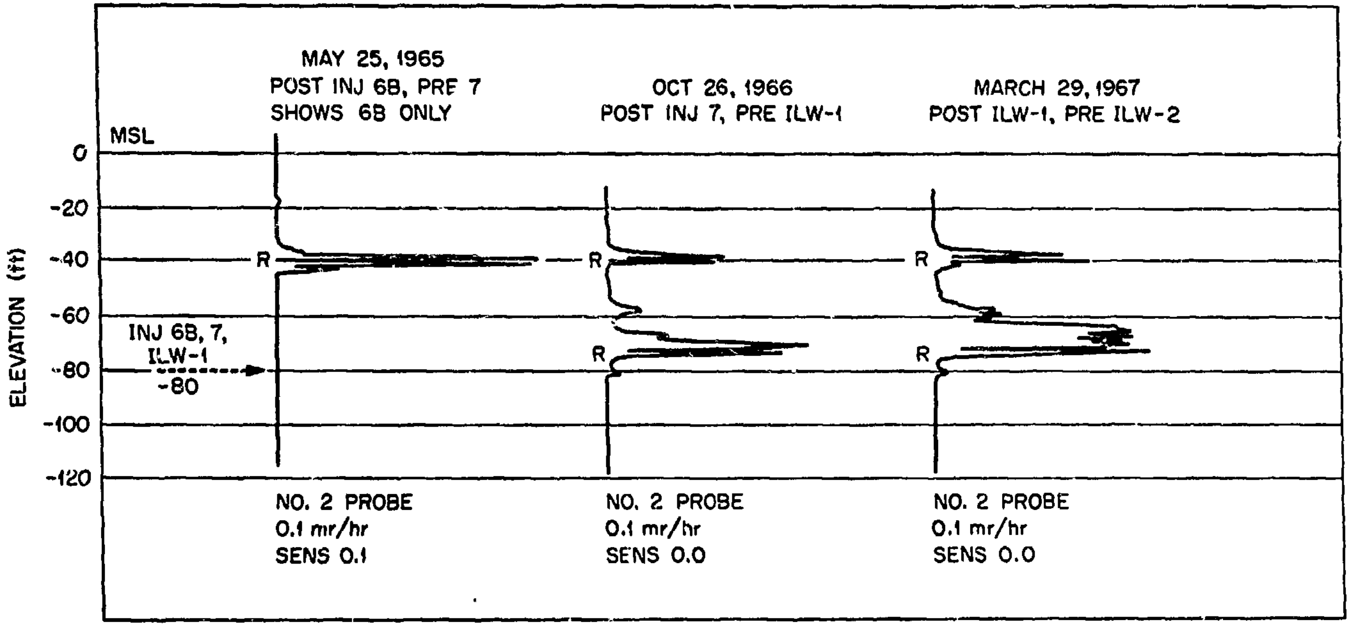

Fig. 3. Series of Gamma-Ray Logs in Observation Well.

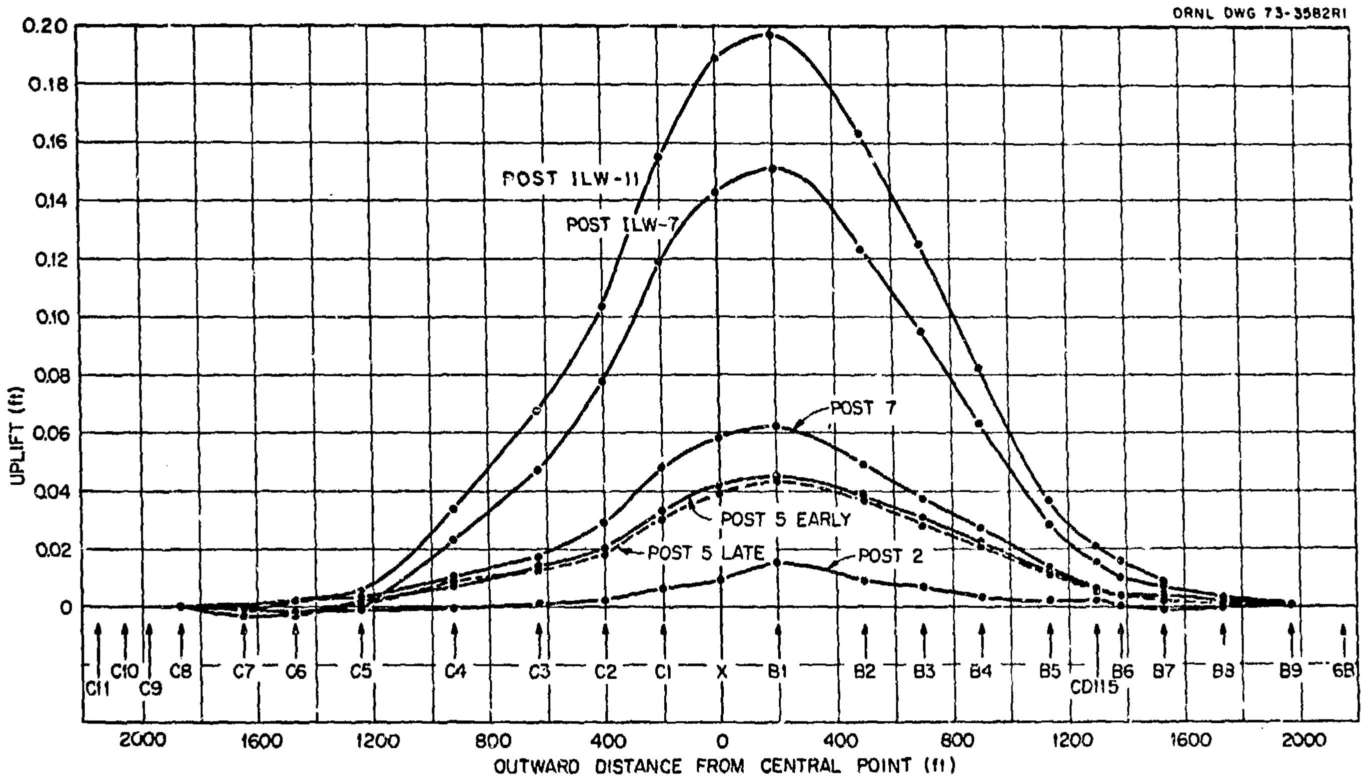

Fig. 4. Surface Uplift at Disposal Site.

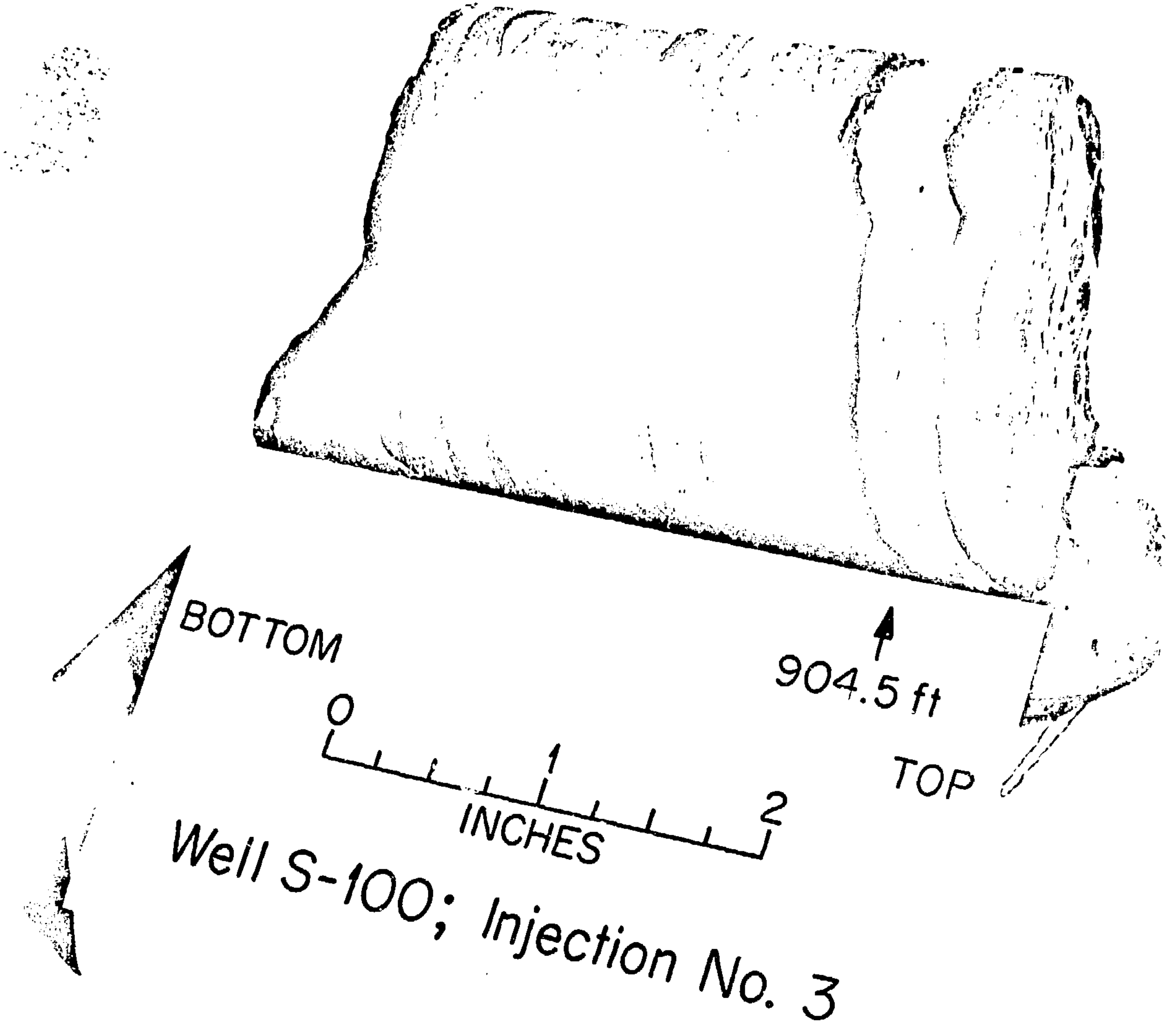

Fig. 5. Core Fragment of Grout Sheet.

by de Laguna et al. (de 68). After the last of these experimental injections, the facility was converted into an operational facility for the routine disposal of a concentrated intermediate-level waste (ILW) solution. This solution is generated by routine ORNL operations; it is alkaline (approximately 1 M in $NaNO_3$) and has a specific activity of about 1 Ci/gal (0.26 Ci/ℓ.), predominately ^{137}Cs. About 80,000 gal/yr (300,000 ℓ./yr) is produced. Some of the parameters of the entire injection series are given in Table 1.

The operation of the shale fracturing facility during this series of injections has had some problems, but most of these difficulties have been comparatively minor. With the exception of two injections (discussed below), the problems have not been serious enough to force the termination or major delay of an injection. They have required, at most, a relatively short shutdown of the injection while repairs were made. These difficulties included such miscellaneous items as (1) eroded check valves in the injection pump, (2) a plugged drain line from the injection pump sump, (3) a ruptured solids supply-line connection, (4) the loss of prime on the waste pump, (5) the jamming of the clutch on the injection pump, (6) the bridging of solids in the feed hopper, and (7) a leak past the sealing ring of one of the high-pressure valves. Each incident has been an isolated occurrence; none has caused serious difficulty.

The one injection that was delayed had a failure of a packing seal of the injection pump. In this case, the facility and well were washed free of grout with the standby pump, repairs were made, and the injection was resumed two days later. The injection that was terminated resulted from an attempt to utilize blended solids that had been stored several

TABLE 1. INJECTION PARAMETERS FOR ROUTINE DISPOSAL OF WASTE SOLUTION

Injection Number	Date	Depth (ft)	Waste Volume (gal)	Waste Plus Water Volume (gal)	Grout Volume (gal)	Mix Ratio (lb solid) (gal liquid)	^{90}Sr (Ci)	^{137}Cs (Ci)	^{244}Cm (Ci)	^{239}Pu (Ci)
__Experimental Injections__										
1-7	Feb. 1964 to Aug. 1965	945 to 872		457,300	678,000		1,436	5,237		
__Operational Injections__										
ILW1A	Dec. 12, 1966	872	36,000	69,931	95,197	6.2	3	19,950	NA*	NA
ILW1B	Dec. 13, 1966	872	26,000							
ILW2A	Apr. 20, 1967	862	86,000	164,800	230,405	6.1	1,050	58,500	NA	NA
ILW2B	Apr. 24, 1967	862	62,000							
ILW3A	Nov. 28, 1967	862	31,000	99,050	146,751	5.5	9,000	17,000	NA	NA
ILW3B	Nov. 29, 1967	862	52,000							
Water Test	Dec. 13, 1967	852		44,709	44,709					
ILW4A	Apr. 3, 1968	852	24,010	97,090	130,675	5.1	4,300	51,900	NA	1.10
ILW4B	Apr. 4, 1968	852	62,180							
ILW5	Oct. 30, 1968	842	81,800	87,110	115,174	5.6	500	69,400	NA	1.15
ILW6	June 11, 1969	842	79,350	91,750	126,331	5.4	8,900	89,000	NA	0.24
ILW7	Sept. 23, 1970	842	83,000	107,650	145,670	5.5	2,747	44,833	19.2	1.77
ILW8	Sept. 29, 1972	832	72,700	81,400	108,605	7.3	45	28,000	0.20	0.13
ILW9	Oct. 17, 1972	832	68,300	75,600	114,000	7.8	231	23,400	6.51	None
ILW10	Nov. 8, 1972	832	84,760	93,570	132,960	7.1	1,330	18,800	26.67	0.37
ILW11	Dec. 5, 1972	832	75,760	82,110	125,490	7.2	1,100	23,500	155.74	None
ILW12	Jan. 24, 1975	822	25,710	30,100	42,100	6.6	1,324	12,752	1.02	None
ILW13	Apr. 29, 1975	822	81,000	85,900	126,100	6.3	3,368	35,750	17.83	0.03
ILW14	June 20, 1975	822	82,970	92,470	138,700	6.7	2,874	30,592	3.58	None
Total ILW			1,114,540	1,303,240	1,822,870		36,766	523,377		

NA = not analyzed

months. The flowability of these solids was poor, and the injection was quickly shut down.

General experience with the shale fracturing facility in fourteen operating injections has been quite good. Large volumes of waste solution have been continuously mixed with dry solids in the desired proportions and injected into the isolated shale bed. The cleanup of small waste spills has been found to be feasible, as has the direct maintenance of mechanical equipment.

OPERATING COSTS

The major operating costs for the injection of a batch of waste are the following: (1) the costs for the mix, (2) the service charges of an oil well cementing company (Halliburton) for making the injection, and (3) the cost of ORNL labor and services for preliminary preparations and assistance during the injection. These costs vary from one injection to the next and, since no injection is entirely typical, no set of costs for a single injection is quite complete; an average for several injections is probably more meaningful.

The injection series ILW 8, 9, 10, and 11 was made between September and December of 1972. At this time 301,500 gal (1.14 million ℓ.) of waste and 31,200 gal (118,000 ℓ.) of water were mixed with solids and injected. The overall costs for this series are given in Table 2.

The extraordinary items listed in Table 2 are the costs for replacement of much of the high-pressure piping in the system, which was done at the start of this particular injection series. The costs of these items are not typical and should be amortized over more than four injections to obtain a more meaningful cost per injection or cost per gallon.

TABLE 2. COSTS FOR 1972 INJECTIONS SERIES

Mix cost	$22,000
Halliburton charges	27,720
ORNL charges	32,800
Extraordinary items	14,500
	$97,020

ENVIRONMENTAL AND SAFETY CONSIDERATIONS

The essential feature of the shale fracturing process is the fixation of the radionuclides in a geological formation that is isolated from contact with the surface environment. Several independent lines of evidence indicate that the formation into which the injections are made is quite isolated and has been so for millennia. There are also some additional features of the process that would provide continued containment of the radionuclides even if the isolation of the disposal formation should be lost. The leach rate of significant radionuclides from the set grout is quite low. Also, those radionuclides that might be leached from a grout sheet would be retained in the disposal zone by the high ion exchange capacity of the shale. The permanence of disposal of radioactive wastes by this process is exceptional.

One potential accident situation is of major concern to the safe operation of the shale fracturing facility. It is possible for the orientation of the fracture formed in the shale during a waste injection to be vertical rather than horizontal, allowing some quantity of grout to reach the surface or formations near the surface that contain circulating water. The formation of such a vertical fracture in the bedded shales at Oak Ridge during a waste injection is considered to be highly improbable. Nearly thirty fractures have been made in the bedded shale at Oak Ridge, and all of these fractures have been essentially horizontal. Even if a vertical fracture should be formed, however, the depth of the injection zone is so great that only a fracture with a very unusual geometry (very long and very narrow) could approach the surface. The consequences of such an incident have been evaluated, however, and have been found to be small. The leach rates of significant radionuclides from any ejected grout would be low, and the net loss of radionuclides would be small, even under the worst conditions.

Drilling operations in the vicinity of the disposal formation are not likely to be of concern. Wells have been drilled through grout sheets at the existing site, and only minor amounts of activity (∿ 10 mCi) have been found in the drilling water.

The overall environmental impact of a shale fracturing facility is beneficial. The facility removes large volumes of potentially hazardous radioactive wastes from the existing surface storage facilities and fixes these wastes in impermeable shale formations, well-removed from the biosphere. All major incident situations that have been postulated are considered to be quite improbable, and the analysis of each case has indicated that the ultimate release of radionuclides to the environment would be small.

PROCESS STATUS

A new shale fracturing facility is being planned; this facility will be designed to handle waste solutions and sludges with a somewhat higher specific activity than can currently be processed (up to 20 Ci/gal) (5.3 Ci/ℓ.). The site of this proposed new facility is about 800 ft (240 m) south of the existing facility; the waste grout from this facility will be injected into another part of the same formation that is now being used. A test injection has been made at the new site, and the injected grout has been detected in at least three of the five observation wells at depths that indicate that bedding plane fractures were formed.

Shale fracturing at ORNL is a specialized disposal technique with a specific waste in a carefully tested rock formation. Application of this technique to other wastes and other geologic formations would have to be done quite carefully. This technique would not at present be suitable for wastes containing transuranium nuclides because of current regulations. There is no technical reason why it could not be used for such wastes, however. It would not be suitable for acidic wastes or for wastes of low specific activity. It does have possible application, however, for alkaline non-transuranic wastes with moderately high specific activity; disposal of this type of waste by shale fracturing might be feasible if the underlying rocks were suitable. The type of program that might be required to establish this suitability is illustrated by the series of tests made at West Valley, N. Y. After a preliminary investigation of the geology of the area, a set of wells was drilled, and several injections were made. According to Sun et al. (Su 74), these injections verified the horizontal orientation of the fractures that were formed and the general impermeability of the formation.

Another possible application of this work would be the use of the mix to fix radioactive solutions or possibly slurries for subsequent surface or near-surface storage. This mix retains radionuclides far better than most cements, it is relative cheap, nonflammable, and adaptable to a fairly wide range of waste chemicals.

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LIST OF FIGURES

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