RECENT HYDROFRACTURE OPERATIONS AT OAK RIDGE NATIONAL LABORATORY*

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ABSTRACT

The hydrofracture process is currently being used at Oak Ridge National Laboratory (ORNL) for the permanent disposal of locally generated radioactive waste solutions and slurries. In this process, the waste solution or slurry is mixed with a blend of cement and other solid additives; the resulting grout is then injected into an impermeable shale formation at a depth of 200 to 300 m (700 to 1000 ft). The grout sets a few hours after completion of the injection, fixing the radioactive waste in the shale formation.

A new facility was commissioned in 1982 at a site adjacent to the original facility. Between June 1982 and January 1984, more than 8 million L (2.2 million gal) of waste containing over 750,000 Ci was mixed with a blend of solids and injected. Various operating problems were experienced and solved.

INTRODUCTION

The hydrofracture process is currently being used at the Oak Ridge National Laboratory (ORNL) for the permanent disposal of locally generated radioactive waste solutions and slurries. A large batch (>400,000 L) of waste solution or slurry is accumulated prior to the injection. During the injection, this waste solution is continuously mixed with a blend of cement and other solid additives; the resulting grout is then injected into an impermeable shale formation at a depth of 200 to 300 m (700 to 1000 ft). During the injection, the grout forms a thin, approximately horizontal, sheet several hundred meters (up to 1000 ft) wide. The grout sets a few hours after completion of the injection and permanently fixes the radioactive waste in the shale formation, which is isolated from contact with the surface environment. Subsequent injections form sheets that are approximately parallel to the preceding sheets. A sketch of the process is shown in Fig. 1.

This process was developed during the period from 1959 to 1965 and used operationally between 1966 and 1979 to dispose of more than 8 million L (2 million gal) of waste containing more than 600,000 Ci

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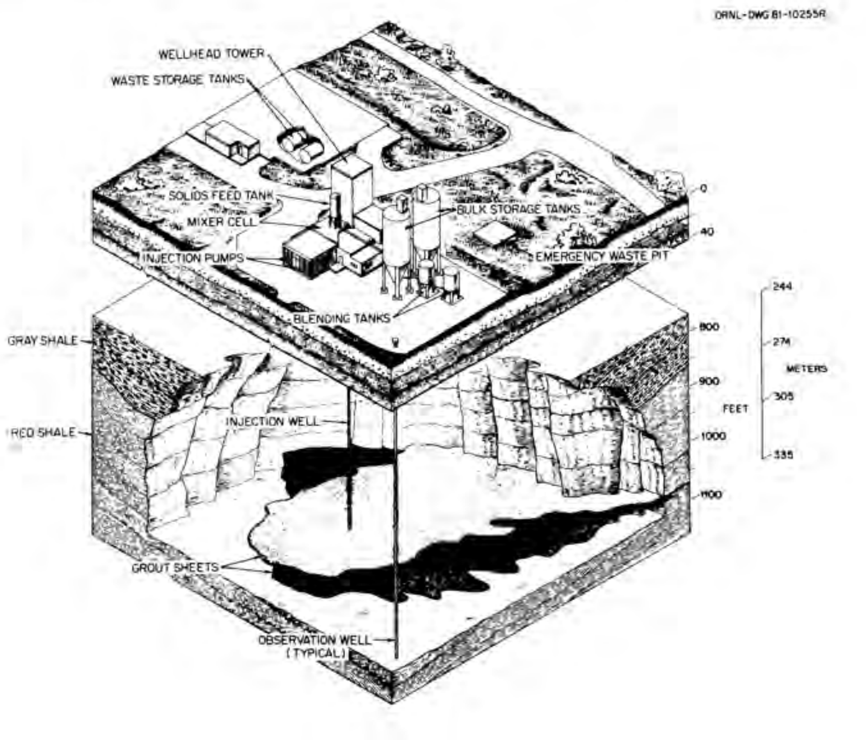

Fig. 1. ORNL hydrofracture process.

TABLE I

Summary of Hydrofracture Injections

INJECTION	DATE	WASTE VOLUME (L)	GROUT VOLUME (L)	ACTIVITY INJECTED (Ci)				
				TRU	^{244}Cm	^{90}Sr	^{137}Cs	OTHER
ILW-19	June 16-17, 1982	600,000	860,000	2	5	156	17,333	347
SI-1	Aug. 10-15, 1982	730,000	1,190,000	72	710	28,500	5,500	2,000
SI-2	Sept. 23-24, 1982	440,000	580,000	73		57,200	4,800	1,400
SI-3	Oct. 26-29, 1982	940,000	1,170,000	290	510	61,000	4,100	1,800
SI-4	Apr. 8-10, 1983	730,000	920,000	130	96	11,000	450	230
SI-5	May 17-18, 1983	600,000	620,000	65	76	7,200	410	160
ILW-20	June 14-15, 1983	420,000	590,000	14	53	3,266	7,140	627
SI-6	July 12-14, 1983	770,000	850,000	240	1,060	67,553	2,750	930
SI-7	Aug. 9-10, 1983	620,000	720,000	84	220	21,630	1,585	160
SI-8	Oct. 25-26, 1983	740,000	916,000	357	2,980	217,400	14,800	3,400
SI-9	Dec. 1-2, 1983	721,600	903,000	404	920	125,000	16,200	990
SI-10	Jan. 25-27, 1984	700,000	946,000	375	763	41,100	5,600	760
ILW-21	Jan. 27-28, 1984	462,000	606,000	19	71	3,500	2,100	510
TOTAL		8,475,000	10,874,000	2,125	7,464	644,505	82,768	13,314

of radionuclides. A new facility was built between 1980 and 1982 to meet more stringent current standards and to handle waste slurries. This facility and the associated safety documentation were completed in the spring of 1982, and the first injection was made in June 1982.

In the 13 injections that have since been made at the new facility, more than 10 million L (2.8 million gal) of waste grout containing over 750,000 Ci of radionuclides has been injected. A summary of these injections is given in Table I.

The waste injection operations at ORNL have been performed under contract by the Halliburton Company, with assistance and overall supervision by ORNL. For each injection, Halliburton supplies a standby truck-mounted injection pump, engineering assistance, and an operating crew.

PROCESS DESCRIPTION

Hydrofracture is essentially a large-scale batch process. Each injection is, however, a semicontinuous operation designed to dispose of an accumulation of about 600,000 to 800,000 L (150,000 to 200,000 gal) of waste solution or slurry. A flow diagram of the process is shown in Fig. 2.

Prior to the injection, the waste solution or slurry is accumulated in the waste storage tanks at the injection site. Also prior to the injection, the dry solids are blended and stored in bins at the injection facility. During the injection, the waste solution is pumped to the mixer, continuously mixed with the preblended solids, and then discharged into the mixing tub. The mixing tub is sized to provide a holdup of about 2 min – sufficient time to allow the grout to deaerate. From the mixing tub, the grout is picked up by the injection pump and is pumped down the injection well, out a slot cut in the bottom of the injection well, and into the shale formation. The injection pressure is about 20 MP_a (3000 psi); the normal grout injection rate is about 1000 L/min (250 gal/min). The resulting grout sheet is approximately 1 cm (1/2 in.) thick and up to 300 m (1000 ft) wide. The orientation of the fracture generally follows the bedding planes in the shale, which are inclined about 10 to 15° to the horizontal.

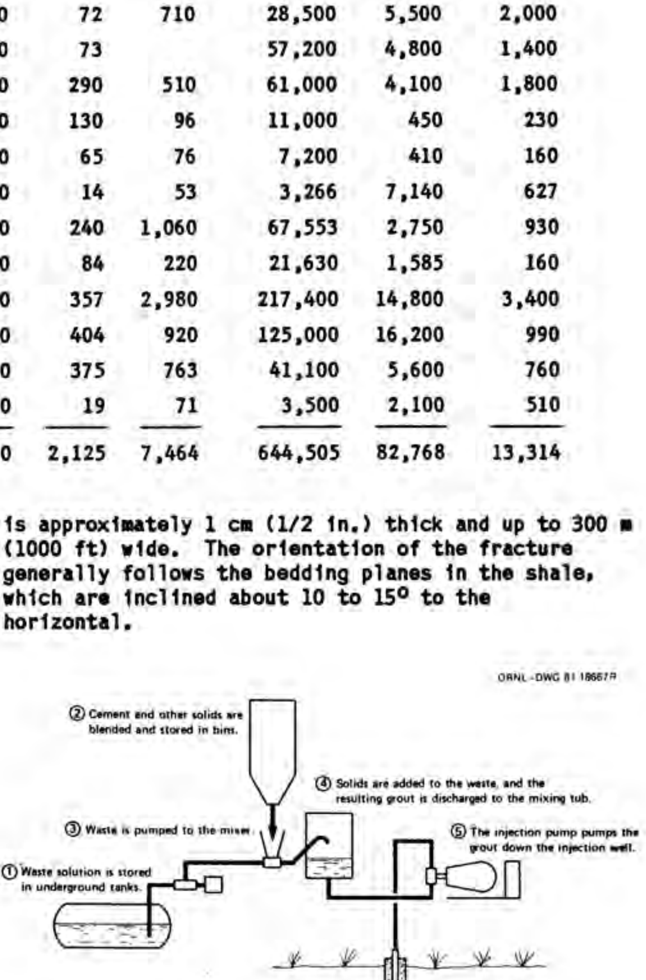

Fig. 2. Shale fracture injection of grouted waste.

An injection may be halted by malfunction or failure of any of several instruments or pieces of equipment. It is stopped, in any event, after about 10 h of operation in order to minimize operator fatigue. For either circumstance, the well is flushed with about 4000 L (1000 gal) of water so that the slot at the bottom of the well will be free of grout and can be reused for the continuation of the injection. After repairs have been made, or the following morning (if the shutdown was a scheduled one), the well is pressurized to verify that the slot is still open; if so, the injection is then resumed. The operation is continued in this fashion until the supply of dry solids has been consumed. The well and slot are then flushed a final time, the wellhead valve is closed, and the injected grout is allowed to set.

The next injections in the series can be made through the same slot in the well; the grout sheets that are formed by this next injection are generally parallel to the grout sheets of the preceding injection but may be displaced up or down a few feet. Following a series of several injections, the slot in the bottom of the well is plugged with a small volume of grout and a fresh slot is cut in the casing of the well about 3 m (10 ft) above the old one. Another series of injections is then made through this new slot.

A few days after each injection, the approximate orientation of the grout sheet is determined by logging the network of observation wells that surrounds the facility. (These are cased wells that extend to the bottom of the disposal formation.) A gamma-sensitive probe lowered into these wells detects the presence of the grout sheet and establishes the depth of the grout sheet at that point. A network of six to eight observation wells is needed to verify the horizontal orientation of the grout sheet.

The type of response obtained from a series of logs made in one observation well is shown in Fig. 3.

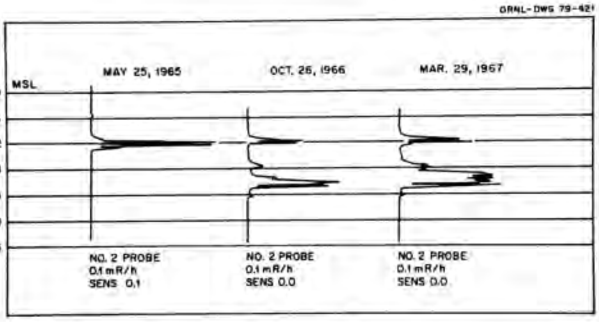

Fig. 3. Gamma ray logs of observation well following three injections.

The log for May 25, 1965 shows the response to the grout sheet that intercepted this well at an elevation 12 m (40 ft) above the point of injection. The log for Oct 26, 1966 shows the response to the grout sheet of the next injection — a response that indicates the presence of several grout sheets at an elevation of from 3 to 6 m (10 to 20 ft) above the point of injection. The third log indicates that the grout sheet from the next injection was slightly above the grout sheet from the preceding injection and about 4.5 m (15 ft) above the point of injection.

Some process water is always injected with the grout. In addition, small volumes of free water can be formed in the disposal zone by phase separation from the grout. This, excess water is recovered from the formation by a bleedback procedure. After the injected grout has set, the wellhead shutoff valve is opened, and as much recoverable free water as may exist is bled back through the injection well and collected. The volume of this bleedback water does not exceed 10% of the injected waste volume and is usually much less.

Following some of the early injections, cores were obtained of the grout sheets. Figure 4 shows one of these grout sheets embedded in the shale matrix.

Fig. 4. Core of Grout Sheet.

The hydrofracture facility was designed to dispose of two different radioactive waste streams:

1) A locally generated evaporator concentrate solution. This solution is alkaline, about 1 to 2 M in $NaNO_3$, and has a radionuclide content (predominately ^{137}Cs) of up to about 0.3 Ci/L (1 Ci/gal). About 380,000 L (100,000 gal) of this waste is generated annually.

2) Resuspended sludge that was generated by cleanout operations at old waste storage tanks. The sludge particles were 100 μm or smaller in diameter; their concentration was up to about 20 wt % in a 2 1/2% bentonite suspension. The predominate radionuclide was ^{90}Sr. There was nearly 8 million L (2 million gal) of this sludge.

Different dry solids mixes, as required for these two waste streams, are listed in Table II.

TABLE II

Composition of dry solids mixes for hydrofracture

Ingredient	Waste solution mix (wt %)	Resuspended sludge mix (wt %)
Cement (Type 1)	38.5	46.0
Fly ash	38.5	46.0
Drilling clay	15.4	
Pottery clay	7.7	8.0

They differ only in the deletion of the drilling clay from the mix for the sludge *injection*. The bentonite that is already in the sludge waste stream serves a similar function.

The two mixes are similar, but not interchangeable, largely because the resuspended sludge contains bentonite, which is a suspender. A combination of waste solution mix and resuspended sludge would therefore contain too much suspender and would be too viscous to pump. The other mix-waste combination (resuspended sludge mix with waste solution) would contain no suspender and phase separation would be excessive.

The pottery clay in the solids mix is a cesium fixer. It binds this isotope so effectively that the measured leach rate from set grouts is approximately the same as from a borosilicate glass.

Two other materials are added to the waste stream during an injection to modify the properties of the injected grout.

1) About 400 ppm of tributyl phosphate is added to improve the rate and completeness of deaeration of the freshly mixed grout in the mix tub. The injection pump knocks excessively if deaeration is not nearly complete.

2) Sufficient set retarder is added to the waste solution to give a concentration of 0.02 wt % in the grout. This concentration will delay final set for at least 24 h.

The mix ratio (the weight of dry solids used per unit volume of liquid) is determined prior to the injection by tests of the waste to be injected. It can be (and frequently is) varied during an injection to accommodate different batches of waste solution. This ratio typically ranges from 0.5 kg/L (4 lb/gal) to 1.0 kg/L (8 lb/gal).

PROCESS DEVELOPMENT

The hydrofracture concept requires that the fracture formed during an injection follow the bedding planes in the shale and move horizontally, not vertically. When the process was first conceived (the late 1950s) it was not at all clear that the desired fracture orientation could be achieved. For this reason, much of the early development work on the process was directed toward verifying that any fractures generated in the formations of interest at Oak Ridge would be essentially horizontal. Three test injections were made in 1959 and 1960 to establish that conformable (bedding plane) fractures could form in the shale formations at Oak Ridge, determine the feasibility of relatively large [~400,000 L (~100,000 gal)] injections, and evaluate monitoring techniques.

These test injections were quite successful; the results provided strong evidence that fractures in the bedded shales at ORNL would follow the bedding planes. Verification of the grout sheet orientation by core drilling and logging was found to be practical and unambiguous but expensive. Tiltmeter readings were difficult to interpret; determination of surface uplift by high precision level measurements was a more useful technique.

The next step in the development program was the construction of a disposal facility so that the process could be evaluated during conditions approximating those of an actual disposal operation.

An injection well and one observation well were installed, and a disposal facility was built. Several mixes suitable for use with a variety of possible waste solutions were developed, and a series of injections was conducted to demonstrate the suitability of these different mixes and evaluate the performance of the disposal facility.

Successful completion of these injections concluded the major part of the process development program; following these injections, the facility was modified for the future routine disposal of ORNL waste solution. Routine injections began late in 1966.[1]

To provide additional proof-of-principle, the U.S. Atomic Energy Commission sponsored an experimental program, carried out jointly by ORNL and the U.S. Geological Survey to test further the concept of radioactive waste disposal by hydrofracturing. The locality chosen was the Western New York Nuclear Fuel Service Center near West Valley in New York. The major aim of this program was to demonstrate the applicability of disposal of radioactive waste in nearly horizontally bedded shale through hydrofracturing at a location other than Oak Ridge.

From 1969 to 1971 inclusive, six hydraulic fracturing injections — all using water except the last one, which employed grout — were made at the West Valley site. Most of the injections were tagged with radioactive tracers. Based on data obtained from these test injections, it was concluded that bedding plane fractures (near horizontal) were formed by those injections in this geologically younger shale formation.[2]

OPERATIONAL EXPERIENCE - TEST FACILITY

From the time the test facility became an operational facility in late 1966 until the end of operations in 1979, a total of about 8.7 million L (2.3 million gal) of waste grout containing about 650,000 Ci of radionuclides was disposed of in 18 operational injections.[3]

General experience with the hydrofracturing facility in these 18 operating injections was quite good. Large volumes of waste solution were mixed with dry solids in the desired proportions and injected into the isolated shale bed. The cleanup of small waste spills was found to be feasible, as was the direct maintenance of mechanical equipment. Observed shortcomings in the process included:

1) improper location of some equipment (with consequent difficulty of maintenance);
2) difficulty in obtaining a steady flow of solids under all conditions; and
3) marginally effective control of solids-to-liquid proportioning.

In four injections, the operating problems were serious enough to force the termination or major delay of the injection. In three of these injections the problem was a malfunction of the injection pump. The termination of the fourth injection resulted from an attempt to use blended solids that had been stored for several months. The flowability of these solids was poor, and the injection was quickly shut down.

By the mid 1970s, the facility was nearing the limit of its useful life. Although the facility had been improved several times during the period of operation, extensive modifications to the surface equipment would have been needed to satisfy the requirements for continued use; this consideration led to the decision to construct a new facility at a new site rather than to modify and retrofit the old one. An additional factor in this *decision* was the imminent requirement to dispose of a large volume, over 4 million L (1 million gal), of resuspended sludge that would be generated by the cleanout of a group of waste storage tanks. This sludge was expected to contain about 1 million Ci of ^{90}Sr; the handling of this waste stream would require improved shielding and containment, which would be much easier to incorporate in a new facility than in modifications to an old one. The chosen site for the new facility was approximately 250 m (800 ft) south of the original facility. The disposal zone is about 60 m (200 ft) deeper at this location; otherwise, the geology of the two sites is similar. A site proof test was made at the new site to verify its suitability for waste disposal by hydrofracture.[4]

OPERATIONAL EXPERIENCE - NEW FACILITY

Initial Injections

An environmental impact statement was written to describe the hydrofracture operations at the new site. This document included operation with either waste solutions or resuspended sludge and concluded that the overall impact would be beneficial.[5] A Safety Analyses Report, QA plans, operating procedures and other necessary documents were written.

Construction on the new facility started in November 1979 and was completed in February 1982. A preoperational test was made in March 1982, and regular operations were started in June 1982.

The first injection at the new facility was an injection of concentrated waste solution (similar to the solution injected at the test facility). About 600,000 L (160,000 gal) of this solution was disposed of during 2 d of operation. The injection went exceedingly well. The flow of solids was smooth and even throughout the injection, and the control of the mix ratio was, in consequence, very good. The measured radiation levels outside the process cells were very low; the levels inside the cells, after washup had been completed, were also generally low. Working time in the well cell, after the injection, for instance, was about 2 to 4 h. The highest total exposure received was 35 millirem.

The second injection was one of resuspended sludge. It was the first experience on a large scale with mixing this slurry with solids and pumping the resulting grout. All previous operations had been either on a small scale or with simulated sludge. The injection was difficult, being characterized by a few periods of relatively smooth operation, process upsets at irregular intervals, and lengthy periods of washup and cleanup in preparation for the next startup. The major difficulty was experienced with the flow of solids in the mix hopper. Periodically (and most particularly when the solids flow rate was high), the solids would bridge or partially bridge in the hopper. When this occurred, the injection had to be halted, the mix tub and the piping manifold washed, and the hopper cleared, resulting in an interruption of several hours. A secondary difficulty arose from the fact that grout containing bentonite tends to gel unless kept in constant motion. The grouts made with waste solution do not exhibit this property to anything like the same degree. The consequence of this grout property was that infrequently used lines plugged, and the mix tub (where agitation was quite adequate for a waste solution grout) tended to accumulate gelled grout in stagnant areas. This gelled grout would not drain from the tub during a shutdown and had to be washed (with difficulty) from the tub during most of the shutdowns.

After 4 d of spasmodic operation (12 shutdowns), stable operation was finally achieved at a restricted solids flow rate, and the injection was completed.

Equipment modifications were made to the facility prior to the start of the next injection to correct the major problems experienced during the preceding injection — the frequent plugging of the mixer hopper and the accumulation of gelled grout in the mixing tub.

Observation of the mixing tub during the preceding injection suggested that the screen in the mixing tub was obstructing flow of the grout and creating dead spaces in the tub in which the grout would gel. The screen had been originally installed in the tub to remove rocks, fragments of caked cement, etc., from the grout, thereby preventing possible damage to the valves of the injection pump. The experience with gelled grout in the preceding injection had, however, shown the need for unimpeded flow in the mixer tub, even at the price of possible trouble with the injection pump. The screen was, accordingly, removed from the tub.

The frequent plugging of the mixer hopper that had occurred during SI-1 had not been previously experienced in hydrofracture operations. One of the major differences in the design of the mixer hopper used at the new facility was that in the hopper used at the old facility the unobstructed distance of fall of the dry solids was about 1/2 m (2 ft); at the new facility, this distance was about 4 m (12 ft). It was postulated that for this distance of fall the impact force of the dry solids against the wall of the hopper could be great enough to result in some dry packing of the solids at the point of impact. This layer of packed solids would build up with continued operation until it bridged and plugged the hopper. A conical flow disrupter was built and installed in the mixer hopper so that the stream of solids would impact the cone and be diverted outward against the wall of the mixer hopper. This arrangement is shown in Fig. 5.

ORNL DWG 81-927R

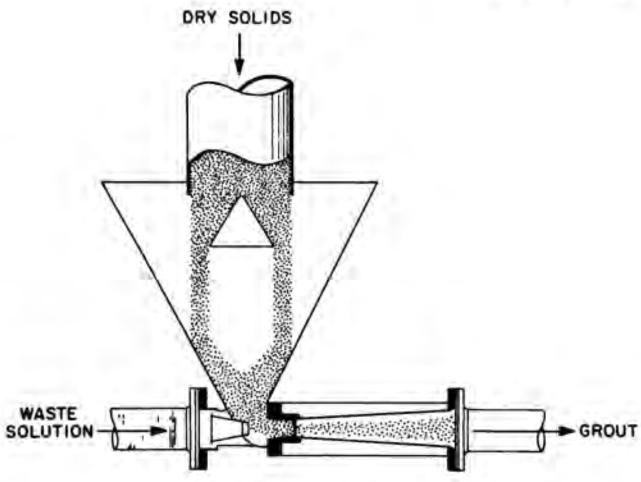

Fig. 5. Revised mixer solids feed.

The next injection (SI-2, a sludge injection) was not afflicted with all of the shutdowns that plagued injection SI-1. The flow of solids was smooth and even throughout the injection, and the control of the mix ratio was, in consequence, very good. No bridging was observed in the mix hopper.

Several shutdowns were experienced in the next injection (SI-3, a sludge injection). At intervals during this injection, the injection pump would operate erratically because of small lumps of caked cement or set grout that lodged in the check valves of the pump and prevented proper seating. This problem was to reoccur several times during the rest of the injection series. The source of the lumps is still not known, and no way has been found to alleviate the problem when it occurs. Careful cleaning of the dry solids equipment seems to help.

Plugging of Injection Well

Prior to the fifth injection in the series, the then current operating procedures specified that the existing slot in the injection well be plugged with grout and a new slot cut 3 m (10 ft) higher in the well. During the preparations for these operations, the injection tubing was found to be stuck in the injection well. An investigation of the situation showed that the well configuration was as presented in Fig. 6.

ORNL DWG 83-8644 R3

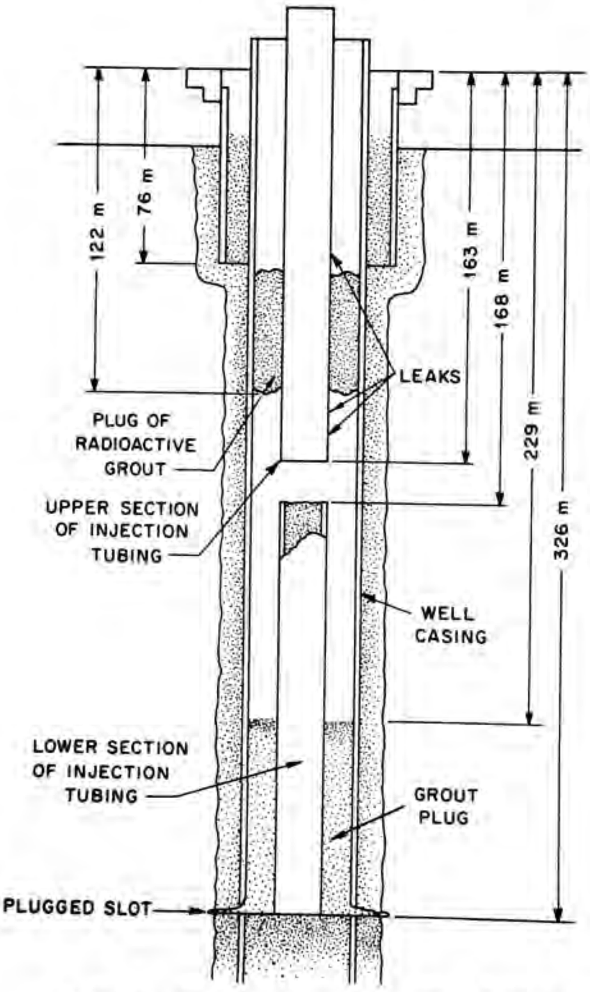

Fig. 6. Well configuration after failure.

The injection tubing had parted and fallen 6 m (20 ft). The upper part of the tubing string was cemented to the casing with radioactive grout, and the bottom half of the tubing string was both plugged and cemented to the casing by the grout plug that had been pumped down the well to seal the existing fracture. In addition, the upper part of the tubing string was found to be leaking at several points.

The immediate cause of the failure of the tubing string was leaks that had developed in the tubing joints at some time during the previous injections. During the injections, grout would have been pumped through these leaks and would have enlarged them by erosion until joint failure resulted.

The cause of the leaks is less clear. No such leaks had developed during 25 injections at the first facility and the occurrence at the new facility was entirely unanticipated. It was finally concluded that any or all of several factors may have contributed:

1) improper makeup of the tubing string,
2) a lower quality joint design than was used in the test facility, or
3) the considerable deviation from vertical of the injection well at the new facility.

Well Recovery

Recovery of the injection well required several sequential steps:

1) a wash-out operation to drill out the tubing string to the bottom of the well,
2) a wash-over operation to drill the annulus between the tubing string and the well casing and to remove the free sections of tubing,
3) insertion of a new tubing string,
4) cementing of the new tubing string in the injection well, and
5) slotting of the new tubing string at the selected depth.

All of these operations were made more difficult by the contamination and by the deviation of the injection well. The wash-over operations in particular required more time and was more difficult than initially anticipated. Recovery of the well was, however, completed in three months, and the facility was returned to operations.[6]

Subsequent Injections

During the succeeding 10 months, seven injections of sludge and two injections of waste concentrate were made, virtually without incident. The injection pump had some transmission problems, the bulk solids system required some repairs, instruments malfunctioned, and, in one injection, cement chips stuck under the injection pump valves (as in the third sludge injection). In general, however, these injections were remarkably trouble free.

ACHIEVEMENT

The logs of the observation wells that were made after each injection showed that the grout sheets were at depths consistent with the formation of bedding plane fractures. No evidence was seen of grout sheet movement as far as the well network at the Old Hydrofracture Facility, which is about 250 m (800 ft) distant.

The uplift of the ground surface was measured by surveying a network of benchmarks before and after the last five injections. These data indicate an uplift pattern similar to that obtained at the Old Hydrofracture Facility with a maximum surface uplift centered on the injection well of about 0.7 cm per million L (1 in. per million gal) injected. The data also indicate that some subsidence occurs between injections.

The cost of the injection series averaged about 25 cents per L (90 cents per gal) of waste injected. This cost includes dry solids, Halliburton's fee for injection assistance, and various maintenance and service charges. It does not include capital costs,the one-time cost of the well recovery operation, or special monitoring charges.

RECENT EVENTS

The injection series was completed in January 1984. Three monitoring wells were drilled the following summer to verify the expected extent of the grout sheets. These wells were located 300 m (1000 ft) from the injection wells of both the old and the new hydrofracture facilities. Unexpectedly, two of these wells encountered contaminated water at a depth of about 270 m (900 ft). The level of contamination was approximately one millionth of that injected and the rate of flow was considerably less than 3 L/h (1 gal/h). In neither well was a trace of a grout sheet found. It is thought that this contaminated water is probably a mixture of formation pore water and incompletely incorporated water from the grout sheet that was squeezed out ahead of the grout sheets. Investigation of the situation is in progress.

Since the completion of the latest injection series, the hydrofracture process is becoming subject to a bewildering array of regulatory oversight. Most of the agencies involved seem to be unsure as to where hydrofracture fits in the scheme of things and seem inclined to erroneously lump hydrofracture with deep well disposal. Clarification is needed but comes slowly. At the moment, the best status description is "unclear."

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