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Water Jet Perforation

A New Method for Completing
and Stimulating In Situ
Leaching Wells

By G. A. Savanick and W. G. Krawza



UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8569

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**UNITED STATES DEPARTMENT OF THE INTERIOR
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WATER JET PERFORATION

A New Method for Completing and Stimulating In Situ Leaching Wells

by

G. A. Savanick¹ and W. G. Krawza²

ABSTRACT

The Bureau of Mines has designed, fabricated, and field tested a water jet cutting device capable of perforating nonmetallic well casings for the purpose of completing or stimulating in situ uranium leaching wells. The device is lowered into the wellbore, where it issues a high-velocity water jet that penetrates either a polyvinyl chloride or fiberglass casing, cement, and from 1 to 4 feet into the surrounding uraniferous sandstone. The resulting perforations allow leaching solution to pass between the sandstone and the wellbore.

This report describes the water jet perforator, tells how it is used, presents cost data, and discusses the results of laboratory and field tests. The tests were designed to (1) determine the optimum operating conditions for water jet perforation, (2) assess the effects of changes in these conditions, (3) evaluate the performance of the water jet perforator under actual conditions, and (4) compare this method with other methods of well completion. These tests showed that water jet perforation is superior to conventional well completion methods for selectively achieving communication between the wellbore and adjacent sand while maintaining sand control, for restoring permeability lost through wellbore damage, for stimulating poorly performing wells for completing wells with casings that have inside diameters as small as 2 inches, and for extending the effective well diameter.

INTRODUCTION

The Bureau of Mines is conducting research to develop improved technology for in situ leaching, an alternative mining method that offers considerable promise for the recovery of minerals found in permeable deposits. This report describes a new technique for establishing fluid flow between the mineralized zone and cased leaching wells. The Bureau has tested this technique extensively at a number of in situ uranium leaching sites, and it is believed the technique could be applied to the recovery of any other commodities that might be mined by in situ leaching.

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In situ uranium leaching is a mining method in which wells drilled from the surface are used to remove uranium in situ from mineralized rock. An oxidizing leaching solution is injected through a series of wells into the uraniumiferous rock, where it dissolves the uranium minerals and takes the uranium into solution. The uraniumiferous solution is subsequently drawn into another series of wells and pumped to a processing plant, where the uranium is extracted from the solution and precipitated as uranium oxide (U_3O_8).

Uraniferous ore is normally poorly consolidated sandstone, so that in addition to providing for fluid flow between the wellbore and the ore, it is necessary to prevent caving of the ore and maintain sand control to protect downhole pumps from sand. This is normally accomplished by placing a well screen at the base of the casing adjacent to the ore.

Well screens are effective in protecting the wellbore from the invasion of sand but have the following disadvantages when used in in situ uranium leaching.

1. Typically, uranium mineralization, as revealed by gamma ray logs, is erratically distributed along the length of the wellbore in irregular lenses that may range from several inches to several feet in thickness. Well screens are manufactured in standard sizes, so it is not possible to match the screen with the irregular mineralization lenses indicated by the gamma log. Thus, either some of the mineralized rock is not leached or some of the leaching solution is injected into barren rock.

2. The permeability of an annulus of sand surrounding the wellbore is impaired by the migration of solids during drilling or cementing of the well. This "skin effect" lowers the injectivity or productivity of a well and cannot be corrected by the placement of a well screen. (Injectivity is a property of a well which indicates how easily the well accepts fluid. It is measured in terms of the flow rate accepted by the well at a given pressure at the wellhead.)

3. The injectivity or productivity of a well commonly degrades with use. This condition can sometimes be corrected by acidizing, but often wells do not respond to this process. A degraded well which does not respond to acidizing must be abandoned.

4. Leachate has a tendency not to flow uniformly through the ore; it flows instead from the injection well to the production well in a narrow band below the surface that is defined by the top of the screens in these wells. This process, known as channeling, leads to low recovery and cannot be corrected if well screens are used.

The purpose of this report is to describe a method for effecting communication between the wellbore and the adjacent ore that overcomes the difficulties enumerated above. This method, called water jet perforation, employs a high-velocity water jet that cuts through the casing and grout and penetrates 1 to 4 feet into the adjacent sandstone.

The Bureau has received a patent³ on the water jet perforator, a device which represents a unique application of water jet cutting. In the past, casing perforators using fluid jets have been used for cutting steel casings in oil wells.⁴ However, these casing perforators employed an abrasive fluid used to enhance the cutting ability of the water jet. The use of an abrasive presents operational problems, particularly in regard to wear. These operational problems are avoided in the Bureau perforator, which uses a single-phase water jet as the cutting medium.

This report describes the equipment used in the perforation operation and discusses the cost of building and operating a water jet perforator. Also presented are the results of laboratory test cuttings of grouted casings and a summarization of the results of field tests conducted in 76 wells at 6 in situ leaching sites in Texas and Wyoming.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation and assistance provided by personnel of Wyoming Mineral Corp., Uranerz U.S.A., Inc., Mobil Oil Corp., Rocky Mountain Energy Co., and Gulf Research and Development Corp. during the field tests of the water jet perforator. The authors particularly wish to thank Grant Buma, Geochemist, formerly with Wyoming Mineral (presently with Rocky Mountain Geochemical Corp., Salt Lake City, Utah), who suggested that the Bureau build and field-test the water jet perforator; Alistair Montgomery, Manager of Uranium Solution Mining Technology for Wyoming Mineral, who provided support during field tests at Lamprecht, Tex.; Chris Froelich, Hydrologist for Uranerz, Denver, Colo., who provided hydrologic data; William McKnight, David Thiede, and James Tyler, Field Engineers for Mobil Oil, who provided field support during the Bruni, Tex., field tests; Pat Phillips, Manager of Operational Research, and Chuck Johnson, Well Field Engineer for Rocky Mountain Energy, who provided field support during the Casper, Wyo., field tests; and Peter Lindley, Research Manager, and Chuck Reid, Field Engineer for Gulf Research and Development, who provided field support during the Sweetwater, Wyo., field tests.

THE WATER JET PERFORATOR

The water jet perforator consists of a pump, a length of high-pressure flexible hose, a swivel, a string of high-pressure pipe, and a nozzle assembly (fig. 1). The pump is connected to the nozzle assembly by the flexible hose, the swivel, and the pipe string. The pipe string and the nozzle assembly are suspended by the swivel.

³Savanick, G. A., and Krawza, W. G. (assigned to U.S. Department of the Interior). Well Perforating Method for Solution Well Mining. U.S. Pat. 4,113,314, Sept. 12, 1978.

⁴Brown, R. W., and Roebuck, A. H. (assigned to the Western Co. of North America Fort Worth, Tex.). Perforating Apparatus. U.S. Pat. 3,130,786, Apr. 28, 1964.

O'Neill, F. E. (assigned to Edith L. O'Neill, Glendale, Calif.). Method and Means of Perforating Well Casing and the Like. U.S. Pat. 2,302,567, Nov. 17, 1942.

Boynton, A. Perforator for Wells. U.S. Pat. 2,315,496, Apr. 6, 1943.

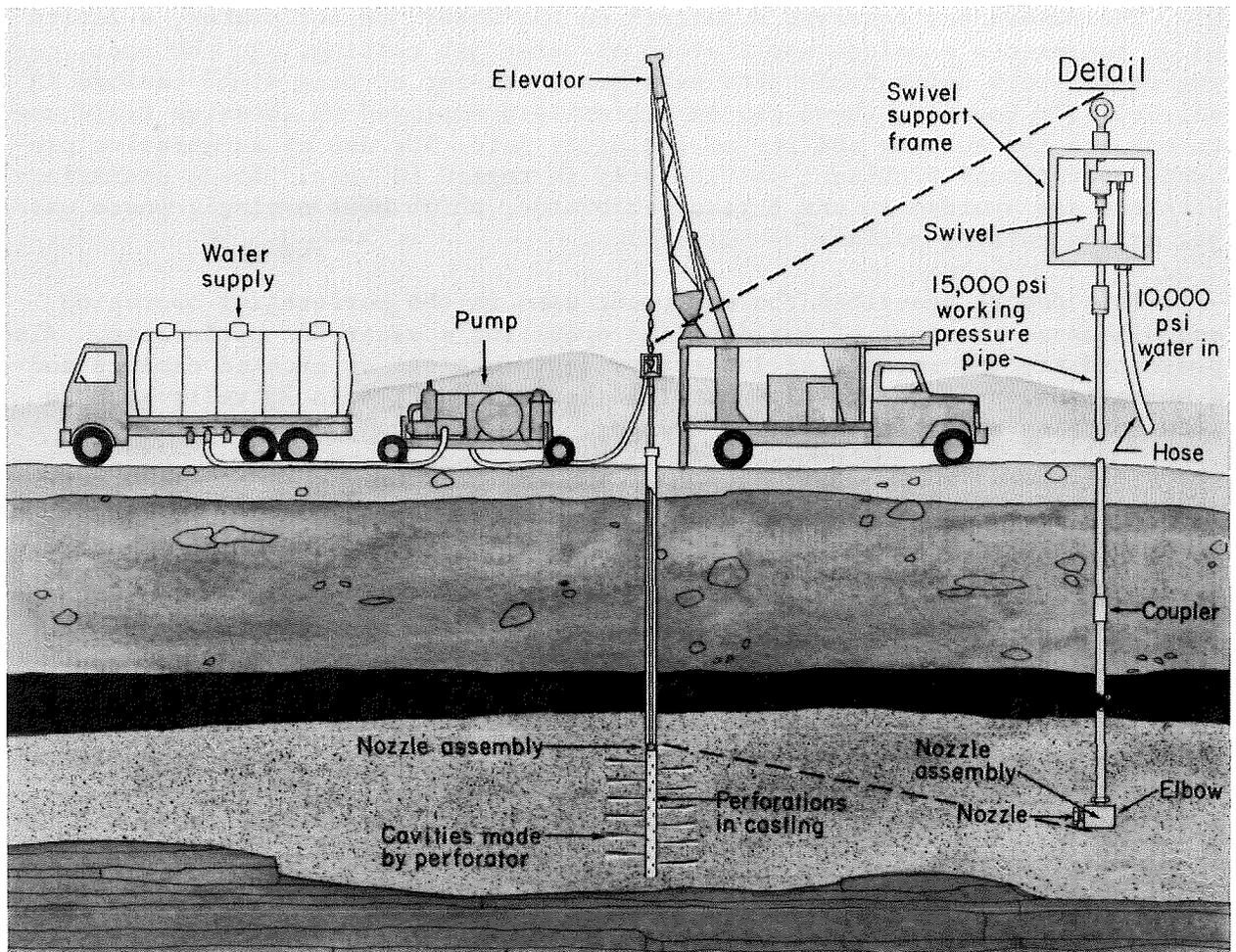


FIGURE 1. - Schematic of the water jet perforator. (Dotted projection lines show the detailed parts of the perforator and the location of these parts within the overall apparatus.)

A flow of water is transmitted from the pump to the nozzle assembly in the following way: The pump generates a pressurized flow of water that is conducted through the flexible hose to the swivel. The swivel, which is mounted at the top of the pipe string, serves as a junction for the hose and the pipe string. It directs the flow of water downward into the pipe string. The pipe string conducts the water through the wellbore to the nozzle assembly, which is attached to the lower end of the pipe string. The downward flow of water through the pipe string is changed by the nozzle assembly to a horizontal flow for exit from the nozzle. The nozzle converts the pressure energy into kinetic energy, thereby creating a high-velocity jet that can penetrate nonmetallic well casings.

The pipe string, which consists of 20-foot sections connected with high-pressure couplers, is held in a vertical position so that it--along with the attached nozzle assembly--can be lowered into the wellbore. The swivel, besides providing a place for connecting the flexible hose to the pipe, permits the pipe string to be rotated so that perforations can be made at various angles.

Pump

The perforator requires a pump capable of generating a flow of at least 7 gpm at 10,000 psi. For all the experiments described in this report, a 30,000-psi horizontal triplex pump driven by a 150-hp 1,800-rpm motor was used. The pump had a 5-inch stroke and could be equipped with either 1-1/16-inch diam or 5/8-inch-diam plunger and liner assemblies. When the pump was fitted with the larger of the two assemblies, it displaced 21 gpm of water at a pressure of 10,000 psi. When the pump was fitted with the smaller assembly, it displaced 7 gpm at 30,000 psi pressure. For these experiments, the pump was fitted with either assembly and the pressure was limited to 10,000 psi.

The pump was driven by an electric motor, which was somewhat inconvenient for field operations because the motor required an electrical generator. This inconvenience could be avoided by using a pump driven by a diesel engine.

High-Pressure Flexible Hose

Twenty-five feet of flexible hose capable of withstanding a working pressure of 10,000 psi was used to connect the pump, via the swivel, to the pipe string. It was necessary for the connector used for this purpose to be flexible so that it could follow the swivel as the pipe string was raised or lowered into the well.

Swivel

The high-pressure hose was connected to a swivel that was capable of rotating the pipe string and nozzle assembly and could pass 21 gpm of water at 10,000 psi. The swivel was mounted in a housing (fig. 2) that was suspended from a derrick.

Derrick

The swivel, pipe, and nozzle were suspended from a truck-mounted derrick (fig. 2). The derrick was fitted with a reel and cable for raising and lowering the suspended components of the water jet perforator.

High-Pressure Piping

The pressurized water was carried down the borehole by a pipe string composed of 20-foot lengths of 316 stainless steel seamless pipe that was able to withstand a working pressure of 15,000 psi. The pipe had a 1-inch OD and a 9/16-inch ID. The 20-foot lengths were connected by high-pressure unions (fig. 3).

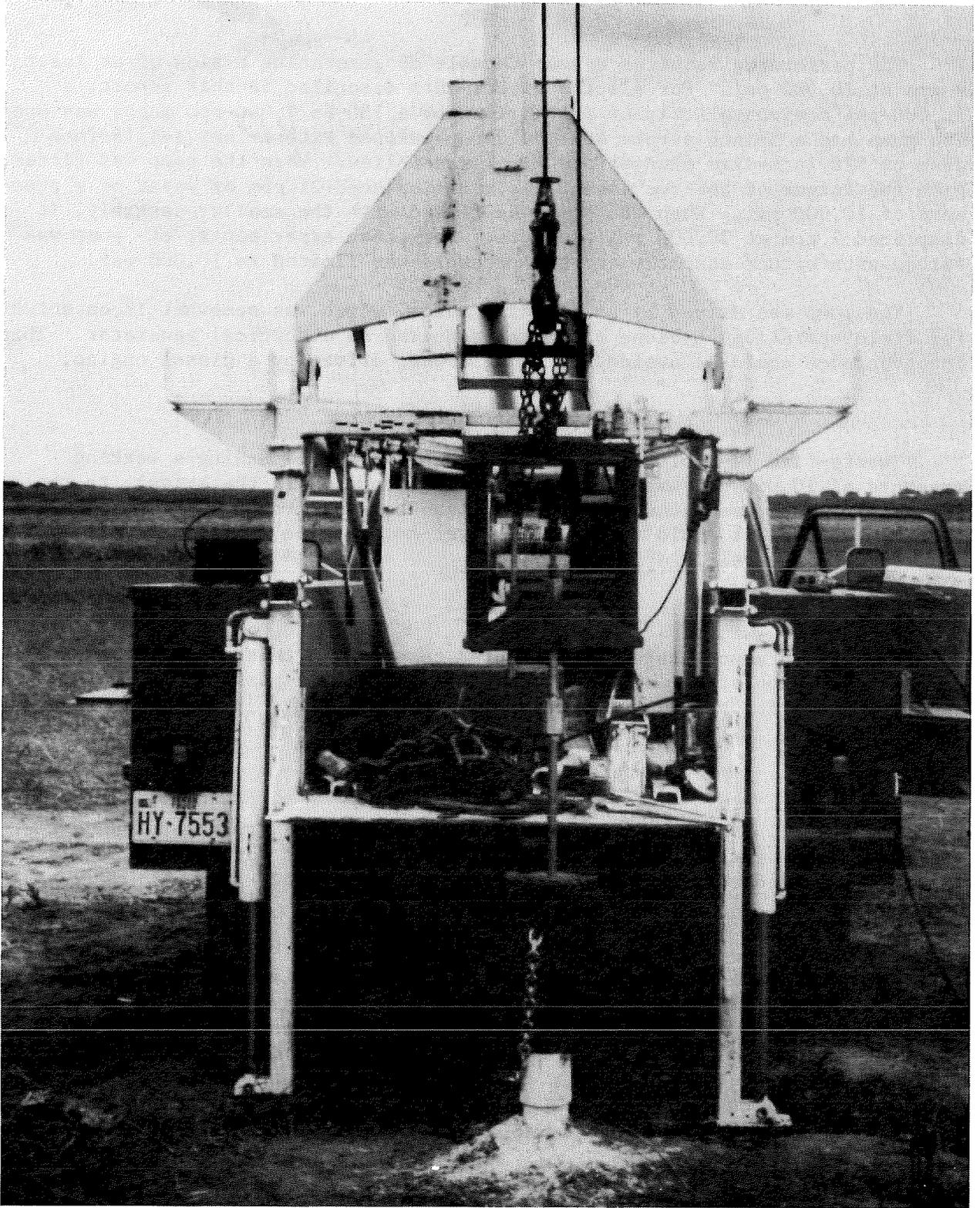


FIGURE 2. - Swivel and pipe string components of the water jet perforator suspended from a derrick. Also suspended, underground at the end of the pipe string, is the nozzle assembly.



FIGURE 3. - Tightening high-pressure tube unions of water jet perforator in the well.

Nozzle Assembly

Either a single-nozzle assembly or a multiple-nozzle assembly can be used in the water jet perforator. A single-nozzle assembly generates a single water jet and is used to cut slots. A multiple-nozzle assembly simultaneously generates multiple jets of water and is used when the job calls for many small point cuts.

The single-nozzle assembly used for the tests described in this report consisted of a high-pressure elbow with a steel centralizer welded to its base and a nozzle held in the outlet port by a nut (fig. 4). The nozzle (fig. 5) had a 13° conical taper with a length of straight section adjacent to the nozzle outlet. It was made of 316 stainless steel. The multiple-nozzle assembly, which was used to generate three jets simultaneously, contained nozzles placed at 120° intervals in a stainless steel holder (fig. 6).

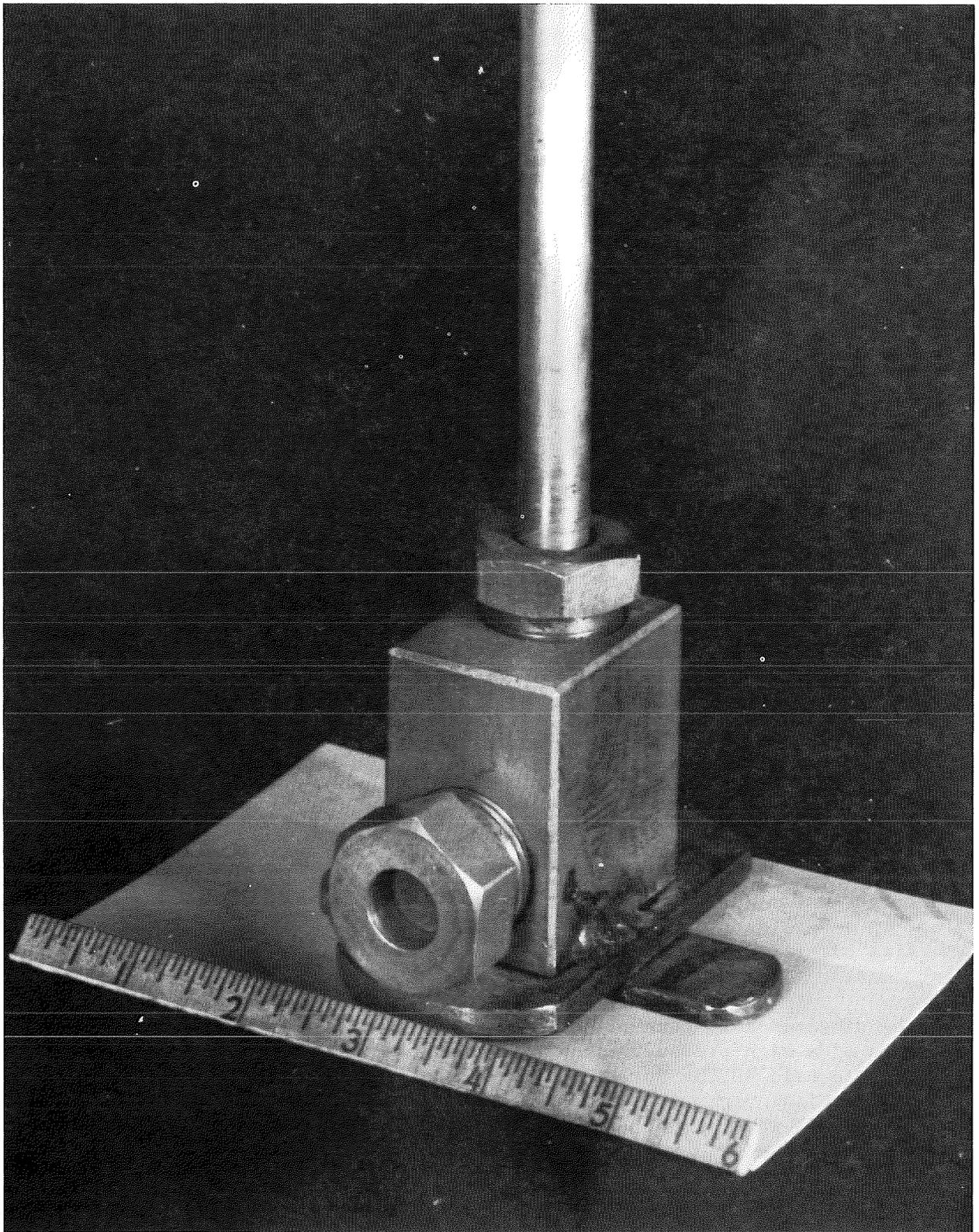


FIGURE 4. - A single-nozzle assembly.

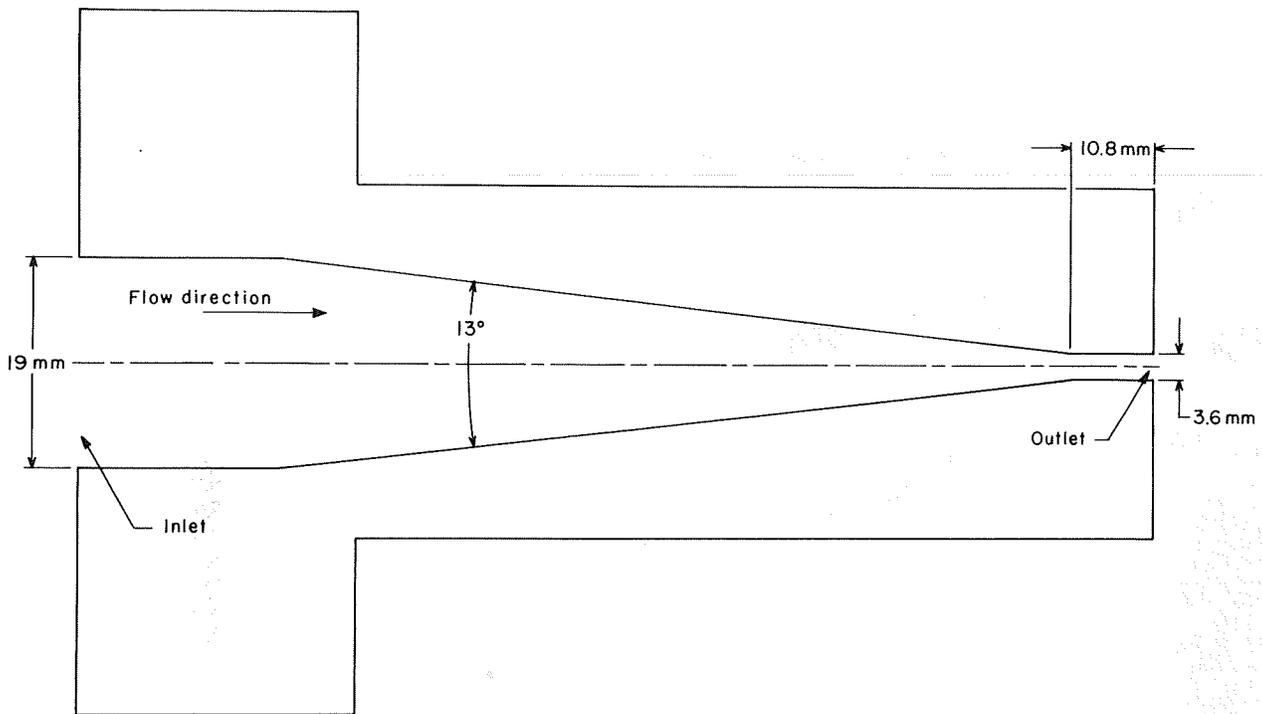


FIGURE 5. - Specifications for nozzle used in the water jet perforator.

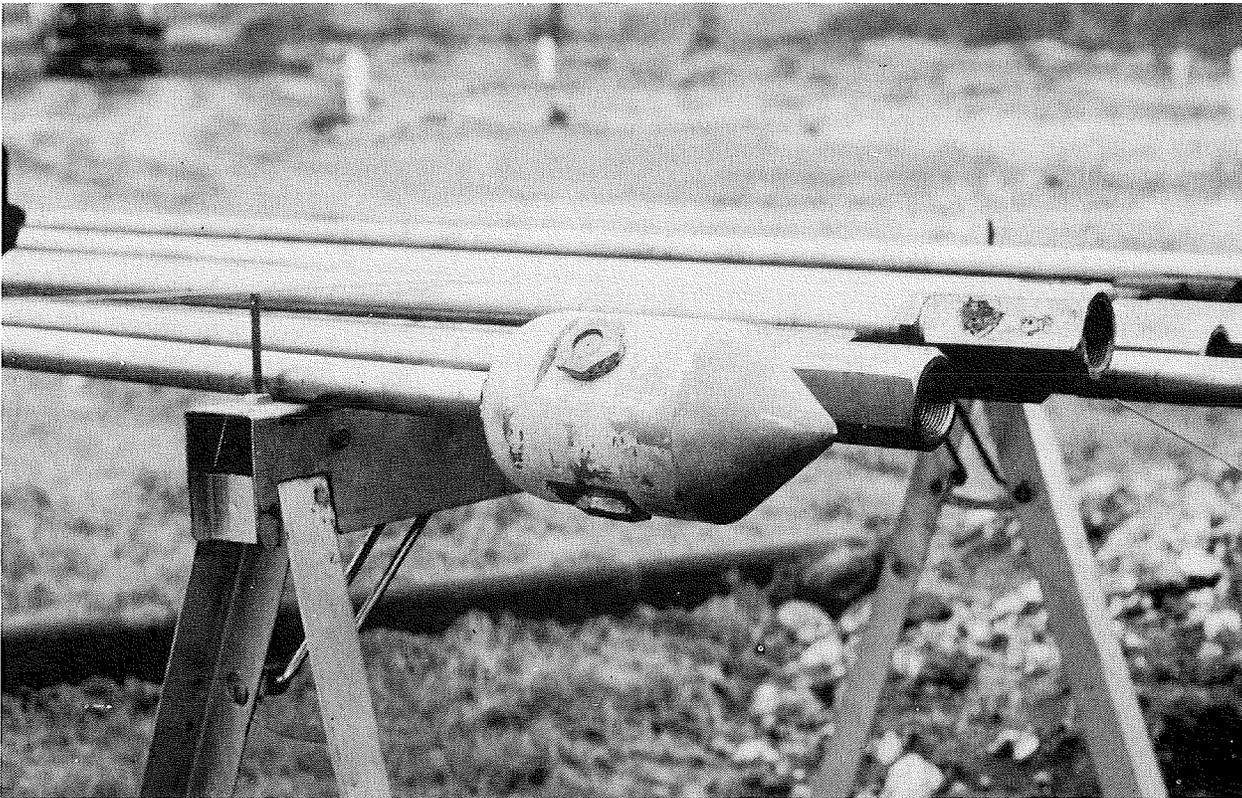


FIGURE 6. - A multiple-nozzle assembly.

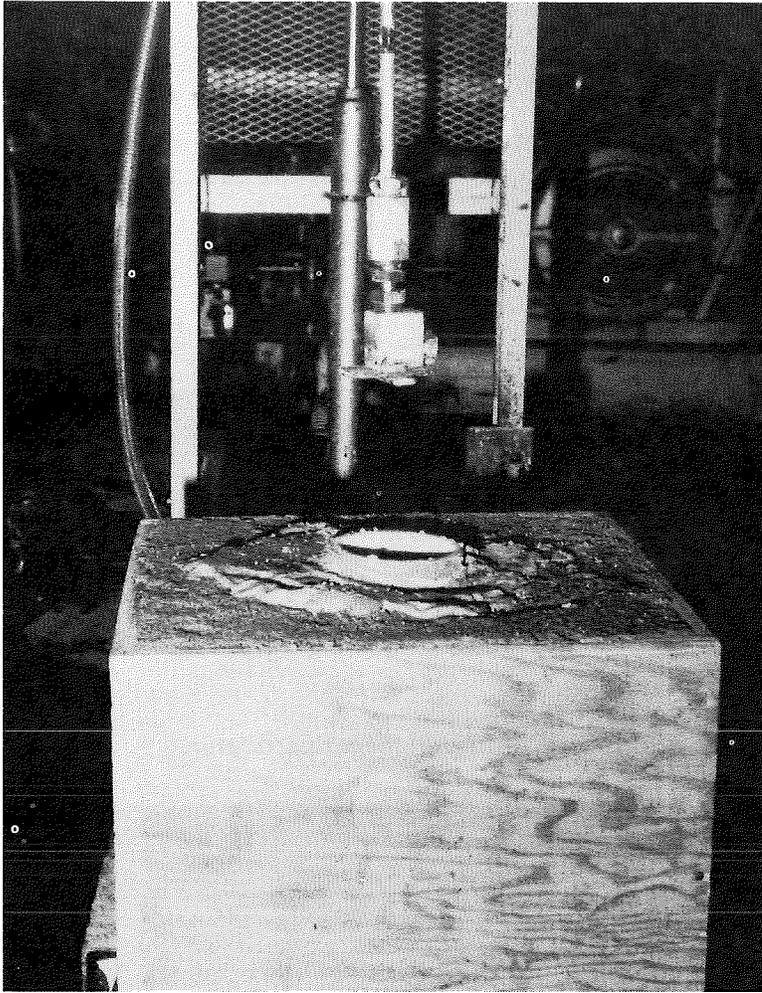


FIGURE 7. - Test sample and perforator nozzle.

LABORATORY EXPERIMENTS

Laboratory experiments were conducted to ascertain the flow conditions necessary to perforate schedule 40 polyvinyl chloride (PVC) pipe encased with 2 inches of grouting. Each sample consisted of a 2-1/2-foot length of 4-inch-diam schedule 40 PVC pipe surrounded by 2 inches of well cement and 9 inches of cemented sand, all contained in a box built of 3/4-inch plywood (fig. 7). The cement was allowed to cure for at least 72 hours before perforation.

Effect of Varying Nozzle Diameter and Standoff Distance

An experiment was conducted to determine what effect varying the nozzle diameter and the standoff distance (the distance between the nozzle exit and the casing) would have on the diameters of perforations made using the water jet perforator. For this

experiment, a procedure for perforating the sidewalls of sample casings was followed repeatedly. For each of the trials, the procedure was the same, except that the nozzle diameters and the standoff distances were varied. The procedure was as follows:

1. The nozzle assembly was connected to the output of the pump and lowered into the casing.
2. The casing was filled with water.
3. The pump was pressurized to 10,000 psi.
4. This pressure was maintained until the casing and grout were penetrated by the water jet. The instant of penetration could be judged by the appearance of water running out the side of the plywood box.
5. The nozzle assembly was removed from the casing.
6. The diameter of the holes in the casing was measured by inserting the shank end of a drill bit.

A nozzle pressure of 10,000 psi was used for each of the trials (with one exception, as noted in table 1). Table 1 shows the results of this experiment and a perforated test casing is illustrated in figure 8.

TABLE 1. - Effect of nozzle diameter and standoff distance on perforation diameter, inches

Nozzle diameter	Standoff distance	Average perforation diameter	Nozzle diameter	Standoff distance	Average perforation diameter
0.018	0.40	0.04	0.035	1.0	0.094
.018	.75	.073	.035	.50	.083
.026	.75	.077	.035	.25	.083
.026	.25	.052	.043	1.0	.108
.030	1.0	.073	.043	.25	.099
.030	.75	.059	.043 ¹	¹ .25	¹ .101
.030	.50	.058	.047	.50	.096
.030	.25	.063			

¹For this trial only, nozzle pressure was 7,500 psi; for all other trials, nozzle pressure was 10,000 psi.

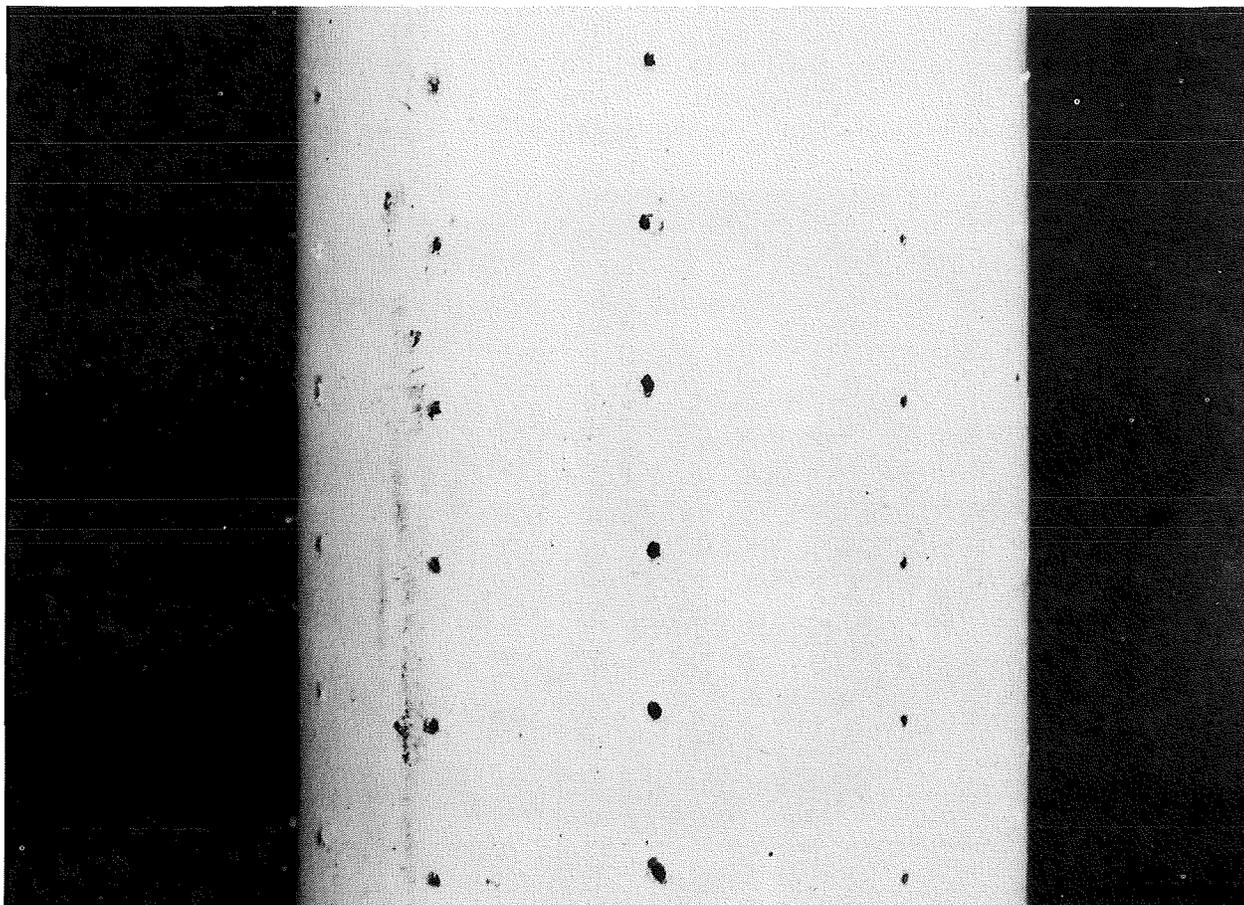


FIGURE 8. - Outside view of a perforated casing.

The time required for perforation ranged from 4 sec, when the nozzle with the smallest diameter (0.018 inch) was used, to less than 1/2-sec when the largest nozzle (0.047 inch diam) was used. The hardness of the cement drastically affected the cutting ability of the smallest nozzle but did not affect the performance of the larger nozzles. The larger nozzles had no difficulty in cutting through the grout and surrounding sand. Subsequent field tests indicated that it was impractical to use nozzles smaller than 0.018 inch in diameter because they became plugged with sand from the formation or with debris (metal filings) from the inside of the perforator.

The data from this experiment were used in conjunction with field tests to determine the maximum size perforation--and thus the largest nozzle diameter--that would control sand in the uranium sands of south Texas. These field tests were conducted at Wyoming Mineral Corp.'s Lamprecht site, near Ray Point, Live Oak County, Tex., and at Mobil Oil Corp.'s Longoria site near Bruni, Tex. Details of the field test at the Lamprecht site are given in the "Sand Control" section of this report.

Penetration Abilities of the Water Jet Perforator

Penetration Into Sand

To estimate the distance that a water jet will penetrate into the sand next to a well, laboratory experiments were conducted to determine how far jets would cut into cemented sand adjacent to a section of grouted schedule 40 PVC pipe. Samples for this test were fabricated by pouring cemented sand (96 pct sand, 4 pct portland cement) into a 21- by 21- by 18-inch plywood box which contained a 5-inch-diam grouted casing. The water jet perforator was

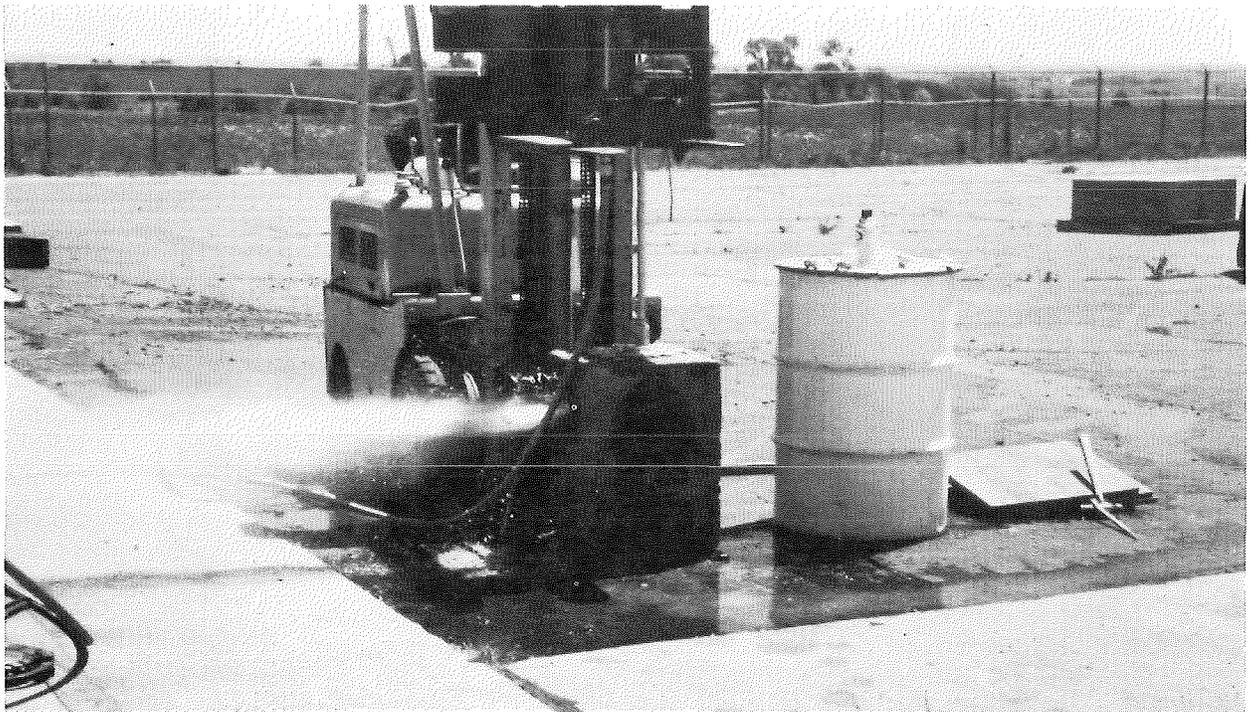


FIGURE 9. - Laboratory test of the water jet perforator, showing water jet after penetration of a test sample.

then placed inside the casing and pressurized by the pump to 10,000 psi to produce a 7-gpm water jet through a 0.043-inch-diam nozzle. When only one test block was used, the water jet broke through the block, as shown in figure 9. Therefore, in order to measure the full extent of penetration, two test blocks were placed face to face while the casing in one of them was perforated. The cavity produced in the cemented sand of both blocks was then measured, and it was found that the jet had penetrated the casing, 2 inches of grout, and 1 foot into the surrounding cemented sand. Similar experiments were run in a 2- by 2- by 7-foot box (fig. 10), using a 0.081-inch-diam nozzle that issued an 18-gpm water jet. This jet penetrated the casing, the grout, and 34 inches into the sand.

Penetration of Well Screens

The ability of the perforator to cut well screens was tested in the laboratory prior to field work. Well screens made of schedule 40 PVC, with a wall thickness of 0.287 inch and slots that were 0.018 inch wide, were perforated with a 10,000-psi 7-gpm water jet (fig. 11). The main concern was

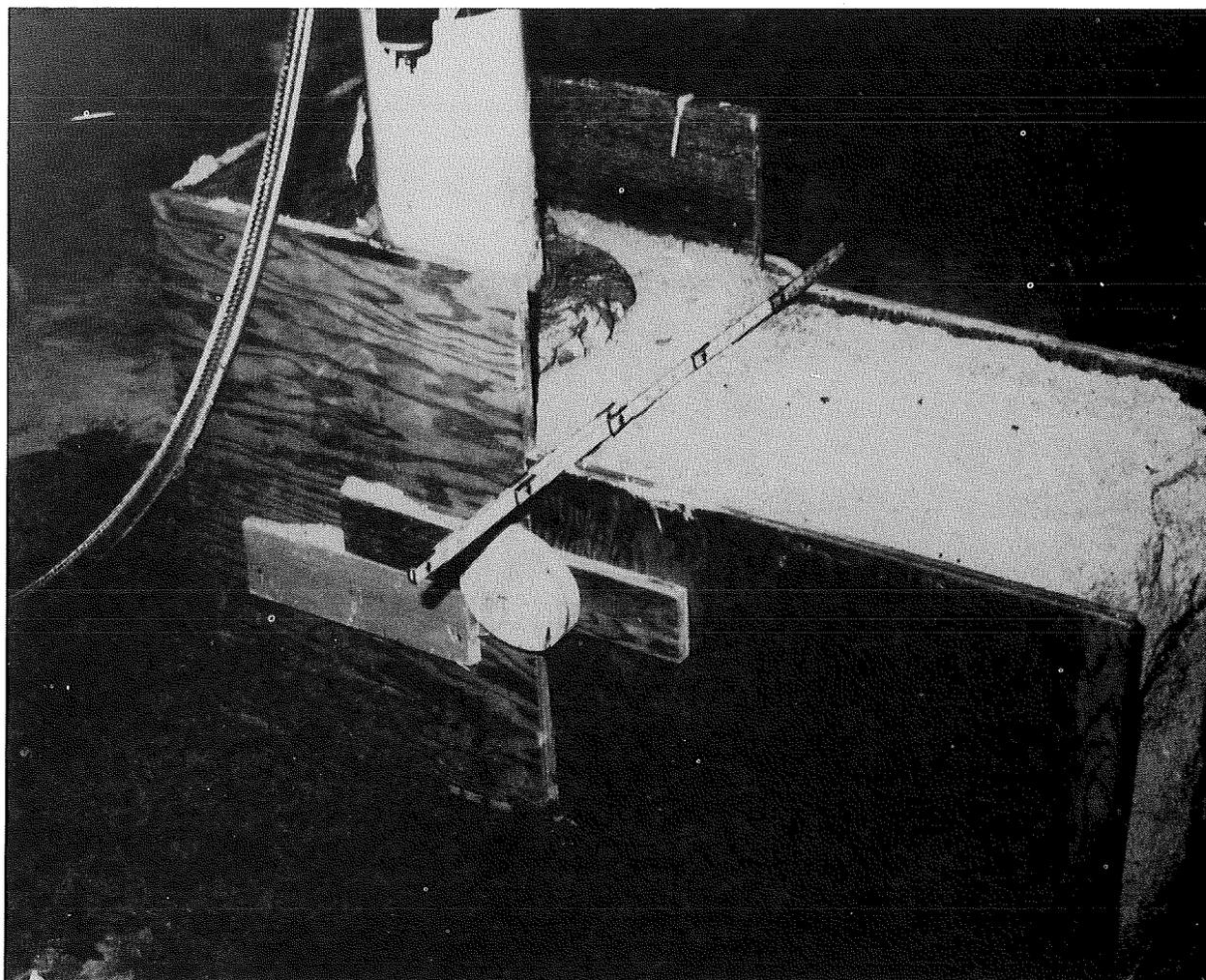


FIGURE 10. - Test sample used to determine length of cut of water jet perforator.

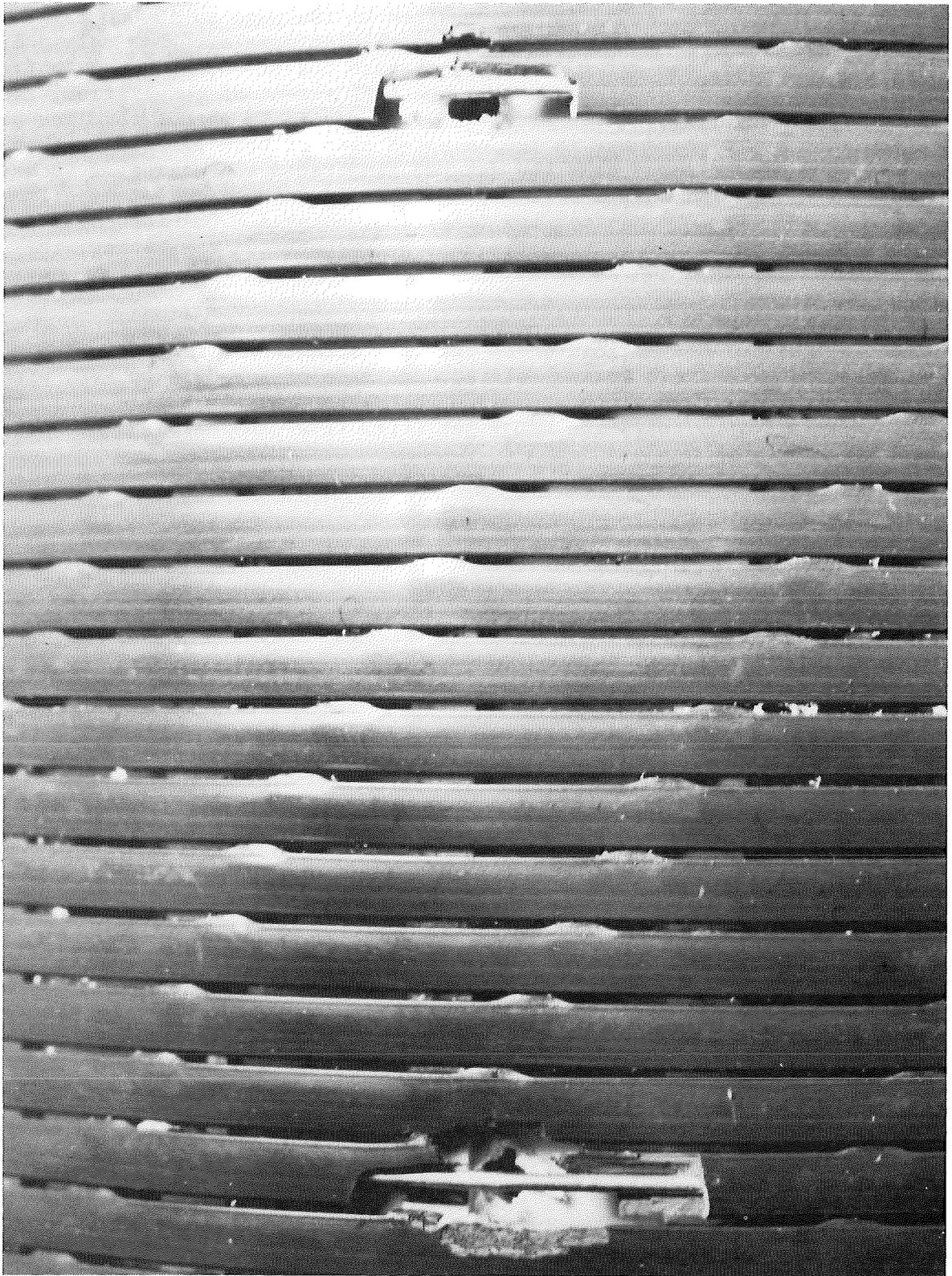


FIGURE 11. - Well screen showing water jet perforations.

that the wire in the screens would impede the jet, but the jet perforated the screen in less than 1 sec and was not materially impeded.

Penetration of Various Casing Materials

Further laboratory experiments indicated that Yelomine⁵ casing perforated much like schedule 40 PVC, except that fiberglass casing invariably developed a blister (of no operational significance) on the inside. Yelomine casings were perforated in Wyoming at Wyoming Mineral Corp.'s Irigaray Ranch in Johnson County and at Rocky Mountain Energy Co.'s Nine Mile Lake site in Natrona County. Yelomine casings are used in Wyoming because they are less likely to crack and are more easily coupled in cold weather than PVC casings. Fiberglass casings are used in deep wells because they have a higher crushing resistance than PVC casings. Fiberglass casings were perforated at Mobil Oil Corp.'s Longoria site near Bruni, Tex., and at the Nine Mile Lake site.

FIELD TESTS

Sand Control

Communication between the wellbore and the mineralized sand must be made in such a way that only sand-free water enters into the bore for pumping to the surface, since sand drastically reduces pump life. In consolidated sandstones, such as the cretaceous Teapot sandstone of Wyoming, no loose sand is found in the well, so sand control is not a problem. However, in unconsolidated Tertiary sands, such as in the Oakville Formation of south Texas, sand control must be maintained by careful sizing of the perforations, which must be large enough to pass the required flow at a reasonable well efficiency.

Nozzle Size Required for Sand Control

The first field test of the water jet perforator took place at the Lamprecht site in south Texas, where the device was used to perforate cemented schedule 40 PVC casings in the mineralized zone of two wells. The equipment was set up as described in the Water Jet Perforator section above. The objectives of this test were to determine the nozzle diameter that would yield perforations capable of maintaining sand control and to determine the number of these perforations needed to pass at least 10 gpm of sand-free water. Laboratory experimentation had indicated that the proper nozzle diameter was between 0.018 and 0.043 inch. The experimental plan for this field test called for perforating one well (well 1⁶) with progressively larger nozzles, starting with the smallest one, until the well yielded a flow of 10 gpm while also maintaining sand control. The plan also called for perforating the second well (well 2) with the 0.043-inch-diam nozzle (the maximum nozzle size considered likely to yield sand control) followed by testing for well discharge and sand control. Well screens were not used in these tests.

⁵Reference to specific trade names is for identification only and does not imply endorsement by the Bureau of Mines.

⁶The well numbers used in this report are those assigned by the investigators for identification purposes during the various field tests.

Recurrent plugging of the 0.018-inch-diam nozzle indicated that it was impractical for use under field conditions. These nozzles were, therefore, replaced with 0.026-inch-diam nozzles, which were used to make 900 holes in the casing of well 1. The holes were distributed over a 20-foot mineralized interval in 50 rings of 18 holes each, with the holes spaced uniformly within each ring. The perforation time was 10 sec for each operation, and two holes were made simultaneously. Airlifting after perforation yielded a flow of 7 gpm, which was less than the optimum desired rate. The diameters of these holes, judging from cutting tests made in the laboratory, should have been about 0.06 inch.

Gamma logs of well 2 showed that the mineralized zone extended between 247 and 255 feet below ground level. Eighty perforations in 8 rings of 10 perforations each were spaced uniformly within this interval, using a single 0.043-inch-diam nozzle pressurized to 10,000 psi. The perforation

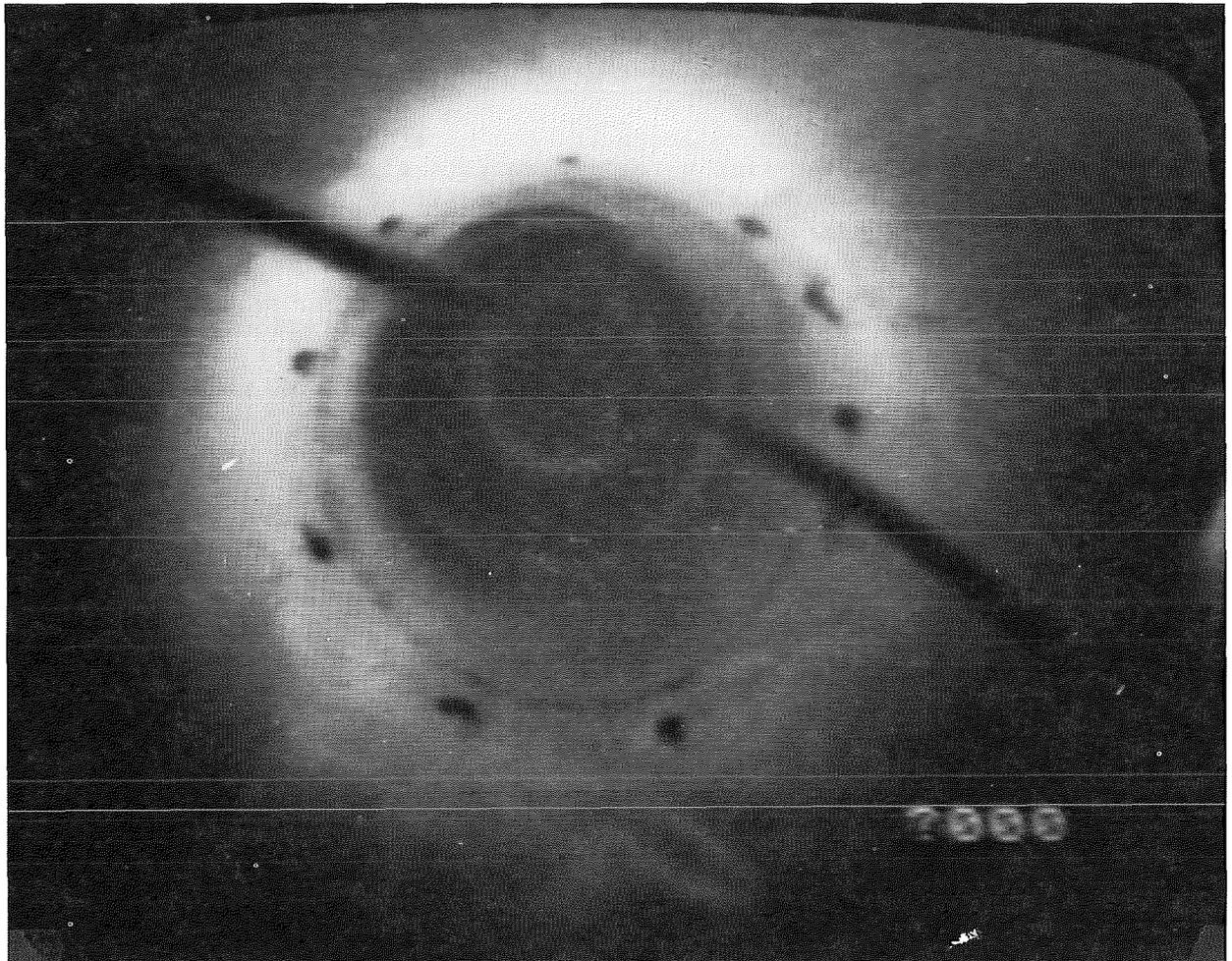


FIGURE 12. - Portion of video tape showing interior of a well (overhead view) perforated with a 0.043-inch-diam nozzle. A ring of perforations, visible as small black dots, can be seen here.

time was 10 sec for each hole. The diameters of these perforations, judging from the laboratory data given in table 1, should have been about 0.1 inch. Airlifting after perforation yielded a well discharge of 24 gpm, which was substantially in excess of the 10-gpm minimum desired flow. This flow of sand-free water represented a successful conclusion to the experiment because it indicated that the largest diameter nozzle capable of maintaining sand control (0.043-inch-diam) had been determined. It was unnecessary to perform a similar experiment using a 0.035-inch-diam nozzle, since the 0.043-inch-diam nozzle had been shown to be acceptable.

A downhole TV camera was used to examine the sidewall of the casings in both wells. This examination showed 50 perforation rings from 2 to 10 inches apart in well 1 and 8 perforation rings 1 foot apart in well 2, in accordance with the perforation plans. Figure 12 is a print of a portion of the video tape taken in well 2.

Pumping Tests

Pumping tests indicated that both wells maintained sand control and that wells 1 and 2 exhibited efficiencies (see footnote 2 of table 2) of 31 and 69 pct, respectively. Table 2 summarizes the hydrological test results for these two wells.

TABLE 2. - Summary of hydrological test results¹

	Well 1 ¹	Well 2 ¹
Diameter of well.....inches..	4	4
Total well depth.....feet..	258	257
Perforated intervals, depths.....do...	235-238, 244-256	247-254
Nozzle diameter.....inches..	0.0267	0.046
Perforation diameters ²do...	0.06	0.1
Number of perforations.....	900	80
Well efficiency ³pct..	31	69
Maximum production rate.....gpm..	27	37
Maximum injection rate.....gpm..	32	44
Production rate per perforation.....gpm..	0.027	0.463
Injection rate per perforation.....gpm..	0.032	0.550

¹Both wells tested were located at Wyoming Mineral's Lamprecht site, Texas.

²Estimated; based on data shown in table 1.

³Well efficiency is the ratio of yield per unit of drawdown actually obtained to the drawdown that is theoretically possible. Efficiency was determined by comparing the theoretical drawdown for a constant rate of production (10 gpm) to the actual drawdown measured for these discharges.

Summary of Sand Control Test Results

This field test of the water jet perforator indicated that--

1. The water jet perforator can perforate PVC-cased and grouted wells so that sand is controlled and an adequate well discharge is maintained.
2. It is unnecessary to use nozzles with diameters smaller than 0.018 inch or pressures above 10,000 psi to make acceptable perforations.
3. Nozzles with diameters of 0.018 inch or less tend to clog and may therefore be impractical in the field.
4. Control over the position of the perforator is sufficiently accurate that perforations can be placed within 1 inch of the desired level in the well.
5. In the nozzle size range from 0.018 to 0.043 inch, the larger diameter nozzles are more effective.

Control of Channeling

Grading Perforation Density to Alter Flow

Leaching solution tends to flow in a production well in such a way that uranium is primarily recovered only from a small band across the top of the mineralized zone. When fluid enters a production well, it flows toward the pump intake, which is usually just above the screen. The physics of the pump suction causes most of the fluid to enter the wellbore at the top of the screen section and to flow across that top. As a result, the mineralization toward the base of the screened section is less accessible to the leachate.

In a second test (which could not be completed) at the Lamprecht site, the objective was to find a way to alter the flow so that uranium would be more uniformly recovered throughout the mineralized zone. The experiment was designed to test the contention that the leachate could be forced to flow uniformly through the mineralized zone by grading the perforations so that the perforation density was greatest at the base of the mineralized zone and least at the top, nearest the pump intake. Although the use of graded perforations might be expected to improve the performance of production wells, their use would not be expected to improve the performance of injection wells in sands with high injectivity, such as those found at the Lamprecht site.

The experiment consisted of placing 522 perforations, graded as described, in a production well 90 feet away from an injection well. The injection well was also perforated, but these perforations were not graded. The distribution of perforations for both wells is shown in table 3. The experiment had to be terminated at this point because the wells were needed for production and the post-perforation assessment could not be performed. The assessment that was planned was to consist of placing a tracer into a solution injected into the mineralized zone through the injection well. It was intended that the tracer would be absorbed by clays in the mineralized zone. The spatial distribution of the absorbed tracer over the mineralized zone (and thus the leachate flow) was then planned to be determined by chemical analyses of cores taken after tracer injection.

TABLE 3. - Distribution of perforations in wells used
for channeling test¹

Injection well 1 ¹		Recovery well 2 ¹	
Depth of perforations from ground level, feet	Number of perforations	Depth of perforations from ground level, feet	Number of perforations
258	14	261	12
257.75	14	260.75	12
257.5	14	260.5	10
256.75	14	260.25	10
256.5	14	260	12
256.25	14	259.75	10
256	14	259.5	10
255.75	14	259.29	10
255.5	14	259	10
255.25	14	258.75	10
255	14	258.5	10
254.75	14	258.25	10
254.5	14	258	10
254.25	14	257.75	10
254	14	257.5	10
253.75	14	257.25	8
253.5	14	257	10
253.25	14	256.75	10
253	14	256.5	10
252.75	14	256.25	6
252.5	14	256	10
252.25	14	255.75	10
252	14	255.5	10
251.75	14	255.25	4
251.5	14	255	12
247.5	14	254.75	10
247.25	14	254.5	10
247	14	254	10
246.75	14	253.75	10
246.5	14	253.5	10
246.25	14	253	10
246	14	252.75	10
245.75	14	252.5	8
245.5	14	252	10
245.25	14	251.75	10

See footnotes at end of table.

TABLE 3. - Distribution of perforations in wells used
for channeling test¹--Continued

Injection well 1 ¹		Recovery well 2 ¹	
Depth of perforations from ground level, feet	Number of perforations	Depth of perforations from ground level, feet	Number of perforations
245	14	251.5	6
		251	10
		250.75	5
		250.5	10
		250	14
		249.5	10
		249	13
		248.5	10
		248	12
		247.5	10
		247	11
		246.5	10
		246	10
		245.5	10
		245	10
		244.5	9
		243.5	9
		243	9
Total.....	² 504		² 522

¹Both wells were located at Wyoming Mineral's Lamprecht site, Texas.

²Perforating time for well 1 was 3 hours and 20 min; the perforating for well 2 was not recorded.

Tests Using Graded Perforations and Slots

In a related experiment performed at the Nine Mile Lake site in Wyoming, the water jet perforator was used to cut intermixed perforations in a graded pattern in both the injection and recovery wells of a five-spot pattern of wells. This was in contrast to the tests at the Lamprecht site, in which only the recovery wells were perforated in a graded pattern. The grading of perforations in the injection wells at Nine Mile Lake was an attempt to increase the injectivity and discharge of the injection and recovery wells, thereby effecting a more uniform flow through the site's low-permeability sands. The sands at Nine Mile Lake were much less permeable than those at Lamprecht, and because of this, the Nine Mile Lake sands accepted less inflow than the Lamprecht sands before becoming saturated. This meant there was a greater likelihood of uneven flow through the Nine Mile Lake sands, since there is a tendency for fluid to flow across the top of the screened interval when a well is forced to accept water at its maximum capacity. (Conversely, the flow of fluids across the screened interval tends to be more uniformly distributed at capacities below the minimum.) By grading the perforations in the injection well, the investigators hoped to achieve a more uniform flow of fluid through the sand.

An entire five-spot pattern of wells consisting of four injection wells and one recovery well was completed at the Nine Mile Lake site. The wells were cased with 5-inch-ID Yelomine and grouted with epoxy resin. Casings were perforated and slotted in zones of the Teapot sandstone at depths from 508 to 541 feet below ground level.

The vertical flow profile into injection well 17 at Nine Mile Lake (fig. 13) was determined by a flow-pack method, that is, by measuring the rate of flow into small lengths of casing that were isolated by packers. This profile shows that certain zones, for example, the zones from 525 to 528 feet and from 532 to 534 feet, accepted very little flow. This may have been a result of plugged perforations or low formation permeability. These low-flow zones had no mineralization.

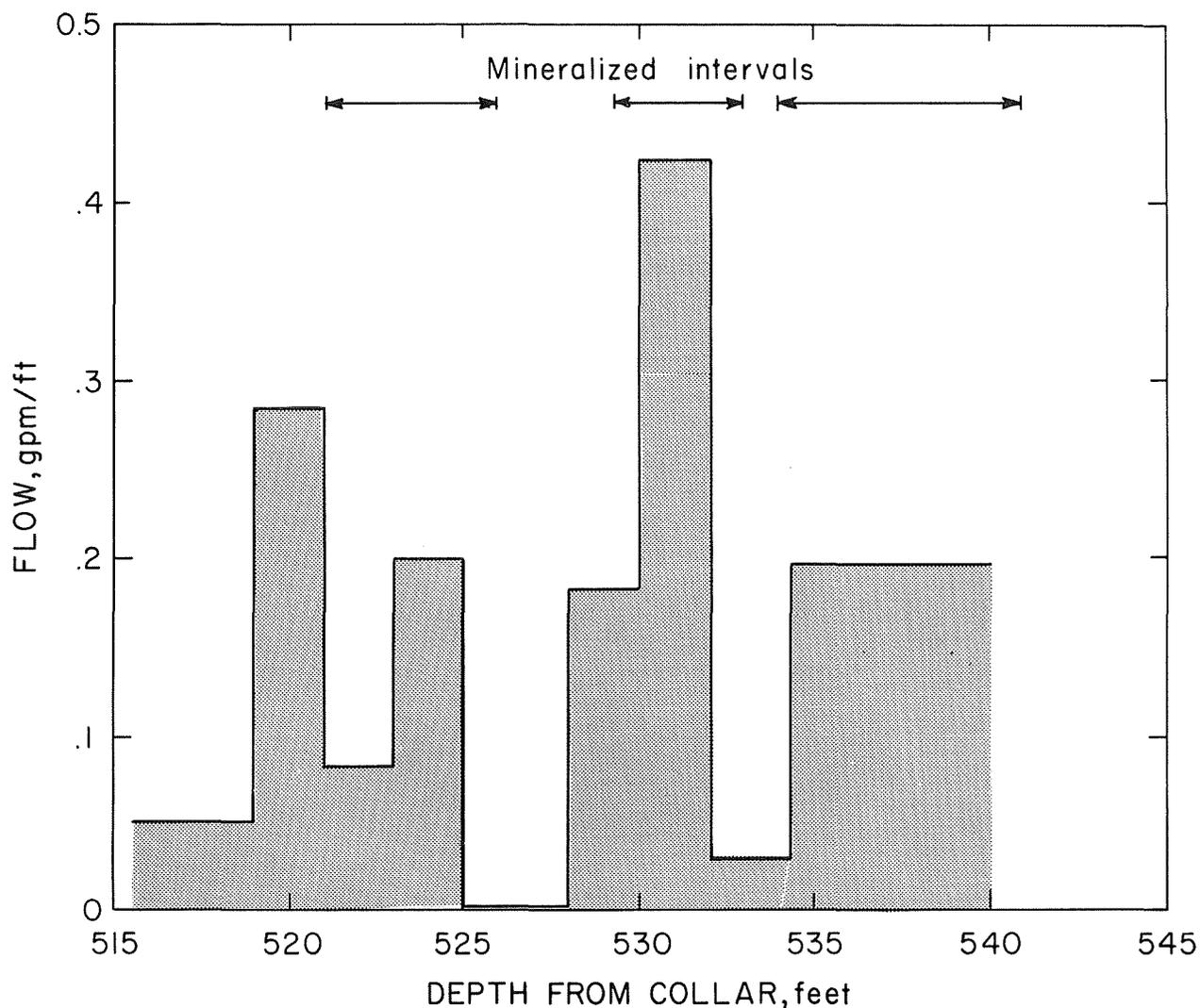


FIGURE 13. - Vertical flow profile into injection well 17 at Rocky Mountain Energy's Nine Mile Lake site, Wyoming.

Initial circulation tests were conducted at 5 gpm per injection well for 46 hours and at 9 gpm per injection well for 9 hours. For these tests, the surface piping leading to the injection wells, wells 1, 2, 3, and 4, was fitted with a pressure gage and flow meter. For the first test, the flow into each of these wells was set at 5 gpm (resulting in a 20-gpm flow into the production well). For the second test, the flow into the injection wells was 9 gpm each (resulting in a 36-gpm flow into the production well). The gage pressures were then read, and the results are shown in table 4. The specific capacity of the production well was 0.29 gpm/1 ft.

TABLE 4. - Circulation test results for wells completed with perforations and slots¹

Well	Well type	Pressure at surface, psi		Efficiency, pct
		5-gpm test	9-gpm test	
1...	Injection.	20	90	33
2...	...do.....	0	12	40
3...	...do.....	0	16	43
4...	...do.....	0	20	85
5...	Production	Nap	Nap	76

Nap Not applicable.

¹Tests were conducted at Rocky Mountain Energy Co.'s Nine Mile Lake site, Wyoming.

The data show that wells 2, 3, and 4 accepted injection more readily than well 1 did. During the 5-gpm test, the gage registered 0 gage pressure in wells 2, 3, and 4 and 20 psi in well 1. This indicated that the weight of the column of water in wells 2, 3, and 4 was sufficient to maintain a 5-gpm injection rate whereas an additional 20-psi pressure had to be applied to well 1 to maintain the same injection rate. In order to maintain an injection rate of 9 gpm, pressure had to be applied to the surface piping leading to all four of the injection wells, but well 1 required significantly higher pressure than wells 2, 3, and 4 did.

These tests demonstrated that the water jet perforator is an effective way to complete in situ leaching wells at Nine Mile Lake. Slot cutting was more effective than simple point cutting. The best well completions were achieved using an 18-gpm jet at 10,000 psi to cut a 180° sector of the casing, which took 1 min.

Well Stimulation

Injectivity Studies

In a cooperative venture with Mobil Oil Corp. at its O'Hern in situ uranium leaching site near Bruni, Tex., the Bureau conducted an experiment to determine if the water jet perforator could be effectively used to stimulate the rate of injectivity of a well through 4-inch-diam screens. Prior to water jet perforation, the injection rates of the wells selected for testing were undesirably low because the flow through the well screens was obstructed. These low injection rates are apparent from the data shown in figures 14 through 17 for November, December, and early January. The selected wells had

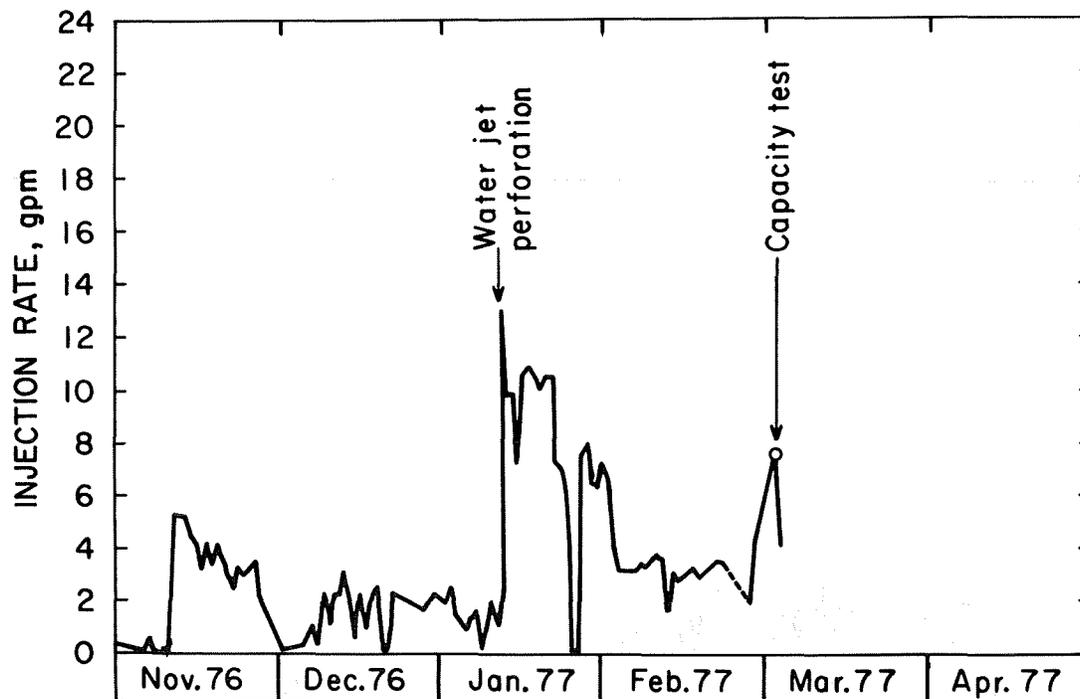


FIGURE 14. - Variation of injection rates during a 4-month period at Mobil's O'Hern site, Texas—Well 1.

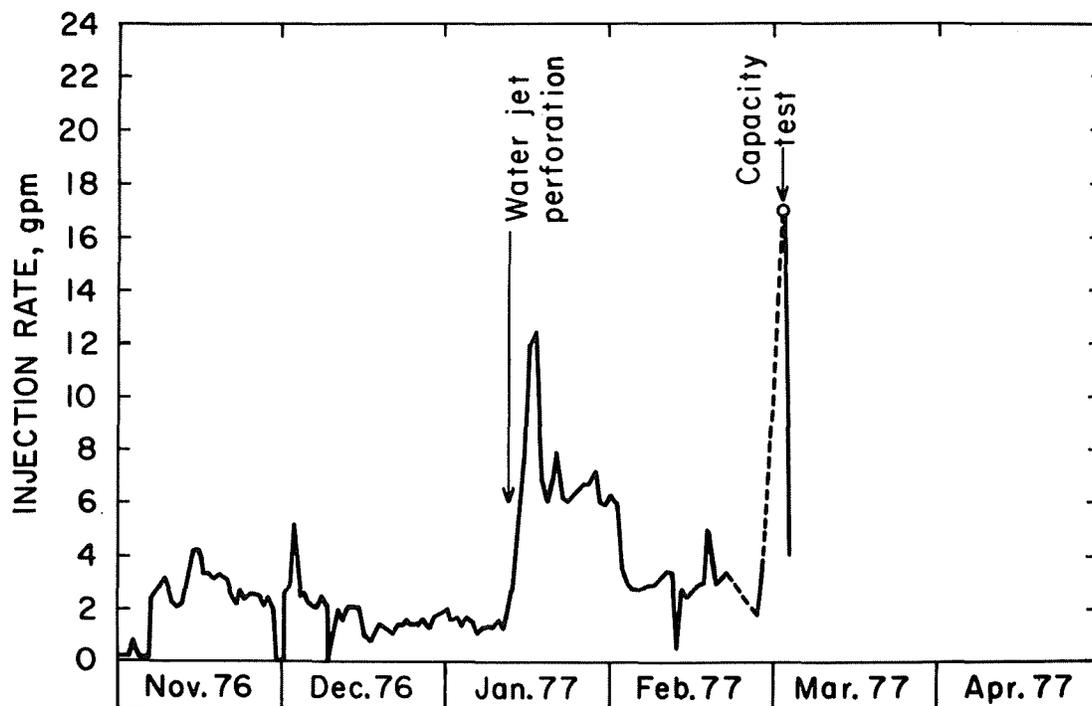


FIGURE 15. - Variation of injection rates during a 4-month period at Mobil's O'Hern site, Texas—Well 2.

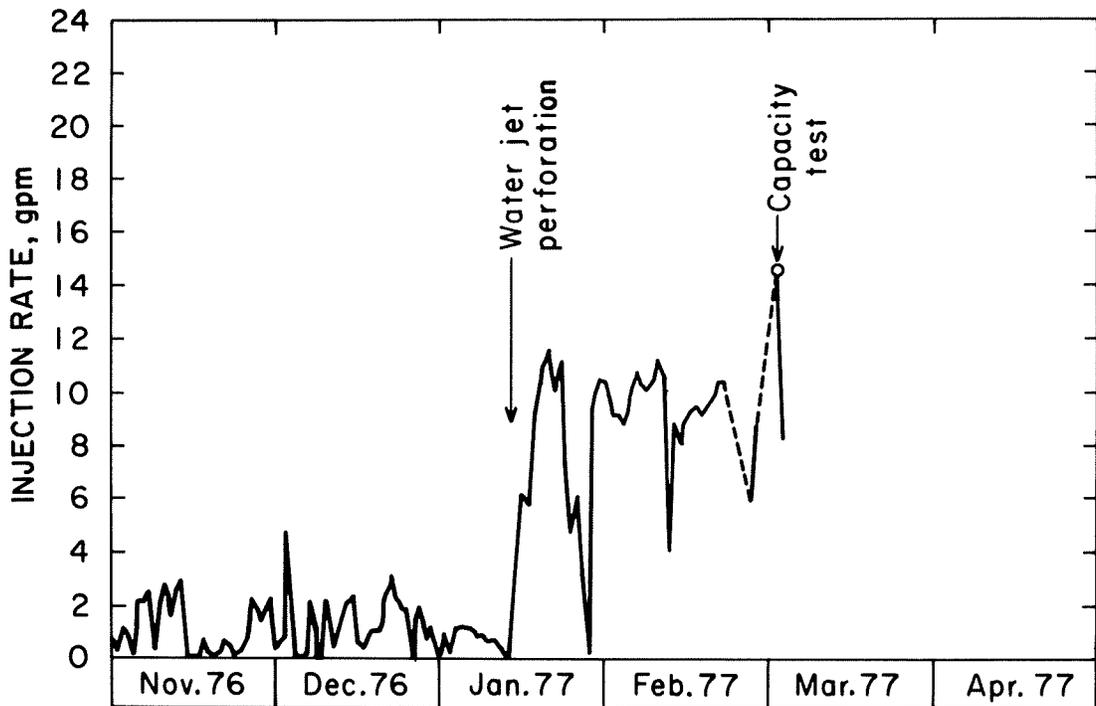


FIGURE 16. - Variation of injection rates during a 4-month period at Mobil's O'Hern site, Texas—Well 3.

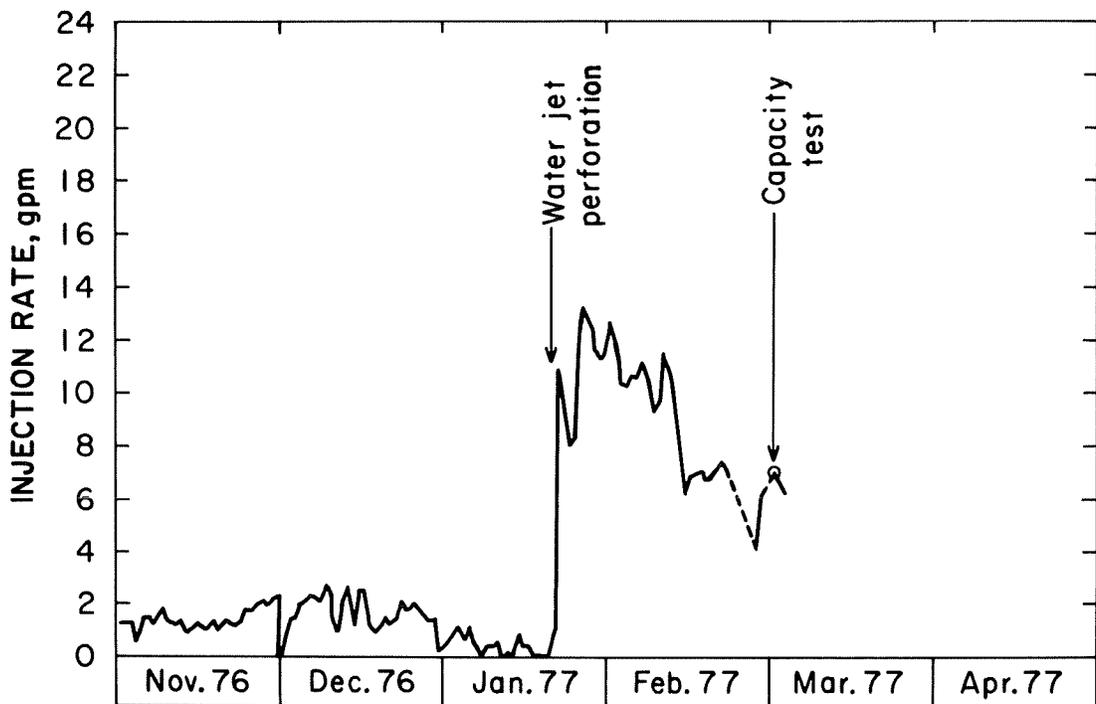


FIGURE 17. - Variation of injection rates during a 4-month period at Mobil's O'Hern site, Texas—Well 4.

sub-par injectivity and did not respond to acidizing, the conventional method of stimulation. Since the wells did not respond to acidizing, it was presumed that their poor performance prior to perforation resulted from cement leaking around cement baskets during cementing or from chemical precipitation around the screen. Figures 14-17 show the injection rates for each injection well for 2-1/2 months before and 1-1/2 months after perforation. There was a dramatic increase in injectivity immediately after the perforation of wells 1, 2, 3, and 4, which were the only wells tested.

The inlets of these wells were throttled during most of the test period to limit injectivity in order to prevent an overload of the processing plant. As a result, most of the data points do not represent the maximum injectivity possible. The results of a 3-hour capacity test (performed on March 1, 1977) at a field injection pressure of 49 psi are shown in each of the graphs in figures 14-17.

Wells 1, 2, and 3 maintained high injection rates nearly 2 months after perforation. Well 4 declined from 12 gpm after perforation to 7 gpm about 1-1/2 months later. This decline was apparently caused by particulate plugging of the screens. After about 9 months, well 4 was perforated for a second time, and injectivity was restored to 12 gpm (fig. 18).

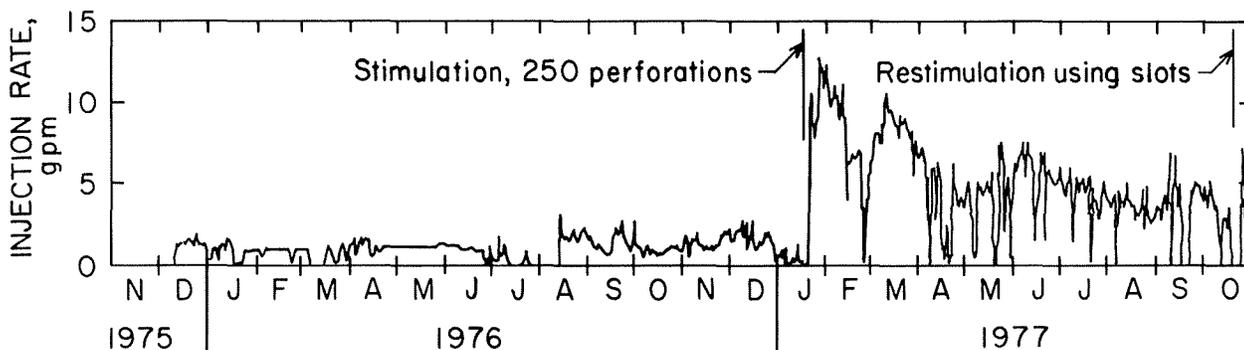


FIGURE 18. - Variation of injection rates during a 24-month period for well 4 at Mobil's O'Hern site, Texas. (Note the low injectivity prior to the first stimulation, the decline of injectivity after stimulation, and the recovery of injectivity after restimulation.)

Comparison of Underreamed Wells With Wells
Completed by Water Jet Cutting

The Bureau performed water jet cutting operations in wells at Union Carbide Corp.'s Palangana Operations, Benevides, Tex., so that these wells could be compared with underreamed wells. The normal method of well completion at Palangana, underreaming, consists of cutting away the cemented casing adjacent to the mineralized sandstone with a tool affixed to the end of a drill pipe string suspended from a rig. This study compared "push-pull" wells (wells in which fluid is alternately injected and then pumped to the surface), completed by water jet cutting with similar wells completed by underreaming, using injectivity and productivity as the bases for comparison. The comparative data are shown in table 5.

TABLE 5. - Injectivity and productivity comparisons of wells completed by water jet perforation and adjacent underreamed wells,¹ gpm

Underreamed wells			Wells completed by water jet perforation					
			Perforated wells			Slotted wells		
Well	Injec- tion rate	Produc- tion rate	Well	Injec- tion rate	Produc- tion rate	Well	Injec- tion rate	Produc- tion rate
1.....	9.12	15.08	5.....	11.38	13.58	8.....	20.16	10.49
2.....	9.19	3.61	6.....	7.00	10.80	9.....	5.08	ND
3.....	3.11	6.29	7.....	8.39	9.92	10.....	5.19	7.01
4.....	5.30	13.76				11.....	22.79	9.04
						12.....	21.06	7.81
						13.....	11.55	7.48
						14.....	20.71	14.63
						15.....	5.09	ND
						16.....	ND	8.07
						17.....	6.86	.96
Average	6.68	9.69	Average	8.92	11.43	Average	13.17	8.18

ND Not determined.

¹Wells used for this comparison were located at Union Carbide's Palangana site, Texas.

Both point and line cutting were performed in selected wells. For point cutting, the cutting apparatus is pressurized, and the nozzle is held in a fixed position. The result is a perforation 0.1 to 0.15 inch in diameter. For line cutting, the nozzle is rotated while the apparatus is pressurized. The result is a slot approximately 0.2 inch wide that extends in a 180° arc. Table 5 shows that the injectivities and productivities were comparable for the wells completed by point cutting, for the wells completed by line cutting, and for the adjacent wells completed by underreaming.

COST CONSIDERATIONS

The total cost of the components used to fabricate the Bureau's water jet perforator was \$42,069 (in 1977 dollars), excluding the cost of the truck-mounted derrick and a water tank. A cost breakdown is presented in table 6. All parts, except the nozzles, are commercially stocked items. In addition to the items listed, a commercial operation would require a truck-mounted derrick, costing about \$25,000, to suspend the perforator in the well, and a water-supply tank.

TABLE 6. - Cost (in 1977 dollars) of components of the water jet perforator¹

Component ¹	Quantity	Unit cost ²	Cost ²
15,000-psi tubing.....	600 feet	\$15.81	\$9,486
20,000-psi tube unions.....	30	57.00	1,710
10,000-psi swivel.....	1	900.00	900
Valves.....	2	56.50	113
Flexible hose.....	25 feet	50.40	1,260
High-pressure fittings.....	6	50.00	300
Diesel-driven pump ³	1	28,000.00	28,000
Nozzles.....	10	30.00	300
Total.....	NAp	NAp	42,069

NAp Not applicable.

¹Not listed are the truck-mounted derrick, which would cost about \$25,000, and water tank.

²Costs given are those of equipment actually used by the Bureau for its tests (except for the pump, as explained in footnote 3). Costs of individual items could, therefore, be more or less than shown, depending on manufacturer, possible price increases, and other considerations.

³Although an electric pump was used in the Bureau's tests, a diesel-driven pump is shown here because it was determined that a diesel-driven pump would be more suitable for use at a fixed location.

The cost to drill and perforate a 300-foot well cased with 5-inch Yelomine casing was \$5,525 (in 1978 dollars), and a breakdown of this cost is given in table 7. This table shows that the perforation cost is only a small fraction of the drilling and casing costs.

TABLE 7. - Cost (in 1978 dollars) to drill and complete a 300-foot well using the water jet perforator

Expense	Unit cost	Cost for 300-foot well ¹
Drilling costs:		
Rig time.....	\$7.30/foot	\$2,190
Services.....	1.65/foot	495
Materials.....	9.00/foot	2,700
Total drilling cost.....	17.95/foot	5,385
Perforation costs:		
Labor ²	10.00/worker hour	120
Amortization of equipment.....	NAP	20
Total perforation cost.....	NAP	140
Total completion cost.....	NAP	5,525

NAP Not applicable.

¹5-inch-diam well with Yelomine PVC casing.

²12 worker hours were required for perforation.

ADVANTAGES OF WELL COMPLETION BY WATER JET CUTTING

Advantages of water jet perforation over conventional methods of well completion are as follows:

1. It costs less.
2. It results in less damage to the wellbore.
3. By selectively agitating the sand adjacent to the wellbore, the water jet winnows clays and thereby enhances the local permeability of the mineralized zone.
4. Openings (perforations) can be selectively placed in the wellbore.
5. Channeling of the leaching solution flow can be avoided by the selective placement of perforations.

These advantages are summarized in table 8.

TABLE 8. - Comparison of well completion by perforation and by conventional methods

Method	Comparative cost	Wellbore damage	Permeability enhancement	Channeling	Placement selectivity
Cement basket and screen.	Similar to perforation.	Unavoidable	No.....	Unavoidable..	5 feet, vertical.
Underream and screen.	Higher than both other methods.	Removed by reamer.	No.....do.....	Do.
Water jet perforation.	Similar to cement basket and screen.	Removed by water jet.	Yes.....	Avoidable by grading perforations.	1 inch, vertical; 1 inch, horizontal.

The two most commonly used methods of well completion involve the placement of a well screen either concurrent with the cementing of the well, using a cement basket, or after the cement is removed with an underreamer. Underreaming is more expensive than either the setting of cement baskets or perforating because a drilling rig must be dedicated for 6 to 8 hours to complete the job.

When the perforation method is used, the water jet penetrates from 1 to 4 feet into the adjacent rock without damaging the wellbore. When other methods are used, however, damage is caused by the migration of cement or drilling mud into the rock, which results in the creation of a layer with poor permeability, or a "sidewall skin."

The smallest vertical interval of the wellbore that can be screened is 5 feet because screens are commonly sold in 5-foot lengths. It is, therefore, unlikely that some barren zones will be screened unless the mineralized zone is some multiple of 5 feet long. Using the perforation method, however, holes can be placed with a vertical precision of 1 inch. Thus, the method is highly selective and is ideal for thin or irregularly mineralized zones.

CONCLUSIONS

Based on field results, the following conclusions may be drawn concerning the use of the water jet perforator for the completion of in situ leaching wells:

1. Perforations made in the well casing can be sized to control sand and obviate the use of well screens, with consequent savings of time and energy.
2. Water jet perforation can stimulate injection wells that exhibit subpar injectivity and do not respond to acidization.
3. The action of the water jet enhances the local permeability of the mineralized zone by winnowing clays.
4. Perforations can be placed in the sidewall of a recovery well in such a way that the leachate flows uniformly through the mineralized zone, rather than channeling at the top of the zone.
5. The accuracy with which perforations can be placed makes it possible to perforate the wellbore only adjacent to the mineralized zones, even if these zones are finely intermixed with barren zones.
6. The perforator can operate in wells with inside diameters as small as 2 inches. Its use could, therefore, reduce the size required for injection wells.

The cost of water jet perforation appears to be comparable to that of using screens in conjunction with cement baskets and is much less expensive than underreaming. Water jet perforation appears to be technologically superior to these conventional well completion methods in enhancing the

permeability of the mineralized zone, avoiding channeling, and limiting damage to the wellbore. Perforation also appears to be a superior method for selectively attaining communication between the wellbore and the mineralized sand, stimulating poorly performing wells, and completing wells with casings as small as 2 inches ID.

The Bureau is presently in the process of transferring water jet perforation technology to industry. Plans and assistance in the fabrication of water jet perforators are available, free of charge, from the Bureau. For more information, write to:

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