SAND--96-1885C SAND96-1885C
CONF-9610163--1

DOE LOST CIRCULATION TECHNOLOGY DEVELOPMENT

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Solution Mining Research Institute
1996 Fall Meeting
Cleveland, Ohio

ABSTRACT

Lost circulation is a problem common in both the geothermal and the solution mining industries. In both cases, drilling is on a relatively large scale (geothermal holes can be as large as 26 inches). Lost circulation technology development for geothermal drilling has been in progress at Sandia National Laboratories for more than 15 years. The initial work centered on lost circulation materials, but testing and modeling indicated that if the aperture of a loss zone is very large (larger than the drill bit nozzles) it cannot be plugged by simply adding materials to the drilling fluid. Thus, the lost circulation work evolved to include:

- Development of metering techniques that accurately measure and characterize drilling fluid inflow and outflow for rapid diagnosis of los circulation and/or fluid balance while drilling.
- Construction of a laboratory facility for testing drillable straddle packers (to improve the plugging efficiency of cementing operations) and the actual testing of components of the straddle packer.
- Construction of a laboratory facility for the testing of candidate porous fabrics as a part of a program to develop a porous packer that places polyurethane foam into a loss zone.
- Implementing (with Halliburton and CalEnergy Company), a program to test cementitious lost circulation material as an alternative to Portland cement.

Rapid and accurate diagnosis of lost circulation while drilling is necessary to minimize fluid loss, reduce treatment costs, and save rig time. A rolling float meter was built, tested, and is being transferred to industry for use in monitoring fluid outflow in partially filled return line pipes. A new generation of commercial Doppler flow meters have been purchased and tested in monitoring drilling inflow rates. Together these flow meters have been used in the laboratory and field to accurately monitor fluid balance and detect los circulation while drilling. An expert system also is being developed to detect lost circulation.

The drillable straddle packer is designed to maximize the volume of cement that flows into the loss zone, to minimize the volume of cement remaining in the borehole, and to reduce dilution of cement from other wellbore fluids flowing into the formation. Its development

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000

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is essentially complete. A prototype has been tested with cement in the ELTF. The ELTF test chamber was loaded with alternating layers of gravel and clay to simulate impermeable rock and loss zones respectively. Facility piping was used to flow water into and out of the gravel beds to model loss and production zones.

Testing of candidate porous fabrics for the wireline porous packer has been completed. While development of the porous packer follows that of the straddle packer, much of the packer technology (bag fabrication, shroud development and deployment, decoupling from a wireline or drill string) will have applicability to the porous packer concept.

The cementitious lost circulation material hardens faster than conventional cement, drills faster, and is more compatible with the drilling fluid, thereby potentially reducing loss-zone, cementing, and mud conditioning costs. The first field trial showed promise and in certain instances saved several hours of rig time compared to conventional methods. The material was reformulated and will be tested this fall.

This work was performed at/through Sandia National Laboratories and supported by the U.S. Department of Energy under contract DR-AC04-94AL8500.

INTRODUCTION

One of the most costly problems routinely encountered in geothermal drilling is the loss of drilling fluids to pores or fractures in the rock formations being drilled. Reducing the cost of lost circulation would help reduce overall project costs.

For this reason, U.S. Department of Energy, Geothermal Division, sponsors the Lost Circulation Technology Development Program at Sandia National Laboratories. The goal of this program is to develop and transfer to industry new technology that would reduce lost circulation costs by 30-50%. The program is developing technology in two general categories: lost circulation diagnostic techniques, and downhole tools for lost circulation control.

Similarly lost circulation is a problem in drilling into salt domes. The caprock can be cavernous or highly fractured or both. It is not unusual to encounter many loss zones when drilling to the top of a salt dome. Because this problem of lost circulation is common to both the solution mining industry and the geothermal industry, this review of the DOE/Geothermal Division sponsored lost circulation work is given.

The paper describes both (1) lost circulation hardware, test, facilities and material and (2) lost circulation detection. The following is discussed under lost circulation hardware, facilities, and material:

- The drillable straddle packer and its tests in the Engineered Lithology Test Facility (ELTF).
- Laboratory and field evaluation of a polyurethane foam for lost circulation control.

- Evaluation of cementitious lost circulation material to stem lost circulation.

And under lost circulation detection:

- Inflow and outflow measuring technology.
- Ongoing Development of an Expert System for Detecting Lost Circulation.

THE DRILLABLE STRADDLE PACKER CONCEPT

1. Background and General Description

Conventional lost circulation treatment in geothermal drilling is to position the lower end of an open-end drill pipe near the suspected loss zone and pump a given quantity of cement (typically 300 cu ft) downhole. The objective is to emplace enough cement into the loss zone to seal it. Because of its higher density relative to the wellbore fluid, the cement often channels through the wellbore fluid and settles to the bottom of the wellbore. If the loss zone is not on bottom, the entire wellbore, below the loss zone must sometimes be filled with cement before a significant volume of cement flows into the loss zone. Consequently, a large volume of hardened cement must often be drilled to reopen the hole, which requires time and contaminates the drilling mud with cement fines. Furthermore, because of the relatively small aperture of many loss-zone fractures, the loss zone may preferentially accept wellbore fluids, instead of the more viscous cement. This also causes dilution of the cement in the loss zone and loss of integrity of the subsequent cement plug. As a result, multiple cement plugs are often required to plug a single loss zone.

2. The Drillable Straddle Packer Concept

The drillable straddle packer has been developed as a means for improving the effectiveness and reducing the cost of a typical lost circulation cement treatment (Glowka, 1995). This is accomplished by maximizing the volume of cement that flows into the loss zone, minimizing the volume of cement that remains in the wellbore, and reducing dilution of the cement caused by other wellbore fluids flowing into the loss zone.

The drillable straddle packer concept is shown in Figure 1. A packer assembly on the end of the drillstring employs two fabric bags that straddle the loss zone and provide zonal isolation. The bags are inflated with cement by the differential pressure that develops across the cement ejection ports in the packer tube, when cement is being pumped. This differential pressure is easily controlled from the surface by controlling the cement flow rate. The highly flexible bags seal against the wellbore wall, thereby forcing most of the cement to flow into the loss zone. In most cases, a bag pressure of 20-40 psi should be sufficient to accomplish this.

As the bags inflate, they also provide blockage to the flow of other wellbore fluids into the loss zone. Drilling mud and connate fluids produced at other wellbore intervals can thereby be prevented from diluting and channeling through the cement.

After pumping a specified volume of cement, the straddle packer assembly is disconnected from the drillstring and left in the wellbore, when the drillstring is tripped out of the hole. The packer assembly is constructed of drillable materials: aluminum, silicon, rubber coated fiberglass cloth, and, in low-temperature applications, CPVC plastic. These materials permit the straddle packer assembly to easily be drilled through after the cement sets.

3. Engineered-Lithology Test Facility (ELTF)

This facility has been used for three full-scale lost circulation treatment tests with cement at full-scale flow rates (Dunn, 1995). The facility consists of a 15 ft x 15 ft x 15 ft concrete box with an open top and one open side. Engineered loss zones are emplaced in the box by alternating layers of clay and gravel, representing impermeable and permeable zones, respectively. Concrete pipe sections are stacked vertically in the center of the box to simulate the wellbore, into which the cement will be pumped (Figure 2). Vertical spacing between sections of the concrete pipe creates simulated fractures of various sizes allowing fluid to flow between the wellbore and the permeable gravel layers. An extensive plumbing system exists outside the box with multiple pipe penetrations through the walls. Fluid, normally water, can thereby be pumped into or out of any permeable zones at rates up to 450 gpm. The fluid can be heated to temperatures up to the boiling point of water. This allows temperature effects on cement to be studied.

Internal wellbore flows are initiated by pumping into one or more of the gravel layers and flowing out of the layer representing a loss zone. In this manner the pressure-gradient conditions that occur in an actual wellbore under lost circulation conditions are simulated. Cement at full-scale flow rates is pumped through an open end drill pipe or straddle packer assembly to test the packer's operation under such conditions. Post-mortem analysis can be performed by excavating the clay and gravel from the facility while mapping the location of the injected, solidified cement. In this way, the effectiveness of sealing off internal wellbore flows and injecting the cement into the loss zone can be determined.

Construction of the ELTF was completed in FY95. Flow meters and pressure transducers are used on the various flow lines, and other diagnostics are emplaced in the test beds to monitor temperature, pressure, etc.

4. Open End Drillpipe and Straddle Packer Tests at the ELTF

The first test was to serve as a baseline for conventional cementing practices, where the end of an open drill pipe is positioned near the suspected loss zone and cement is pumped into the open wellbore. In large-diameter wellbores typical of the upper sections of geothermal wells, density differences between the cement and drilling fluid often dominate over all friction effects, causing the cement to settle to the bottom of the wellbore. Sufficient cement must then be pumped to fill the wellbore below the loss zone before any significant volume of cement will enter and plug the zone.

For the first test, three twelve-inch-thick permeable gravel layers were emplaced in the facility, sandwiched between impermeable clay layers. The middle layer was intended to simulate a loss zone, with the exterior plumbing leading out of the zone being open to the atmosphere. The upper layer was intended to simulate a production zone, with water being pumped from the exterior plumbing, through the gravel zone, and into the wellbore. The bottom layer was intended to simulate additional wellbore volume, with no outlet to the exterior plumbing. It was therefore expected that most or all of the cement would flow by gravity into the lower permeable zone, similar to the manner in which cement flows to the bottom of a large-diameter wellbore before it flows into the loss zone. Two pressure transducers and twenty thermistors were distributed throughout each gravel layer. Halliburton Services mixed and pumped cement using geothermal materials and procedures.

Two problems occurred during the test. First, a major "blowout" occurred in the clay surrounding the lower permeable zone; thus, the lower zone became a simulated loss zone instead of a closed wellbore volume. When the cement flowed into the lower zone, it therefore could not be argued that this was due to density differences between the cement and the water in the wellbore. Second, a larger volume of cement (~ 3x) was inadvertently pumped by Halliburton. Upon excavation of the facility after the test, it was discovered that the lower zone was completely filled with cement, but the middle and upper zones also had a significant amount of cement in them. Thus, although it is believed that the cement flowed into the middle and upper zones only after it had completely filled the lower zone, it could not be proven that this was the case.

For the second ELTF test, the method for containing the gravel zones within the clay was modified and the volume of cement pumped was more closely controlled. Each permeable gravel zone was encased in a plastic geomembrane box to prevent fluid leakage paths from developing in the surrounding clay. The geoboxes, a geomembrane structure in which gravel or other actual lithologic material is placed, were sealed around respective sections of concrete pipe simulating the borehole. There were 1/2 inch spacers between sections of the concrete pipe for water to enter or exit the production or loss zone respectively and an 8 inch spacer at the lower permeable level to simulate additional length of borehole. The second and third (see below) tests were thus configured like the first tests with minor engineering modifications in the lithology.

There were some plumbing construction leaks in the top two layers of the second test due to the clay settling. However, the geomembrane confining the permeable gravel was successful and overall the test was more realistic than the first. The results were similar to the first test. Upon excavation of the test bed, it was found that significant cement was in all three zones. In fact in the second test, all three permeable zones had approximately the same amount of cement. From the results of these tests it is surmised that the cement from the open end drill pipe, being more dense than water, or drilling fluid in the wellbore, fills permeable zones starting from the bottom. Thus the tests indicate that open drill pipe cementing can fill a loss zone. However, other zones may also ingest cement and the wellbore to the bottom of the hole can be filled with cement. Thus the open pipe "baseline" method is rather indiscriminate of the type of permeable zone it fills.

For the third ELTF test, the straddle packer was inserted across the simulated loss zone as in Figure 2. The top of the upper straddle packer bag was seated just below the top simulated production zone. The bottom of the lower straddle packer bag was seated just above the lower gravel layer. The "lithology" was further modified in that the clay was correctly compacted to ~95% fill density.

Again, cement was pumped into the wellbore by Halliburton. The pressure transducers showed the bag inflated properly, and that the thermisters in each gravel bag indicated that all the cement flowed into the simulated loss zone which was straddled by the packer bags. Test bed excavation showed that there was to be negligible cement except where intended--in the simulated loss zone. **The first scaled up straddle packer test was therefore entirely successful insofar as the cement entered only the loss zone, virtually to the exclusion of cement entering either of the other zones.** We are currently documenting our test data in order to interest a geothermal operator or service company in participating in a field test of the drillable straddle packer.

LABORATORY AND FIELD EVALUATION OF POLYURETHANE FOAM FOR LOST CIRCULATION CONTROL

1. Background

In a cooperative effort between the geothermal drilling industry and the U.S. Department of Energy, the potential for using a two-component polyurethane foam for lost circulation control has been investigated with laboratory and field testing.

In 1980, Sandia National Laboratories contracted with Southwest Research Institute (SwRI) to test a two-component polyurethane foam formulation supplied by Poly Plug, Inc., at elevated pressures and temperatures(Glowka, et al, 1989). The Poly Plug formulation was designed to expand appreciably and remain stable under downhole conditions. The testing was done at SwRI because of the existence of SwRI's Deep Ocean Simulator. Test results indicated that the Poly Plug foam formulation was capable of undergoing significant expansion at elevated pressures and temperatures. Densities from 8.1 to 18.3 lb/ft^3 were measured in the 900 psig tests, compared with a water density of 62.4 lb/ft^3 and an initial liquid chemical density of 75 lb/ft^3; thus the chemicals expanded 4 to 9 times their original volume at 900 psi. The compressive strengths of the foam samples ranged from 150 to 300 psi. Fluid-loss test results indicate that the foam samples had very low permeabilities.

Based on these results, it was concluded that the Poly Plug foam formulations may produce a suitable downhole material for lost circulation control in geothermal drilling.

2. Prototype Tool Demonstration

Poly Plug was granted a patent in March, 1980, and designed a self-contained device for deploying and mixing the constituents of a polymeric foam system downhole (Baughman and Doyle, 1980). The tool could be lowered downhole on a drill string and activated using the surface mud pumps (Figure 3).

In the spring of 1984, a demonstration of the operation of the prototype tool was conducted at Sandia in cooperation with Poly Plug and NL Baroid (Polk et al, 1985). A simulation of a wellbore in a lost circulation zone was built above ground to facilitate post-mortem analysis and documentation.

The tool successfully mixed and delivered the foam chemicals in this atmospheric-pressure test. Measured foam properties were similar to those measured in the SwRI tests conducted under atmospheric conditions.

3. Geothermal Drilling Organization Field Test

In February 1987, an agreement was signed among members of the Geothermal Drilling Organization (GDO) and others to field test the Poly Plug foam formulation and downhole tool. The participants of the project were:

- H. & H. Tool Co.
- Grace Drilling Co.
- Unocal, Geothermal Division
- Geothermal Resources International
- Sandia National Laboratories for DOE
- Baroid, NL Industries

The GDO-sponsored field test was conducted in the Geysers, January 19-22, 1988, in Unocal Geothermal well OF51-11. Although lost circulation was not encountered as anticipated in the 2500-3100 ft level, the decision was made to discharge the tool in the open hole to evaluate the function of the tool and to determine the potential for using the rigid foam as a bridge plug. A run was successfully completed. The test was run in a 20-5/8 inch section of open hole, 87 ft long, that was drilled below the final casing shoe to a depth of 3222 ft. The tool was lowered to a depth of 3191 ft and was discharged according to procedure.

The tool was tripped out, and a junk basket was lowered to the bottom of the hole without foam plug. Upon resumption of drilling, several pieces of brittle polymer were washed out of the hole and recovered at the mud pit. Densities of 35.0 and 37.4 lb/ft^3 were measured with two of the samples, indicating that the foam chemicals approximately only doubled in volume under the imposed downhole conditions. This was considered a relatively small expansion, compared with the 4-10-fold expansion reported in the SwRI tests at 900 psi. Examination of the recovered samples and the lack of hole fill indicated that the foam chemicals did not conglomerate together to form a plug before solidifying, even though the tool apparently functioned as intended.

4. Laboratory Tests Under Downhole Conditions

Sandia attempted to resolve some of the uncertainties associated with the field results by building a laboratory facility in which all pertinent downhole conditions could be simulated. In March 1988, twelve tests were run in the Foam Test Facility under various conditions to determine the cause of the foam's failure to expand sufficiently and form a plug in the Geysers field test.

The effects of drilling mud on foam expansion were found to be minor, but mud was found to have a significant effect on the structure of the resulting polymer. Foam samples generated in drilling mud from the Geysers field test were noticeably structurally weaker.

In the case where drilling mud was used as the ambient fluid, however, the evidence indicates that foaming began immediately as the chemical exited the static mixer port. In this case, the chemical may simply stick to the wellbore wall or float upward as expansion continues, instead of flowing to the lost zone before expanding, as it apparently did in the Geysers test. Drilling mud additives may therefore cause foam emplacement problems in addition to reduced structural strength of the solid polymer.

The major problem was found to be fluid pressure. The polyurethane foam chemical formulations employed in this study are sensitive to jet mixing with water in the downhole environment. At elevated pressures, a significant fraction of the CO_2 gas generated in the chemical reaction is apparently dissolved in the ambient water, thereby reducing the available free gas to expand the foam. As a result, foam samples generated by injecting directly into pressurized water are much denser than foam samples generated in an inert environment, or those generated within a porous bag that prevents jet mixing of the chemicals with the surrounding fluid. Upon re-examination, it was found that the successful SwRI lab tests had, in fact, used canvas bags to contain the foam chemicals as they expanded.

5. Discussion

Because of the failure of the two-component foam to expand sufficiently and the limited mass of chemicals available downhole with the foam tool tested in the 1980's, that two-component system was not suitable for use in lost circulation control. In contrast, a one or two component system which could be pumped from the top of the well may have some promise because a larger initial volume of chemicals could be emplaced downhole. The isocyanate used in most rigid polyurethane foam systems is a promising starting point for the development of one-component formulations. This chemical, polymeric MDI (polymethylene polyphenyl-isocyanate), will react with itself to form rigid, thermally stable polymers.

Another possible solution is the concept of a porous packer that would consist of a porous bag into which mixed polyurethane foam chemicals are injected. The bag would prevent the chemicals from mixing with the drilling fluid as they are injected, and it would confine the chemicals as they react and start to expand. When the foam fills the bag, it would seep through the porous fabric and into whatever loss zone the bag is spanning. The bag could be delivered with a wireline-deployed service module that carries the foam chemicals, mixing pump, power source, and timer. After the foam is delivered to the bag, the service module would disconnect from the bag and be retrieved uphole with the wirelines.

Some work on this concept has been completed. A facility for testing candidate fabrics for the porous packer was designed and built. A few tests were run, but a manpower shortage forced us to concentrate first on the drillable straddle packer. Since the porous packer can use some of the technology developed in the drillable straddle packer project, the porous packer project is currently on hold.

EVALUATION OF NON-CEMENTITIOUS LOST CIRCULATION MATERIAL

A project on the field evaluation of Halliburton's non-cementitious lost circulation material (LCM) for lost circulation control was initiated in FY95 (Dunn, 1995). The plug material hardens faster than conventional cement and is compatible with the drilling fluid, thereby potentially reducing loss-zone cementing and mud conditioning costs. In addition to Halliburton, other participants in the project include CalEnergy and Sandia. CalEnergy is providing access to their geothermal wells, Halliburton is providing development and laboratory testing of the mud, and Sandia is providing rig instrumentation, downhole logging, and data analysis.

The first phase of the project was completed early in FY95 at a California geothermal field. Sandia instrumented the drill rig with inflow and outflow meters, and also paid for several borehole televiewer logs for examining loss-zone fractures before and after the cementitious LCM treatments. Multiple loss zones were encountered throughout the well. In some of these zones, conventional cement was used to treat the zones; in others, the plug material was used. The results of these tests indicated that: (1) the LCM was effective in sealing small-aperture loss zones, but not large-aperture zones; and (2) where it worked, the cementitious LCM was responsible for saving several hours of rig time compared with conventional cement. These results indicated that the viscosity of the cementitious LCM needs to be better controlled in order to make it more effective and less temperature dependent.

Based on these results, Halliburton reformulated their plug material and a second field test was undertaken. In this phase, a geothermal well in Oregon was used. Sandia again instrumented the well for inflow and outflow measurements. Unfortunately (from the standpoint of this project), no lost circulation zones were encountered in this well. Consequently, the plug material could not be tested there. Plans were being made to continue the project in a California geothermal field during early FY97.

INFLOW AND OUTFLOW MONITORING TECHNOLOGY

PRESENT INDUSTRY STANDARDS

1. Paddlemeters

The standard industry device for measuring drilling fluid outflow is the paddlemeter. The paddlemeter employs a single, spring-loaded paddle or vane that protrudes into the flow and is deflected upward by the force of the flowing fluid. The magnitude of the deflection can be correlated with flow rate to provide an approximate measure of the outflow while drilling. This meter suffers from inaccuracy due to unsteady interaction between the paddle and the drilling mud stream (i.e., paddle bounce); this causes an unsteady and inaccurate meter reading [2]. The output is often displayed simply in terms of percentage of full flow and is used more as a flow/no-flow indicator than in providing a quantitative measure of the outflow rates.

2. Pump-Stroke Counters

The standard industry device for measuring inflow rates is the pump-stroke counter (PSC). By multiplying the number of strokes by the theoretical volume of fluid pumped per stroke and the mud-pumps efficiency, the approximate inflow rate to the well can be determined. Problems with this approach arise in several areas. Pump efficiency changes as the pump wears. Efficiency also changes with the type and viscosity of the fluid being pumped and with the amount of lost circulation material (LCM) in the fluid. If the suction line becomes plugged or if debris is sucked into the pump, the pump can easily be pumping less than the PSC would indicate.

NEW FLOW-METER TECHNOLOGY

3. Doppler Flowmeters

In an effort to find an accurate, non-intrusive inflow meter, Sandia experimented with several types of commercial Doppler flowmeters (Whitlow, et al, 1996). The basic problem with the older type of analog acoustic flowmeters was the ambient rig noise present on all drill rigs.

Significant recent technological improvements have been made in Doppler flowmeters by Peek Measurement, Inc. Better RF liquid excitation has been achieved by using larger crystals to transmit and receive. The larger crystals are impedance-matched with the electronic circuitry to operate at higher energy levels. Operating at a higher energy level helps overcome pipe impedance. This allows more RF energy to enter the fluid and provide a larger signal for retrieval, thus minimizing the interference from spurious noise signals such as vibration.

Another major improvement has been the incorporation of digital filtering techniques to analyze the reflected signal. This signal can be viewed in the frequency spectrum and any unwanted "spikes" or interference signals can be filtered. This feature allows the operator to filter out unwanted acoustic signals caused by the drill rig.

4. Rolling Float Meter

The rolling float meter (Figure 4) was designed by Sandia to measure fluid flow in a drilling fluid return line in a manner that minimizes the problems associated with conventional paddlemeters. The meter is easily installed on the return line and causes little interference with the flow, requiring only one data channel. The meter employs a rolling float that is counterbalanced so that it rides on the surface of the fluid. The angle of the float pivot arm (and therefore the height of the float) is measured with a pendulum potentiometer. The fluid accelerates as it flows under the spinning float, causing a lower pressure beneath the float so that it adheres to the fluid surface through the Bernoulli effect. In this manner, the float accurately measures the height of the fluid in the pipe and thus the flow rate, in the return line.

5. Magnetic Flowmeters

Magnetic flowmeters have accuracies of ±0.25% to ±0.5% but have several limitations for use on drill rigs. Magmeters are typically very costly (approx. $1,000 per inch of pipe diameter). They also have pressure requirements that limit their use to the suction side of the mud-pumps. Mud-pumps typically require large diameter pipes on the suction side, thus making cost a factor. Magmeters should not be installed in a location where the pipe is subject to silting. However, due to the horizontal orientation and relatively low velocity of the drilling fluid in pipes on the suction side of mud-pumps, silting is hard to prevent. If silting does occur then inaccuracies in the magmeter will exist. The magmeter was used as a field calibration device for the Doppler flowmeters.

FIELD TESTING

6. A California Geothermal Field

In 1994, Sandia instrumented a well being drilled by an operating geothermal energy company in California. Two magmeters operated correctly and accurately until they began to experience silting. When silting occurs, inaccuracies exist, and it is very difficult to clean the meters due to their size (approx. 200 lbs) and their location.

The performance of the Doppler flowmeter was excellent. The capability to minimize the effects of rig noise allowed it to track the flow accurately. The measured Doppler flow was compared to the total of the two magmeters and found to be as accurate, but without the problems associated with intrusive type flowmeters.

The rolling float meter proved invaluable in diagnosing lost circulation on this well. The rolling float meter was sensitive enough to detect a 25 gpm loss out of a nominal flow rate of 450 gpm. Two problems were noted. First drilled cement solids settling out in the line caused the float to artifically ride high, and the float settled on debris in the flow line when flow was stopped, giving an indication of outflow when in fact there was none. Both of these problems were caused by a shallow (<2.5°) return-line angle. The rolling float meter was designed to operate with return line angles of between 5° and 12°. At proper angles the fluid velocity is sufficient to prevent the cuttings from falling out of suspension and settling in the return line.

On one occasion while drilling this well, a large mass of lost circulation material was pulled into the suction side of the mud-pump. This plugged the pump and resulted in the outflow of the mud-pump dropping to zero. This went undetected by the driller, as the PSC was still indicating that there was flow. However the magmeters, Doppler, and rolling float meter all correctly indicated no flow.

7. An Oregon Geothermal Field

In 1995, Sandia instrumented a well being drilled by an operating geothermal energy company in Oregon. The performance of the Doppler flowmeter was again excellent. It was possible to observe the frequency spectrum and make necessary changes in the filters as drilling conditions changed.

The rolling float meter was installed on the return line, which was at an angle of 15°. As previously stated, the rolling float meter was designed to be installed at angles of 5-12°. The extreme angle used on this well caused two problems. First, the float exhibited higher than normal bouncing, which had to be electronically filtered. Second, the higher velocities and abrasive nature of the cuttings caused excessive wear on the float (which is made of closed-cell high density polyurethane foam). This resulted in a reduction of 1/4 inch on the 9 inch float diameter after 3 months of operation. Despite these problems, the rolling float meter worked very well, detecting the minor losses encountered on this well, 20-30 gpm out of a nominal flow rate of 600 gpm.

On one occasion while drilling, it was observed that the inflow rate measured by both the Doppler flowmeter and rolling float meter decreased by approximately 150 gpm, although the PSC did not indicate a reduction of the pump-stroke rate. The pump was eventually taken off-line and examined. It was found that a bucket that was sitting on a catwalk had fallen into the mud pit and been sucked into the mud pump. Being able to detect this type of problem can prevent costly repairs and downtime.

8. Experience on Coring Rigs

Sandia was involved in the drilling of two core wells in 1995. The Doppler flowmeter worked very well in monitoring inflow rates. It proved to be much more accurate than the conventional PSC. The spectrum did have to be monitored on a fairly regular basis to change the filtering as drilling conditions often changed the rig noise frequency and level. The rolling float meter, however, did not accurately measure outflow rates. The low flow rates of coring rigs, resulted in insufficient displacement of the float in the return line, thus making the output signal too low to accurately resolve the flow. As a result, a 3" magmeter was installed on the outflow line to replace the rolling float meter. This magmeter did work, but required periodic cleaning; and to simulate a full pipe (necessary for a magmeter to operate), the returns had to be routed through a 3" pipe, with the magmeter installed on a low spot in the pipe.

On one occasion, in Oregon, the drill string became differentially stuck. A totalizer function on the Doppler flowmeter proved to be invaluable in spotting mineral oil at precisely the right location to rectify this problem.

9. Second-Generation Rolling Float Meter

As a result of problems identified in field testing the Sandia-designed rolling float meter, Sandia has designed a second-generation rolling float meter. The major technological improvements are as follows: (1) Improved resolution; (2) Wear-resistant float; (3) Flow/No flow indicator; (4) Pressure-resistant enclosure.

Testing of the second-generation meter is being done in Sandia's Wellbore Hydraulics Flow Facility. Testing in this facility has shown the rolling float meter to be accurate up to 915 gpm, as well as being able to detect losses as low at 8 gpm. The accuracy of the second generation rolling float meter was compared to both a Doppler flowmeter and a magmeter, at various return line angles and viscosities of fluid.

After field testing by Sandia, this second-generation rolling float meter will be made available for industry evaluation.

ONGOING DEVELOPMENT OF AN EXPERT SYSTEM FOR DETECTING LOSS CIRCULATION

The Department of Energy through Sandia and the Geothermal Drilling Organization, in collaboration with Tracor Inc., Austin, TX, is in the preliminary stages of developing an expert system for lost circulation diagnosis in geothermal drilling. This work will use and build upon Tracor's *Well Site Advisor* software which Tracor has developed for gas kick detection and treatment for petroleum drilling applications. That software compares acquired hydraulic data with predictions, detects differences in predicted and actual data, determines the causes for these differences, alerts the user of a possible anomaly and presents the user with a set of company specific rules for dealing with the anomaly. The objective of this project is to demonstrate how this methodology can be adapted to geothermal drilling.

Three steps are planned in this stage of the project: (1) Establishment of a Geothermal Drilling Case Study Database. Actual data from an operating geothermal energy company's well shall be provided. (2) Preliminary Algorithnm Design and Testing. Determine when significant differences between measured and predicted parameter values occur and properly diagnose the cause of these differences. (3) Assessment of statistical test accuracy. Determine how well the algorithms accurately determine lost circulation events. If the first phase is successful in demonstrating the utility of an expert system for lost circulation control and diagnosis, the system will be developed and implemented in the field over a two year period.

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DRILLABLE STRADDLE PACKER

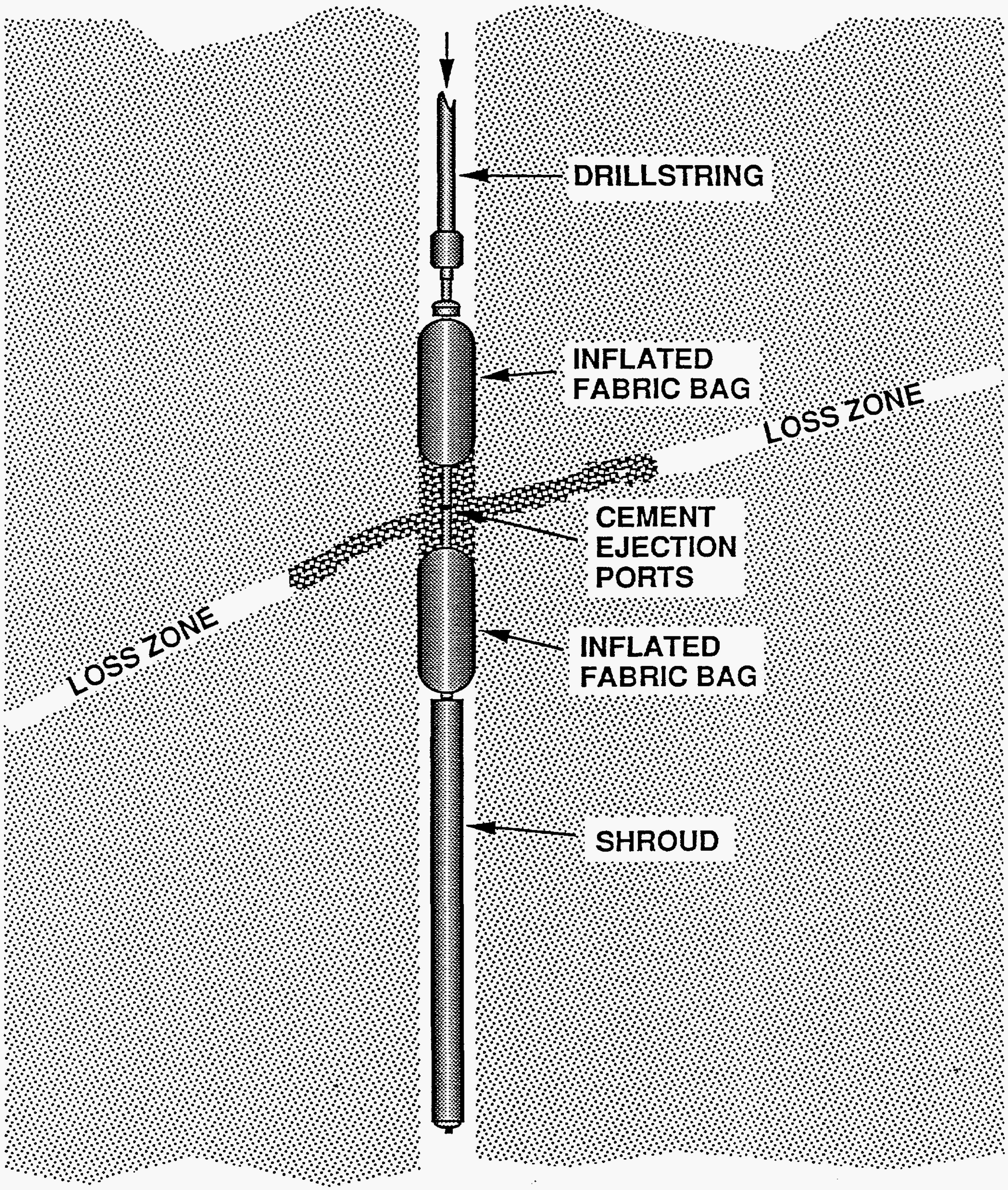
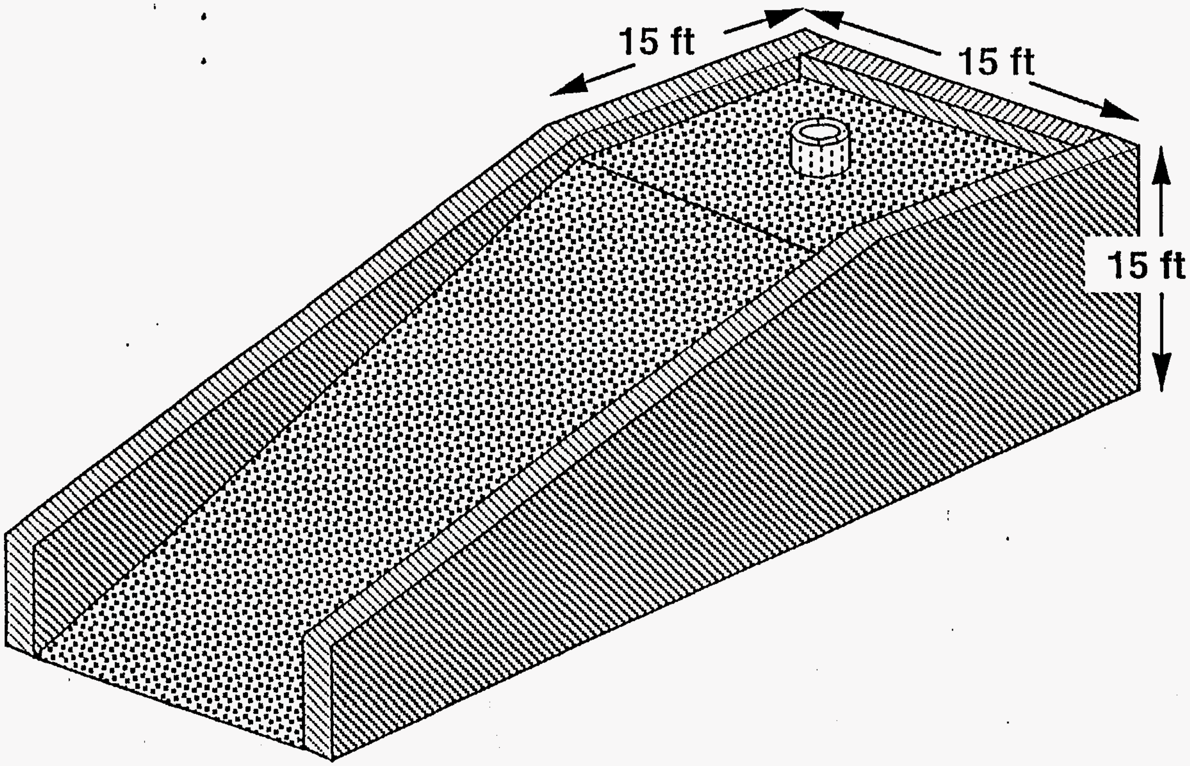
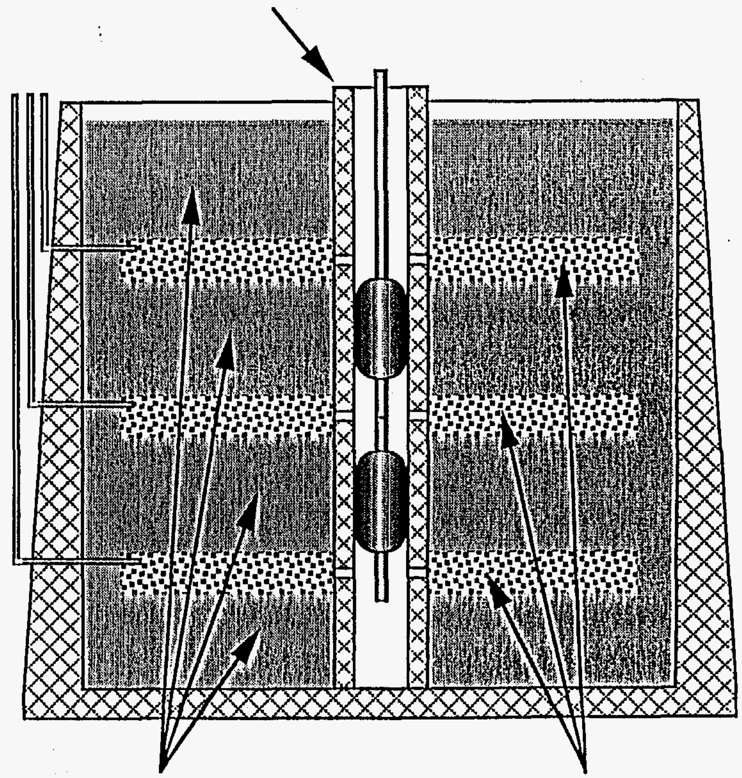


FIGURE 1

ENGINEERED-LITHOLOGY TEST FACILITY

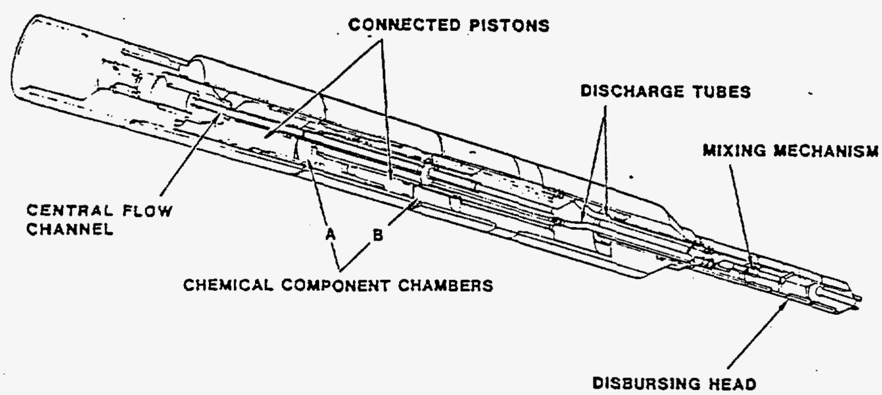




OBLIQUE VIEW

CROSS-SECTIONAL VIEW

FIGURE 2



Schematic of Poly Plug polyurethane foam tool.

FIGURE 3

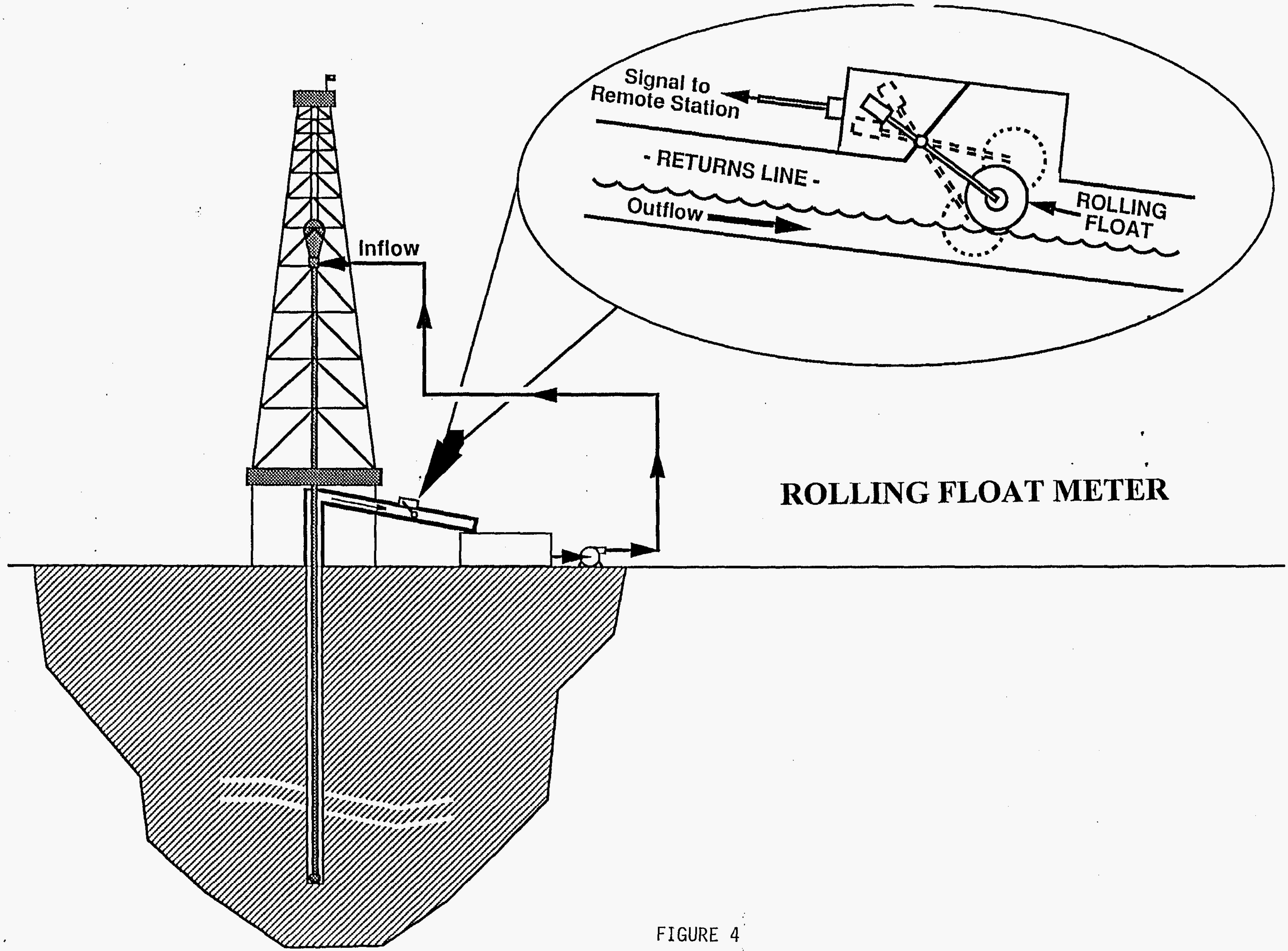

Signal to
Remote Station
- RETURNS LINE -
Outflow
ROLLING
FLOAT
Inflow
ROLLING FLOAT METER

FIGURE 4