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PROGRESS IN THE LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROGRAM

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ABSTRACT

Lost circulation is the loss of drilling fluid from the wellbore to fractures or pores in the rock formation. In geothermal drilling, lost circulation is often a serious problem that contributes greatly to the cost of the average geothermal well. The Lost Circulation Technology Development Program is sponsored at Sandia National Laboratories by the U. S. Department of Energy. The goal of the program is to reduce lost circulation costs by 30-50% through the development of mitigation and characterization technology. This paper describes the technical progress made in this program during the period April, 1990 - March, 1991.

BACKGROUND

The most costly problem routinely encountered in geothermal drilling is lost circulation. This occurs when the drilling fluid, pumped downhole to cool the bit, carry rock chips out of the wellbore, and in some cases control the well, is lost to the rock formation rather than circulating back to the surface. Such a loss of circulation is caused by an incompetent or permeable rock formation (characterized by porous matrix, fractures, vugs, or caverns) which does not have adequate physical integrity or pore-fluid pressure to support the hydrostatic pressure inside the wellbore.

Although drilling can often continue under lost circulation conditions, it is generally imperative that the fluid loss be stopped as soon as possible after it is discovered, for several reasons:

- Drilling fluid is expensive (typically $5/bbl), so pumping thousands of barrels into the formation can significantly increase drilling costs;
- Changes in the rock formation being drilled cannot be easily detected if rock chips are not circulated out of the wellbore; rock chips lost to the formation can also flow back into the wellbore when drilling stops, thereby sticking the drillstring in the hole;

- The well may be difficult or impossible to control if a high-pressure zone is encountered with the wellbore only partially filled with drilling fluid;

- Drilling fluid invasion of the surrounding rock formation alters *in-situ* conditions and therefore affects the logging response of the formation;

- Freshwater aquifers associated with loss zones can be contaminated by drilling mud and connate fluids produced at other wellbore intervals; and

- Loss zones not treated during the drilling phase can cause cement to be lost to the open formation during completion operations, resulting in a poor or incomplete bond between the casing and the rock formation and requiring expensive remedial action to prevent inter-interval flow and possible casing collapse when the well is put on production.

Lost circulation problems tend to be more severe in geothermal drilling than in oil and gas drilling because of the highly fractured and underpressured nature of many geothermal formations. Bridging materials used as drilling mud additives for lost circulation control in oil and gas drilling are ineffective in plugging large fracture apertures, particularly under high-temperature conditions.

As a result, the standard lost circulation treatment in geothermal drilling is to fill the loss zone surrounding the wellbore with cement. This is an expensive operation in terms of both material costs (typically several hundred cubic feet of cement at $\$15/ft^3$) and rig time (typically 24 hours at \$300/hr) spent on the cementing operation, on waiting for the cement to harden, and on drilling through the cemented zone to reach new rock formation. Consequently, the costs of lost circulation in a typical geothermal well may range from several thousand to several hundred thousand dollars, depending on the severity and number of loss zones encountered.

Lost circulation costs represent an average of 10% of the total well costs in mature geothermal areas (Carson & Lin, 1982), and they often account for over 20% of the costs in exploratory wells and developing fields. Well costs, in turn, represent 35-50% of the total capital costs of a typical geothermal project (DOE, 1989). It can thus be concluded that lost circulation accounts for roughly 5-10% of the total costs of a typical geothermal project.

These direct costs and the unknown costs associated with possible contamination of freshwater aquifers provide strong incentives for a technology development program to address these problems. DOE sponsors the Lost Circulation Technology Development Program at Sandia National Laboratories for this purpose. The five-year goal of this program is to develop and transfer to industry new technology to reduce lost circulation costs by 30-50%. The Level III programmatic objective adopted by DOE is to reduce the costs associated with lost circulation by 30% by 1992 (DOE, 1989). This objective combines with others to produce a Level II objective of reducing the life-cycle cost of hydrothermal electricity by 10-13% through improvements in fluid production technology by 1992. Expectations for technology improvements in several areas combine to produce a Level I objective of reducing the life-cycle cost of hydrothermal-produced electricity to 3-7 cents/kWh by 1992. This compares with a cost of 4-15 cents/kWh in 1986.

LOST CIRCULATION PROJECTS

There are currently 11 projects in the Lost Circulation Technology Development Program at various stages of development. Table I lists these projects, which are grouped into three categories: technology to plug porous and minor-fracture loss zones; technology to plug major-fracture loss zones; and technology to characterize loss zones. These projects are described in Glowka (1990). Significant progress was made in some of these projects during the reporting period (April, 1990 - March, 1991). This progress is described in the following sections.

TABLE I

LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROJECTS

Porous and Minor-Fracture Fluid Loss Control:

1. Bridging Model Development
2. High-Temperature Lost Circulation Material (LCM) Development

Major-Fracture Fluid Loss Control:

3. Development of Cementitious Mud Formulations
4. Development of Cementitious Mud Flow Models
5. Downhole Injector Development
6. Porous Packer Development
7. Drillable Straddle Packer Development
8. Packer Emplacement Feasibility Study

Loss Zone Characterization:

9. Wellbore Hydraulics Model Development
10. Development of Wellbore Hydraulics Data Acquisition System
11. Borehole Televiewer Fracture Characterization Study

V-L METER DEVELOPMENT

As part of Project 10 (Development of Wellbore Hydraulics Data Acquisition System), a meter for measuring the outflow rate from a well was designed and tested. This meter, called the V-L (Velocity-Level) Meter, is intended to provide an accurate, reliable, economical, and simple means for measuring the rate of drilling fluid flow in the partially filled mud return line that runs from the top of the wellbore to the mud pit. There is currently no commercial device with these characteristics that can be used for lost circulation detection in geothermal wells.

A simplified schematic of the V-L meter is shown in Figure 1. The transducer consists of a rolling float that measures both the fluid velocity and level in the return line. Detailed design and fabrication of a prototype of the meter were completed during the reporting period. A photo of the assembled prototype is shown in Figure 2. The meter uses a pendulum resistor to measure the wheel moment-arm angle and thus the fluid level. A magnetic switch is used to measure the wheel rotary speed and thus the fluid velocity. The box in which the meter is housed is mounted directly on top of the mud return line. Transparent panels were provided on the prototype box to aid in evaluation of the meter operation.

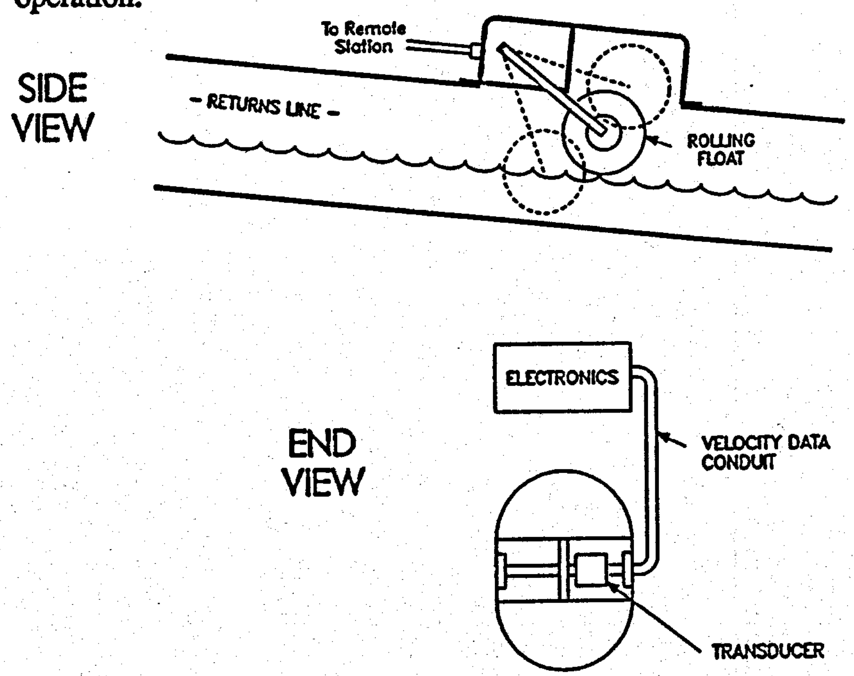

Fig. 1 - Schematic of Velocity-Level (V-L) Meter concept.

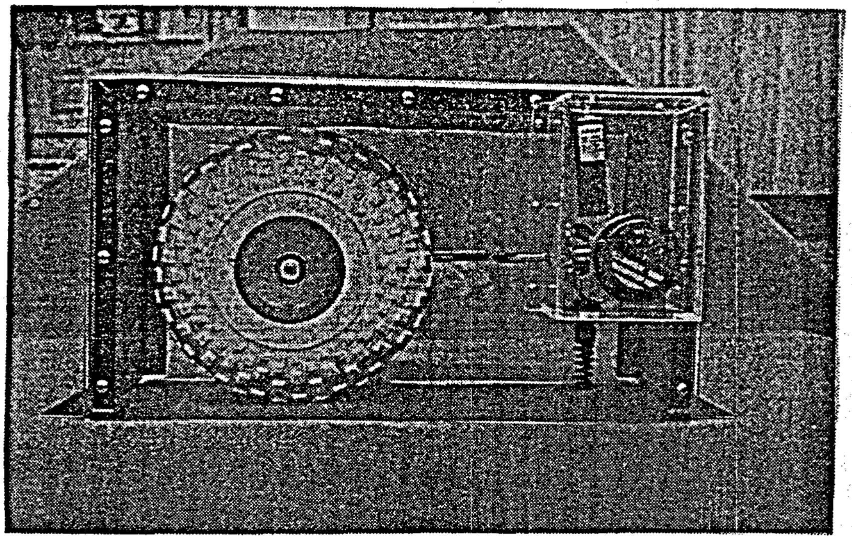

Fig. 2 - Assembled prototype V-L Meter.

A Wellbore Hydraulics Flow Facility was also designed and constructed during this reporting period. This facility is used to evaluate both inflow and outflow meters for lost circulation detection and quantification. A photo of the facility is shown in Figure 3. During operation, water or drilling mud is pumped from the mud tank (shown on the left) by a 1000-gpm centrifugal pump (shown on the right). The fluid flows up a vertical section of pipe and through a commercial magnetic flow meter, which provides an accurate measurement of flow rate in the filled pipe. The fluid then flows into the top of the simulated wellbore (upper right), which provides annular flow similar to that in an actual wellbore. The fluid exits the simulated wellbore and flows through the transparent return line back to the mud tank. The transparent return line allows visual evaluation of the flow meter operation and direct measurement of the fluid level. The prototype V-L Meter is shown mounted to the top of the return line.

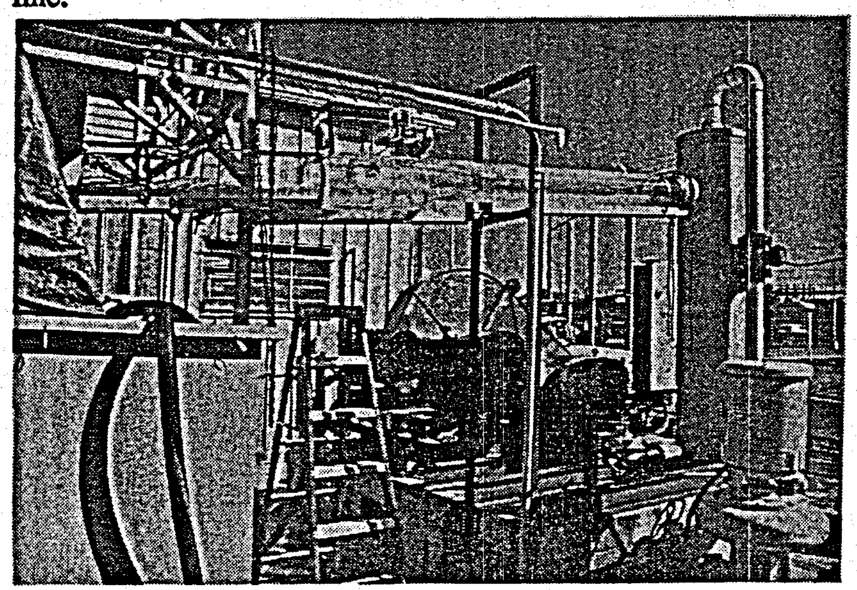

Fig. 3 - Wellbore Hydraulics Flow Facility

Prior to testing the V-L Meter, analytical modeling was performed to determine the theoretical fluid velocity and level in the mud return line. The model is based on an energy balance of the flow in a circular open channel. Typical results from the model are shown in Figure 4 for a cross-section 3 ft downstream of the return line entrance. Shown here is the theoretical fluid level plotted as a function of fluid flow rate and return line angle (with respect to horizontal). Also shown are experimental results obtained by direct measurement of the fluid level in the transparent flow line. The agreement between theoretical and experimental results indicates that the analytical model is successful in accurately predicting the unperturbed fluid level in the inclined flow line.

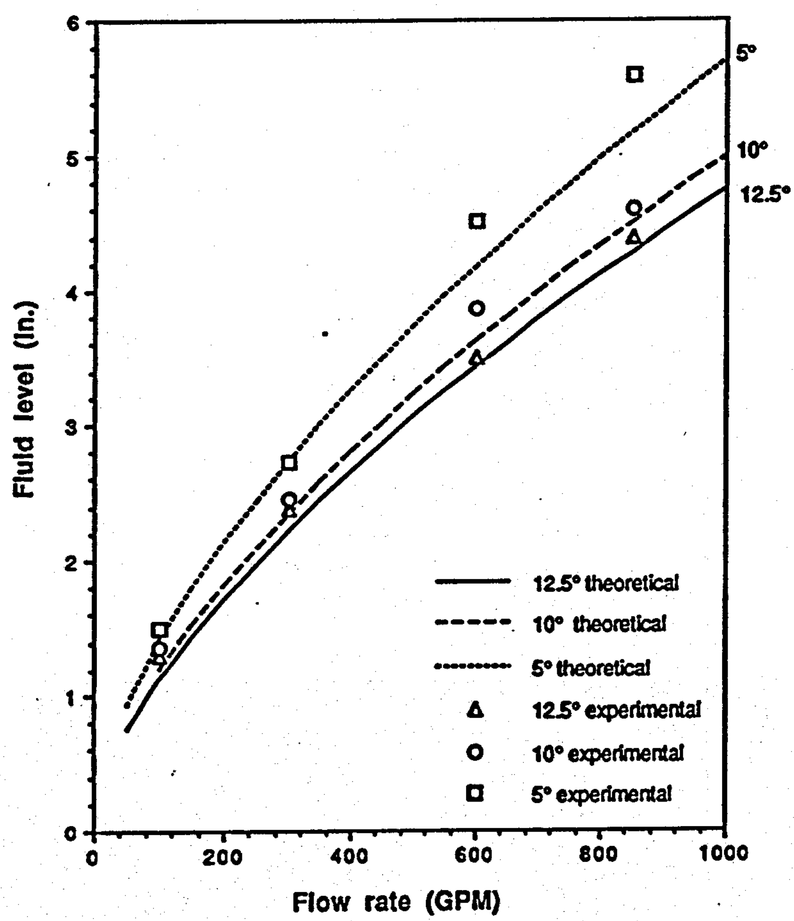

Fig. 4 - Theoretical and experimental return line fluid level for various return line slopes.

The prototype V-L Meter was tested with water during this reporting period. Typical results are shown in Figures 5 and 6. Shown here are the measured fluid velocity and level as a function of flow rate. Two conclusions can be drawn from these results. First, the measured fluid level is a monotonic function of the flow rate, while the measured fluid velocity reaches a peak and then experiences a negative slope. This implies that a correlation between the measured fluid level and the flow rate can be easily developed, but a reliable correlation between the measured fluid velocity and the flow rate would be more difficult to implement in the field. Secondly, the measured fluid level displays significant repeatability with the flow rate. This implies that a correlation developed in the field between the flow rate and the measured fluid level should be a reliable indication of the outflow rate from the wellbore under varying flow rate conditions.

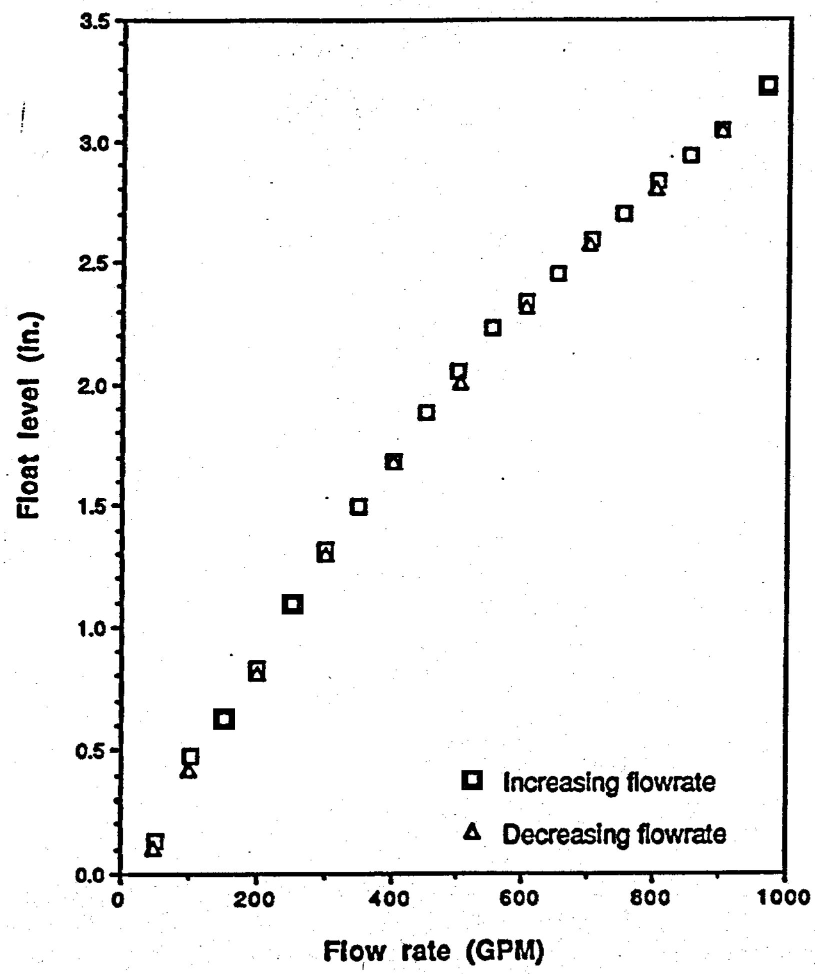

Fig. 5 - Measured fluid level with the V-L Meter as a function of flow rate.

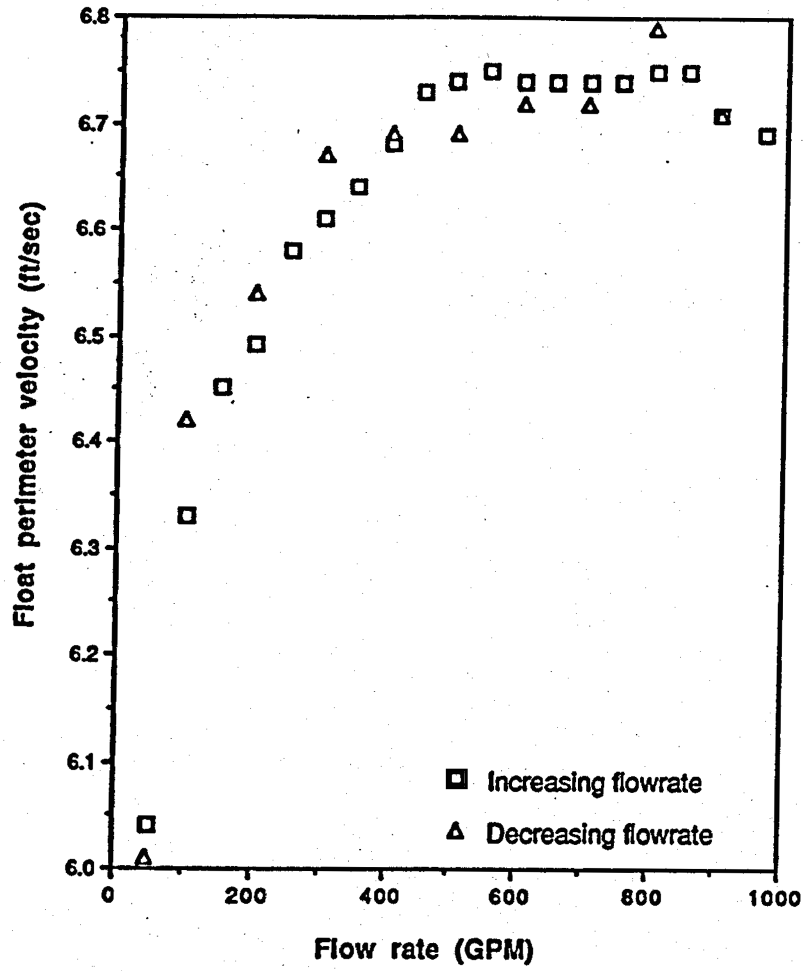

Fig. 6 - Measured fluid velocity with the V-L Meter as a function of flow rate.

Various design parameters of the V-L Meter were also evaluated. Typical results are presented in Figure 7, which shows the effects of the excess wheel weight after being partially balanced by a counterweight. These results indicate that the results are relatively insensitive to the excess wheel weight; thus the correlation developed between fluid level and flow rate should not be greatly affected by drilling mud accumulation on the wheel during operation.

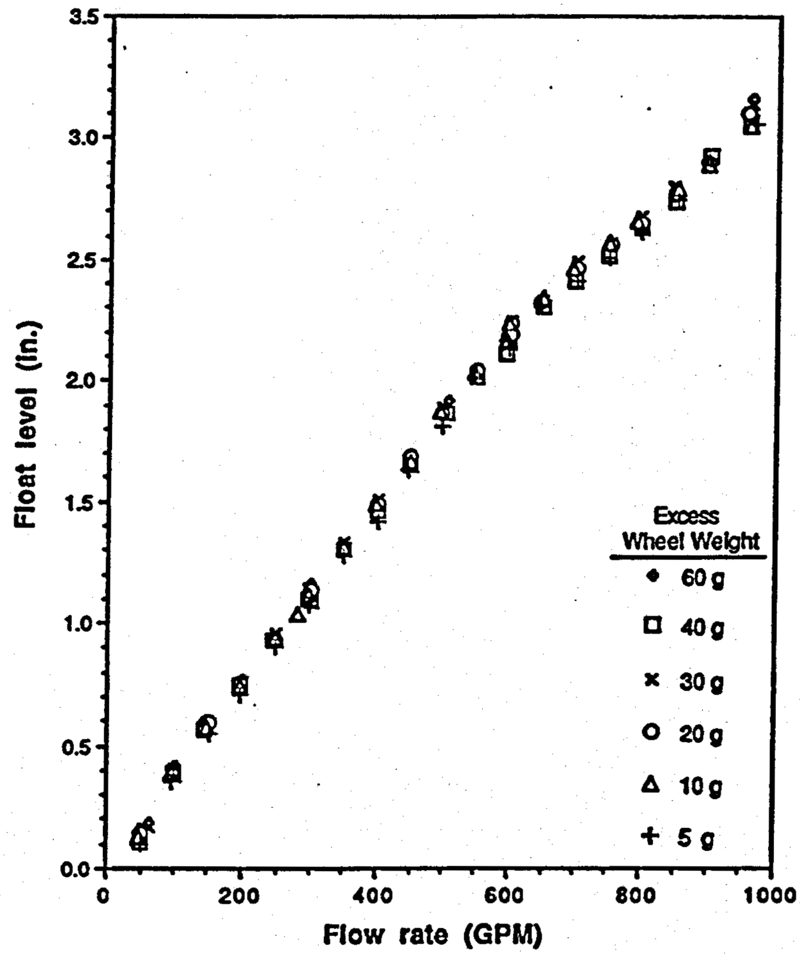

Fig. 7 - Effect of excess wheel weight (weight-counterbalance) on measured fluid level.

Other design parameters investigated include: the wheel shape, diameter, and width; the wheel moment-arm length; and the dashpot setting (used to dampen the wheel movement). Optimal settings for these parameters were determined.

Near-term future work on the V-L Meter includes an investigation of the effects of mud viscosity and density and development of a data acquisition and display processor that can be used in the field. Ruggedization of the V-L Meter design will also be completed before field trials begin in the Summer of 1991.

DRILLABLE STRADDLE PACKER DEVELOPMENT

The Drillable Straddle Packer under development (Project 7) is a packer assembly for directing the flow of cement into a selected loss-zone interval, as shown in Figure 8. It is intended to prevent channeling of the cement through the mud to the bottom of the wellbore, which is a common problem during lost circulation cementing operations, particularly in large-diameter wellbores. During operation of the Drillable Straddle Packer, cement flows down the drillstring, through the upper packer element, out the exit ports, and into the wellbore and loss zone. The differential pressure that develops across the exit ports causes both the upper and lower packer elements to inflate. This is the primary difference between this packer concept and current commercial packers, which use downhole valving to inflate the packer elements and thus are relatively expensive and cumbersome to use for lost circulation control. The goal of the Drillable Straddle Packer development project is to develop a packer assembly that can be constructed for $500 or less.

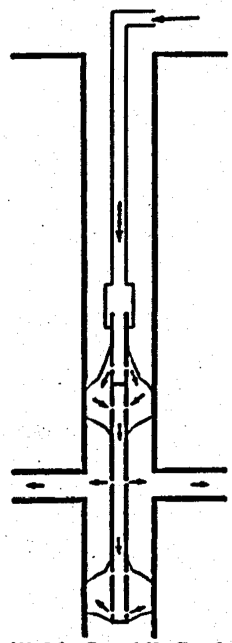

Fig. 8 - Drillable Straddle Packer concept.

The Drillable Straddle Packer is designed to remain downhole after the cementing operation through the activation of a releasable coupling between the packer assembly and the drillstring. Upon completion of the cement pumping operation, a brass ball is dropped down the drill pipe, where it activates the release mechanism to free the packer from the drillstring. The drillstring is then withdrawn from the hole, a drill bit is coupled to the drill pipe, and the packer assembly is drilled through after the cement has set.

Progress made in this project area during the reporting period includes detailed design and fabrication of a prototype drillstring coupler and design and construction of a Packer Test Facility. A photo of the drillstring coupler is presented in Figure 9. The coupler, shown mounted to a stand, would be attached to the bottom of the open drill pipe. Below the coupler is the packer pintle, constructed of CPVC plastic, which would constitute the upper end of the packer assembly. When the brass ball reaches the coupler, it impinges on a sliding piston, which breaks several shear pins and causes the grappling hooks inside the coupler to release the pintle. Two different designs of this coupler have been fabricated and will be evaluated in the near future.

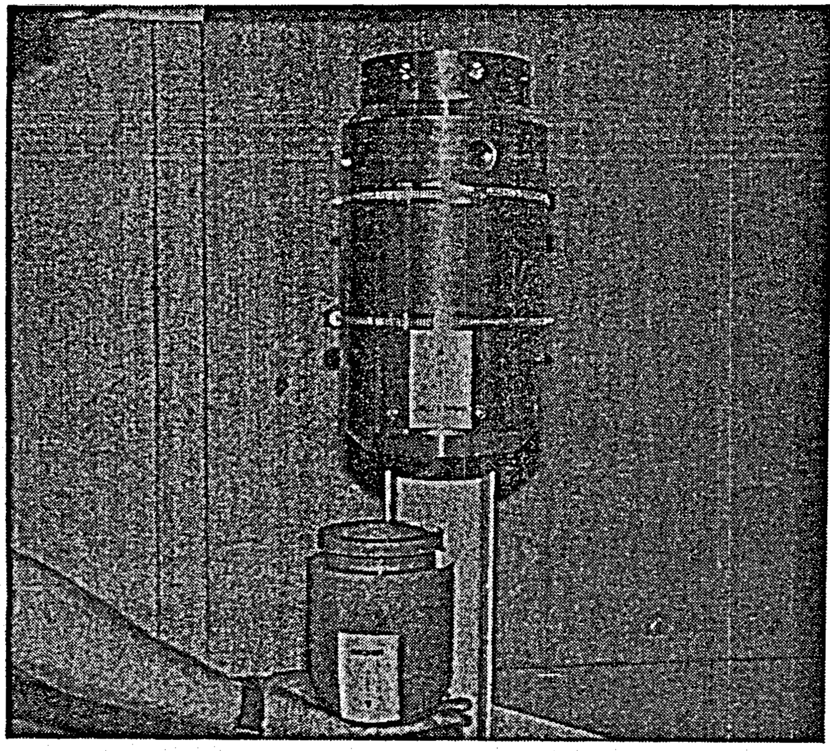

Fig. 9 - Prototype drillstring coupler for the Drillable Straddle Packer.

The Packer Test Facility is shown in Figure 10. This facility is designed to allow evaluation of full-scale packer assemblies. A schematic of the facility is shown in Figure 11. During operation, a packer assembly is placed inside the 16-inch-diameter (14-ft-high) casing, which simulates a wellbore. Drilling mud or water is pumped through the packer, thereby inflating the packer assemblies. The fluid then flows through the packer exit ports and out a port in the side of the casing that simulates a loss zone. Side inlets at the top and bottom of the casing simulate production zones, and fluid is pumped into these inlets with a centrifugal pump to simulate wellbore production. As the packer assemblies inflate, pressure builds behind the packer assemblies. This pressure buildup and the measured flow rates at various points throughout the facility provide a measure of the sealing effectiveness of the packer assemblies against the wellbore wall. Roughness elements attached to the inside surface of the casing provide a simulation of a rough wellbore wall. This test facility can also be used to test the drillstring coupler at the top of the packer assembly. Testing of a prototype Drillable Straddle Packer is planned in the near future.

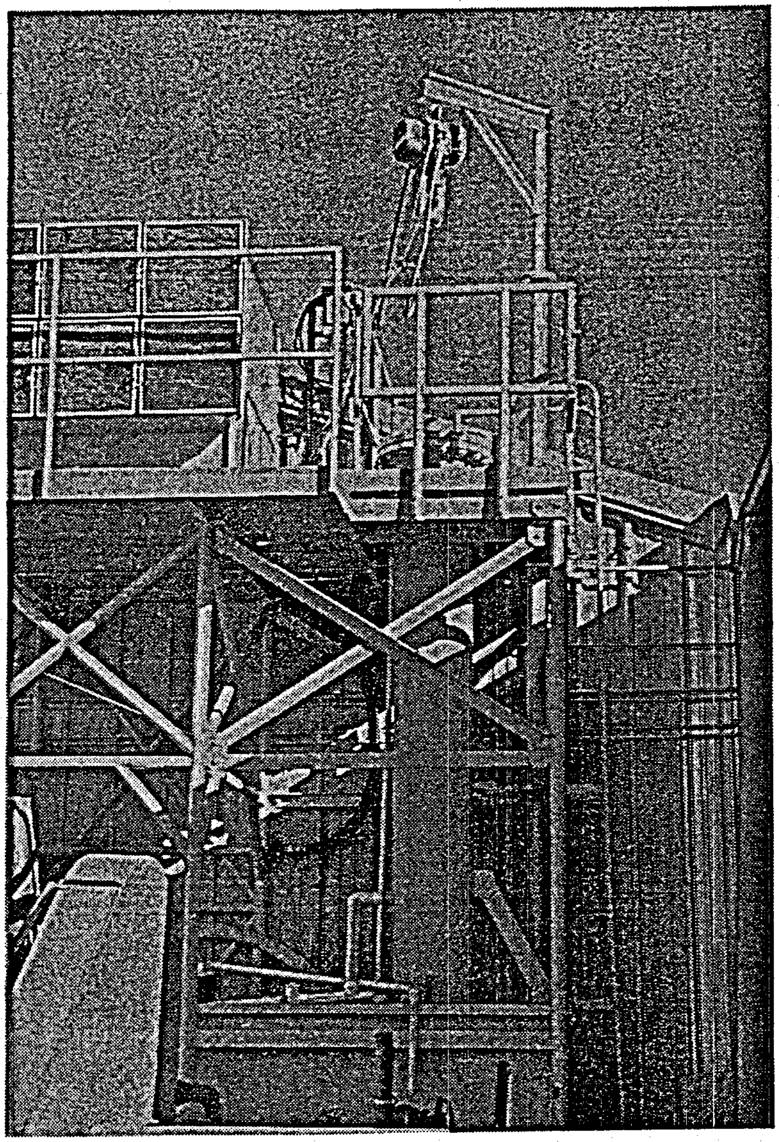

Fig. 10 - Packer Test Facility for testing full-scale packer assemblies.

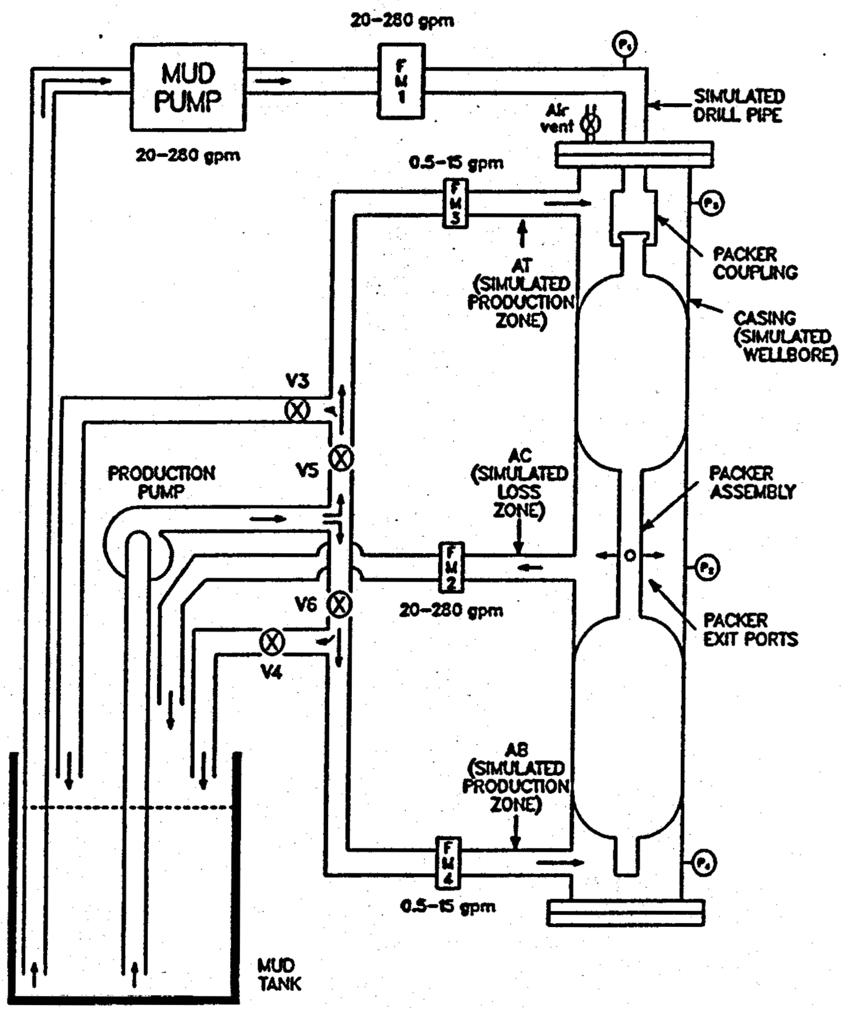

Fig. 11 - Schematic of Packer Test Facility.

POROUS PACKER DEVELOPMENT

The Porous Packer under development (Project 6) is a single-element packer assembly that employs a permeable fabric. The concept is shown in Figure 12. The packer is deployed either as a wireline-emplaced or drillstring-emplaced assembly. During operation, a fast-setting fluid such as polyurethane foam or other polymer is pumped into the packer element. As the packer becomes pressurized and expands, the setting fluid "leaks" through the fabric at a rate controlled by the fabric permeability, fluid viscosity, and downhole pressure. Expansion of the packer against the wellbore wall temporarily prevents or retards the flow of wellbore fluids produced at other formation intervals from entering the loss zone and washing away the setting fluid. Leakage of the setting fluid through the fabric allows the fluid to enter the loss zone and bond with the wellbore and fracture walls. Upon completion of the pumping operation, the packer assembly is uncoupled from the service module (if wireline-deployed) or drillstring (if drillstring-deployed). The packer assembly is then drilled through upon the resumption of drilling.

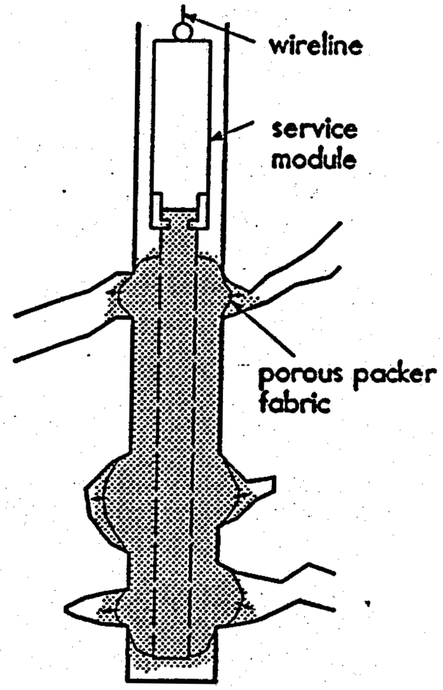

Fig. 12 - Porous Packer concept.

The feasibility of the Porous Packer in large part depends on the feasibility of employing a permeable fabric in the manner required. Consequently, the Packer Fabric Test Facility shown diagrammatically in Figure 13 was designed and constructed. This facility allows a 1-inch-diameter fabric sample to be tested for permeability by extruding a viscous fluid through the sample. Corn syrup is being used as the test fluid because its viscosity can be varied over several orders of magnitude by changing its temperature. During a test, the flow rate of the corn syrup, its temperature, and the pressure drop across the fabric are recorded. This data allows the permeability and strength of various types of fabric to measured and the viscosity requirements of the setting fluid to be determined.

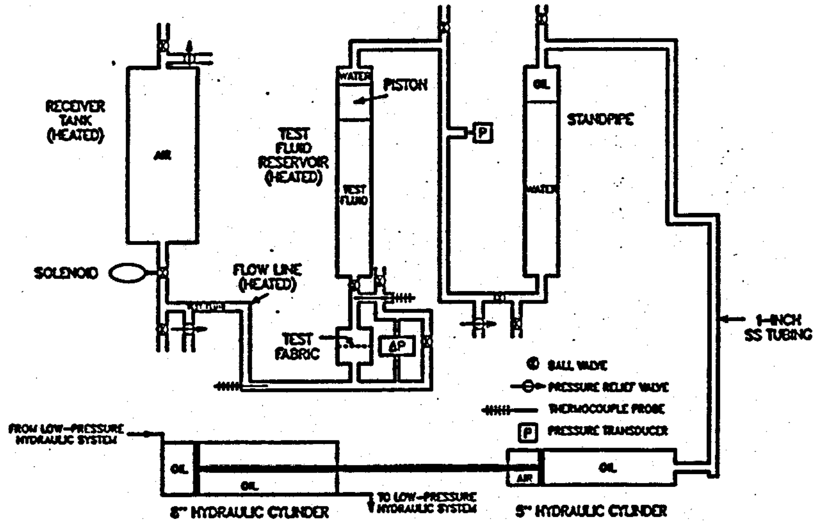

Fig. 13 - Schematic of Packer Fabric Test Facility.

During the reporting period, testing procedures for the facility were developed, the data acquisition and control software were written, and testing was initiated. The fabric samples shown in Figure 14 are currently being tested. These fabrics are various grades of woven fiberglass, some of which are coated with Teflon to control permeability. Testing of these fabrics is expected to be completed in the near future.

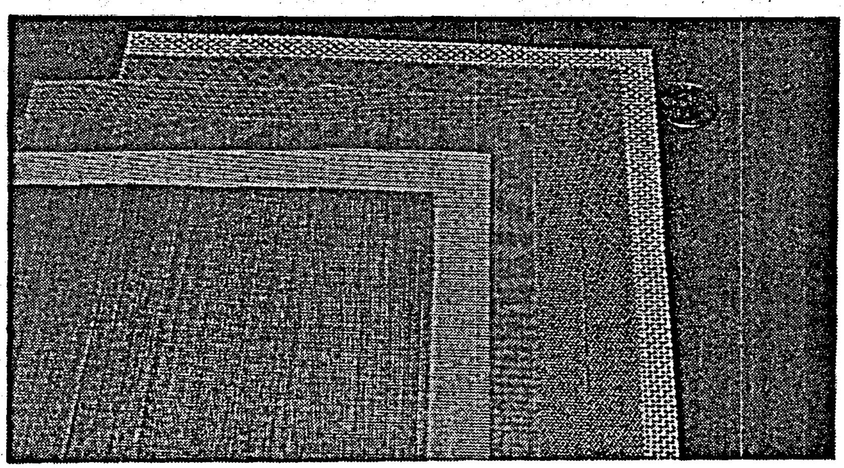

Fig. 14 - Woven fiberglass fabrics under evaluation for the Porous Packer.

PACKER EMPLACEMENT FEASIBILITY STUDY

A conceptual design study of alternative packer emplacement methods (Project 8) was initiated during the reporting period. This study was contracted to Science and Engineering Associates (SEA), Inc., of Santa Fe, NM. SEA has a patent pending on an inversion technique for emplacing membranes downhole for fluid sampling in monitoring boreholes drilled around hazardous waste sites. The concept, shown schematically in Figure 15, employs a thin-fabric membrane that is inverted by internal pressure and forced against the borehole wall. The similarity of the membrane to a packer assembly suggests that this inversion technique might be used to emplace downhole packer assemblies, such as the Porous Packer.

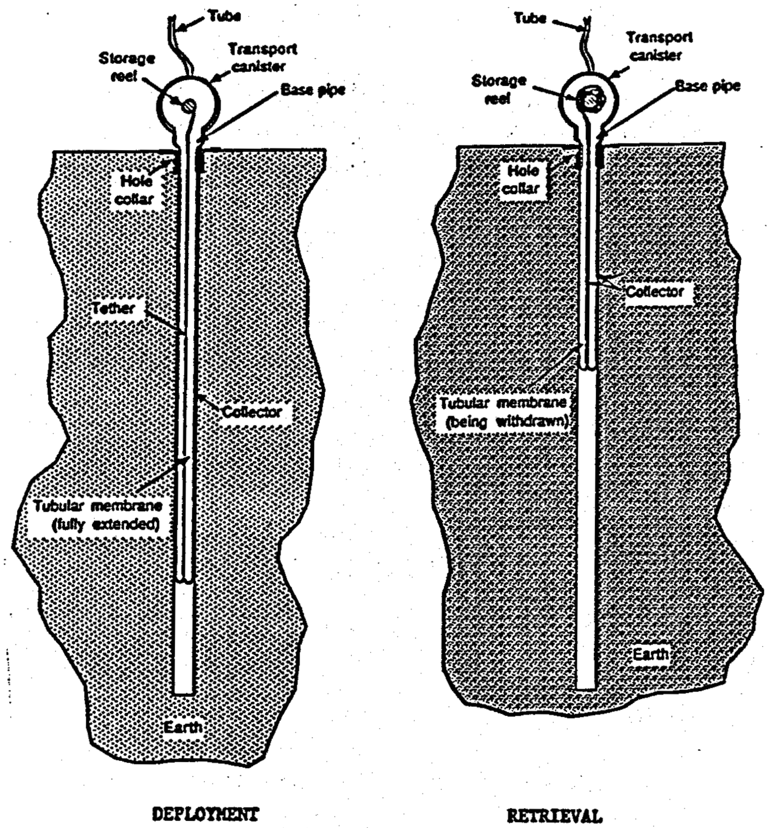

Fig. 15 - SEA-MIST (Membrane Instrumentation and Sampling Technique) concept for pore-fluid sampling.

The contract with SEA provides for development of conceptual, advanced conceptual, and detailed designs of at least one system for emplacing a packer downhole at a depth of 4,000 ft. If the contract is successful in identifying a feasible design, prototype fabrication and testing of such a system may be conducted in later phases of the project.

During the reporting period, conceptual designs for a number of different systems were developed. From these, Sandia selected two systems for advanced conceptual design. When these designs are completed in the near future, a single system will be selected for detailed design. Fabrics selected for the system will be tested in Sandia's Packer Fabric Test Facility.

TECHNOLOGY TRANSFER

The design of laboratory equipment developed under Project 2 (High-Temperature LCM Development) was transferred to two corporations in the oil drilling industry during the reporting period. The detailed design and operating procedures for the Modified API Bridging Materials Tester were sent to these organizations, which had requested the information in order to build their own capabilities for testing their LCMs for oil and gas drilling applications. The API Tester is a bench-scale device for pressuring LCM-laden drilling mud against a machined-steel slot and measuring the slot-plugging capability of the LCM. Experimental data obtained by one of the organizations using the tester was found to compare favorably with predictions of the analytical bridging models previously developed at Sandia (Loeppke *et al.*, 1990).

At the request of one of the industry organizations, we also used our Particle Material Properties Tester (PMPT) to measure the mechanical properties of ground walnut shell particles after soaking in water and mineral oil. Such particles are of interest as a second component of a combination LCM that the industry organization is developing. By soaking the particles in water and in mineral oil, the effects of water- and oil-based mud on the compressive strength and elasticity of the particles were determined. It was found that mineral oil does not significantly affect the mechanical properties of walnut shells at room temperature but that water tends to make the shells slightly more elastic. An elevated temperature of 200°F does not significantly affect the water-soaked shells, but it does increase the elasticity of the oil-soaked shells.

SUMMARY

As described above, several lost circulation projects have advanced during the period April, 1990-March, 1991. The primary accomplishments for the year are: design, fabrication, and initial testing of the V-L Meter; and the development of three laboratory test facilities that will allow us to fully evaluate our lost circulation hardware before it is taken to the field. In addition, work on several other projects is underway but has not progressed significantly enough to merit reporting at this time.

The V-L Meter and Drillable Straddle Packer should be ready for field testing this year. Other technologies, such as the Porous Packer and cementitious mud formulations, will require significantly more development and laboratory testing before they will be ready for field trials.

As discussed in Glowka (1990), the technologies being developed under the various projects are estimated to reduce lost circulation costs by an average of 27-48%. These estimates are based on detailed cost and time estimates for using the various technologies in lieu of the standard cement treatment currently in common use in geothermal drilling.

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