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# A FEASIBILITY STUDY OF THE EFFECTIVENESS OF DRILLING MUD AS A PLUGGING AGENT IN ABANDONED WELLS

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16. ABSTRACT

The main objective of this feasibility study was to test the hypothesis that properly plugged wells are effectively sealed by drilling mud. While achieving such an objective, knowledge of the dynamics of building mud cake on the wellbore-face is obtained, as well as comprehension of changes that occur in drilling mud from the time it is placed in a well until it reaches equilibrium.

A system was developed to simulate (a) building mud cake in a borehole, (b) plugging the well, and (c) injecting salt water into a nearby well, with concomitant migration of salt water into the plugged well. The system "duplicates" reservoir pressures, mud pressures, and reservoir-formation characteristics that develop while mud cake is built, as in drilling a well. Salt-water injection is simulated, to monitor any fluid migration through the reservoir.

A 2100-ft. well and ancillary equipment was constructed to permit controlled measurement and variation of simulated depth, porosity and permeability of reservoir rock, fluid composition, fluid pressure, injection pressure, and mud properties. Data can be recorded continuously by computer.

The in-place system provides for extensive testing of the many variables that influence effective plugging of boreholes with drilling mud.

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# FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil, and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

This report presents the results of research on methods for determining the effectiveness of drilling mud as a plugging agent in abandoned wells to assure the protection of human health and the environment.

Clinton W. Hall

Clinton W. Hall
Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

The Hazardous and Solid Waste Amendment of 1984 requires the Environmental Protection Agency to assess environmental suitability of liquid-waste injection into subsurface rock. Accordingly, the reaction among injected wastes, reservoirs, and original formation fluids is under evaluation.

The main objective of the feasibility study described here was to test the hypothesis that properly plugged wells are effectively sealed by drilling mud. While achieving such an objective, knowledge of the dynamics of building mud cake on the wellbore-face is obtained, as well as comprehension of changes that occur in drilling mud from the time it is placed in a well until it reaches equilibrium.

A system was developed to simulate (a) building mud cake in a borehole, (b) plugging the well, and (c) injecting salt water in a nearby well, with concomitant migration of salt water into the plugged well. The system "duplicates" reservoir pressures, mud pressures, and reservoir-formation characteristics that develop while mud cake is built, as in drilling a well. Salt-water injection is simulated, to monitor any fluid migration through the reservoir.

A 2100-ft. well and ancillary equipment permit controlled variation of simulated depth, porosity and permeability of reservoir rock, fluid composition, fluid pressure, injection pressure, and mud properties. Data can be recorded continuously by computer.

The synthetic-sandstone reservoir is cylindrical, 3 ft. in diameter and 2 ft. thick. It has porosity and permeability similar to those of several natural reservoirs.

Pressures commensurate with those in 5000-ft.-deep wells were to be measured; associated differential pressures were required. A system developed to measure differential mud pressures includes undiminished pressure-transmittal by diaphragm-interface.

Also, a high-pressure, low-flow-rate, high-accuracy flow meter system was developed to monitor the slightest amount of fluid movement. Flow meters were developed to measure (a) fluid from the reservoir, (b) mud-column flow from above the reservoir, and salt water being injected.

An in-place system provides for extensive testing of the many variables that influence effective plugging of boreholes.

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## SECTION 1

## INTRODUCTION

The Environmental Protection Agency is required by the Hazardous and Solid Waste Amendment of 1984 to assess the environmental suitability of injection of liquid wastes into subsurface formations. The Agency's approach to this matter is composed of three general activities: (1) to evaluate the construction of injection wells and the capability for monitoring them, in order to detect failures, (2) to assess the relationship among the rock-stratigraphic units, the fluids injected, and the integrity of the bounding confining beds, and (3) to evaluate the reaction among the injected waste, the formation, and the formation fluids.

The primary objective of the research described here is to test this hypothesis: Drilling mud in abandoned, properly plugged wells effectively seals the borehole. Therefore, if fluids injected into reservoirs at depth were to migrate up the boreholes of properly plugged wells, filter cake nevertheless would prevent passage of these fluids into other reservoirs. The alternate hypotheses need no elaboration.

A 2100-ft. well and ancillary facilities are described in pages that follow. This system permits controlled variation of simulated down-hole conditions, including depth, porosity and permeability of reservoirs, compositions of fluids, pressures of fluids, injection pressures, and properties of plugging agents. Instrumentation was designed and assembled, or manufactured, in order to test the feasibility of monitoring variation in pressures and rates of flow of fluids, under several regimes of injection. Computer software was written for continuous reception and recording of data. Methods were developed for construction of an artificial sandstone reservoir; porosity and permeability of this reservoir and some actual reservoirs are similar.

## SECTION 2

## CONCLUSIONS

1. Feasibility of designing and equipping a shallow well for the purpose of the experiment has been demonstrated.

2. A technique and hardware were developed to measure down-hole pressure gradients accurately.

3. A multiplexer to transfer data from down-hole to the surface was designed and built, as were a computer board and software, to process and store data.

4. Other equipment designed, built and developed included a diaphragm-seal housing assembly, a temperature-sensor circuit, a flow-meter and flow-control system (for uncommonly low rates of flow at high pressure), and a mud-maintenance, mud-flow network and control system.

5. An artificial reservoir with lithic properties, porosity and permeability similar to actual injection-formations was constructed, complete with housing and attendant instrumentation. After initial guidance by Halliburton Company, techniques were developed for composing, mixing, emplacing and consolidating reservoir material, to obtain porosity and permeability within specified limits. Moreover, methods were developed to isolate and measure radial flow through the large artificial reservoir.

6. A cased-well system, designed and constructed, allows simulation of conditions below the artificial reservoir of depths as great as 2000 ft., and controlled injection of fluids at depths of 100 to 2000 ft. The facility could, and should, be used to define the entire array of critical conditions of mud-plugging. Also, it should be employed for experimentation and development of new products and techniques for protecting fresh-water aquifers.

## SECTION 3

## RECOMMENDATIONS

Developments of a unique facility are essentially complete. The facility will allow investigation of many phenomena associated with wells, reservoirs, fluids and methods of measurement. To utilize this facility for tests to include but not be limited to the following topics is recommended.

1. Test the existent artificial reservoir, despite the fact that it seems to be fractured. Build mud cake on it and determine the amount of mud and the invasion required to build the mud cake. Test the adequacy of the mud cake to resist invasion under injection at various pressures.

2. Complete a series of tests to determine the performance-envelope of parameters that could affect the plugging and protection of a rock formation. This would include various mud properties, various injection-fluid properties, various reservoir porosity and permeability values (including fractured layers), various combinations of injection-zone and protected-zone depths and injection pressures.

3. Develop a tool and associated instrumentation which could be inserted into an abandoned, plugged well and determine the in-place mud properties. These properties, in conjunction with the results of Recommendations 1, above, could provide a method to estimate the adequacy of fluids in plugged wells.

4. Investigate additives that could enhance the mud-plugging of high-porosity zones and fractured zones. These could be evaluated during the mud-cake build-up period and then during injection of disposable fluids.

5. Determine the effect of leaching in mud-plugged wells and the conditions that allow the phenomenon to occur.

SECTION 4

# TEST FACILITY DESIGN, DEVELOPMENT AND FUNCTION

## INTRODUCTION

### DESCRIPTION OF FACILITY

The facility is designed for testing under conditions that simulate a well plugged with mud, for abandonment. A zone in the upper region of the hypothetical well is an underground source of drinking water (protected zone, Figure 1), and the intention is to not contaminate it. Below the fresh-water-bearing formation is a formation used for injection (Figure 1), pressurized by disposal of salt water into a nearby well. Pressure is translated through the injection zone to the abandoned well. Therefore, a potential exists for the salt water to migrate up the wellbore and invade the underground source of drinking water. The purpose of the testing design is to determine the array of conditions that could allow invasion of the zone of drinking water to occur.

The testing facility is divided into four basic areas, which are associated with zones in a plugged and abandoned well, shown diagrammatically in Figure 1. These areas are dedicated to study of the wellbore above the reservoir being protected (region 1), the protected reservoir and wellbore (region 2), the wellbore below the protected reservoir, and the salt-water disposal reservoir (region 3), and the overall part of the facility that simulates drilling the well and building mud cake on the wall of the wellbore. Regions 1 and 2 shown in Figure 1 are simulated by facilities located above ground level, whereas region 3 is an actual well, 2100 ft. deep. The part of the facility that simulates building of mud cake is also above ground.

In the following sections, the various components or assemblies that combine to form the facility are discussed. Included is a brief description of each component, statement of its purpose, salient design features, description of its interaction or connection with other components or assemblies, controlling features, associated instrumentation and the type of data produced.

### TOTAL-FACILITY SCHEMATIC DIAGRAM

Figure 2 is a plan view of the facility. Individual systems are required to obtain quantitative data on results of injecting salt water into a reservoir and the effects of

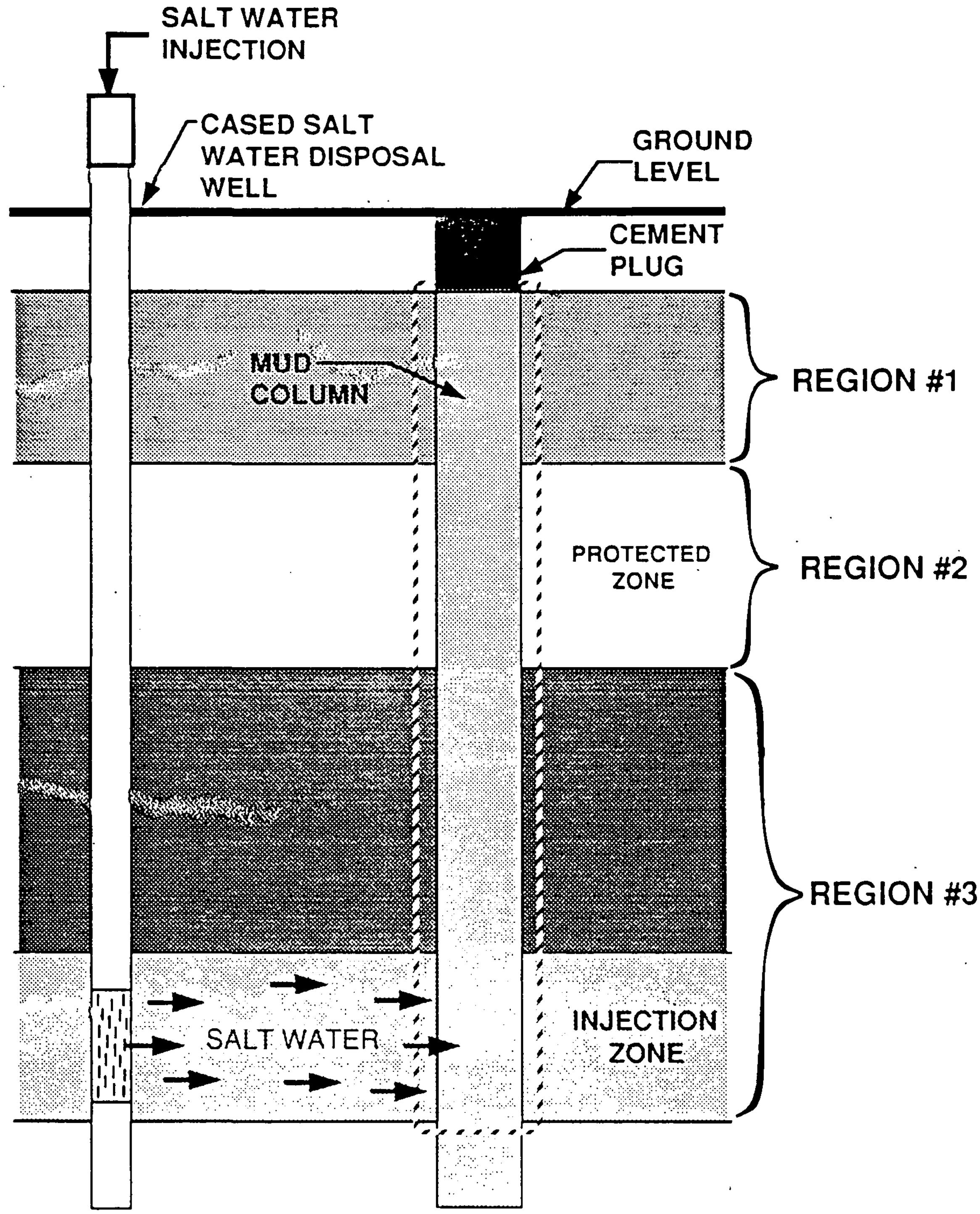


Figure 1. Representative injection and abandoned well.

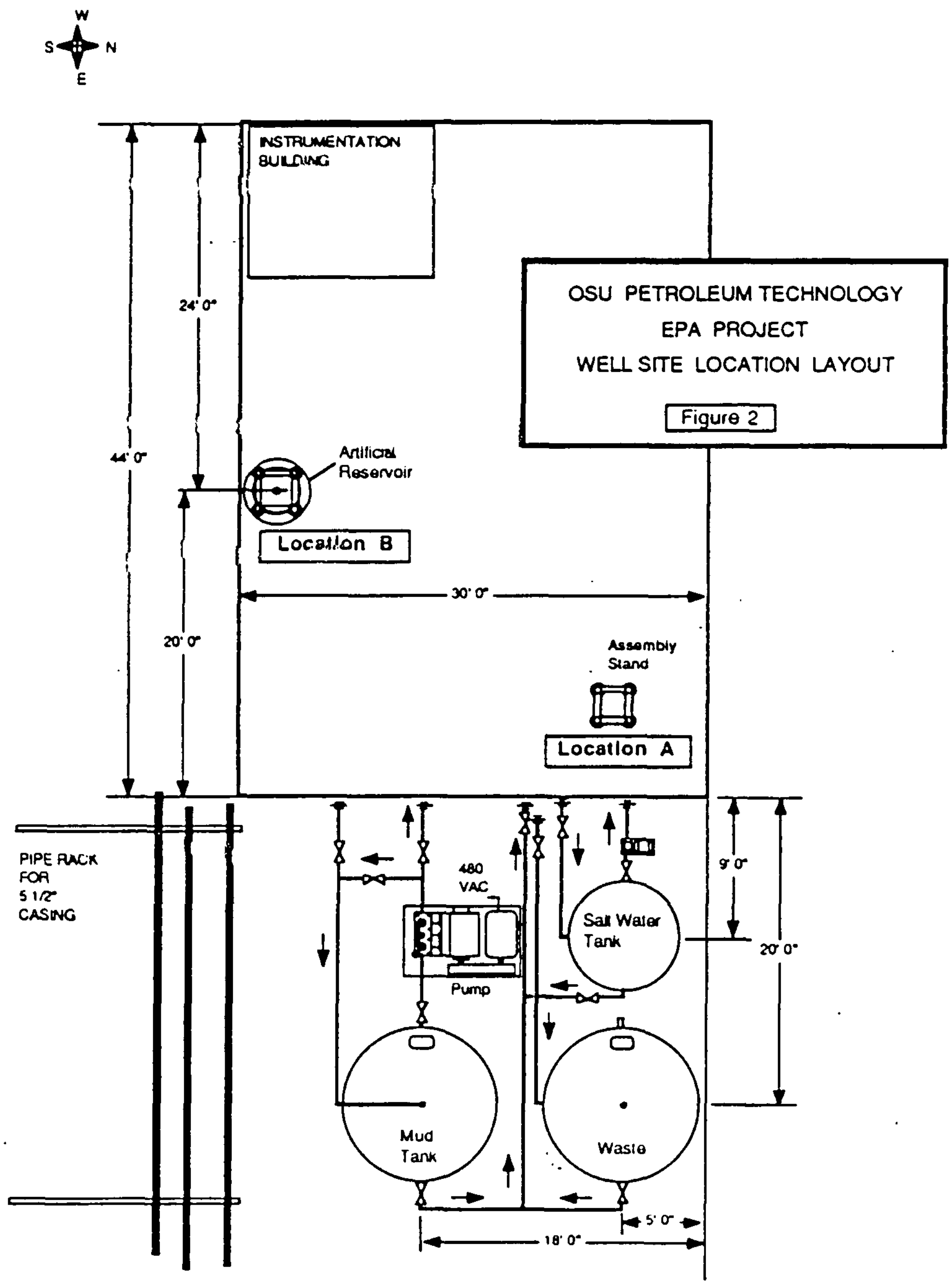


Figure 2. Plan-view schematic drawing of test facility.

invasion on a shallow, fresh-water-bearing formation in nearby abandoned well. The Instrumentation Building houses the computer used for data acquisition. About 15 ft. east of the building, at the site labelled "Artificial Reservoir" (Figure 2) is the Instrumentation Console, the main source of test data. The Assembly Stand (Location A, Figure 2) is the mounting stand for the reservoir housing, used when the artificial reservoir material is poured and for determining porosity and permeability of the reservoir. The salt-water tank, lines and pump, effluent tank and connecting lines, mud tank, mud mixer, mud pump, controls and pipe network are clustered in the northeastern part of the facility (Figure 2). Casing and tubing are stored on the pipe rack, and are moved to Location B through the v-door on the northern part of the pipe rack.

Figure 3 is a functional schematic drawing of the system. It shows the general configuration of the components, their interconnections, controls and instrumentation. Groupings of these components will be referred to in the following discussion.

## COMPONENTS SIMULATING THE WELLBORE ABOVE THE ZONE OF FRESH WATER

### INTRODUCTION

In actual wells, the wellbore above the protected zone (Figure 1) is to be filled with drilling mud and capped with a cement plug. The specific requirements are in regulations set out by the States. The simulation described herein is designed according to the well-plugging requirements of the Oklahoma Corporation Commission. Pressure on the wellbore would be dependent upon mud weight and depth in the well. Therefore, to simulate the depth of a formation it is sufficient to impose a pressure commensurate to the value determined by mud weight and depth. Because the cement plug is stationary, but because the mud below it can move down the wellbore and into formations under less pressure, it is necessary to provide fluid sufficient to simulate this condition. Also, pressure must be maintained during movement of fluid down the wellbore. As pressure increases in the wellbore due to injection, the mud would move against the cement plug, and pressure in the entire wellbore would increase. This condition also must be simulated.

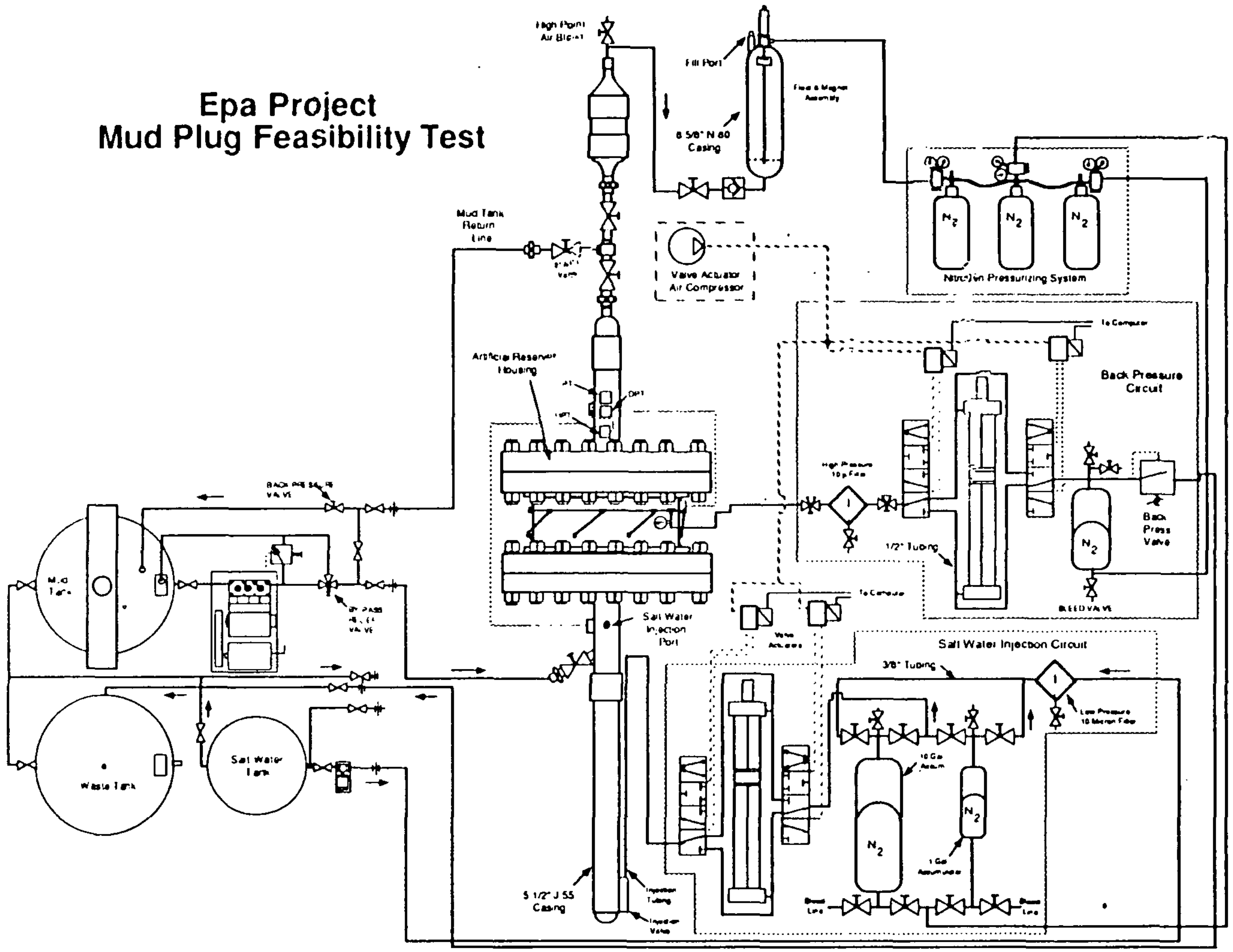


Figure 3. Functional schematic drawing of test facility.

SIMULATED WELLBORE-AND-MUD COLUMN

A section of 7-in. casing was sized to hold enough mud to sweep about one-half the pore volume of the most porous medium that we expected to test (container at "High Point Air Bleed," Figure 3). This amount of mud is expected to place a final seal on the mud cake (if indeed the extra mud is required) after circulation of mud through the wellbore. If one container-full is insufficient, then the valve arrangement is designed so that the container can be refilled during the test, with minimal disturbance of test results. When the mud column is filled with mud and air is bled from the system, then the nitrogen pressure is adjusted to make pressure in casing above the artificial reservoir be commensurate to pressure in an abandoned well, at the given depth. This nitrogen pressure is impressed upon water in the mud-column flow meter and transmitted through the line between the flow meter and the simulated wellbore-mud column. If the fluid level moves, fluid either has gone out the effluent line or out a leak in the system. The system is designed so that data from the three flow meters will determine whether a leak exists or fluid is being discharged to the effluent tank.

Appendix A contains a drawing and specific information about design of the simulated wellbore-mud column. Some of the design features associated with this part of the system are a fill tee and bleed valve at the top of the column, a flow tee and three valves at the bottom of the column, and a line connecting the column to the flow meter and to a check valve and a shut-off valve on the flow meter end (See diagram near "High Point Air Bleed" container, Figure 3).

During filling operations the valve next to the check valve (to the left of check valve, top-center, Figure 3) is closed so that mud will not get into the check valve. Before mud is placed in the column, the line from the flow meter is filled with water. The high-point air-bleed valve on top of the column is open and the two in-line valves in the flow tee below the auxiliary mud container are open, but the leg of the tee to the mud tank is closed. Mud pumped slowly from a line connected to the bottom of the reservoir flows up the casing until all water in the casing is forced out, and only mud remains. At this time the high-point air-bleed valve is closed and the mud-tank return-line leg of the tee is opened. With this condition the system is ready for other operations, such as building mud cake, impressing pressure to begin the equilibration phase, or to maintain pressure during the injection phase.

If, during operation, mud in the simulated wellbore-mud column has been replaced by water from the flow meter, then the in-line valve on the bottom of the bottom tee (Figure 3, atop the casing-stem that projects from top of artificial reservoir and below tee on mud-tank return line) must be closed and the valve adjacent to the check valve must also be closed. Upon opening the high-point air-bleed valve, pressure will cause fluid to flow into the temporary line connected to the effluent tank. Valves in the mud-line network are then adjusted to route mud from the mud pump to the cross-flow leg of the bottom tee ("Mud Tank Return Line," Figure 3). Mud is pumped until the column is full.

MUD-COLUMN FLOW METER

A set of design drawings for the mud-column flow meter is in Appendix A, along with some design information. Additional information is in Appendix F, in connection with the wheel-mounted instrumentation console. A section of 7-in. casing was used to make the body of the flow meter. This flow meter is mounted vertically and has a Temposonics linear-position transducer that extends from end to end in the body. A magnet is attached to a float that indicates the location of the fluid level (Figure A2) and the differential position of the float is calibrated to give flow rate. On the top of this vessel is a nitrogen line that is connected to a regulator and high-pressure nitrogen bottle. Also on the top of this vessel is a fill port for water. The flow meter monitors the flow rate from the mud column and for control, also transmits nitrogen pressure to the column. A nitrogen regulator maintains the set pressure of the mud column even though the rate of flow may vary.

For the case where the injection pressure causes pressure at the reservoir to become more than the set nitrogen pressure -- which is the simulated wellbore pressure -- then mud begins to move up the column until the check valve at the bottom of the flow meter stops flow and simulates backing-up against a cement plug. At this point the injection pressure controls pressure in the wellbore, just as it would in an actual well.

This simulated wellbore-mud column is very important in simulations of drilling operations to build a mud cake on the walls of the reservoir. These details are given in the section of this report entitled "Simulation of Drilling Process to Build Mud Cake," on page 16.

## SIMULATED WATER-RESERVOIR ZONE

### INTRODUCTION

An abandoned well necessarily has gone through a drilling stage and then the plugging stage. The simulated condition must follow the same steps. First, the reservoir is filled with water under the pressure commensurate with the depth being simulated. Then the drilling operation is simulated by circulating mud from bottom to top past the porous medium, which is maintained at reservoir pressure. Mud in the column is maintained at the pressure appropriate for depth of the well and density of the mud. This process is continued until the mud cake is fully developed -- when there is no more flow of filtrate into the artificial reservoir. In the test this is determined by the flow meter that measures effluent from the reservoir.

Flow is radial from the wellbore into the reservoir; thus a cylindrical section was used to simulate the reservoir. A medium with permeability and porosity similar to those of natural reservoir rock is necessary for accurate simulation. Radial, non-converging planar flow from the wellbore outward is required to be similar to that in a large-volume reservoir. This was accomplished by pouring a mixture of resin and graded sands into a cylindrical housing. This process is described in Appendix B; see especially Figures B5 through B9.

This artificial reservoir was poured in two steps. The first was a 1-in. shell in the outer periphery of the cylindrical housing. This is a coarse-grained, highly permeable synthetic sandstone that has very little resistance to flow. The main part of the reservoir is a vertical-walled cylinder with flat top and bottom; the outer walls are bonded to the outer, highly permeable shell and to the top and bottom flanges of the steel reservoir housing.

A borehole in the center of the cylinder is the same size as the casing that simulates the wellbore. A bonded interface between the top of the reservoir housing and the rock and the bottom of the housing and the rock is required to insure that flow does not take a path having different permeability than the rock. Because permeability of the outer shell is much larger than the that of the core of the reservoir, then the axial (vertical) pressure gradient is very small and the driving force comes from the radial pressure difference between the wellbore and the outer shell. Therefore, flow would be planar and radial. To assist in maintaining this planar, radial flow in the core of the artificial reservoir 24 holes are distributed around the side walls of the cylinder. This series is shown schematically in Figure 3.

An explanation was given of how mud pressure in the wellbore is to be maintained to simulate conditions in the well. The artificial-reservoir pressure must also be maintained, but independently of the mud pressure. In large reservoirs, at places distant from the borehole, virgin reservoir pressure is maintained until a large amount of fluid is injected into the reservoir. Because a virgin fresh-water reservoir is simulated in the case at hand, and because this reservoir pressure would influence the full development of mud cake, then a constant reservoir pressure must be maintained. Pressure is developed by a nitrogen-filled accumulator bladder in contact with the effluent water. The nitrogen pressure regulator maintains pressure at the desired value, which is just below the reservoir pressure. A high-precision pressure-regulated bypass valve is set at the reservoir pressure so that when, or if, pressure of the core fluid becomes greater than that in the virgin reservoir, the bypass opens and flow exists but pressure is maintained. Controls to achieve this constant reservoir pressure are shown schematically in Figure 3.

ARTIFICIAL-RESERVOIR HOUSING

The largest feasible artificial reservoir was desired. Expense and handling-operations were the limiting factors. The resulting dimensions of the reservoir housing are 2 ft. in height and 3 ft. in diameter. The housing had to be strong enough for high-pressure operation, to allow simulation of a range of reservoir depths. Along with the pressure requirements, the housing was designed to permit emplacement and replacement of artificial rock,to give the capability of using a sequence of different reservoirs. The final design used welded flanges on a 3-ft.-diameter pipe section with mating modified blind flanges on the top and bottom. With the flanges that were used in the design the allowable operating pressure is 1450 psi, which translates to an equivalent depth of about 3000 feet. This pressure required that the flange bolts be torqued to 2500 foot-lbs. A 5-1/2-in. casing sub was welded in the center of each of the two modified blind flanges. These are to simulate the borehole and to provide a means of connecting to the upper simulated wellbore-mud column and the lower wellbore. Design drawings and design information are given in Appendix B.

Associated with this housing is a hose system, to provide a path for fluid forced out of the reservoir to be directed to the effluent tank (Figure 3). These hoses were sized to insure that the pressure drop attributed to these were much less than the pressure drop through the reservoir, for the range of flow rates expected in the reservoir. The number and array of these hoses were designed to give relative uniform flow along the side walls of the housing. In addition, positioning of hoses was to allow a wrench to be placed on the flange nuts and to minimize entrapment of air in the lines. Flexible lines were used to accommodate the compound curvature when going from row to row.

In order to minimize path of flow and provide a simulation of drilling, a 2-in. line for the mud-pump connection is welded to the 5 1/2-in. casing sub at an angle to the axial line of the casing and tangent to the wall of the casing. This will cause the fluid to take a spiral path up the casing, to simulate the rotation of drill pipe in the borehole (Figure 3, below bottom blind flange).

Another line connection is welded on the lower 5 1/2-in. casing sub, but above the mud-pump connection (In Figure 3, elliptical dot on casing sub, a few inches below bottom flange of reservoir housing.). This is to provide a source of fluid to run permeability tests. It is above the mud-pump connection, so space is available between the two to place an inflatable plug in the line; this plug is to keep the reservoir from being drained when the bull plug on the bottom end of the casing is removed in preparation to connect to the casing in the hole. The inflatable plug is removed by the mud's displacing it out the top, to keep from affecting the water in the reservoir. If sufficient deflation of the plug can be accomplished, an alternate removal method is to pull the plug out slowly with a wire line, to allow replacement of the displaced volume with water from the upper 5 1/2-in. casing sub.

Hammer unions in the upper and lower casing subs are required because of the need to assemble and disassemble in close tolerances without rotating the casing.

Information from this reservoir housing is acquired with differential-pressure transducers, pressure transducers, temperature sensors and a flow meter. To determine the pressure gradient across the reservoir in the axial direction a differential-pressure transducer was mounted was mounted on the casing pup just above the upper modified blind flange; pressure lines are connected to a diaphragm housing above the top flange and to one below the bottom flange. Information gained from this transducer is change in pressure drop during mud cake build-up, and change in fluid gravity during static tests and salt-water injection tests.

Three differential-pressure transducers are manifolded,so each can be isolated when the radial pressure gradient goes out of its range. To maintain good accuracy at all pressure differences it was necessary to have one transducer measure from 0 to 50 psid, one from 0 to 250 psid and the third from 0 to 1000 psid. Pressure differences will increase as the injection pressure increases and the test can not be shut down or interrupted to change transducers. These will measure the pressure from the same diaphragm housing above the top flange to the radial effluent line. These data, in conjunction with the axial differential pressure, will provide the reservoir radial pressure gradient. This gradient will be used for permeability calculations and for correlating the potential invasion flow rate across the mud cake.

A pressure transducer is mounted on the casing sub above the top flange; its purpose is to monitor the mud-column pressure. A temperature sensor is mounted in the same general position. These two values and the axial pressure gradient will define the state of the mud in the casing sub.

The effluent line goes to a flow meter, which measures from about 0.0005 gallons per hour to about 32 gph. Included with this assembly is a back-pressure valve that is set to control the back pressure precisely. Adjacent to it is an accumulator that is operated from a regulated nitrogen bottle, to initialize the reservoir pressure and adjust to the desired value. From the outlet of the back-pressure valve, fluid goes to a tank that contains the effluent until it is properly disposed of.

SIMULATED RESERVOIR ROCK

Actual reservoir material has a large range of permeabilities and porosities. A single value was chosen for each of these properties for the first test, but the capability exists to simulate a broad range of values. A detailed account of the development process to achieve the design requirements is in Appendix B.

Figure B9 shows the reservoir rock in an intermediate stage of the reservoir development. The dark-colored rock is the highly permeable rock shell that was discussed above; the light-colored rock was mixed and emplaced to have the designed porosity and permeability. The center mold forms the "well bore". Of course the cylinder was filled completely with the light-colored material, which was bonded to the top flange gasket. The center form is removed after the top flange is placed on the cylinder and the material has cured. A high-density polyethylene liner is between the wall of the cylinder and the outer high-permeability shell, to allow easy removal of the reservoir rock from the cylinder after tests are run. Resin will not adhere to the liner and the rock will slide out. This liner must be penetrated to allow fluid to flow from the 24 ports to the effluent flow meter. The high-pressure flexible- hose connections were designed to allow easy access for drilling these holes in the liner.

## Rock Porosity and Permeability Measurements

The porosity-measurement technique begins even before the artificial rock is placed in the reservoir housing. With the housing completely assembled and a bull plug on the bottom of the attached 5 1/2-in. nipple, the void is filled with water by pouring from a 1000-ml. graduated cylinder. This yields the bulk volume. After the artificial rock is placed in the reservoir housing, the void space is filled with water from the peripheral effluent lines, through the salt-water-injection flow meter assembly. Knowing the overall dimensions of the rock placed into the housing, along with the two water volumes and the porosity of the coarse rock, allows determination of the porosity of the simulated reservoir rock. The coarse outer-shell porosity was determined from the Amoco sample porosity tests.

After the tests are run and the artificial rock is removed, then samples are to be taken from the rock and these samples are evaluated for values of porosity, permeability and mud content.

When the reservoir is full of water, then the steps to measure permeability can take place. The line from the saltwater-injection flow meter is connected to the 1/2-in. fitting welded to the 5 1/2-in. casing nipple. The effluent line is connected to the effluent tank. A flow rate is established by adjusting the pressure differential across the reservoir radius. This is done by adjusting the back-pressure valve on the effluent line and the nitrogen pressure in the associated bladder. By measuring the flow rate, pressures, differential pressures, temperatures and obtaining the viscosity of the water, then permeability can be calculated.

Measurement of porosity and permeability is discussed under Operating Procedures 6.1 and 6.2, Appendix G. It should be noted that after these tests are conducted, then the artificial reservoir housing must be moved, centered over the well, and connected to the casing string. The assembly stand (Location A, Figure 2) is designed to make this transition; the four legs have adjustable jacks to provide easy connection with the casing (without unseating casing from the slips).

## SIMULATION OF DRILLING PROCESS TO BUILD MUD CAKE

During the drilling operation the mud pressure coming through the drill pipe, drill bit and up the annulus must be sufficient to move the fluid against the head pressure and also to overcome friction. Because of this, the pressure to build mud cake is higher than the static pressure of mud sitting in the hole. Initially the reservoir being penetrated has inherent pressure, then the reservoir is exposed to the stagnation pressure of the flowing mud and then to the flowing static pressure. The sides of the wellbore are subjected to mud at the flowing static pressure over the greatest period of the drilling operations. Thus mud cake in the test procedures described here is to be done at this flowing static pressure. This will create a different pressure differential to form the mud cake at each reservoir depth in the test series.

A pressure-operated bypass valve is in the mud-line network to keep over-pressurization from occurring during start-up and operation. Prior to mud being circulated to build a mud cake, it is necessary to have the test-simulated wellbore full of mud. Pressure in the reservoir is to be brought up slowly to equal the virgin reservoir pressure by adjusting the accumulator pressure in the effluent flow meter system and simultaneously adjusting the nitrogen regulator in the mud-column flow meter, to make the mud-column pressure equal to the reservoir pressure.

During this pressure build-up time, valves in the mud flow lines coming from and returning to the mud tank are closed at the wellbore connections (Figure 3). Concurrently the mud pump circulates mud through the bypass valve, which was pre-adjusted to a specified increment above the static flowing mud pressure. The back-pressure valve in the return line from the reservoir must be pre-adjusted to be equal to the static flowing mud pressure. Then when the valves leading to and from the wellbore are opened a surge of mud will flow up through the reservoir in a swirling fashion, which will simulate the drilling fluid dynamics. The pressure differential between the mud and the reservoir pressure will cause a mud cake to be built up on the porous wall of the reservoir. Initially there will be some flow into the reservoir to build the mud-cake. But once there is no flow into the reservoir under these flow conditions, then it is established that a mud cake is completely formed. This would be determined by the effluent flow meter. How long this process takes will be defined by the flow-meter output.

To not disturb the mud cake, the shut-down process becomes important. While the mud is circulating, the mud-column pressure source is adjusted to be equal to the static mud pressure (which is less than the flowing static pressure). Then the back-pressure valve is adjusted to cause the flowing pressure to be equal to the static mud pressure. At this point, the supply valve is shut off and the bypass valve routes the mud back to the tank. The return line is then shut off and the mud is confined to the wellbore and reservoir system at the appropriate pressure.

## SIMULATED WELLBORE AND INJECTION ZONE BELOW THE RESERVOIR

### INTRODUCTION

Because communication from an injection well through a subsurface injection zone has the potential of mixing salt water with drilling mud and considerably raising the pressure in the mud column, it is not sufficient to simulate only the direct effect that depth and borehole volume have on the process. Thus it was determined to make possible a range of depths from about 200 ft. feet to 2000 ft. This was accomplished by drilling the 2100-ft. well, cementing it from bottom to top, and placing a full open head on the top casing joint with 5 1/2-in. slips. Casing can be run in the hole to the desired depth and hung on the casing-head slips. Rather than drilling an adjacent well and injecting salt water in it, hoping that some of the salt water would get to the test wellbore, the simulation is done by running a string of 1 1/4-in. tubing on the outside of the 5 1/2-in. casing and supplying salt water directly into the casing at the injection point. A check valve is in the tubing at the injection point to allow fluid to be supplied to the casing, but not to come from the casing to the tubing. Specific design drawings and design information on tubular materials and components associated with the down-hole part of the facility are in Appendix C.

The pressure of the mud at the injection point is governed by the pressure set for the simulated reservoir section, the depth of the casing string in the hole, and the density of the mud. As discussed previously, this pressure can be varied to simulate wells as deep as 3000 ft. to the upper reservoir, and by adding the 2000 ft. of casing down to the injection point, the total well depth that can be simulated is 5000 feet.

### WELL CONFIGURATION

Sixteen-inch-diameter surface casing is set to 333 ft. and cemented bottom-to-top. The long string, a 10 3/4-in. casing, was run to 2100 ft. and cemented from bottom to top with light cement.

Screwed to the 10 3/4-in. casing is a 10 3/4-to-5 1/2 casing head. This is a full open head to allow all the 5 1/2-in. inch casing and 1 1/4-in. tubing into the 10 3/4-in. casing. The slips were modified to allow the instrumentation lines and salt-water injection tubing to pass through while the casing is set in the head. A transition piece was made to reduce the 1 1/4-in. tubing to 1/2-in. tubing and a 1/4-in. tubing for venting purposes.

In order to simulate any depth between 100 ft. and 2000 ft., the 5 1/2-in. casing and the 1 1/4-in. tubing is run into the hole simultaneously until the injection point is reached. At that depth, the casing is set in the head.

MEASUREMENT AND CONTROL

Injection pressure for the saltwater is supplied by an accumulator with nitrogen in the bladder and the column head of salt water going to the injection point. The accumulator forces fluid through a flow meter and into the line going to the injection point. If the pressure is sufficiently high then flow will exist; otherwise the pressure will be statically impressed upon the mud column. A detailed set of drawings and design information for the flow meter and controls is set out in Appendix F.

In order to determine the mud characteristics and dynamic behavior of the mud column in the injection area, a sequence of differential-pressure transducers was placed on the 5 1/2-in. casing and run down-hole. Strategically placed pressure transducers and temperature sensors were also placed on the pipe. Considerable design and search was required to accomplish this task. Original design concepts were to run each wire from the individual sensor to the top of the borehole, but this became quite problematic after calculation of dimensions and weights, and review of the required operations. An application from Oklahoma State's space research resolved the problem, through design of a multiplexer that required only one cable from the surface. Multiple sensors would be attached to it from a series of locations below the multiplexer. The multiplexer can serially select a given sensor and send that part of the signal up-hole, cycle to the next and repeat the operation until all sensors are sampled; then the cycle repeats. On the surface a computer program sorts the data and stores it in an array for further use. These instruments and controls are shown in detail in Appendices D and E.

Information from the down-hole instrumentation provides a means of determining the average properties of mud in sections of the pipe defined by the pressure connections on the differential-pressure transducers. The rate of change of these properties would yield information about the dynamics of equilibration in plugged wells and of wells having injection fluids impinged upon a long mud column. Specific locations of the instruments are shown in drawings in Appendix C.

## SECTION 5

## INSTRUMENTATION DESIGN AND APPLICATION

### INTRODUCTION

Instrumentation design includes the design of the system of sensors, the selection of components and the design of the instrument itself, in some cases. In the case of flow meters, many hours of searching the literature for various sensors failed to provide instruments that would fit all the criteria. Also, literature was searched for differential-pressure transducers that had the accuracy, line-pressure range and small size to satisfy the constraints of the project. A discussion of these features will be covered in this section of the report. Specific design drawings are in Appendix D.

### INSTRUMENTATION DESIGN FEATURES

#### TEMPERATURE SENSORS

The temperature sensors were selected on the basis of accuracy, stability and signal output. The unit chosen was the AD 590 KF temperature sensor, which yields a high current output. Accuracy and linearity were enhanced by designing a circuit to cover the design range expected in the test series. Accuracy of the sensors, as designed, is about 0.3 deg. C.

#### DIAPHRAGM HOUSING

Two problems existed that resulted in design of the diaphragm-seal housing. Some of these problems arose because of the small lines connecting the pressure transducer to the pressure source. First, mud in the system has a potential of being in a different mixture as time changes; therefore we can not rely on knowing the properties as a standard. Secondly, the potential existed of mud's hardening in small lines and affecting the pressure measurements. In addition, mud and salt water, which could get into the pressure lines, could have detrimental effects on the transducer material -- unless, of course the material were corrosion-resistant.

During verification of the differential-pressure measurement technique it was found that in the transition from atmospheric pressure to 3000 psi, air in a line will compress to less than 2 percent of its original volume. Therefore, air-to-mud interface in an instrument line is not feasible for high pressures. Further calculations showed that water will compress in a 1/4-in. tubing to the extent that a displacement takes place of about 3.5 in. in a 30-ft.-long tube when pressure increases from atmospheric to 3000 psi. These circumstances led to design of the bellows diaphragm. A Bellofram rolling diaphragm was chosen to eliminate essentially any resistance to transmitting pressure, so that an accurate measurement can be achieved. The volume of the half-displacement was selected to be equal to the 3.5-in. displacement in a 1/4-in. tubing. The final configuration, shown in Figure D1, is to fit the contour of the pipe, keep air bubbles from being trapped, fit in the annulus in the well, allow replacement of the diaphragm, seal the pressure, and adapt to the plumbing requirements. Applications of this diaphragm are shown in Figures H7 and H8.

## PRESSURE TRANSDUCERS

A search of commercial pressure-transducer sources revealed that most designs on the market are not conducive to placement in a small annulus. There were several choices but some were eliminated because of the extremely long delivery time, some because of accuracy, and some because of cost. Two types were chosen; one is a Validyne P305A absolute-pressure transducer and the other is an ICSensor 115 pressure transmitter. More information is located in Appendix D.

Each of these transducers was plumbed to the diaphragm housing with 1/4-in. tubing and fittings so that it could be filled with water, to allow air to bleed from the lines. These diaphragms were mounted on the casing or on special brackets that provided communication directly with the fluid being measured. Holes into the cavity of the diaphragm are configured so that as fluid is being placed in the casing air will not be trapped in the cavity. Also the surface where the holes are drilled will not cause disconfiguration of the diaphragm seals, due to the differential pressure of the instrument fluid and the air in the casing before water or mud is placed in it.

Pressure ranges vary for the different pressure transducers based on the potential location in the well, the maximum reservoir pressure anticipated, the maximum injection pressure and the maximum simulated mud-column depth to the upper reservoir. A list of these pressures is in Appendix D.

## DIFFERENTIAL-PRESSURE TRANSDUCERS

Unlike the pressure transducers, the differential-pressure transducers were limited to only one choice. Only the Validyne P305D transducer would fit the accuracy, line-pressure range, differential-pressure spans, size and configuration criteria.

The differential-pressure measurements require that two sources of pressure be tapped into. Thus, a diaphragm housing is required at each location. The distance between the diaphragm housings, and the density of the fluid being measured dictate the pressure span for each transducer. The maximum pressure expected in the vertical sources is based on the density of bentonite. A list of pressures associated with a given differential-pressure transducer is shown in Appendix D.

All instrument lines are configured similar to that discussed for the pressure transducers, but the high-pressure side of the differential transducer extends down the casing several feet. Figure C2, Appendix C, shows lengths between the down-hole differential-pressure transducers. This part of the line acts as a manometer and is part of the data-reduction equation to find the mud density; therefore density of the fluid in this line is required.

At one point,each of the transducers is connected to the same pressure source since the diaphragm seal is large enough to accommodate expansion into each of the lines. Each of the differential-pressure transducers is coupled one to another, so that the sum of the pressure drops theoretically should equal the pressure difference between the pressure transducers at the two extreme ends, as a check in the readings. The measurements are not expected to be exactly the same because the pressure transducers measure the full value of the pressure; this results in a different reading accuracy than for the differential pressures.

PISTON FLOW METERS

An extensive search was made to find a flow meter that would measure very low flows accurately while operating in a high line pressure, and that would extend to moderate flow rates. Because none could be found to fit the criteria, a flow meter was designed. Several concepts were reviewed before the design, as seen in Appendix D. The design had to allow for continuous or intermittent flow, and measure with accuracy flows as small as about 0.0005 gph or as large as about 32 gph. Basically, the method is to know accurately the location of a piston in a cylinder at a given time and at subsequent times. In order to accomplish this a Temposonics linear-displacement transducer was inserted into a cylinder. This transducer reads the position of a magnet that is mounted onto a piston. A seal is between the shaft and piston and between the piston and cylinder wall. Displacement volume versus time results in a known flow rate.

To allow continuous flow, fluid moves into one end and out the other with the piston being the interface. When the piston gets to one end of the cylinder the flow must reverse rapidly. To accomplish this a set of Vindum three-way, four-position valves was purchased, which has a valve operating-time of less than 0.1 second. For the flow-rate range concerned with here, this has negligible effect on accuracy during turn-around. Both valves are connected to the two ends of the cylinder; one controls the inlet and one the outlet. Controlling the cycle is done with a circuit that was designed to operate off the Temposonics position signal. Output of the Temposonics is sent to the multiplexer and stored on the computer hard disk. Figure D is an assembly drawing of the flow meter. There is one flow meter for effluent flow and one for injection flow. Photographs of these flow meters are in Appendix E.

FLOAT FLOW METER

The float flow meter operates in a vertical mode; it does not allow continuous flow monitoring. When the fluid in it is depleted, then the unit must be deactivated and refilled with water before placement back into operation. To have this flow meter in continuous flow is not critical, because the volume of the casing that contains the meter insures an ample supply of fluid, in most instances. This design is similar to that of the piston flow meter, but the magnet for the Temposonics is mounted on a float and water level is measured with time. This unit acts as a pressure source for the simulated mud column; nitrogen pressure is regulated to ullage above the water in the vessel. Therefore it supplies the mud column flow potential and measures flow when it occurs.

Output of this flow meter also is also sent to the multiplexer and stored on the computer hard disk. Drawings of this meter are in Figure A2; a photograph of it is in Appendix E, Figure E10.

MEASUREMENTS OF PERMEABILITY AND POROSITY

Instrumentation discussed in the previous subsections is applied to define the parameters necessary to calculate the values of permeability and porosity. Pressure differences, flow rate and temperature are used to determine of permeability. Information from the flow meter is necessary for the volume of liquid required to fill pores, and temperature and pressure are used to define the state of the fluid.

## APPLICATIONS OF INSTRUMENTS

Differential-pressure transducers will supply information on mud density; measurements by temperature sensors at the same positions and knowledge of mud constituents will permit the down-hole characteristics of mud to be determined.

Time history of pressure gradients will come from the differential-pressure transducers; these will provide an indication of when mud in a long column equilibrates.

Output of differential-pressure transducers and measurement of local pressure will show the behavior of a column of mud when it is subjected to injection pressure at a given depth.

Permeability and porosity data derived from these instruments will supply a method of relating test data to field data in similar situations.

For a given formation pressure, formation depth and permeability, flow-meter data will determine the amount of mud that invades a formation prior to the building an effective mud cake.

A combination of the instruments will provide the data to determine the amount of fluid, if any, that penetrates a mud cake for given values of injection pressure, reservoir depth, injection depth, reservoir pressure and permeability.

## SECTION 6

## DATA-ACQUISITION SYSTEM

### INTRODUCTION

The Data-acquisition System for the project was designed and developed by the Oklahoma State University Electronics Research & Development Laboratory. Several unique design challenges and considerations were met in making this system functional.

Design criteria included limitations of size and weight, and a relative long distance to the farthest sensor. Miniaturization of the data-acquisition system was imperative, as size was limited to less than 2 in. of spacing between down-hole piping. The data-acquisition system was to be "sandwiched" between the 10 3/4-in. casing and the 5 1/2-in. casing. Weight factors were a key consideration in development, because the system was to be attached to the down-hole pipe. Individual wiring to each of more than 50 sensors -- as might be considered in a standard acquisition system -- would have accumulated to too much weight in this case. With 100 ft. of single-shielded twisted wire weighing approximately 2.3 lb., multiplication of this factor by the number of sensors (with the farthest one at 2000 ft.) made this method infeasible. With these limitations in mind, a multiplexing scheme was developed that provided adequate sampling of each sensor and greatly reduced the size and weight of the system.

Instruments running constantly can yield voluminous, unwieldy data. A good data-acquisition system guards against this situation. The system must also act as a control for particular, potentially hazardous conditions. Because this test system will not be attended 24 hours a day, the design of the data-acquisition system also includes sorting and storage of data.

### REMOTE MULTIPLEXER

The remote multiplexing scheme was developed as a derivative of a proven design used for uplink command telemetry of a suborbital space vehicle. In the data-acquisition system, an address is generated by the system computer, transmitted to a remote multiplexer station where the address is decoded, and the proper down-hole multiplexer is selected. The analog output from the selected sensor is converted to a common 0-to-20 milliampere current loop and carried to the I/O board in the

AT-compatible computer. The current is converted into a 0 to +10 voltage-value through a precision resistor and fed into the computer's 12-bit Analog-to-Digital converter. This digital value (with approximately 2.5 mv./LSB) is read and stored in a data table. Complete acquisition control can be maintained with this method because each sensor is selected individually. Sensors may be "polled," with all sensors being sampled in one cycle, or a random sampling of sensors may be selected. The binary value of the select address corresponds to the sensor number.

## COMPUTER INTERFACE

The computer interface I/O board was also developed as a part of the total acquisition system. Here, the computer-generated address for selection of the multiplexer input is encoded into a Pulse Code Modulated (PCM) bi-phase level format for transmission to the remote multiplexer. The bi-phase format has an inherent advantage in that the clocking can be regenerated. By reconstructing the clock at the decoder in the remote multiplexer, synchronized address/data transmission is achieved. In addition to the address encoder, the current-to-voltage converter, analog-to-digital converter and associated logic hardware to interface with the computer are on the I/O board.

A 0-to-20 milliampere current loop was chosen for serial sensor data transmission to the computer. With this method, any number of remote multiplexers may be added to the single current loop. When a multiplexer station is not selected, the voltage-to-current converter at that station will remain in an off or zero state and will not degrade the data sample taken from another multiplexer.

An interface card that plugs into an IBM-AT was designed and built to address a multiplexer input and convert the analog data to digital data. Data are stored on a disk, scanned, and if appropriate signals are detected, then signals are sent to shut the system down or to sound a warning.

Two multiplexers were designed and built, one for the instruments on the surface and the other for instruments down-hole. These multiplexers are connected to an array of sensors and this information is fed serially to the interface card.

## COMPUTER

The computer is a PC-AT compatible with a 40-megabyte hard disk drive, one 1.2-megabyte 5 1/4-in. floppy disk drive, and one 1.44-megabyte, 3 1/2-in. floppy disk drive. It has an 8287 mathematics co-processor and a Phoenix BIOS.

## SOFTWARE

Software for the data-acquisition system was developed by staff and students at Oklahoma State University using Microsoft "C" language. Features of the software include sensor address generation, data sample rate, conversion of the data digital-value into volts and engineering units, storage of data, including date-and-time stamp, and real-time display of sensors monitored.

Under normal conditions, a binary address value is generated, which corresponds to the sensor to be sampled. A software delay allows the sensor to be sampled and the analog data to settle before conversion to digital format. Once conversion takes place, the computer reads the digital output of the analog-to-digital converter and stores this information (in voltage units) on the hard disk drive. The computer generates the next address/sensor and the process repeats. When the computer has polled all sensors one time, a delay is built-in to wait for approximately 10 min. before another sample is taken. At midnight, the file of the data stored that day is closed and named with a date stamp. A new file is started for the next day's data.

Data are stored in ASCII and are retrieved easily for data reduction by many popular versions of spreadsheet software. Although data are stored in voltage units, real-time display can be seen in engineering units. Pressure in pounds per square inch and temperature in degrees Centigrade provide a handy quick-look picture of the system.

## FLOW-METER CONTROLLER

The flow meter provides an analog output of 0 to +10 volts relative to the position of the sensor inside the flow meter. A method was designed and developed that would limit and reverse the direction of the flow meter. This method employed a two-level comparator circuit that compares the relative voltage of the flow-meter sensor to a limit voltage. The limit voltages are pre-set for each individual flow meter, with voltage of a few tenths of a volt being set for the lower end, and a limit voltage of a few tenths of a volt below 10 volts for the higher end. The comparator uses an operational amplifier configuration for the circuit. As the flow-meter sensor reaches a limit, voltage from the sensor compares with the limit voltage and drives the operation amplifier into saturation. This provides a "high" output, which is used as a digital input to a buffer/inverter circuit. The buffer circuit controls the spool-valve relays which in turn control the flow direction of the flow meter. At this point, the relays are engaged (or disengaged) changing the direction of the flow meter. When the flow-meter sensor reaches the opposite end, the comparator again compares the flow-meter analog voltage with the limit voltage, and the operation amplifier is driven to a low state, reversing the condition of the buffer/inverter circuit, and therefore reversing the flow of the flow meter. The two-stage comparator will remain in a steady state, regardless of the intermediate analog voltage as the flow meter moves from one end to the other. Only when the analog voltage compares with the high- or low-limit voltage will it change the state of the controlling relays.

## SECTION 7

## TEST RESULTS

### INTRODUCTION

Test results discussed in this section include porosity tests, permeability tests and preliminary abandoned- and plugged-well tests.

### POROSITY TESTS

Prior to beginning the porosity tests, the instrumentation console was moved from the Electronics Laboratory (where a series of calibration tests were run on the three flow meters in series at various pressures) to Location A in Figure 2. Because the series of flow-meter tests was not run at atmospheric pressure, another calibration was run at Location A to obtain the conversion from Temposonic voltage output to flow volume. This was done with the computer recording voltages, pressures and time, while water from the system was being measured with a graduated cylinder. This was the same 4000-ml. graduated cylinder that was used to measure the initial volume of water placed in the reservoir.

Initially, the reservoir housing was assembled with all effluent lines on the periphery, a bull plug on the bottom of the 5 1/2-in. casing sub (Figure H7), and the valve assembly removed (at the hammer union) from the 5 1/2-in. casing sub on top of the reservoir housing. Using the 4000-ml. graduated cylinder, the reservoir housing was filled to the lip on the inside of the lower hammer-union connection, for a consistent reference point. Milliliters were converted to gallons and the total volume was measured as 104.20 gallons. This volume is the bulk of all lines, connections, casing, and reservoir housing.

After constructing the artificial reservoir in the housing and reassembling the system to the same external configuration that was tested for the bulk volume, measurements were conducted to find the volume of void space.

Several changes had been made in the flow-meter circuits, such as amplifiers, buffers and similar components, since the first flow-meter calibrations were made. Also, the flow-meter tests were run at elevated pressures. For these reasons, calibration of the flow meters was made at atmospheric pressure, with the new components. Several 4000-ml. calibration tests were made and the average of these readings was calculated to evaluate the calibration coefficient. The average was 806.45 ml./volt on the salt-water flow meter, which was used for this test.

A low flow rate was desired for filling the reservoir from the flow-meter system through the effluent lines around the periphery of the reservoir, so as to eliminate air pockets. The line to the effluent connection was filled before the valve to the effluent lines was turned on. Because flow from the effluent lines went to the high-permeability shell around the reservoir core, the shell filled prior to any fluid's going into the primary artificial rock. A long period of flowing into the reservoir took place prior to our seeing any sign of water in the 5 1/2-in. casing. When water did appear, it was just as beads in a thin layer at the bottom of the artificial reservoir. As time continued the flow coming into the reservoir was monitored by looking inside casing and watching the level of beads of water come out of the artificial rock. This level was about halfway up the rock (about 1 ft.) before the bottom of the casing began to fill. Beads were forming on the surface of the rock and then running down the sides, covering the entire surface up to the water level. This is an indication of the amount of permeability.

About 2 hr. and 13 min. were required to fill the void space in the housing to the lip on the hammer-union connection. During this time total voltage of the salt-water flow meter was measured as 102.355 volts. Because the flow meter is a reciprocating type, the direction-change voltage level was required; it was consistent at 9.69 volts at one end and 0.38 volts at the other end, as measured by a digital voltmeter. Each cycle (or part of a cycle at the beginning and end of the test) was summed to obtain the total voltage. Using the calibration coefficient and converting the answer to gallons resulted in 21.86 gal.

Some items in the reservoir housing were not in the initial bulk-volume measurements; they must be accounted for. These include gasket material, top and bottom; layers of RTV adhesive sealer, top and bottom, the HDPE liner adjacent to the wall, the high-permeability shell between the liner and the reservoir rock, and of course, the reservoir rock. Porosity of the high-permeability shell was assumed to be the same as was measured by Amoco, 34.5 percent (Appendix B, Attachment B2). Since dimensions of the solid components are known, then individual volumes can be calculated. These are shown in gallons:

Volume of gasket material = 2(0.4877) gal.
Volume of RTV sealer = 2(0.2858) gal.
Volume of HDPE liner = 0.2152 gal.
Volume of shell = (1-0.345)*16.235 gal.
Volume of reservoir = $(1-\phi)$*80.04 gal.

It is noted that the reservoir volume did not include the hole through the center, which is the same as the internal diameter of the 5 1/2-in. casing. The common volumes are the inside volume of the casing projected top to bottom, all the effluent lines and fittings and the void spaces in the two rock mixtures. A relationship is defined to determine the porosity of the rock:

Initial Bulk Volume = Void Space + Displacement by Solids

The initial bulk volume was 104.20 gal. and the void-volume that remained after placing the defined solids in the reservoir housing was measured as 21.86 gal. By adding the volumes of solids, the relationship becomes:

$$104.20 = 21.86 + 12.396 + (1 - \phi)*80.04$$

Solving this equation for $\phi$ gives a value of 12.5 percent for porosity. This was in the range of porosity that compares with actual reservoirs.

## PERMEABILITY TESTS

Once porosity is determined, then permeability tests can be conducted. The supply line is changed from the peripheral direction to the fitting just below the reservoir housing, so that flow will be in the direction of flow that is potential during salt-water-injection-tests. A value near 126 md. is expected for this test, based upon the value of porosity (12.5 percent) and test results from Amoco (Figure B6).

During preparation for these tests it was found that components in the data-acquisition system should be placed in a dry environment. Several components were replaced and considerable time was consumed in detecting problems. For some sensors, voltage output from the sensor read with a digital voltmeter and by the computer did not compare favorably. Operational amplifiers were replaced to correct the problem. Challenges such as this delayed progress.

Tubing fittings leaked at the 200-psi range and higher, and although the leak was minute, it adversely affected the sensitive differential-pressure transducer output. A new valve leaked, which also required devising an alternate procedure and eventually the replacement of it. These are just a few of the procedures that are typical with experimental projects; thus delays follow.

Permeability tests were run with nominal pressure in the artificial reservoir, about 400 psi, because of the calibration characteristics of the differential-pressure and pressure transducers. A set of expected values was calculated for the test reservoir; at a radial differential pressure of 14 psi the flow rate was expected to be 1397 ml./min. A source pressure was adjusted to provide in excess of the 14 psi differential pressure. The back-pressure by-pass valve was adjusted so that it just was on the verge of opening at the nominal reservoir pressure. Testing began with the drain valve open, which is downstream of the back-pressure valve, so the effluent could be placed in a graduated cylinder to compare with the flow-meter data. The pressure-source valve was opened and as pressure increased the back-pressure by-pass valve opened and effluent was caught in a bucket until count-down time. This was done in order to direct flow into the cylinder for a period of a minute; then flow was redirected into the bucket. During this time the computer recorded data on flow rates, pressures and differentials at nine locations, as well as date and time. Time and selected pressures were also simultaneously recorded by hand. After a period of flow the system was returned to a static condition. This process was repeated several times.

Using the radial-flow equation, the test average results and the measured dimensions of the artificial reservoir, a value of permeability was calculated. Only a differential pressure of 1.246 psi was measured for a flow rate of 1315 ml./min., which resulted in a permeability value of 1257 md. According to the porosity measured for this artificial reservoir, the permeability was too great. At this point in the contract schedule, there is not time left to analyze fully the reasons for the permeability results being so large. During one of the many times of instrumentation and system debugging, when the reservoir was brought to pressure, a distinct "pop" or "crack" was heard. The present working hypothesis is that bonding between the top of the reservoir rock and the overlying gasket parted and that the parting allows flow communication -- an explanation of the high permeability.

## DRILLING-FLUID TESTS

Choosing a drilling fluid to test has a large latitude. The requirements are at least 9.0 lb./gal. mud with viscosity of 36 sec./qt. or more. There does not appear to be a "typical" mud used for plugging. Our primary criteria were that mud would meet the characteristics listed, that all critical properties of the mud were measured in the laboratory, and that the reaction with 8.7 lb./gal. salt water would be observed and documented.

It was decided that 70 bbl. of mud would be hauled from a well-location, from which mud was being used currently to plug wells. Weight of the mud was described as 9.0 lb./gal. In the initial tests, the mud weighed 8.99 lb./gal. and viscosity was 34 sec./qt. While circulating mud through the mud-calibration pipe section, back pressure changed erratically. Pressure varied from about 300 psi to 800 psi; previously, when water was run through the system, pressure was very steady. Cottonseed hulls were discovered in the mud; these periodically plugged the back-pressure valve port and caused erratic pressures. (In the future, to test with such additives in the mud would be of value, but for the initial tests a deviation from fresh mud of this magnitude would not be advisable.)

A full sequence of tests was not achieved, because of the great amount of development time necessary to place into operation a facility as complex as the one described here. Many of the procedures involved were close to state-of-the-art. Of positive importance is the fact that the system is at a point in development where refinement will produce good results. Also, several products that could be patentable were developed during the course of this research.

# APPENDIX A

## ASSOCIATED DRAWINGS AND DEVELOPMENT FOR THE UPPER WELLBORE SIMULATION

Figure A1 shows dimensions of the vessel that holds the mud, and that is connected to the top of the artificial reservoir.

A Temposonics transducer is placed in the top of the float type flow meter shown in Figure A2. Details of parts of the flow meter are shown in Figure A3.

## Mud Column - Simulated Wellbore Section

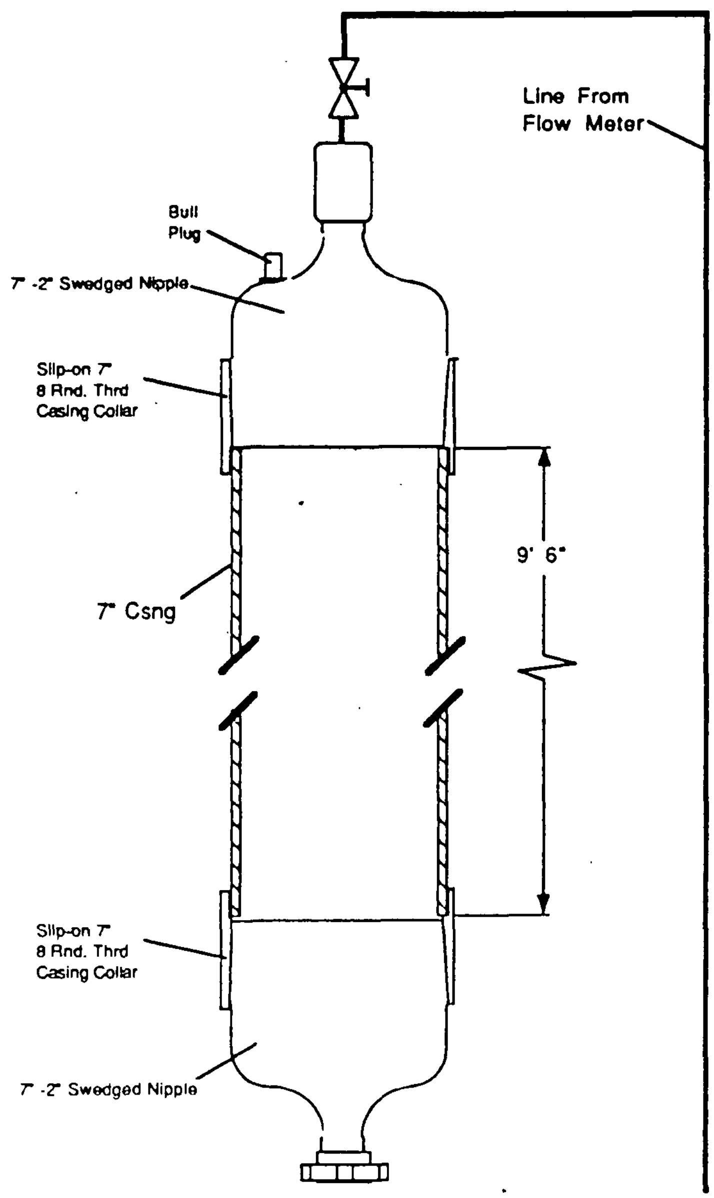


Figure A1. Simulated wellbore - mud column above the reservoir zone.

Mud Column Simulator
Flowmeter and Reservoir Assemblies

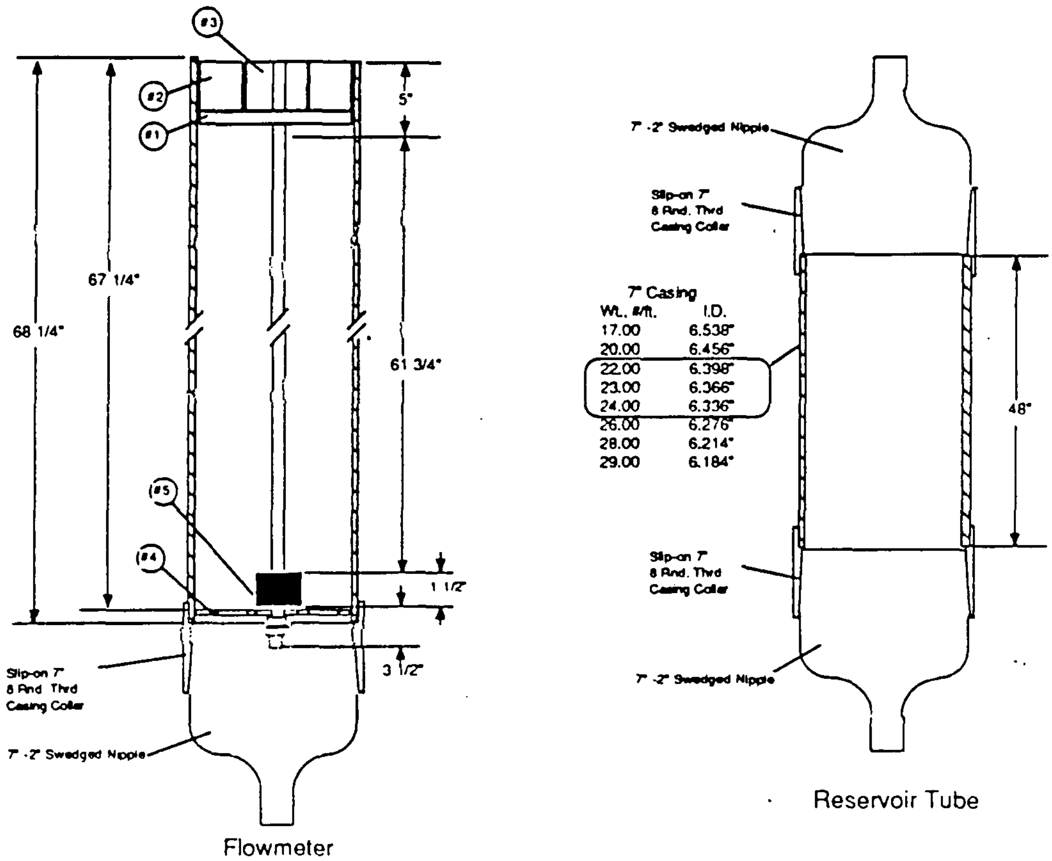


Figure A2. Mud-column flow-meter assembly.

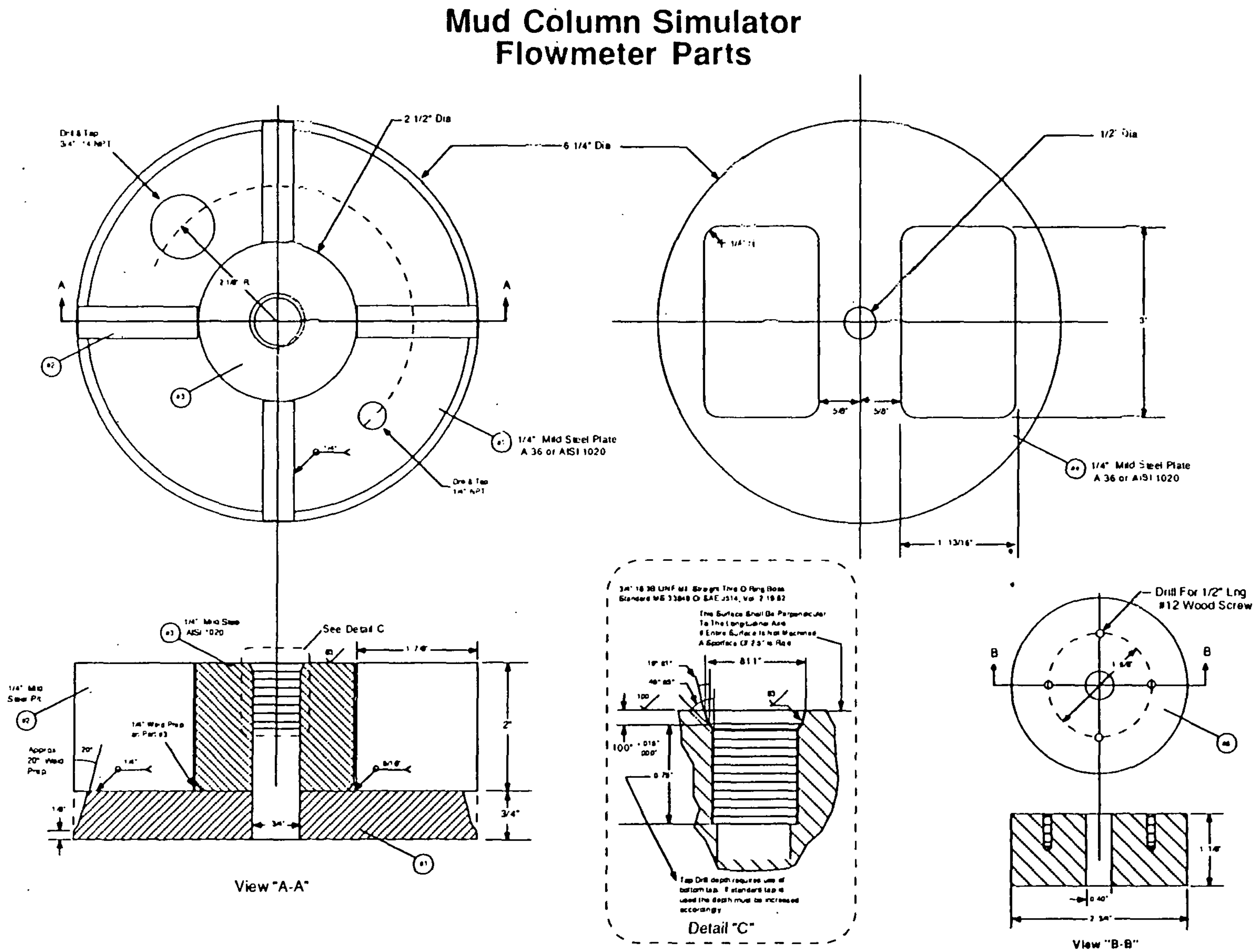


Figure A3. Detailed drawing of parts, mud-column flow meter

## APPENDIX B

## DRAWINGS AND DEVELOPMENT ASSOCIATED WITH THE ARTIFICIAL RESERVOIR

## ROCK DEVELOPMENT, TESTING AND POURING PROCEDURE

### DEVELOPMENT AND PLACEMENT OF THE ARTIFICIAL RESERVOIR

The artificial reservoir was designed to simulate general injection-zone conditions of rock type, porosity and permeability. Sampling of shallow formations of sandstone in areas near Oklahoma State University indicated that porosity in the range of 15 percent to 20 percent, and permeability near 200 millidarcies would be close to the average properties of injection zones.

In order to conform to petroleum-industry standards, advice was sought from Halliburton Services, a company known to have experimented with construction and treatment of artificial reservoirs. Their valuable advice, cooperation and assistance were given generously, as was the assistance of Amoco Production Company, in the testing of samples of artificial reservoir. Experimentation with composition and methods of compaction of the artificial reservoir stemmed from suggestions given by Mr. J. Murphey (see Attachment B1 of this appendix).

Principal components of the artificial reservoir are very fine grained, clean quartz sand, coarse grained quartzose sand (commonly used as a propping agent in fracturing of formations), and a binder of resin (Figures B1, B2). Experimentation and construction of bench models initially were modeled after the Standard Proctor Test, used extensively in Civil Engineering to determine the moisture content at which soil is at maximal density and maximal strength. Mixtures of sand and resin were placed in a Proctor mold and compacted in various measured amounts with a 5.5-lb. sliding hammer, dropped consistently through a distance of approximately 11 in. (For example, see Figure B3, and discussion of Sample 1, p. B2.2, Attachment B2, this appendix.) Sand-and-resin mixtures do not compact in the manner of soils, first being "fluffy," and then becoming "rubbery." From the outset, porosity and permeability of the artificial reservoir were judged to be strongly dependent on the extent and technique of "tamping."

The first sample of reservoir was made according to recommendations of Halliburton Services. Its appearance and heft indicated strongly that the rock would have porosity and

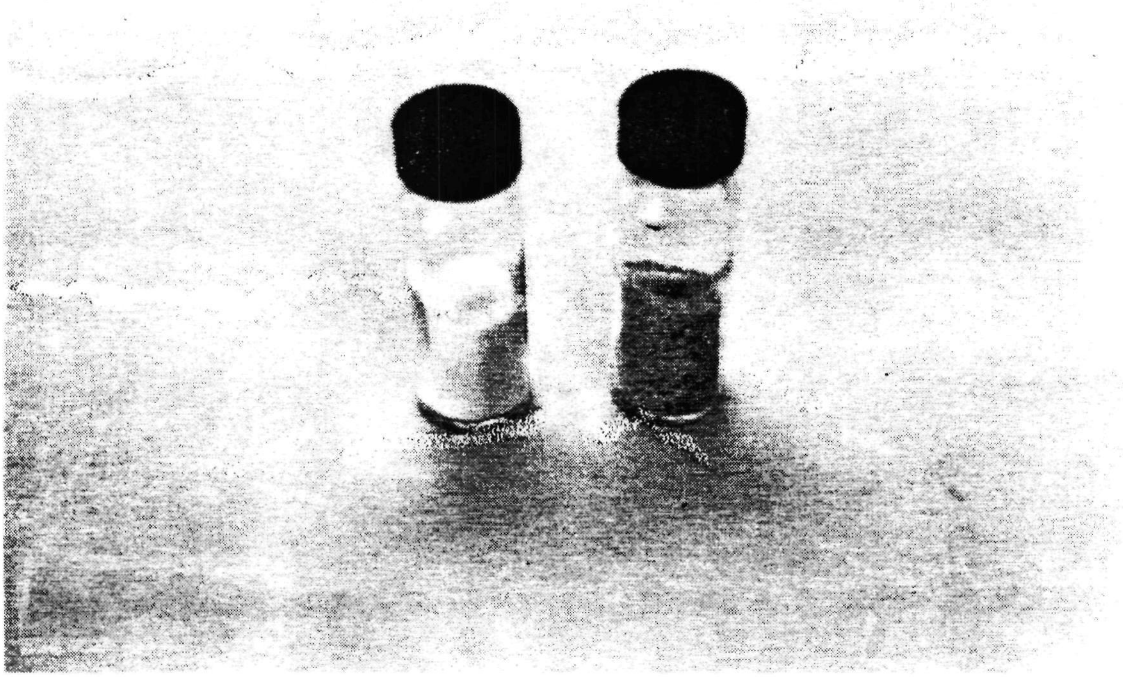

Figure B1. Vials of very fine grained Oklahoma No. 1 quartz Sand (left), and coarse grained, quartzose "12/20 mesh frac sand," the chief components of the artificial reservoir.

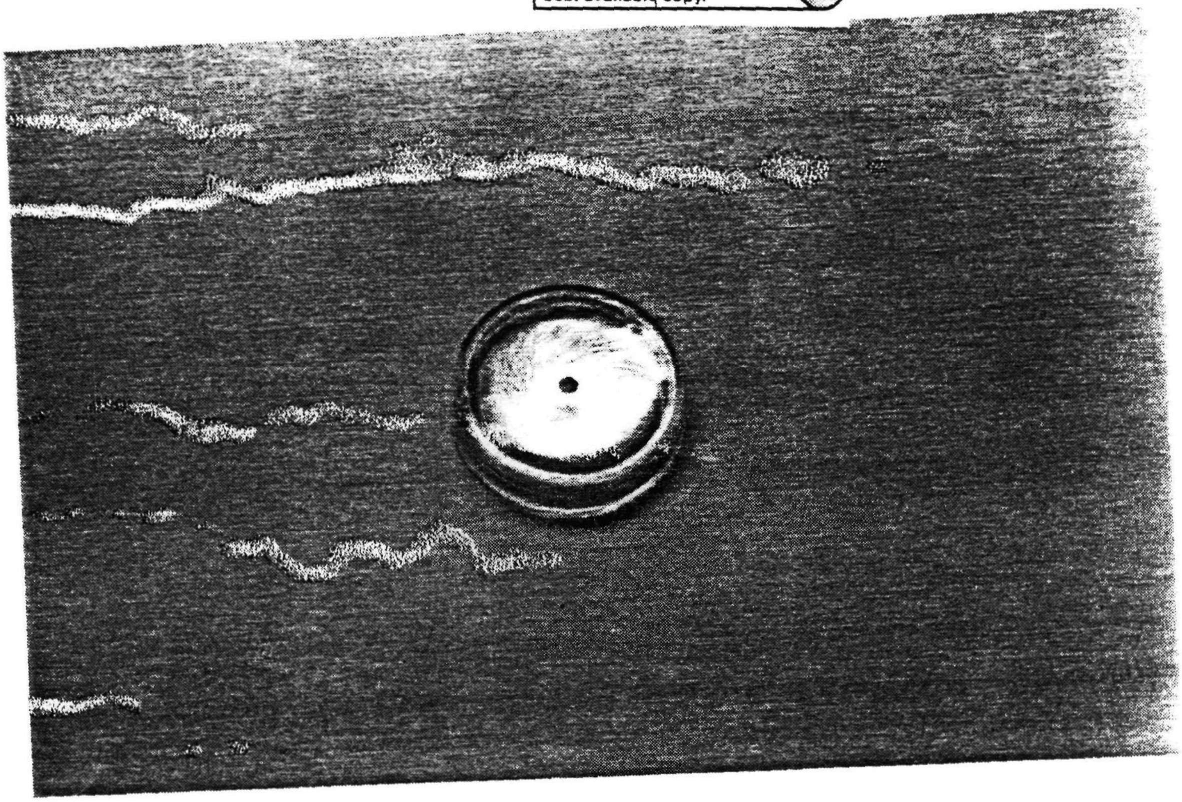

Figure B2. Disc of hardened resin, the cementing agent in the artificial reservoir.

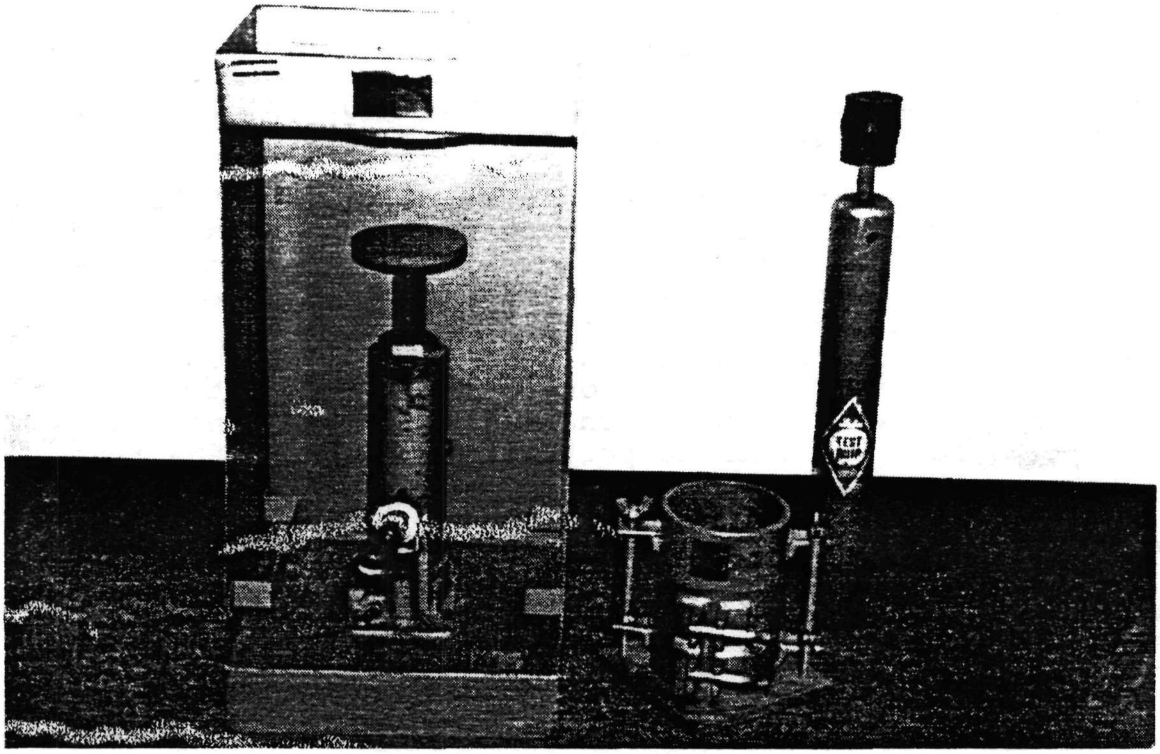

Figure B3. Standard Proctor mold (center), hammer (right), and hydraulic-jack sample remover.

permeability in amounts smaller than required for the overall purposes of the experiment. (The correctness of this hypothesis was demonstrated by tests conducted by Amoco (Attachment B2, p. B2.2).) Numerous other samples were made, in general keeping the proportions of sand as recommended by Halliburton, but reducing the amounts of resin to fractions of the originally recommended volume (Figure B4; Attachment B2).

A matter of additional concern was the outer "skin" shown by several samples; at the interface of resin-and-sand and the mold (coated on the inside with a waxy parting-agent), resin formed a hard, lustrous surface, indicative of a layer of too much cement, and strongly suggestive of a membrane of much less permeability than the interior of the artificial rock. As discussed elsewhere in this report, the design of the artificial reservoir requires that fluid move radially through the disc of rock and then to ports in the wall of the reservoir housing. To test the hypothesis that resin-skin-effect could be eliminated, and radial and peripheral movement of fluid at the wall of the reservoir housing could be insured, a "shell" of coarse grained sandstone was added in bench models of the reservoir (Figure B5). The skin effect was eliminated; the outer shell of the reservoir is rock of enormous permeability (Attachment B2, Sample 8).

Overall results of the several samples tested by Amoco are shown in Figure B6. Samples 5 and 6 are in the general range of porosity and permeability expected in actual injection-formations; these samples contained only about 80 percent of the standard Halliburton recommendation, and both samples were compacted in the Standard Proctor manner (Attachment B2).

Construction of the full-scale artificial reservoir was modeled after the properties of Samples 5 and 6, Figure B6. Amounts of sand and resin proportioned to yield a mixture of approximately 80 percent of the full Halliburton recipe were placed inside a coarse-grained shell, in several "lifts" (Figures B7 through B9). The sand and resin necessarily were mixed in batches in a mortar box, first by hand, then by use of a small roto-tiller (with the better results). Each lift was compacted by hand, with tools designed to have tamping-effects similar to those of the Proctor hammer, and with technique intended to duplicate the effects of the Proctor hammer, insofar as possible.

## SEALING OF RESERVOIR AT CONTACTS WITH BLIND FLANGES

Conditions of the experiment require that all fluid that is injected into the reservoir flow generally in radial paths, to discharge through ports in the side of the reservoir

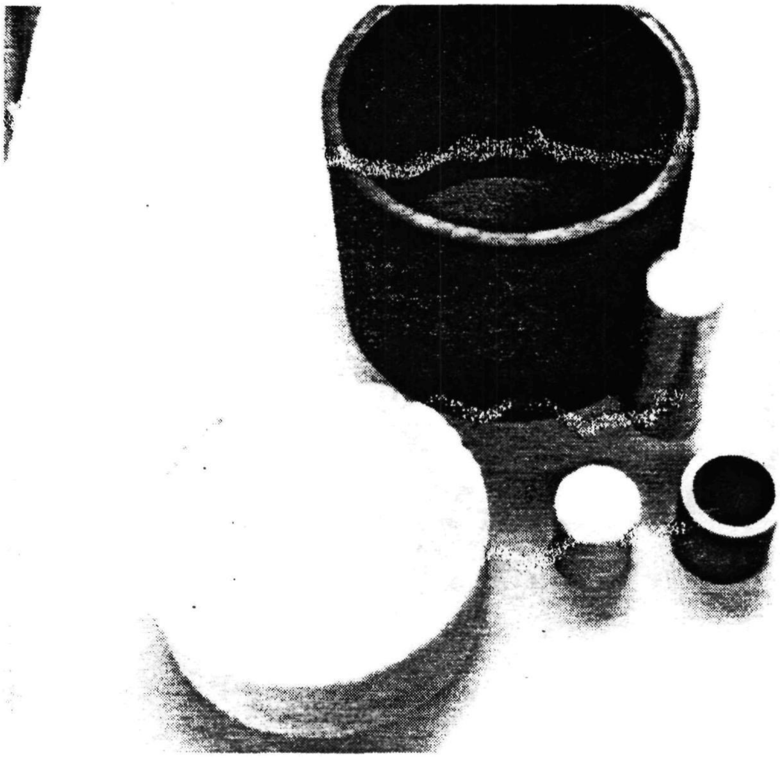

Figure B4. Molds 4 in. and 1 in. in diameter, and bench-test samples of artificial reservoir. Samples were poured to test methods of tamping the wet reservoir mixture, to test porosity and permeability and to test parting-compounds. Parting-compounds were to insure that reservoir would not stick to housing of artificial reservoir.

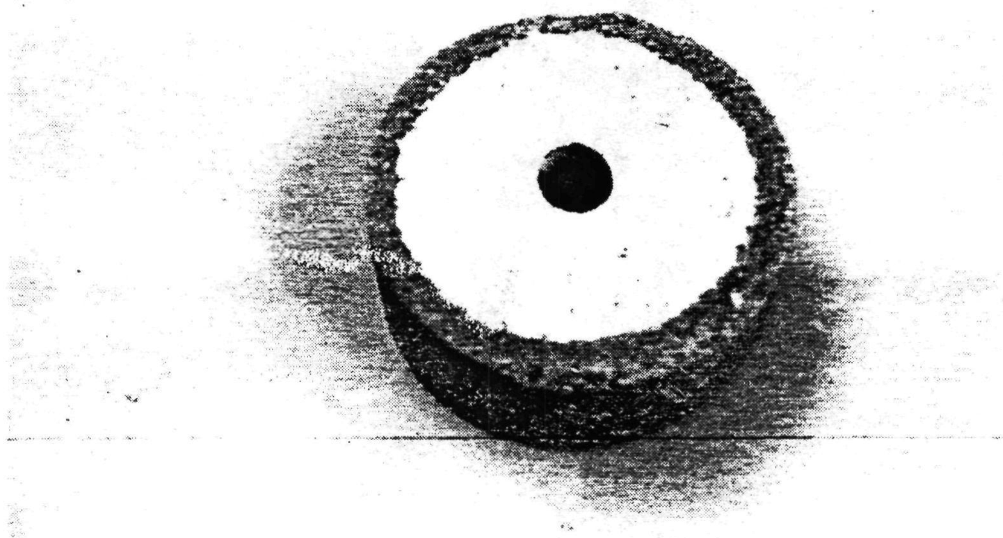

Figure B5. A model of the artificial reservoir composed of sand with resin binder. Light-colored portion mostly is very fine grained quartzose sand. Outer portion is coarse grained sand, with the smaller proportion of resin. The outer "shell" was designed to permit fluid to move freely at the periphery of the reservoir, toward ports in the wall of the artificial-reservoir housing.

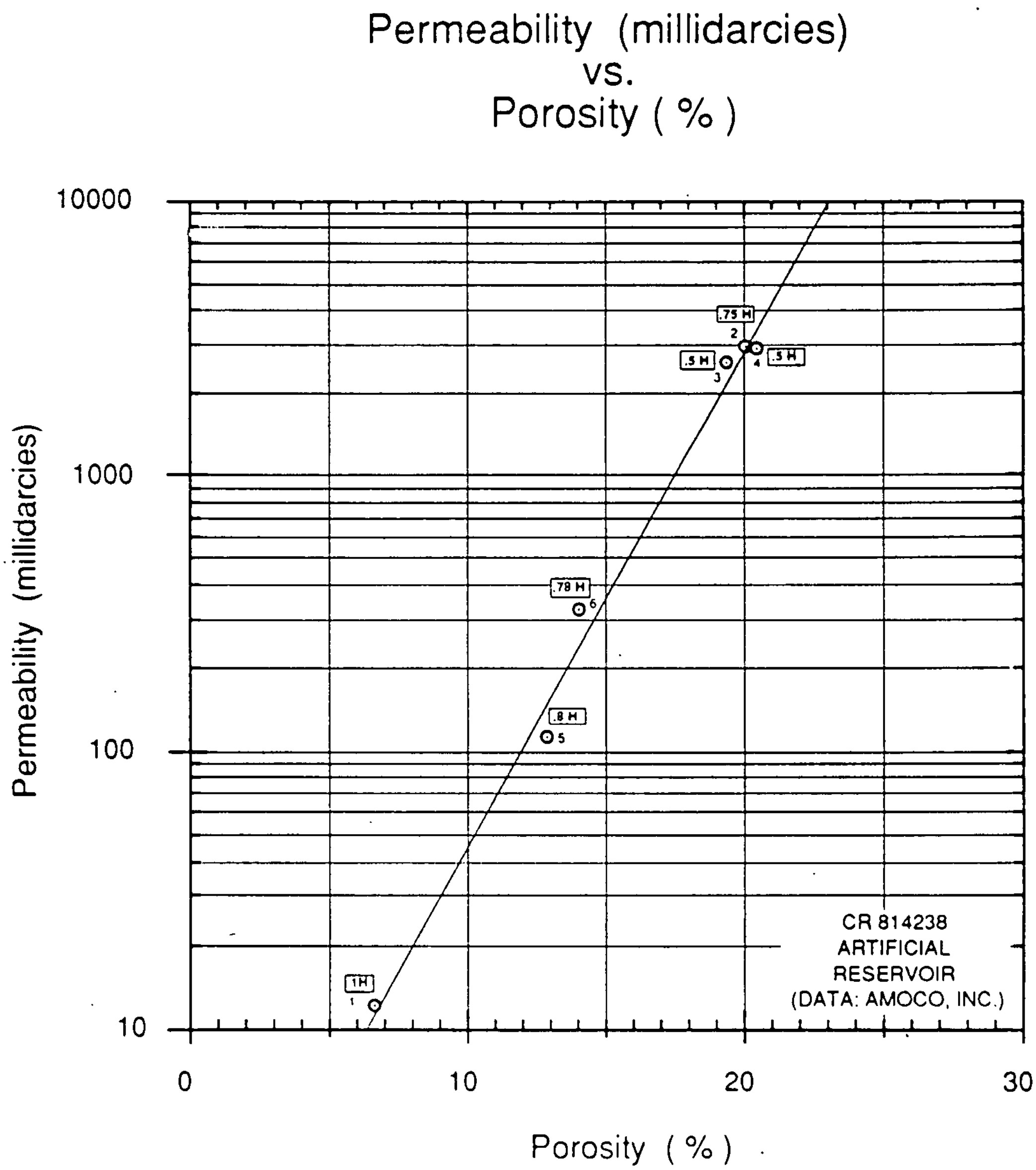


Figure B6. Plot of porosity compared to permeability, samples of artificial reservoir. Tests conducted by Amoco Production Co. (See Attachment B2, Appendix B).

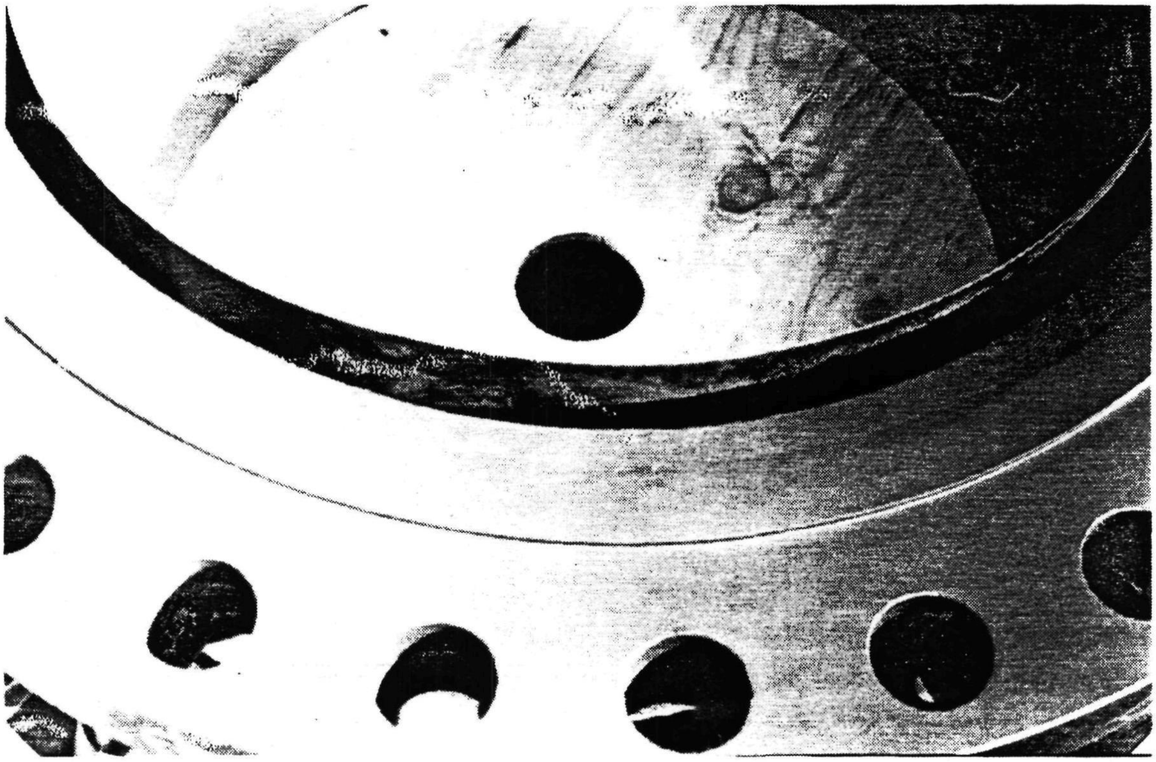

Figure B7. Artificial-reservoir housing, showing view into empty central chamber. Plywood disc supported sheet-metal cylinder, which extended to within 1 in. of outer wall of reservoir housing. Within this 1-in. space, coarse grained sand and resin were poured to form highly permeable outer part of reservoir.

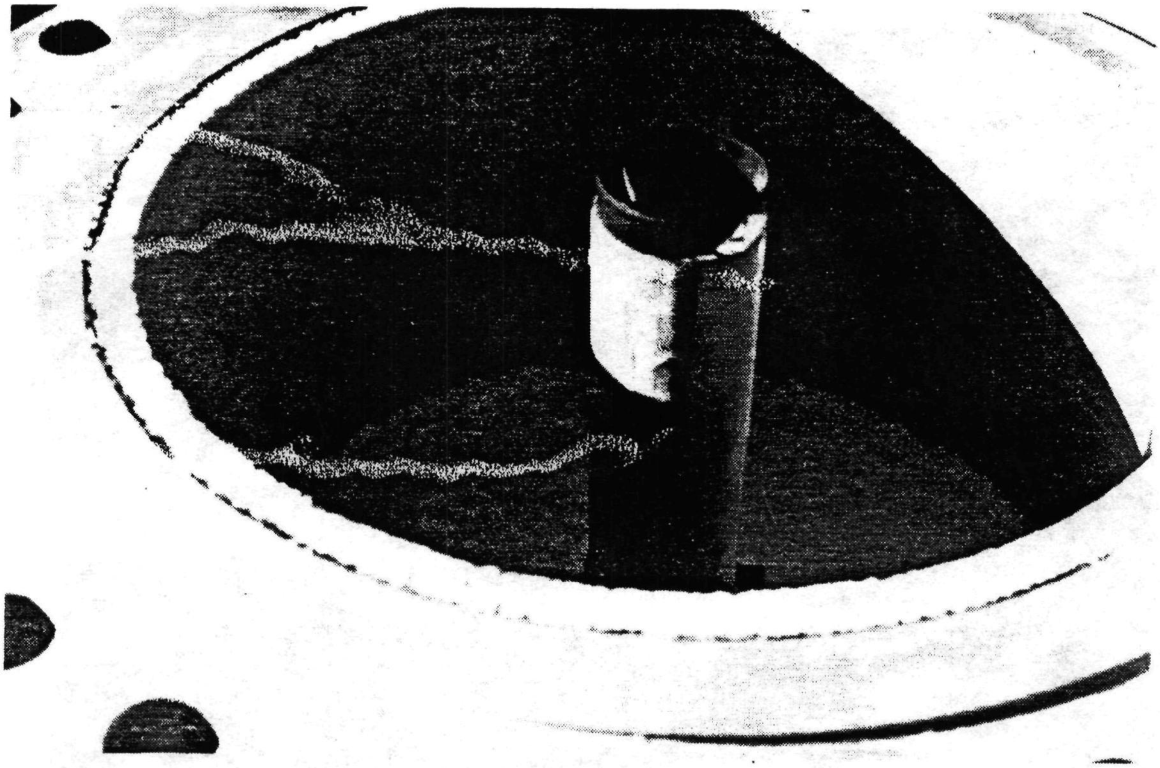

Figure B8. Interior of artificial-reservoir housing, during emplacement of central part of reservoir. Average size of grains in outer part of reservoir suggested by loose grains atop housing-flange. A "lift" of compacted fine grained sand with resin binder partly fills reservoir housing. Coarse-grained outer part of reservoir is separated from metal of artificial-reservoir housing by a thick, stiff high-density polyethylene liner, to which the sand is not bonded.

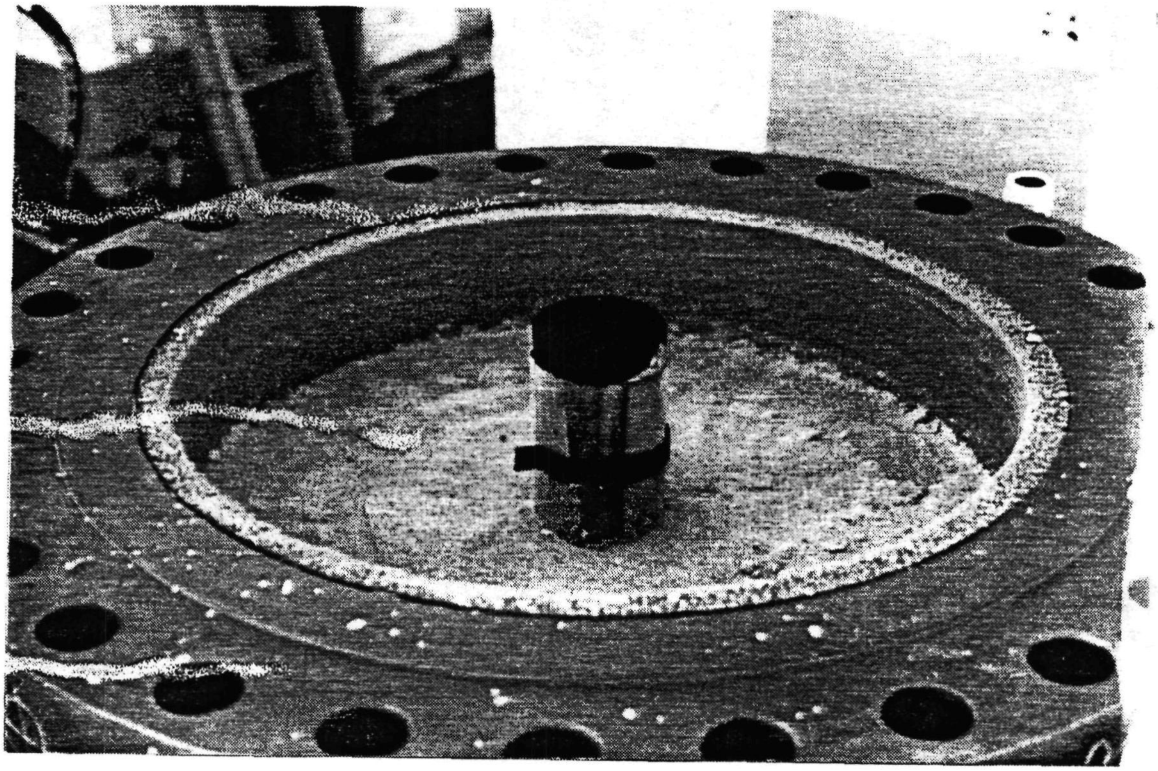

Figure B9. Nearly completed artificial reservoir. Several "lifts" of fine grained material emplaced and compacted within the hardened, coarse-grained outer shell of reservoir.

housing. Fluids are not to travel along the interfaces between the top and bottom of the reservoir-disc and the blind flanges of the reservoir housing (Figure B10). Numerous tests were conducted to find strong, sealing adhesive material that could be placed on the top (and bottom) of the artificial reservoir, under gasket material that would separate reservoir and blind flange. Strength and flexibility are necessary properties of the bonding material.

Adhesives tested were of three general types: acrylates, epoxies, and silicones. Gasket materials tested were polycarbonate plastics, mineral-based fiber materials, and high-density polyethylene sheeting. Each adhesive was tested for bonding-ability between the artificial reservoir and the gasket materials (Figure B11). Two adhesives were effective to acceptable levels: Hardman Acrylic-04050, and Permatex RTV clear silicone; Hardman Acrylic-04050 is not available in quantities required for this experiment. A second attribute of Permatex RTV silicone was tested closely: strength of bonding to the Klinger C-4401 mineral-based fiber gasket material. A knife-edge compression test (Figure B12) showed that compressive force of 15,250 psi was required to separate the adhesive and the gasket material; in a tensile-strength test, (Figure B13) a load of 1,100 psi was required to separate the adhesive from the gasket material and from the reservoir material. All gasket materials were tested for compressive strength; all withstood compressive loads of more than 15,000 psi without damage.

Permatex RTV clear Silicone Adhesive Sealer 66B was used to form bond and seal between the artificial-reservoir material and the Klinger C-4401 mineral-based fiber gasket material. Because none of the ten adhesive substances tested would cling to the high-density polyethylene sheeting (HDPE), this material was used as the liner between the artificial reservoir and the walls of the reservoir vessel (Figure B8), so that the reservoir can be extracted.

ARTIFICIAL-RESERVOIR SYSTEM

Figure B14 shows the relationship of the artificial rock to the reservoir housing and the wellhead assembly. Just the housing is shown in Figure B15.

The radial location of the effluent lines is shown in Figure B16 and the side view of these effluent lines is shown in Figure B17.

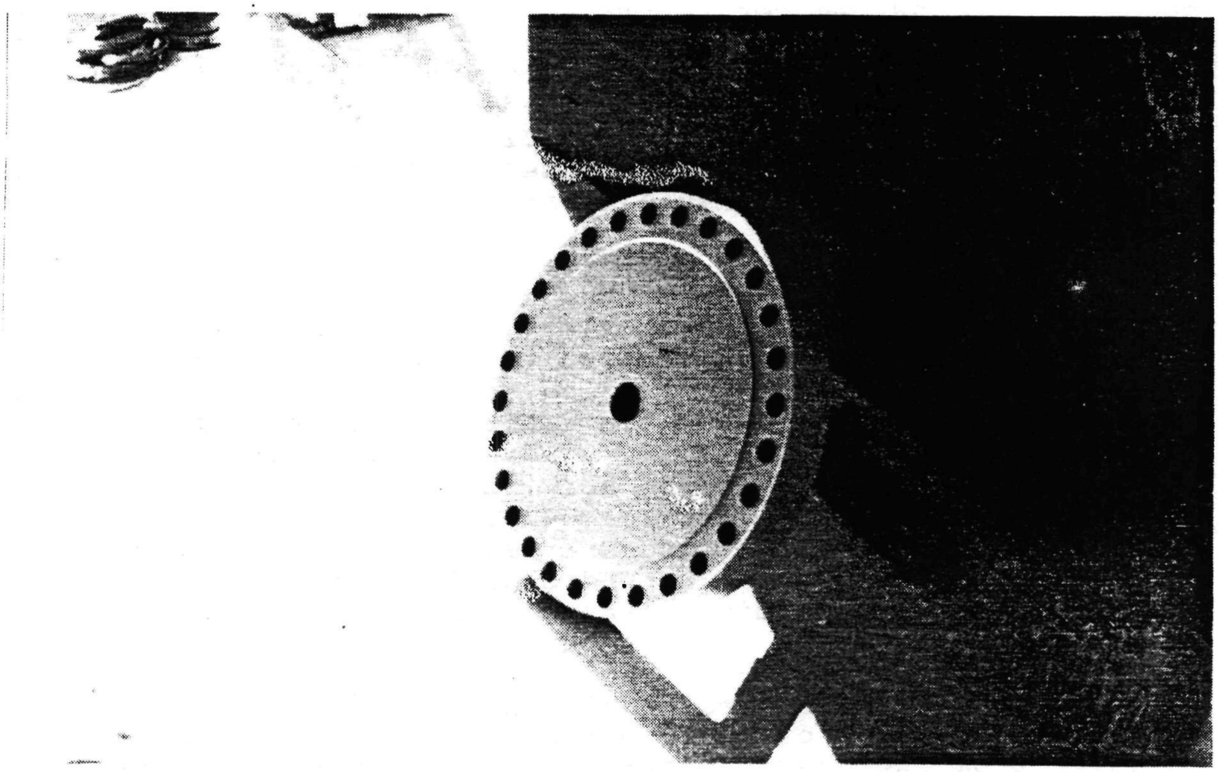

Figure B10. Inner (lower) side of top blind flange of the artificial-reservoir housing. The elevated smooth surface between the outer ring of holes and the central hole will be on top of the artificial reservoir.

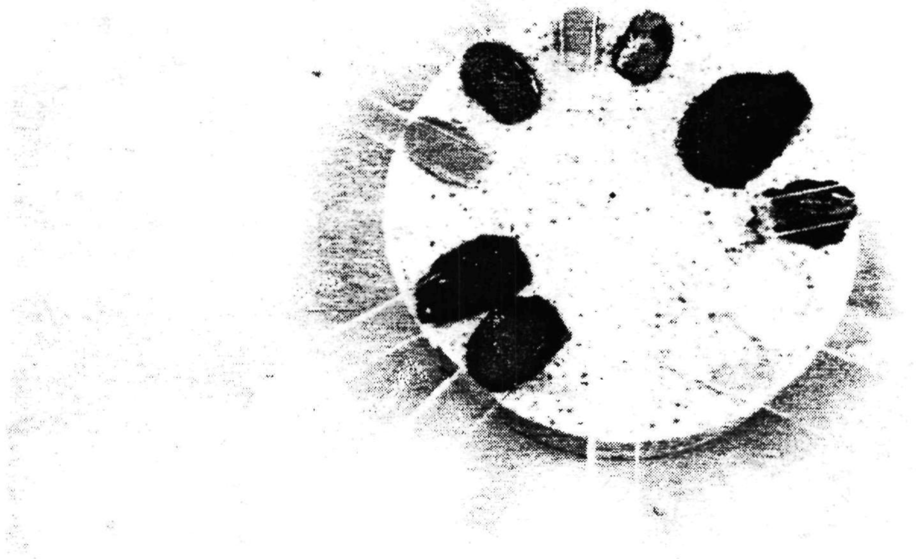

Figure B11. Tabs of polycarbonate gasket material attached to sample of artificial reservoir, for testing the strengths of bonding agents.

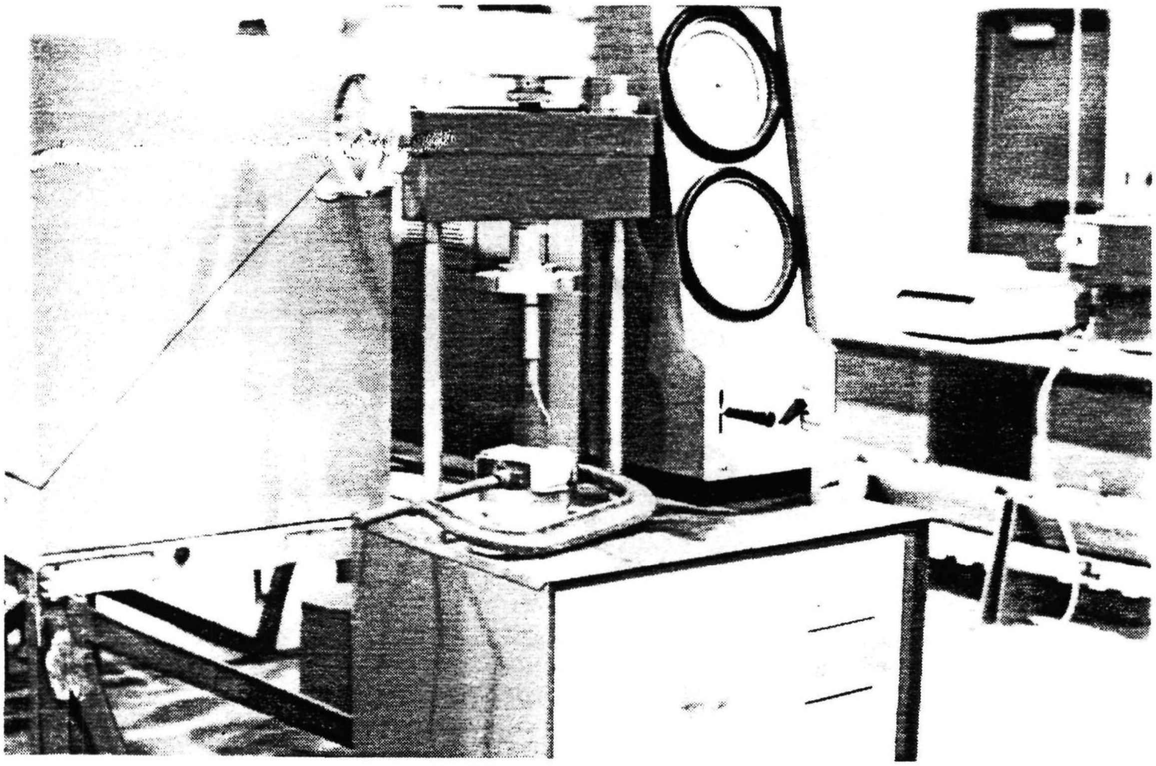

Figure B12. Knife-edge compression test of sample of artificial reservoir, on Versa-Tester Model 1000 compression-testing device. Test designed to measure splitting-resistance of adhesive (not visible) that binds two pieces of rock. The adhesive was tested for effectiveness of bonding artificial reservoir to gaskets between reservoir and flanges of artificial-reservoir housing. Compression of 15,250 psi was required to separate the materials.

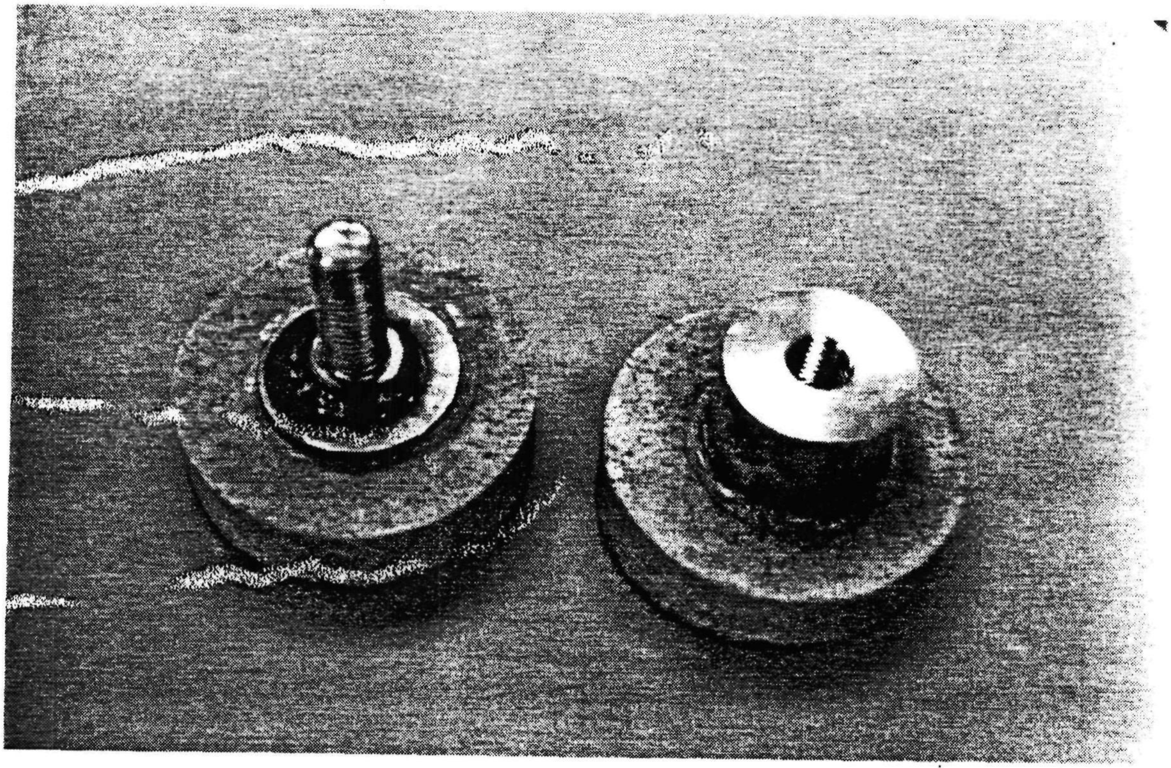

Figure B13. Specimens of artificial reservoir bonded to parts of devices used in testing for tensile strength of material. Adhesive was tested on a Riehle Test Machine, for effectiveness of bonding artificial reservoir to gaskets between reservoir and flanges of artificial-reservoir housing.

# APPENDIX B

## ATTACHMENT B1

HALLIBURTON SERVICES

CHEMICAL RESEARCH AND
DEVELOPMENT DEPT.

DRAWER 1431, DUNCAN, OKLAHOMA 73536

REGINALD M. LASATER, Manager
RONNEY R. KOCH, Assistant Manager

May 8, 1989

Dr. Marvin Smith
499 Cordell, South
Oklahoma State University
Stillwater, OK 74078

Dear Dr. Smith:

As I mentioned on the phone in our conversation, the following formulation using epoxy resins and fairly large sand should provide the 200 md "synthetic" formation you need. While this is not the formulation we routinely use, it should be suitable for your application since no high temperature cure is required. This limits usage of product to temperatures below 120°F. At higher temperatures the epoxy resin will soften. The final permeability is dependent upon the effort used in tamping the resin coated sand down in to the mold. The resin coated sand will have the texture of a stiff mortar before it hardens.

The following formation will mix about 2.3 cu. ft. It can be handled in a small cement mixer:

150# Okla. #1 Sand
50# 12/20 mesh frac sand
19# mixed epoxy resin (mixed separately, then blended into the mixed sands.)

Epoxy resin mixture (has a pot life of about 1 hour)

14# 13 oz. of epoxy resin (ER-1)
67 cc. of Silane A-1120

Mix the above for about 5 minutes before continuing.

3# no oz. of epoxy hardener (EPSEAL C-4)
1# 3 oz. of accelerator (EPSEAL C-1)

Avoid adding the accelerator until just before adding the resin mix to the sand. Allow 3-5 minutes to completely mix the accelerator into the other chemicals and then add the mixed resin to the sand.

Your test chamber sounds like it is about 13 cu. ft. As this is probably too large an amount for a single batch, I want to stress that you should tamp the coated sand in firmly, rough up the surface so that it will blend in with the next batch and repeat the mixing procedure.

Clean the mixer at least every hour, using hot soapy water and a polar organic solvent. Acetone, isopropyl alcohol, methyl ethyl ketone, methyl chloroform are examples of material which may be used. The resin must be removed from the mixer and all working tools before it hardens.

The following materials should provide for two tests.

2000# Okla #1 sand
600# 12/20 frac sand
20 gal (182#) ER-1 epoxy resin
6 gal (40#) EPSEAL C-4
2 gal (13#) EPSEAL C-1
1 qt. (946 cc liquid) Silane A-1120)

I hope that these are satisfactory.

Sincerely,

Joe Murphey
Research Chemist
Water & Sand Control - CRD

JM:sc

cc: R. R. Koch
C. H. McDuff
J. A. Knox
J. M. Wilson
J. D. Weaver
C. W. Smith

APPENDIX B

ATTACHMENT B2

AMOCO PRODUCTION COMPANY

LARGE CORE

CORE ANALYSIS DATA RECORD

LAB NO.: 2585801
DATE: 10-18-89

WELL: Oklahoma State University - Artifical Cores

STATE: ____

FIELD: ____

API WELL NO.: ____

| Sample Number | Depth (ft) | Permeability-Millidarcies | | | Porosity % | Saturation % - PV | | Grain Density | Description |
|---|---|---|---|---|---|---|---|---|---|
| | | Maximum | 90° from Max. | Vertical | | Oil | $H_2O$ | | |
| 1 | --- | | | 12. | 6.7 | | | 2.27 | * |
| 2 | --- | | | 2960. | 20.1 | | | 2.53 | * |
| 3 | --- | | | 2570. | 19.4 | | | 2.52 | * |
| 4 | --- | | | 2890. | 20.5 | | | 2.53 | * |
| 5 | --- | | | 111. | 12.9 | | | 2.40 | * |
| 6 | --- | | | 324. | 14.1 | | | 2.43 | * |
| | | | | | | | | | |
| | | | | | | | | | |
| | | *Refer to attached OSU document (89293ART0104) which describes the make-up of each artificial core. | | | | | | | |
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SRD
89291ART0021

AMOCO PRODUCTION COMPANY

SMALL CORE

CORE ANALYSIS DATA RECORD

LAB NO.: 2585801

DATE: 10-18-89

WELL: O.S.U. - Artifical Core Plugs STATE:

FIELD: API WELL NO.:

| Sample Number | Depth (ft.) | Permeability Millidarcies | | Porosity % | Grain Density | Sat. % - PV | | Description |
|---|---|---|---|---|---|---|---|---|
| | | Horiz. | Vert. | | gm/cc | Oil | H2O | |
| | | | | | | | | |
| 7 | --- | 7.8 | | 17.0 | 2.39 | | | * |
| 8 | --- | ≅103,000 | | 34.5 | 2.57 | | | * |
| | | | | | | | | |
| | | | | | | | | |
| | *Refer to attached OSU document (89293ART0104) which describes the make-up of each artificial core. | | | | | | | |
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SRD
89291ART0050

DESCRIPTION OF SAMPLES OF ARTIFICIAL ROCK, DELIVERED TO J. BOWEN, AMOCO, BY M. SMITH, OKLA. STATE UNIV., 22 AUG. 89, P. 1/3

Sample 1: Dated 26 July 89 and labelled, in blue, "Full Halliburton Mix With Standard Three-lift Proctor Compaction.*"

1. Oklahoma No. 1 Sand: 1020.6 gm
2. "12 - 20" Frac sand: 340.2 gm
3. Epoxy Resin-1: 100.7 gm**
4. Epseal C-4 (hardener): 20.4 gm
5. Epseal C-1 (accelerator): 8.1 gm
6. Silane: 1 cu cm

Silane was mixed with Epoxy Resin-1 for 5 minutes. To this mixture were added Epseal C-4 and C-1. The composite fluid was mixed for 5 minutes, then added to sand in small stream that was blended continuously by hand mixing.

* The term "Standard Proctor Compaction" refers to the consolidation of soil in a mold that is 4 inches in diameter and 4.5 inches high, part of a process to test soil for optimal density. In standard procedure the mold is filled with three "lifts" of soil; each lift is compacted by the dropping of a 5.5-pound hammer through 12 inches for 25 repetitions, distributed "evenly" across the upper surface of the mold.

The mixture of sand and resin was compacted in a Proctor mold, by dropping the 5.5-pound hammer through approximately 11 inches. (The mixture of sand and resin was of a "fluffy" consistency, which allowed the hammer to penetrate too far and which led to forcing of the mixture into the air-discharge holes in the tubular hammer-guide.) Twenty-five blows were distributed "evenly" across each lift of sand-and-resin.

**All weights of fluids, as shown, are misleadingly exact. Measurement could be controlled to 0.1 gm. However, actual amounts poured together and ultimately mixed into sand were somewhat less than shown here, because of retention of fluid on sides and bottoms of containers. If measurements of amounts retained are wanted, useful approximations of the average amounts retained on vessels can be furnished.

Sample 2: Dated 28 July 89 and labelled: 3/4H, w/ Standard Proctor (Compaction).

1. Oklahoma No. 1 Sand: 1020.6 gm
2. 12 - 20 Frac Sand: 340.2 gm
3. Epoxy Resin-1: 75.5 gm
4. Epseal C-4: 15.3 gm
5. Epseal C-1: 6.1 gm
6. Silane: 0.8 cu cm

Description, samples, artificial rock to J. Bowen, AMOCO, from M. Smith, OSU, 22 Aug. 89, p. 2/3

Note: Compacted in standard Proctor fashion, with final compaction of 25 blows onto rigid plastic disc atop sand-and-resin mixture.

Sample 3: Dated 31 July 89 and labelled: "1/2H, w/ Full Proctor (Compaction)."

1. Oklahoma No. 1 Sand: 1020.6 gm
2. "12 -20" frac Sand: 340.2 gm
3. Epoxy Resin-1: 50.4 gm
4. Epseal C-4: 10.2 gm
5. Epseal C-1: 4.0 gm
6. Silane: 0.5 cu cm

Five compacted lifts were required to produce a full mold. Compaction seemed to be effective for a few blows, after which the material developed a rather resilient toughness. Topmost lift was compacted evenly across the surface, but last impact left a "footprint." The final compaction was done by putting a rigid plastic disc atop the sand-and-resin mix, and hammering the disc 25 evenly spaced blows.

Sample 4: Dated 8-3-89 and labelled: "Modified Proctor, 1/2 (Halliburton) Mix."

1. Oklahoma No. 1 Sand: 1020.6 gm
2. 12 - 20 Frac Sand: 340.2 gm
3. Epoxy Resin-1: 50.4 gm
4. Epseal C-4: 10.2 gm
5. Epseal C-1: 4.0 gm
6. Silane: 0.5 cu cm

Compaction: With Proctor hammer, to "rubbery" consistency.

Sample 5: Dated 16 Aug. 89 and labelled: "80+."

Sample mixed using standard amounts of sand, but content of resin only about 80 percent of amount shown in listing under Sample 1. Standard Proctor compaction.

Description, samples, artificial rock, to J. Bowen, from M. Smith, OSU, 22 Aug. 89, p. 3/3.

Sample 6: Dated 16 August 89 and labelled: "78%".

Sample mixed using standard amounts of sand, but content of resin only 0.78 of amount shown in listing under Sample 1. Standard Proctor compaction.

Sample 7: 1 inch in diameter and labelled: "ER"

Molded sample with amount of sand proportional to Halliburton specifications, but 75 percent of Halliburton specifications for resin. Compacted by hand, moderately. One end of sample had full mixture of resin "floated" onto surface.

Sample 8: 1 inch in diameter and labelled: "12/20."

Molded sample of 12 - 20 frac sand only, with 75 percent of standard Halliburton resin. Compacted by hand, moderately.

SRD:sdg
89293ART0104

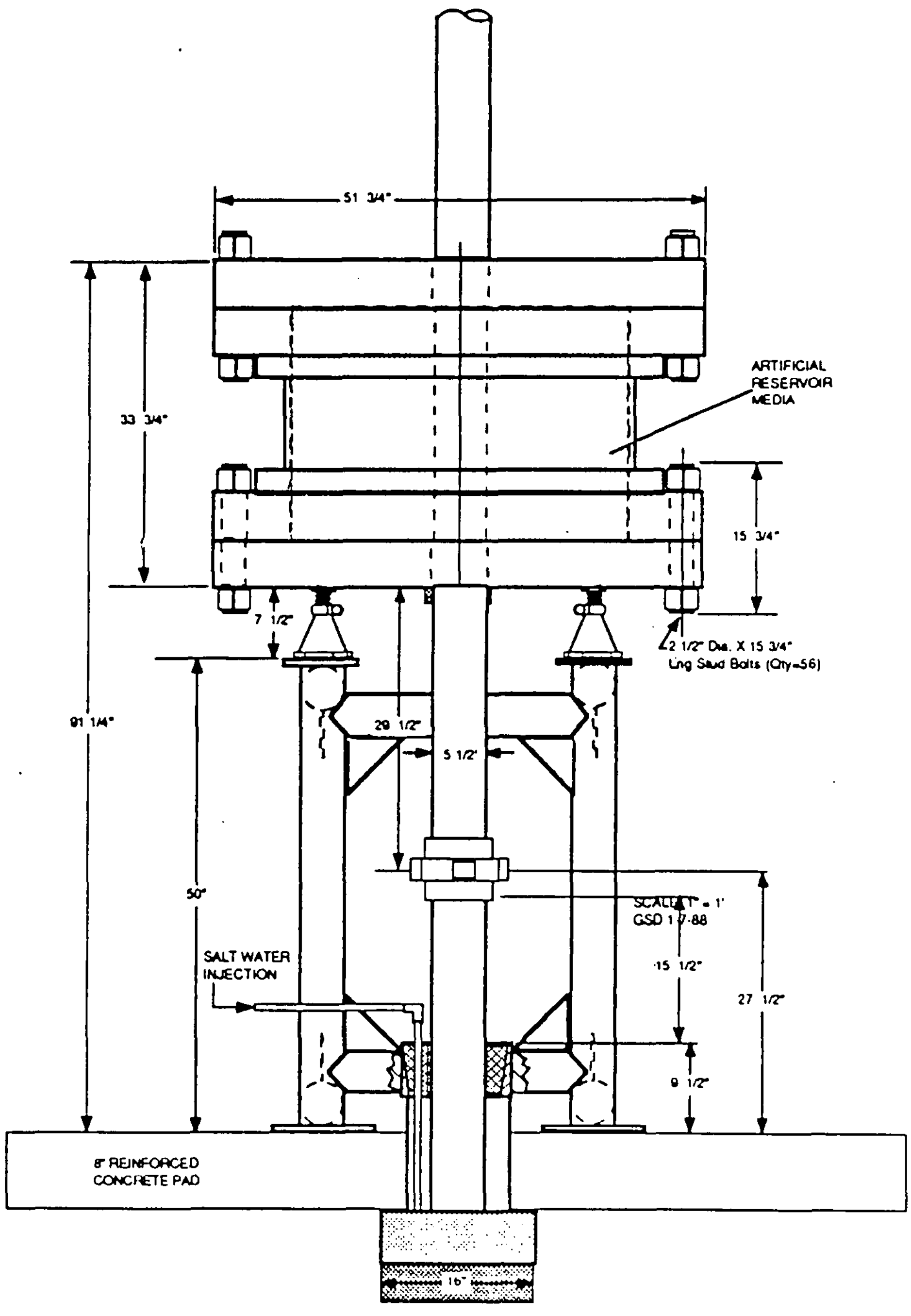
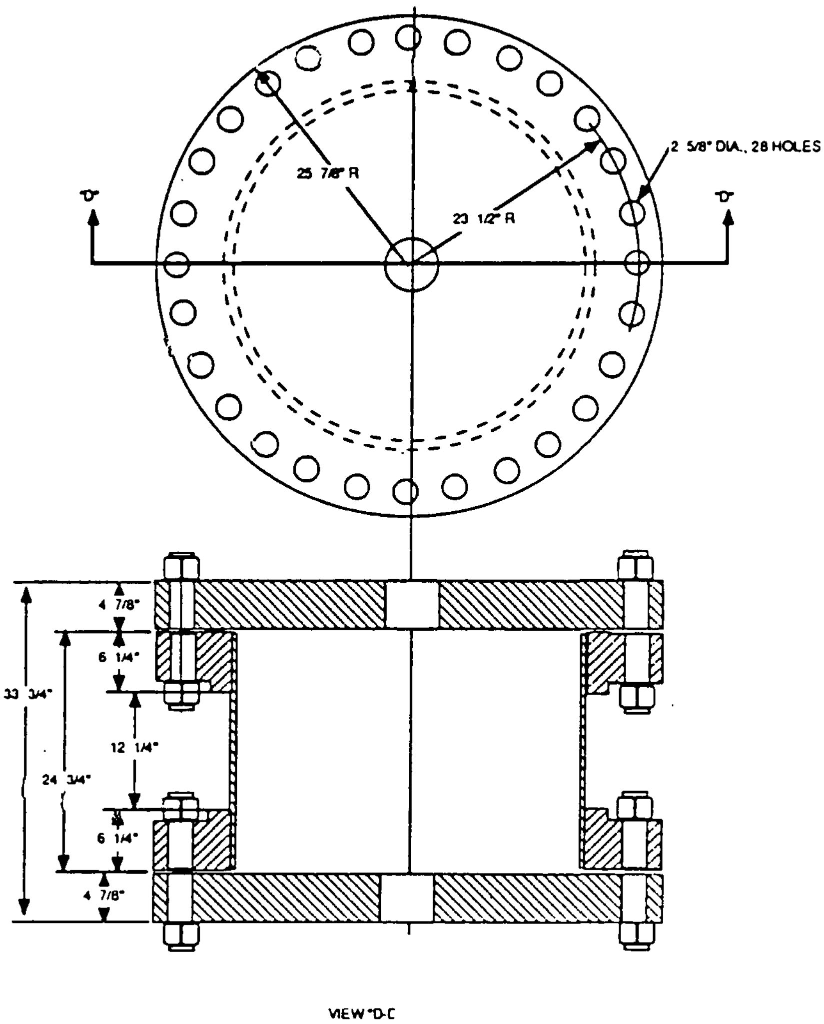



Figure B14. Shaded area shows placement of the artificial reservoir rock.

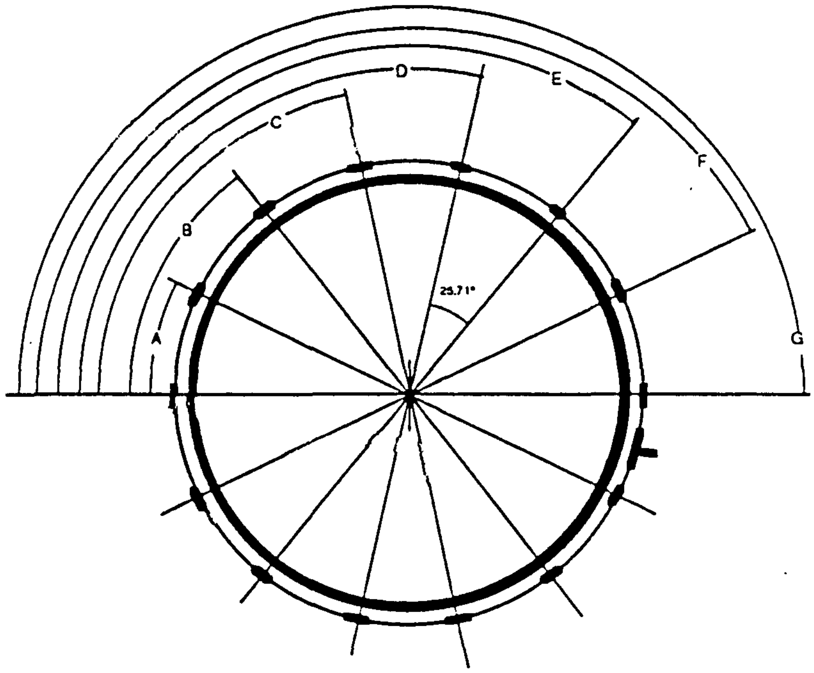
# RESERVOIR SPOOLPIECE




SPOOLPIECE MT'L: 36" O.D. X .750 WALL
API 5LX-X65HT .383
2440 p.s.i. Test Pressure

Figure B15. Artificial-reservoir housing with modified blind-flange end pieces.

Figures B18 through B25 are details of the wellhead assembly, and connection with the housing assembly, and the reservoir-housing support stand.




| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| 8" | 16 1/8" | 24 1/4" | 32 5/16" | 40 3/8" | 48 1/2" | 56 9/16" |

NOTE. THE LOWER RING OF RESERVOIR LEAKOFF HOLES ARE OFFSET BY APPROXIMATELY 26° FROM THE TOP RING.

Figure B16. Locations of reservoir-housing effluent lines.

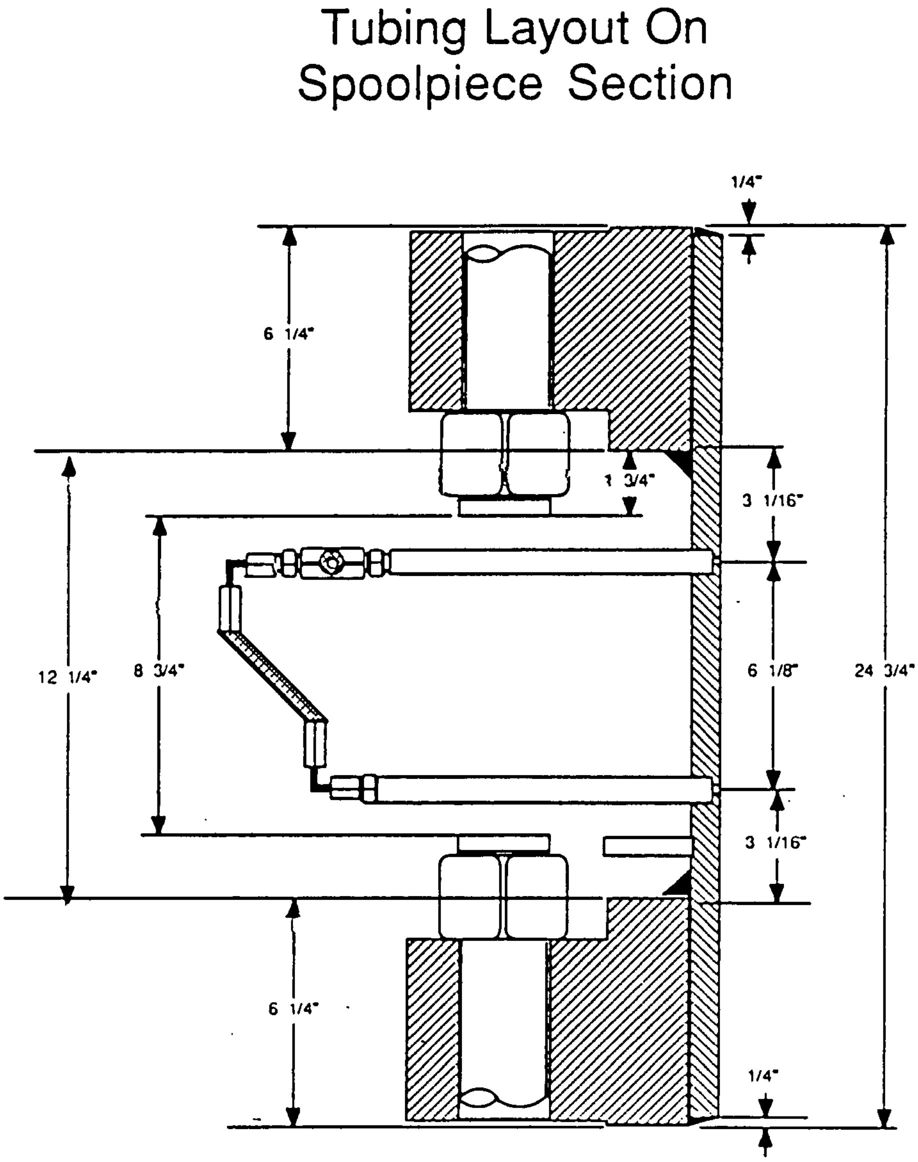



Figure B17. Configuration of reservoir-housing effluent lines.

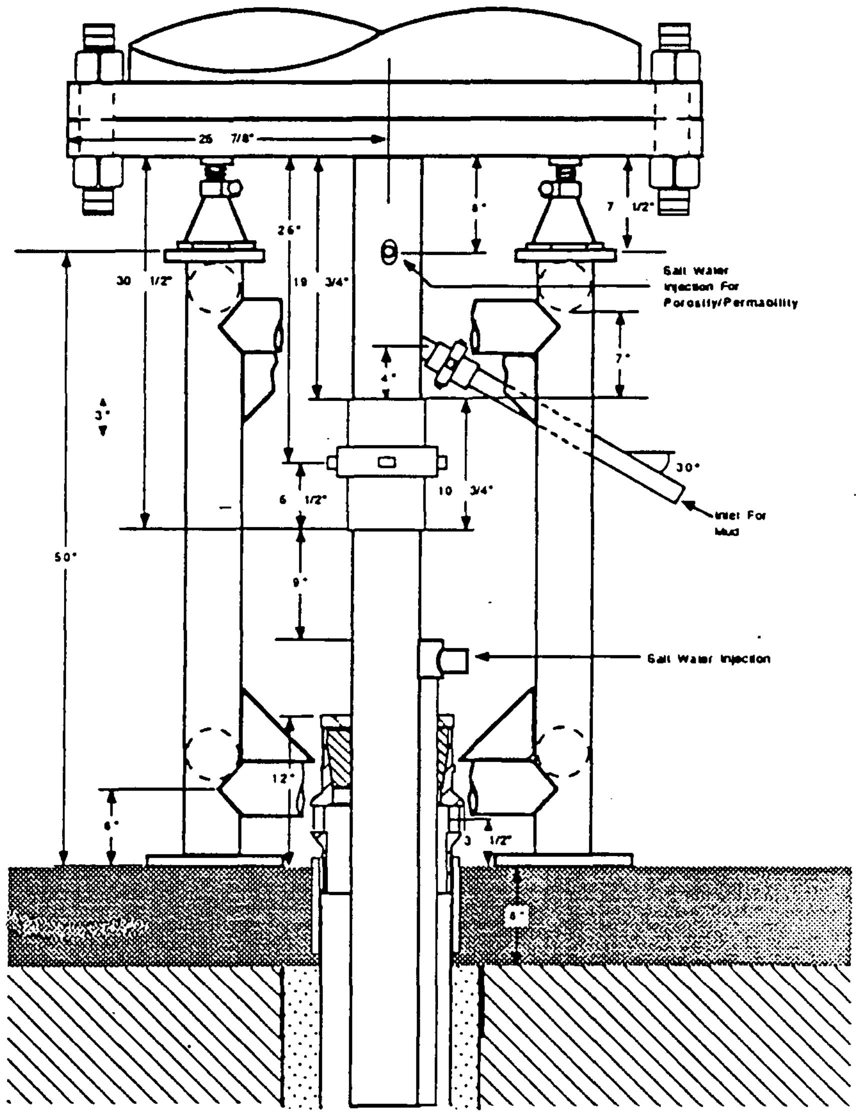


Figure B18. Water connections, mud connections, and well-head configuration below the artificial reservoir.

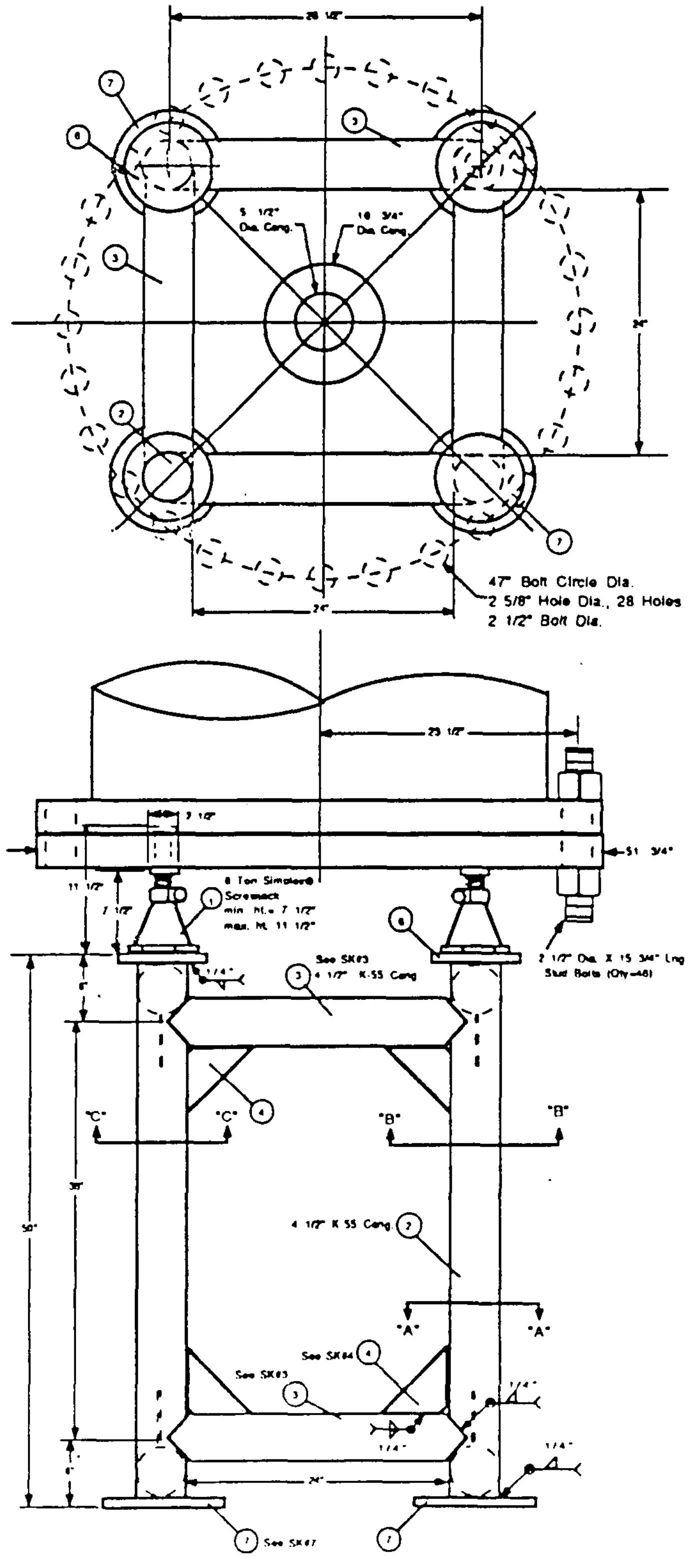



Figure B19. Artificial-reservoir-housing support stand.

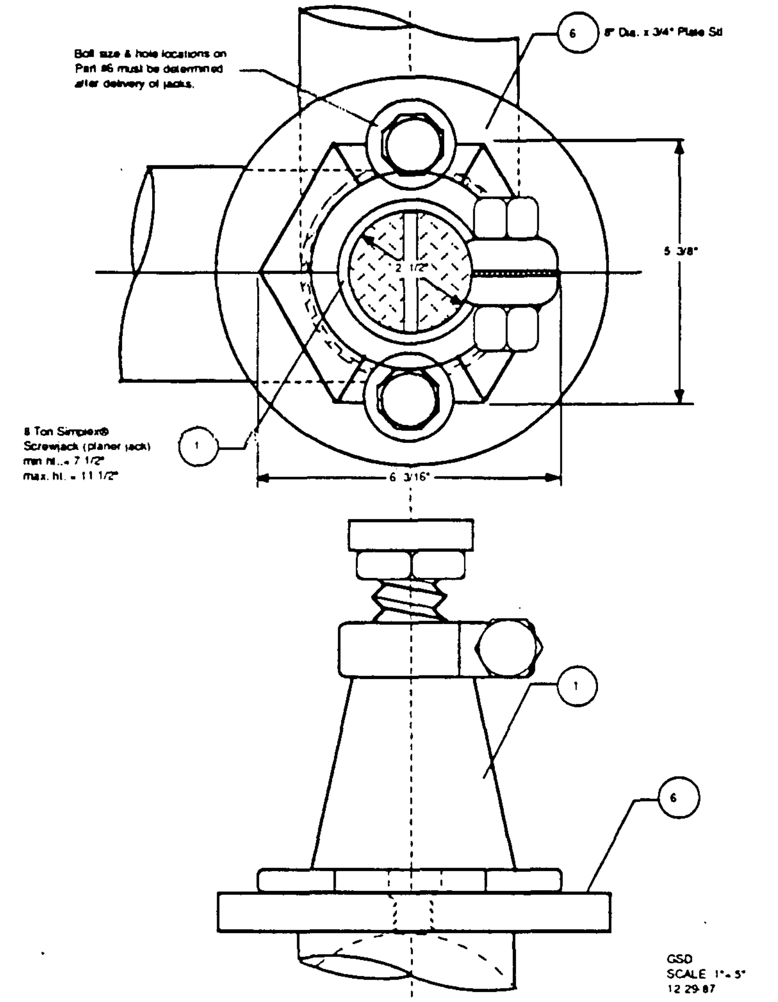



Figure B20. Adjusting-jacks for artificial-reservoir stand.

<u>Note</u>: SK#7 is a
flat steel plate,
10 1/2 in. in diameter
and 1/2 in. thick.
Other numbers with
prefix SK are in
Figures B20 through B24.

HORIZONTAL SUPPORTS

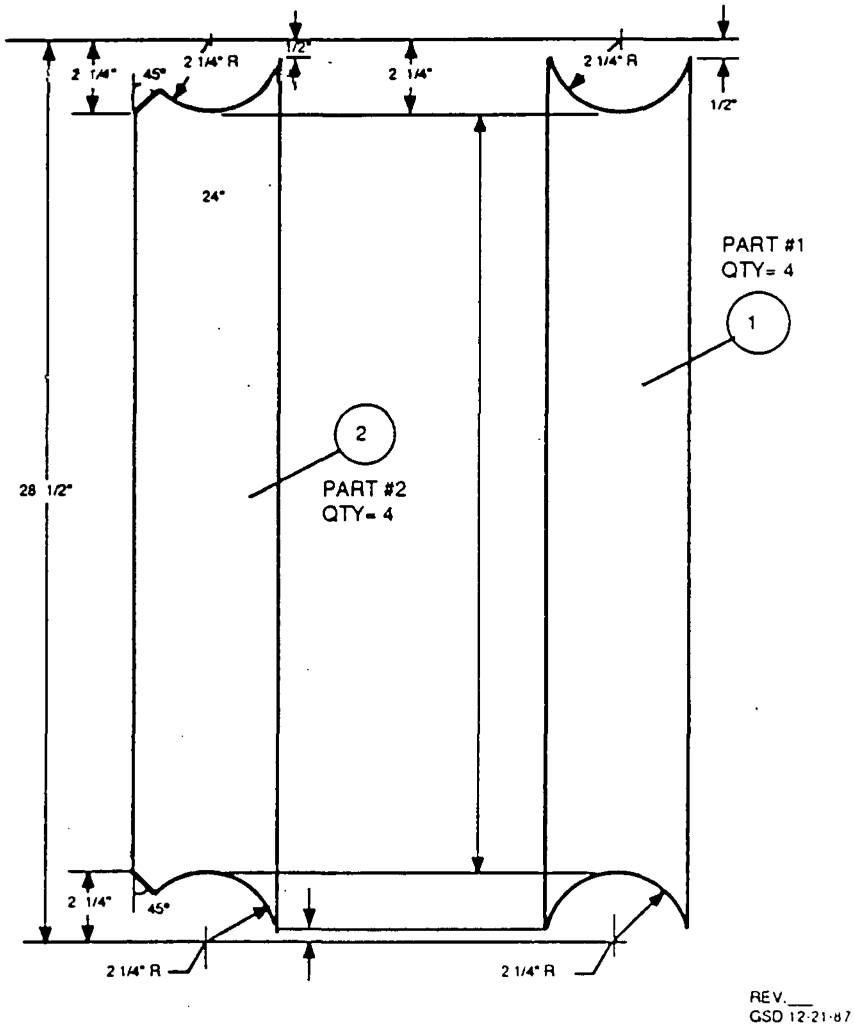



Figure B21. Details of supports for reservoir stand.

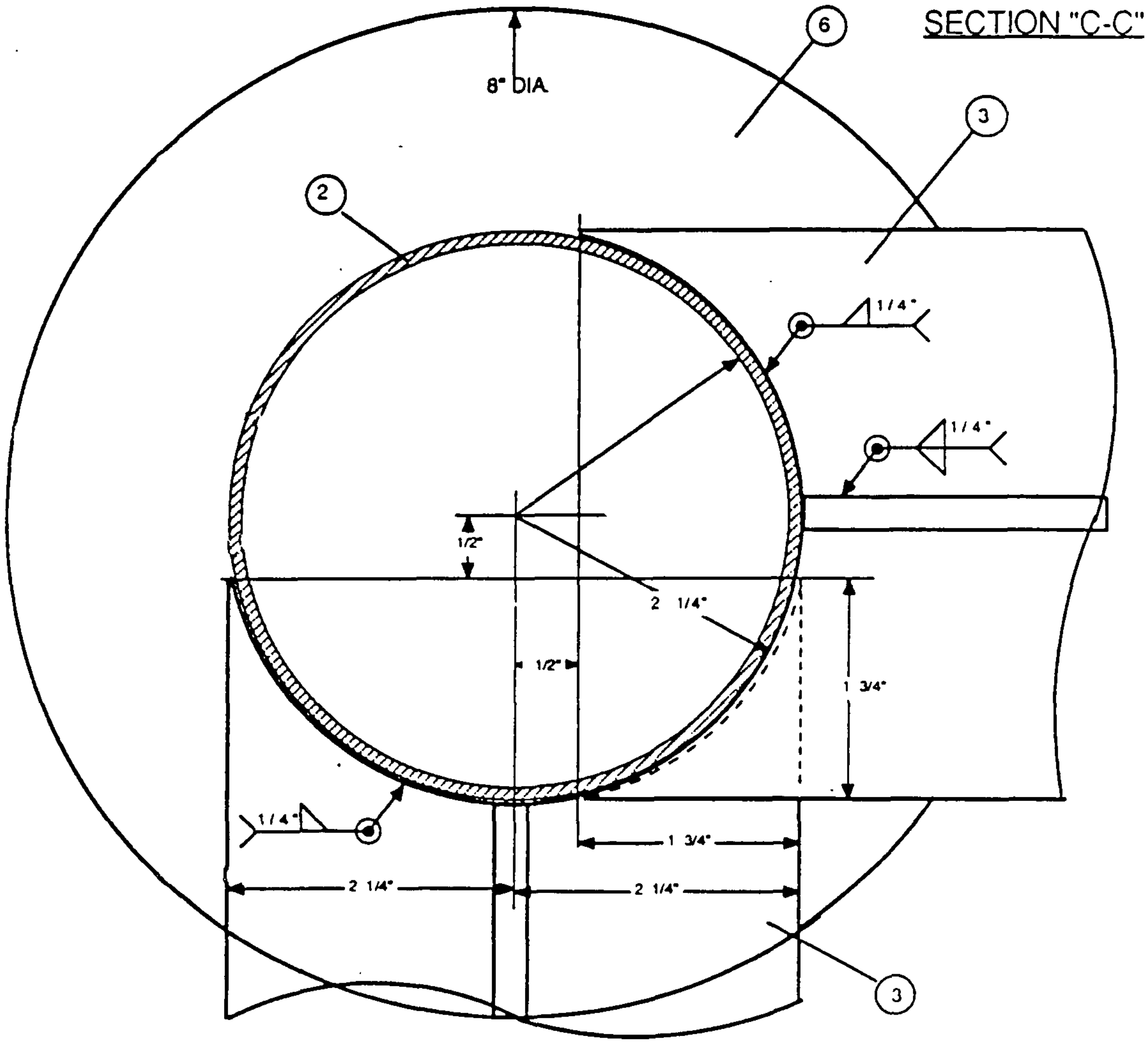



Figure B22. Details of cross-member configuration for reservoir stand.

## SKETCH "4": CORNER GUSSETS

MAT'L = 1/4" THICK, A-36 PLT. STEEL (A.I.S.I. 1010)
QTY. = 16. (SHEAR OR BURN)

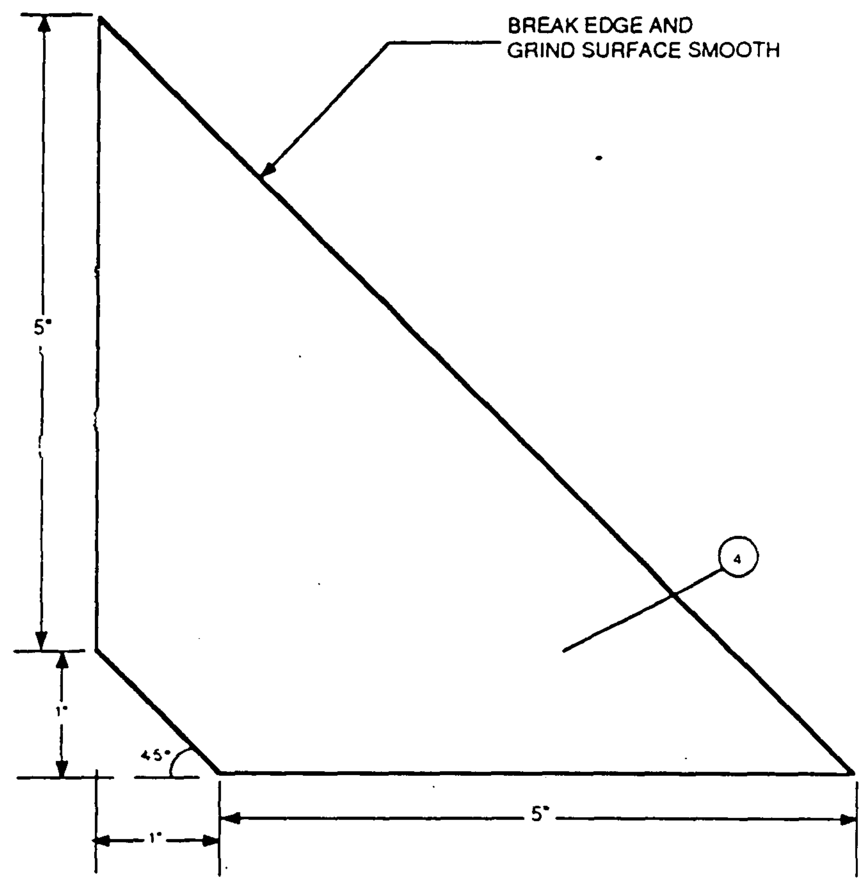



Figure B23. Gusset details for artificial-reservoir housing stand.

## SKETCH #3: PIPE LAYOUT

INSTRUCTIONS: Layout (2), 45° angles from a drawn center of the tubing, and trim as shown. On the opposite end repeat the operation so that the apexes of the 45's are on the same axial centerline.

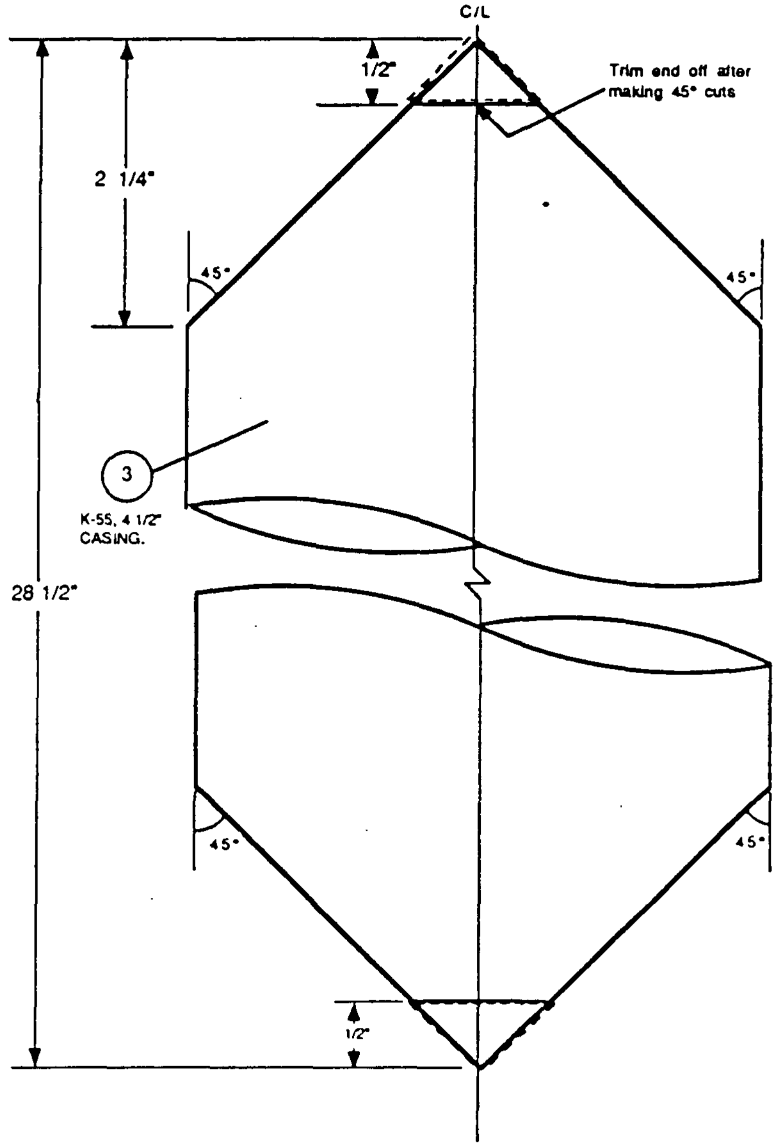



Figure B24. Details of dimensions to cut pipe for welding.

# ASSEMBLY STAND FOR ARTIFICIAL RESERVOIR

NOTES:
- ALL TUBING SHALL BE 4 1/2" CASING
- ALL WELDS SHALL BE MINIMUM OF 1/4" FILLETS

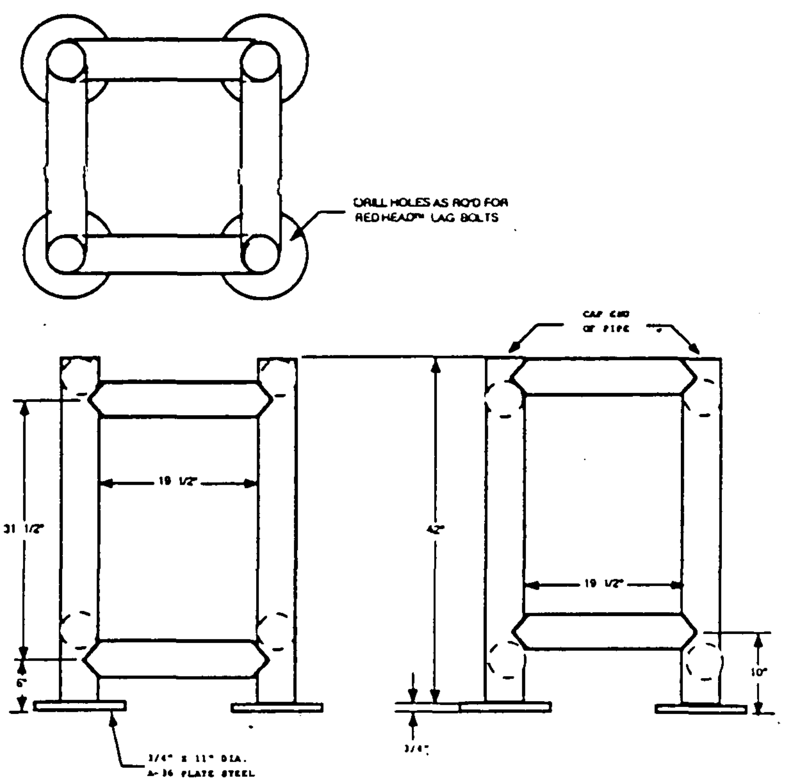



Figure B25. Assembly stand for artificial-reservoir housing.

# APPENDIX C

## SIMULATED LOWER WELLBORE DRAWINGS

Figure C1-A shows how the wellhead slips had to be cut away in a sector to provide a conduit for the instrument lead lines and the salt-water line. An adapter was made for the salt- water line so that the 1/2-in. and 1/4-in. tubing passes through the head and is connected to the 1 1/4-in. tubing below the slips. Figure C1-B shows a detail of this adapter.

A detailed arrangement of the casing and tubing string and the mounting of instruments is shown in Figure C2.

Figures C3 and C4 show how casing was arranged by size to accommodate the series of tests at different depths.

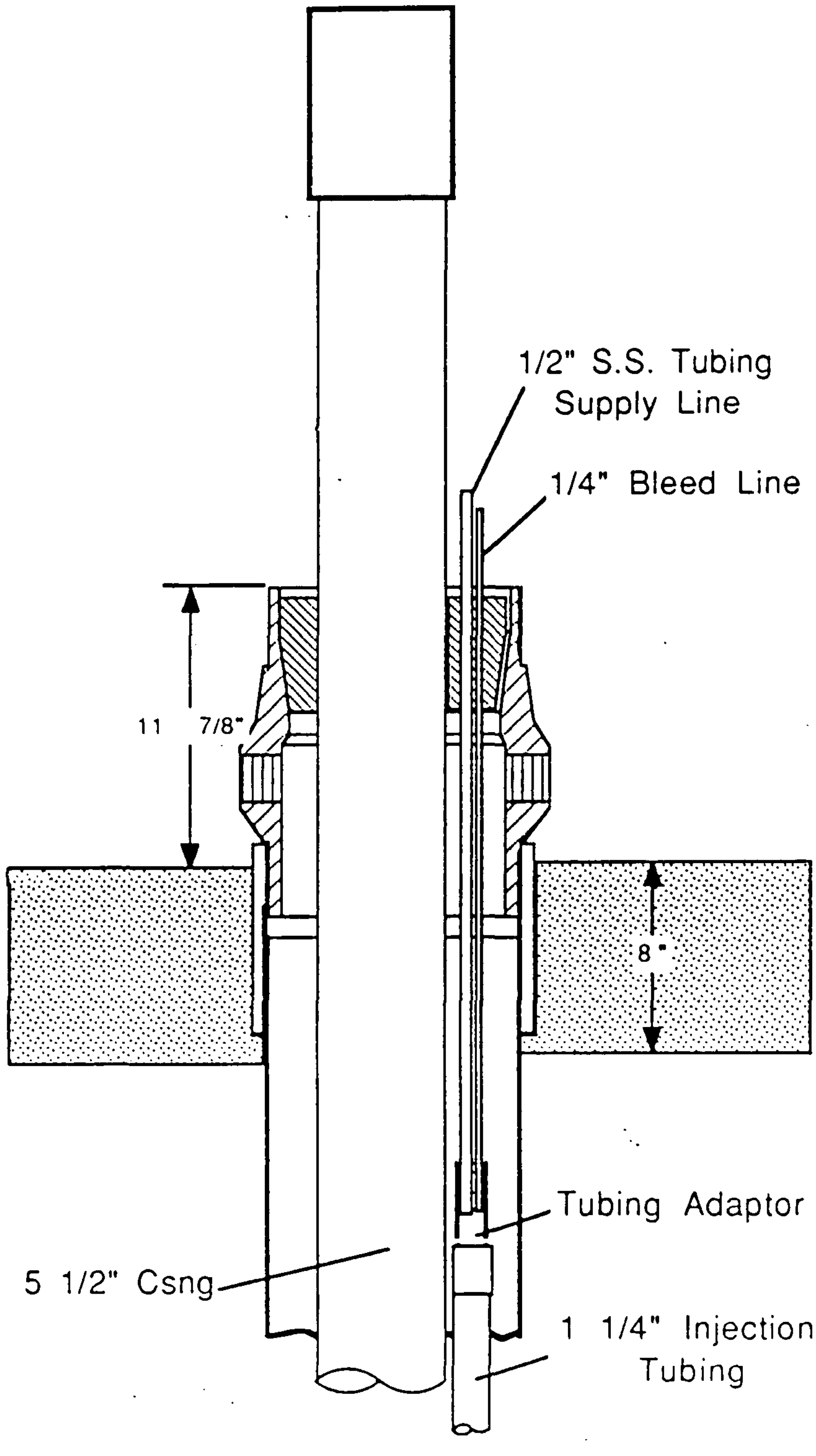
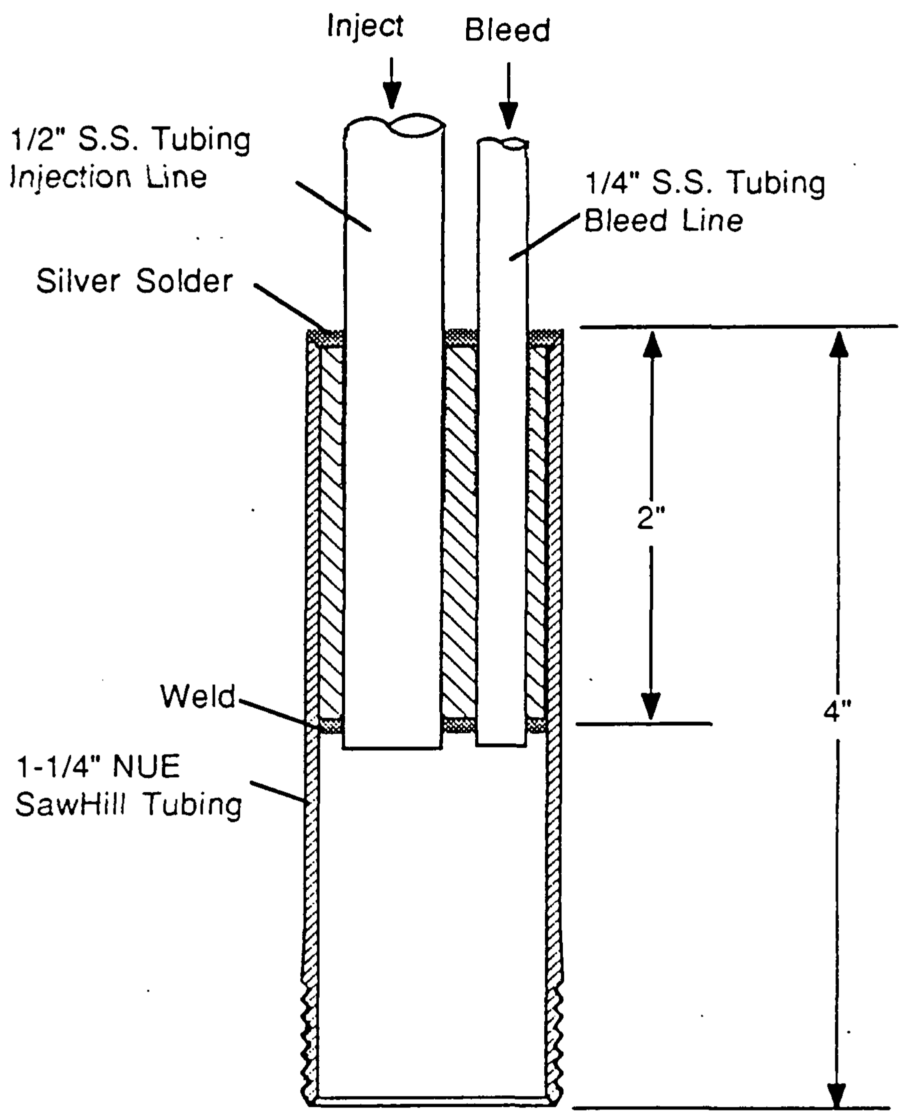



Figure C1-A. Well-head configuration of tubing and casing.




Tubing Adaptor

Figure C1-B. Tubing adapter, salt-water injection system.

## Casing String Instrumentation Location Chart For EPA Test #1

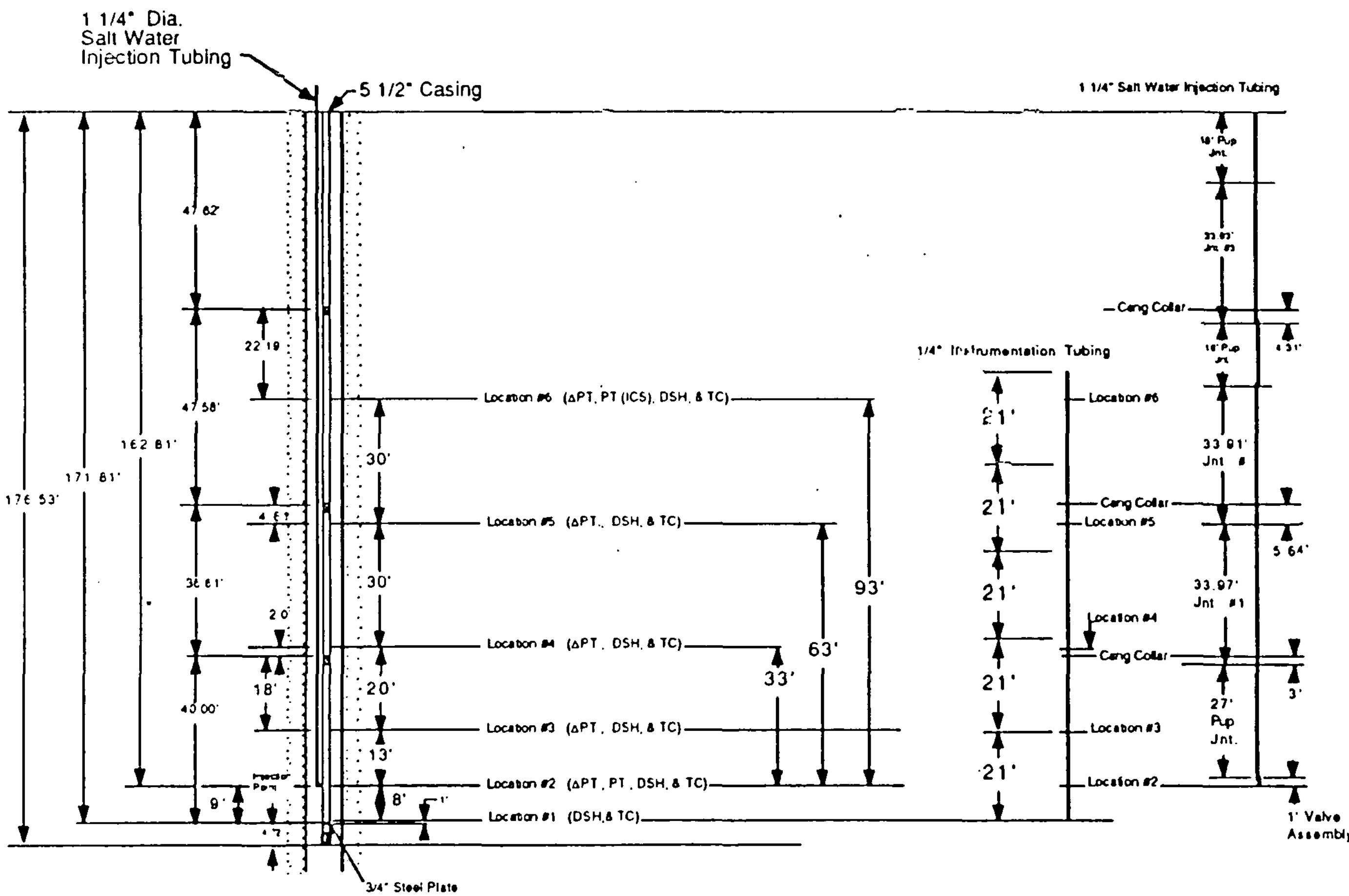
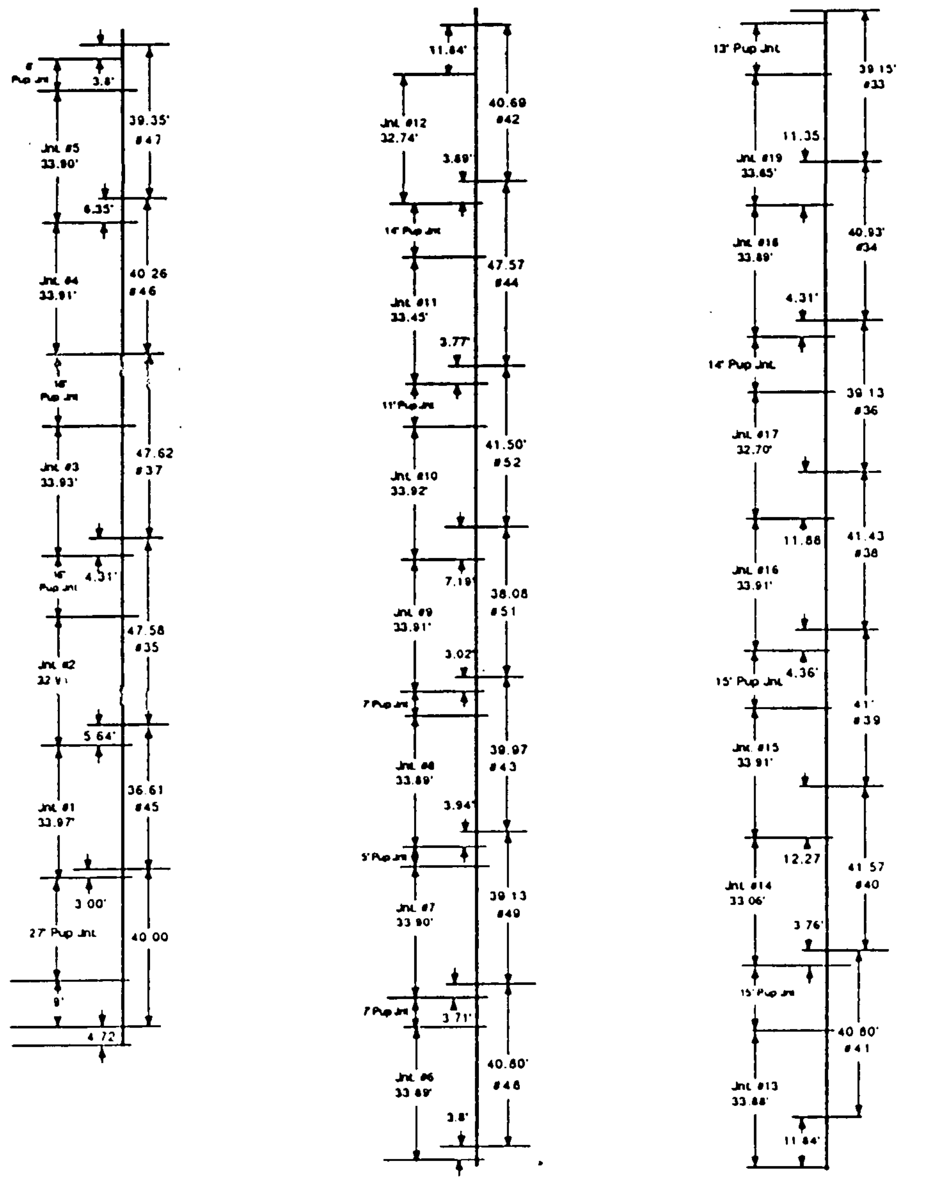



Figure C2. Location of tubing and instruments, Test No. 1.

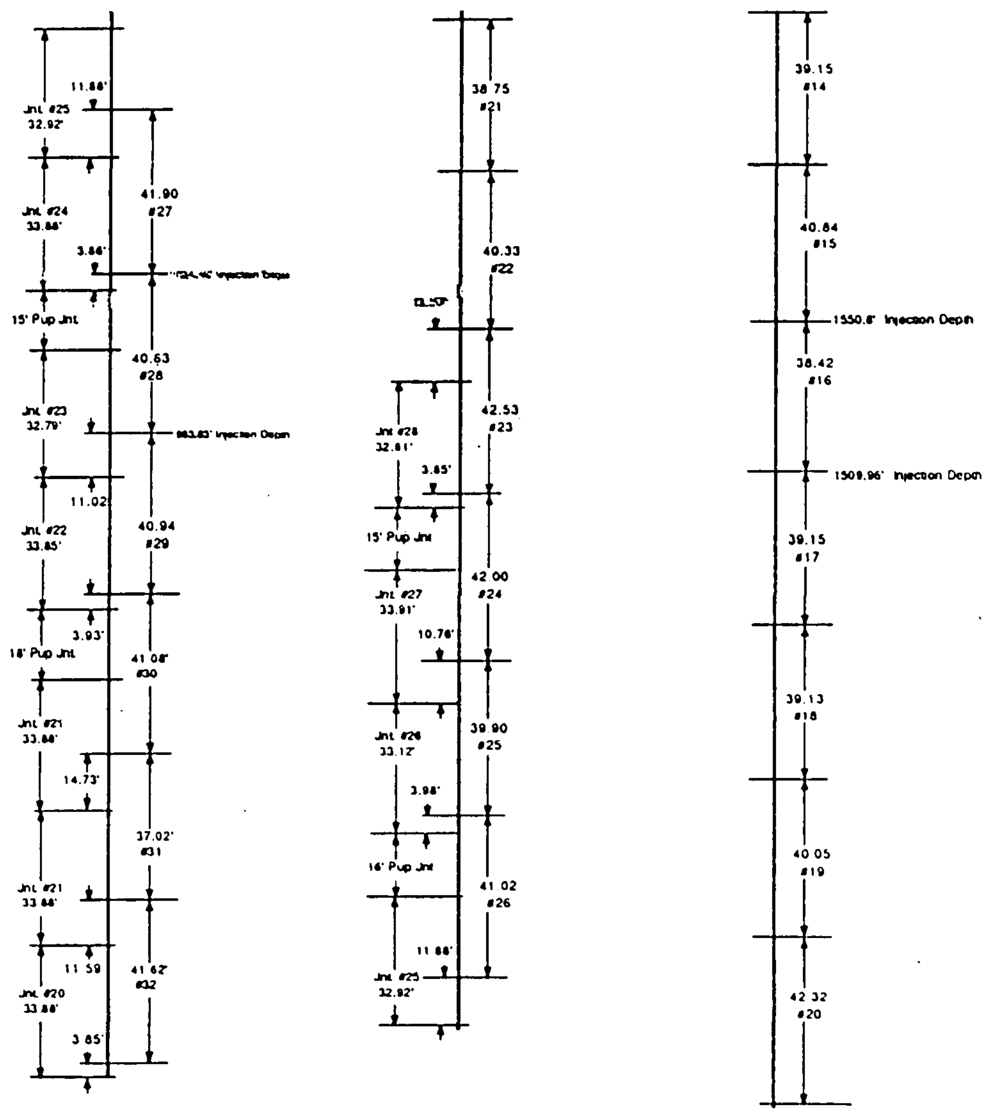
Casing & Tubing
String Layouts
For EPA Tests



Page #1

Figure C3. Location of joints of casing by number and dimensions as they are placed in 10 3/4-in. casing.

Casing & Tubing
String Layouts
For EPA Tests




Page #2

Figure C4. Continuation of Figure C3.

# APPENDIX D

## DRAWINGS AND DEVELOPMENT OF INSTRUMENTATION

### DIAPHRAGM HOUSING

The diaphragm-seal housing shown in Figure D1 serves as an interface between fresh-water mud in 5 1/2-in. casing and distilled water in the tubing connected to the pressure and differential-pressure transducers. Accuracy of data collected from the pressure and differential-pressure transducers is dependent on maintaining this interface. The following is a discussion of problems and solutions associated with sealing the diaphragm-seal housing.

The diaphragm has a flange-type configuration with a 180-deg. convolution. Calculated torque, based on a 15-percent compression of the gasket portion of the diaphragm, was approximately 25 in-lb.

A test diaphragm-seal housing was assembled by welding a diaphragm housing to a short section of 5 1/2-in. casing approximately 3 ft. long.

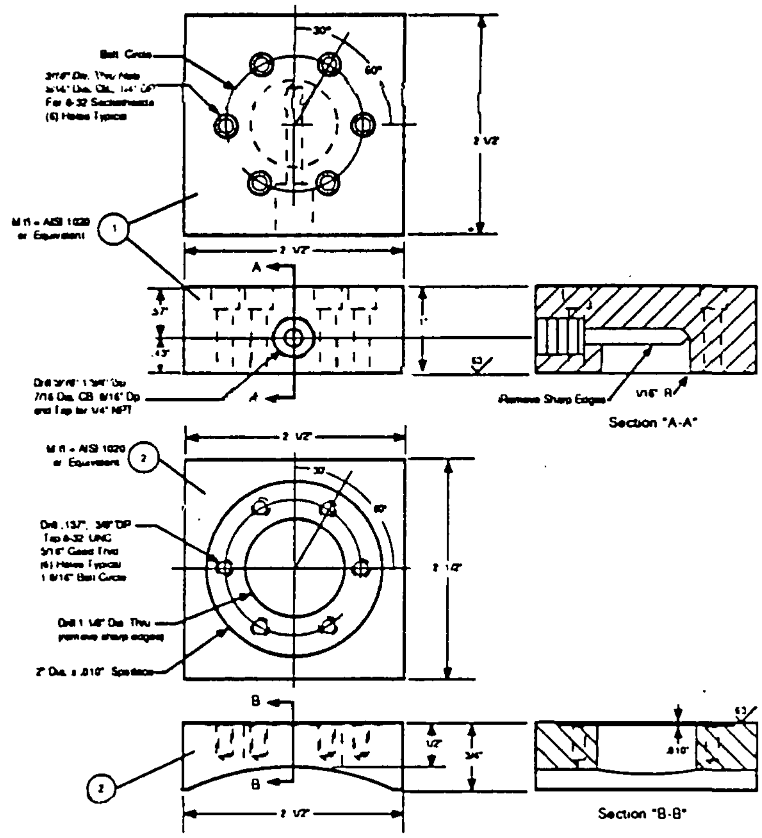
A test pressure of 3000 psi is required. It was assumed that when the diaphragm was put in place, the housing assembled, and the flange bolts torqued to 25 in-lb. that a water-tight seal at 3000 psi would result. However, the seal leaked at approximately 800 psi.

The diaphragm was checked for flaws or tears, etc. None were detected. The diaphragm housing was also inspected for possible flaws, machine marks, foreign particles, but none were detected.

The diaphragm-seal housing was reassembled and hydrostatically tested under the conditions described above. Again, the seal leaked at approximately 800 psi.

Torque on the flange bolts was increased by increments of 10 in-lb. to a maximum of 55 in-lb. Each condition resulted in a leak at the seal. A no-leak maximum of 1000 psi was obtained.

A series of gasket material, sealing compounds, adhesives, and combinations thereof was attempted with minimal success. Results are tabulated in Table D1.




Diaphragm Housing
( Diaphragm Installed)

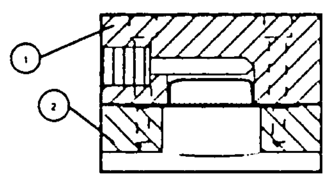


Figure D1. Detail of the diaphragm housing for interface between mud and water.

TABLE D1. DIAPHRAGM-SEAL TEST RESULTS

| Description of Seal | Torque on Flange Bolts (in-lbs.) | Seal Leak Pressure (psi) | Comments |
|---|---|---|---|
| Red Rubber Gasket Material | 25 | 400 | |
| | 35 | 450 | gask. extruding |
| | 45 | 450 | " " |
| | 55 | 450 | due to torque |
| Black Rubber Fabric Gasket (1/32 inch) | 25 | 800 | |
| | 35 | 900 | |
| | 45 | 1200 | |
| | 55 | 1250 | due to pressure |
| Black Rubber Fabric Gasket (1/16 inch) | 25 | 825 | |
| | 35 | 1000 | due to pressure |
| | 45 | 1100 | " " |
| | 55 | 1150 | " " |
| Diaphram with Loctite Master Gasket | 25 | 600 | due to pressure |
| | 55 | 650 | " " |
| Diaphram with Loctite Ultra Blue | 25 | 450 | due to pressure |
| | 55 | 500 | " " |
| Diaphram with J.B. Weld | 25 | 1500 | very small leak |
| | 55 | 1850 | " " |
| Diaphram with Loctite Fast Cure Epoxy 45 | 25 | 2200 | very small leak |
| | 55 | 2800 | " " |
| | 60 | 3200 | " " |
| | 60 | 3000 | no leak |

Loctite Fast Cure Epoxy 45 proved to be reliable for the 3000 psi test pressure and was adopted for use for Operating Procedure 3.0.3.

It was later determined that due to flexing of the 5 1/2-in. casing, the seal of the diaphragm seal-housing was good only to 2000 psi. No pressures greater than 2000 psi were expected for the first test. Therefore the assembly procedure was maintained, at least for the first test.

Consideration of a new design of the diaphragm seal housing is suggested for subsequent tests.

PRESSURE AND DIFFERENTIAL-PRESSURE TRANSDUCERS

Figures D2 and D3 show configuration of the connections for specific locations in the test system. The six down-hole locations shown in Figure C2 are related to configurations in Figure D3. Note that the bottom location (No. 1) does not have a transducer. It is the bottom leg of the differential-pressure transducer in Location 2. Location 2 is at the salt-water injection point.

DESIGN OF PISTON-TYPE FLOW METER

A piston assembly with inner and outer seals rides on stainless steel tubing inside of cylinder (Figure D4). A magnet is shown in the left-hand part of the figure; this is the element that the Temposonics transducer senses, to find position in the piston. A detailed view is shown in Figure D5.

The inter-relationship of the Temposonics transducer and the piston is shown in Figure D6. The effective travel is indicated.

Figure D7 shows the complete assembly of the flow meter. Flow comes in either end cap and exits at the opposite end cap, depending on the specific direction of flow. The position of the magnet with respect to time is translated to flow rate.

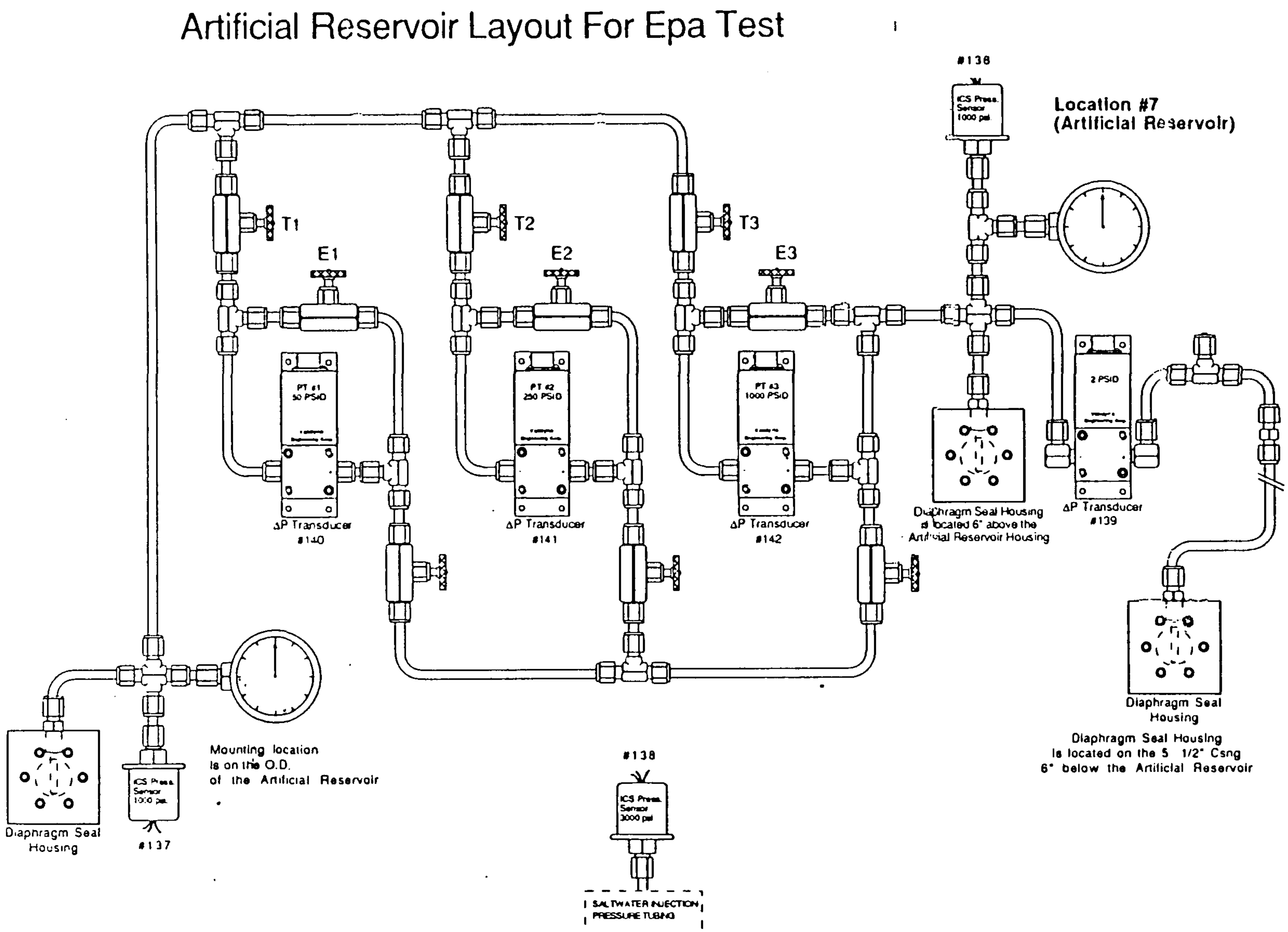



Figure D2. Configuration of above-ground pressure transducers.

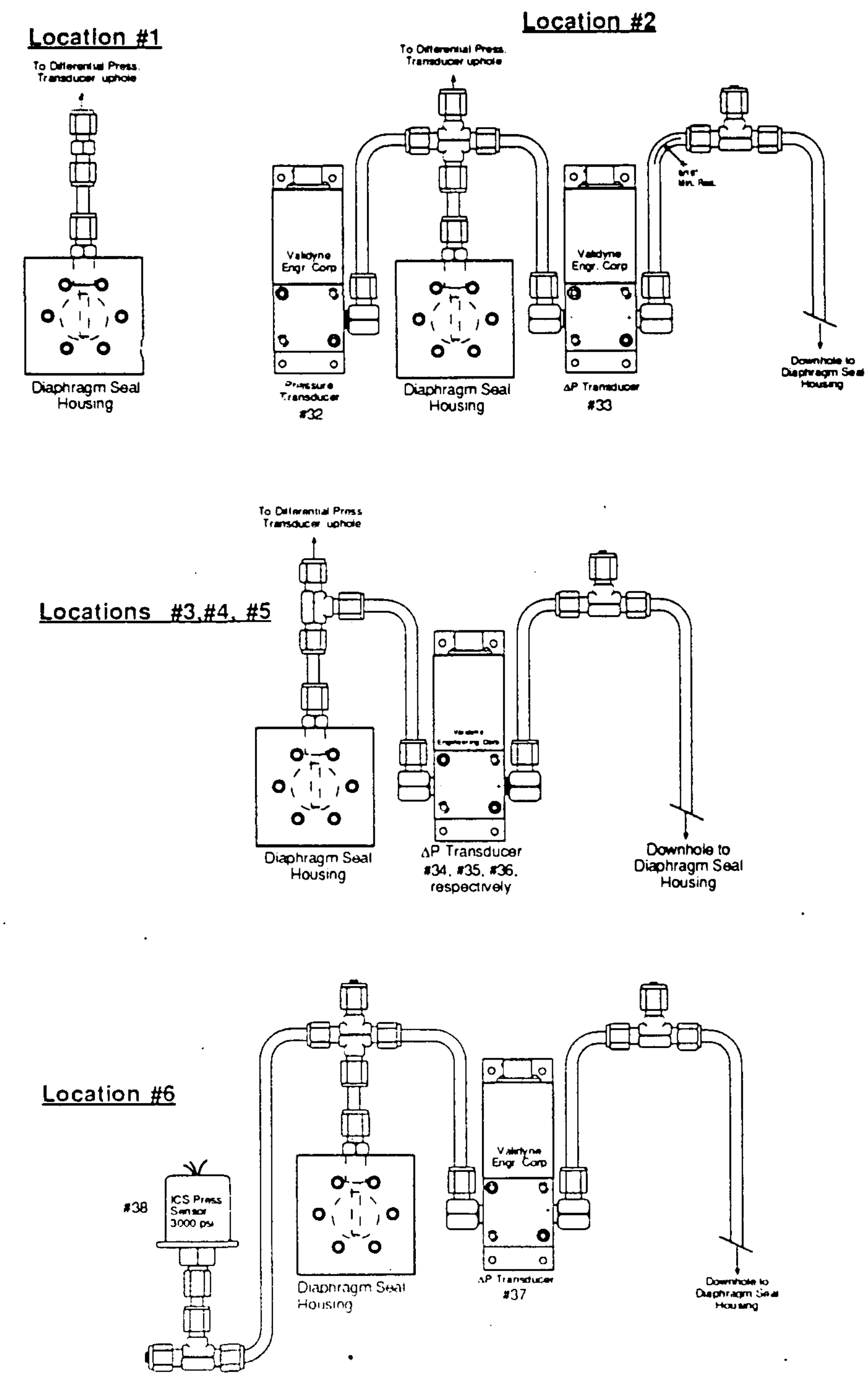



Figure D3. Configuration of pressure transducers mounted on 5 1/2-in. casing and located down-hole.

## Flow Meter Piston Assembly Drawing

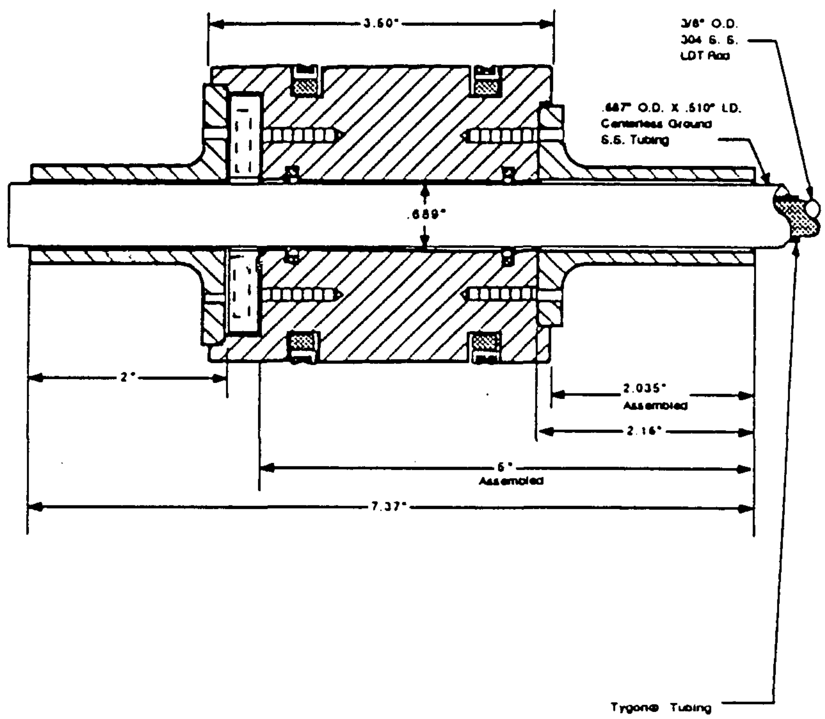
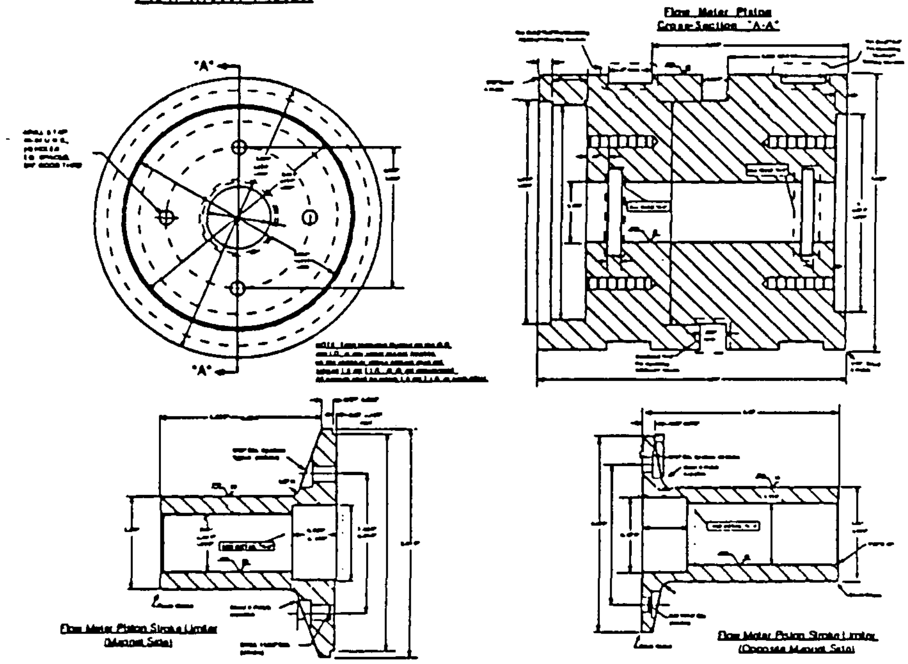



Figure D4. Flow-meter piston assembly.

Flow Meter Piston




Flow Meter Piston Assembly Drawing

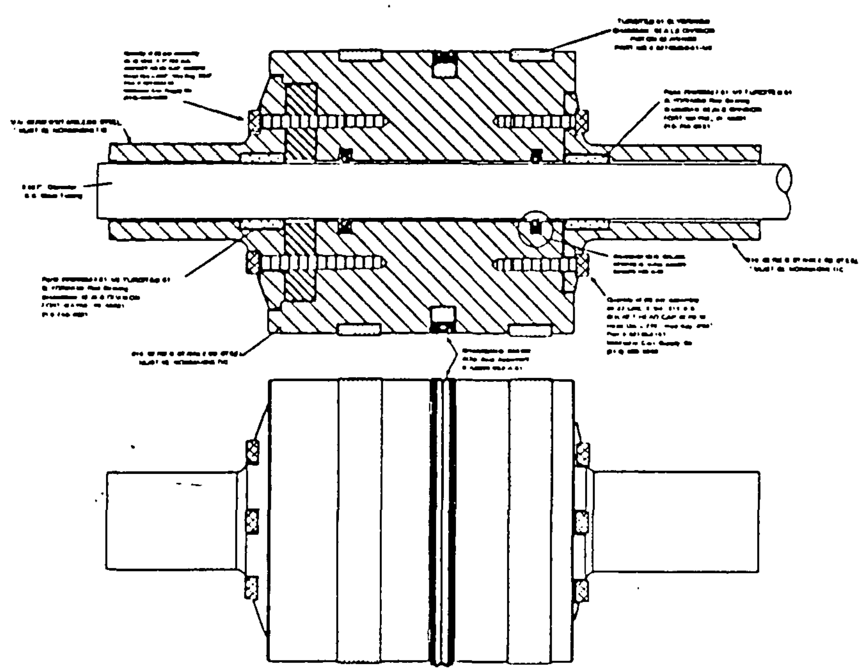


Figure D5. Magnet/piston assembly for the effluent and salt-water flow meters.

LINEAR DISPLACEMENT TRANSDUCER ASSEMBLY
FOR
FLOWMETER

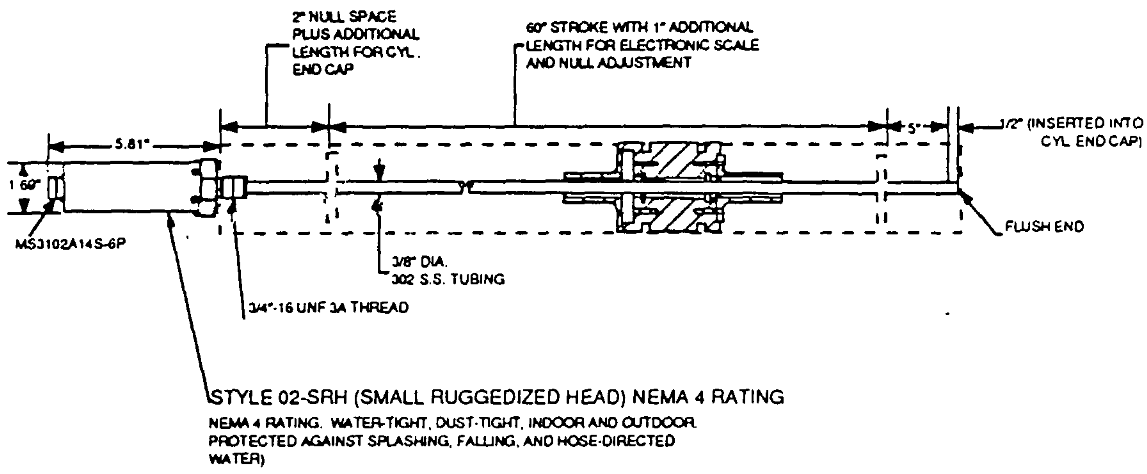



Figure D6. Temposonics linear-displacement transducer and magnet/piston for the effluent and salt-water flow meters.

# FLOWMETER ASSEMBLY

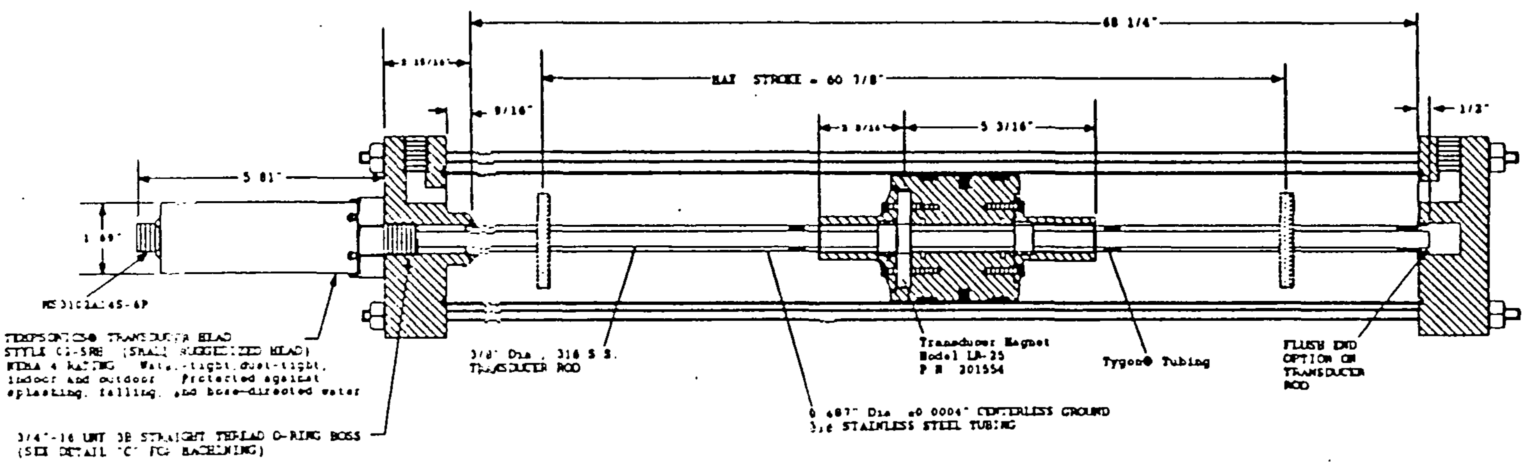



Figure D7. Flow-meter assembly for the effluent and salt-water systems.

# APPENDIX E

## INSTRUMENT CALIBRATION

### PRESSURE TRANSDUCERS AND DIFFERENTIAL-PRESSURE TRANSDUCERS

Time and equipment were donated by Conoco, Inc. in Ponca City. A pressure-measurement system was taken to Conoco's facility and their DH 5501 deadweight-pressure-tester system was used. This is a highly sensitive and accurate system. Calibration could not have been done without the cooperation of Conoco.

All of pre-sized cables, the computer and software, multiplexer, pressure transducers and differential-pressure transducers were taken to the site. Before calibration, these were assembled in the configurations that they would have in the test system. Because of the time required to balance the system for each pressure, because of the multiple line pressures, and because of the sensitivity of the diaphragms, calibration was long and tedious. Conoco supplied an operator and a supervisor, but our own personnel assembled the systems to be calibrated and operated the two computers.

In Figure E1 the DH 5501 is seen in the left-hand portion of the photograph. Instruments, multiplexers, data-acquisition system and computer are elsewhere in the photograph. The data-reduction computer system is shown in Figure E2.

A closer view of the required system is shown in Figure E3. The long lengths of wire are to connect sensors to the multiplexer in the down-hole configuration; the long wire was used to take into account any line-losses. Each transducer was connected to the appropriate position on the appropriate multiplexer, and the output was seen on the digital voltmeter and on the computer screen. All steps were taken that are required in the actual test-configuration. Data were stored on floppy disks; these were used in the data-reduction computer.

In order to keep from damaging the differential-pressure transducers a special flow network was designed and built. It is shown in Figure E4.

Results of this calibration procedure are in Table E1.

### FLOW METER CALIBRATION

Three flow meters are mounted on the Instrumentation Console (Figure E5). These three act separately in normal

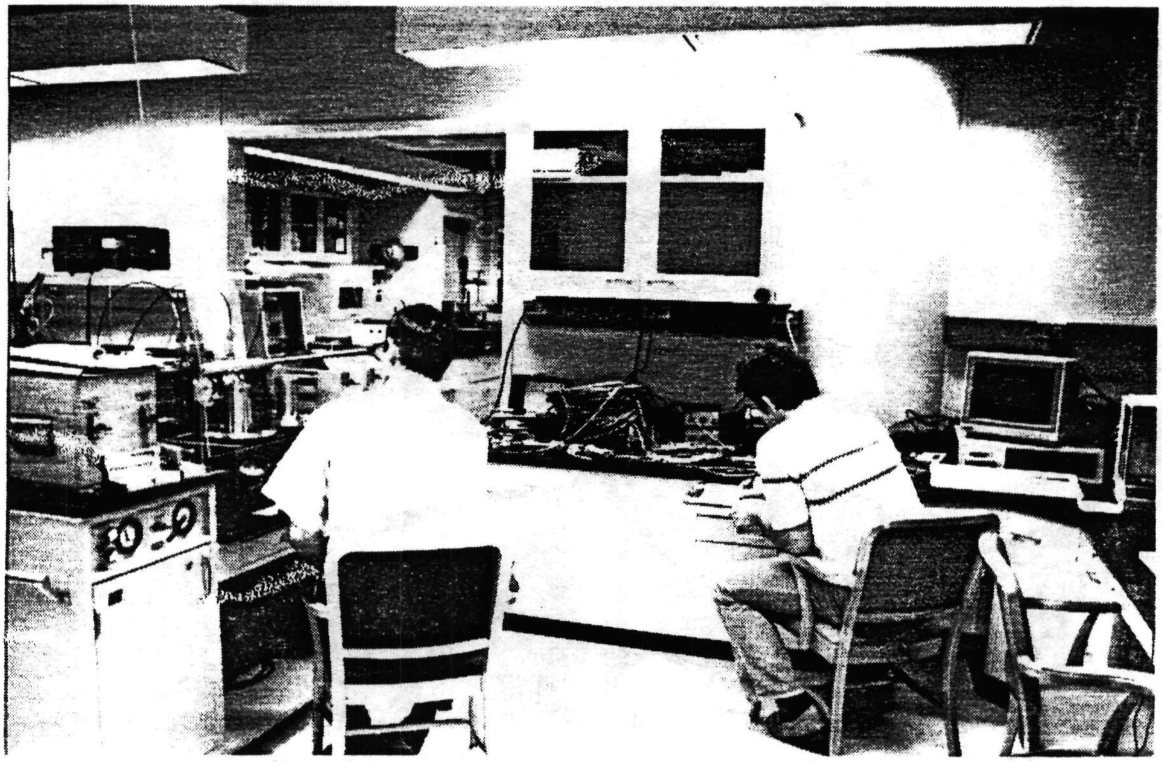


Figure E1. Overview of pressure- and differential-pressure calibration process at Conoco, Inc.

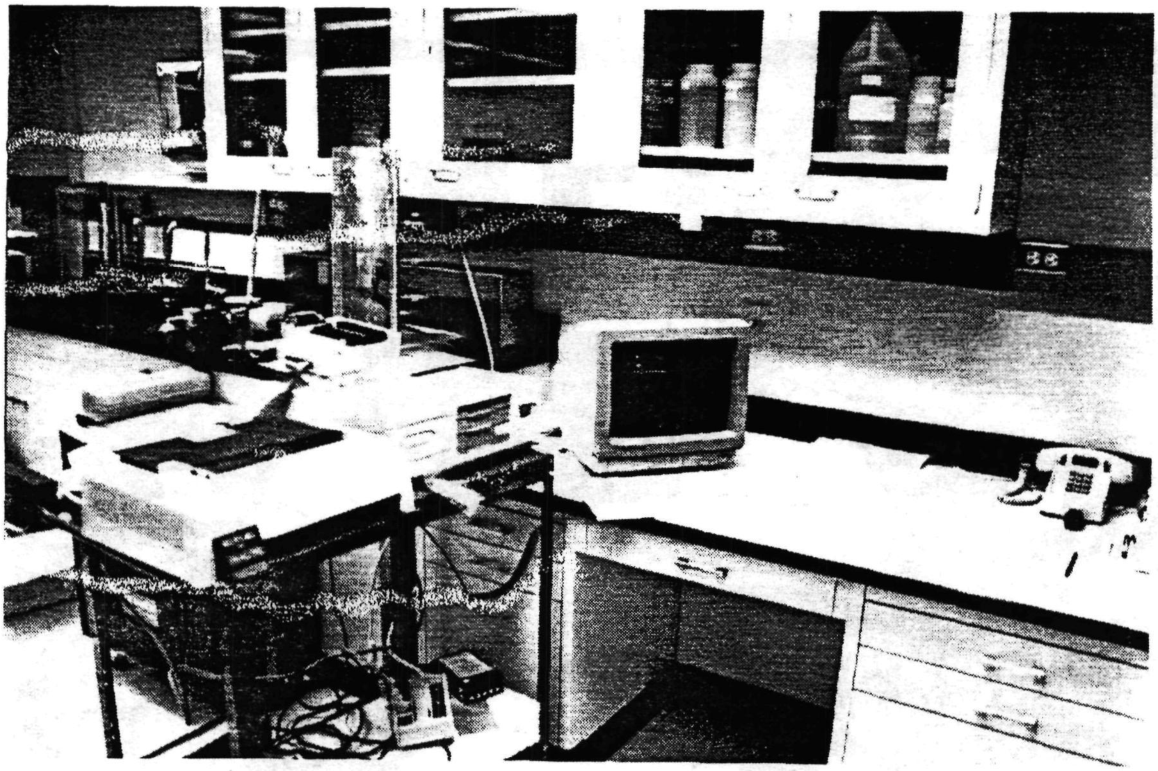


Figure E2. Computer system used in the overall calibration process at Conoco, Inc.

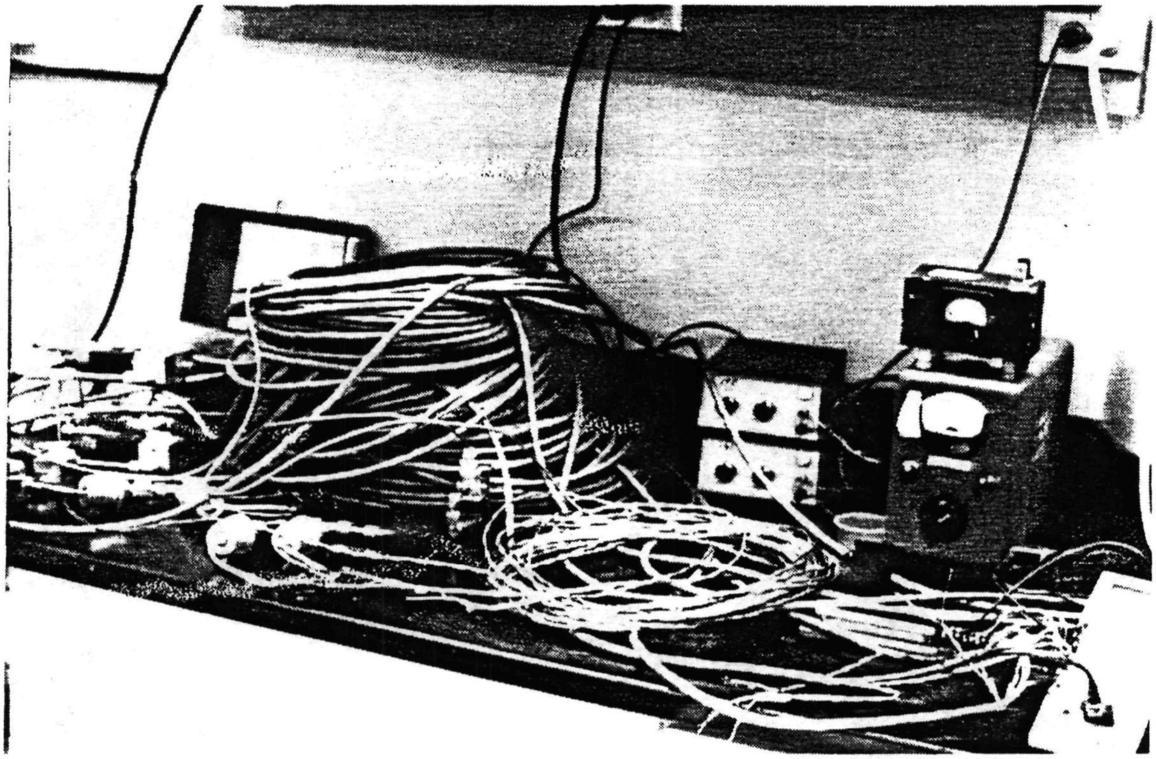


Figure E3. Instrument lead-lines, transducers, multiplexer and digital voltmeter used in pressure- and differential-pressure-transducer calibration process at Conoco, Inc.

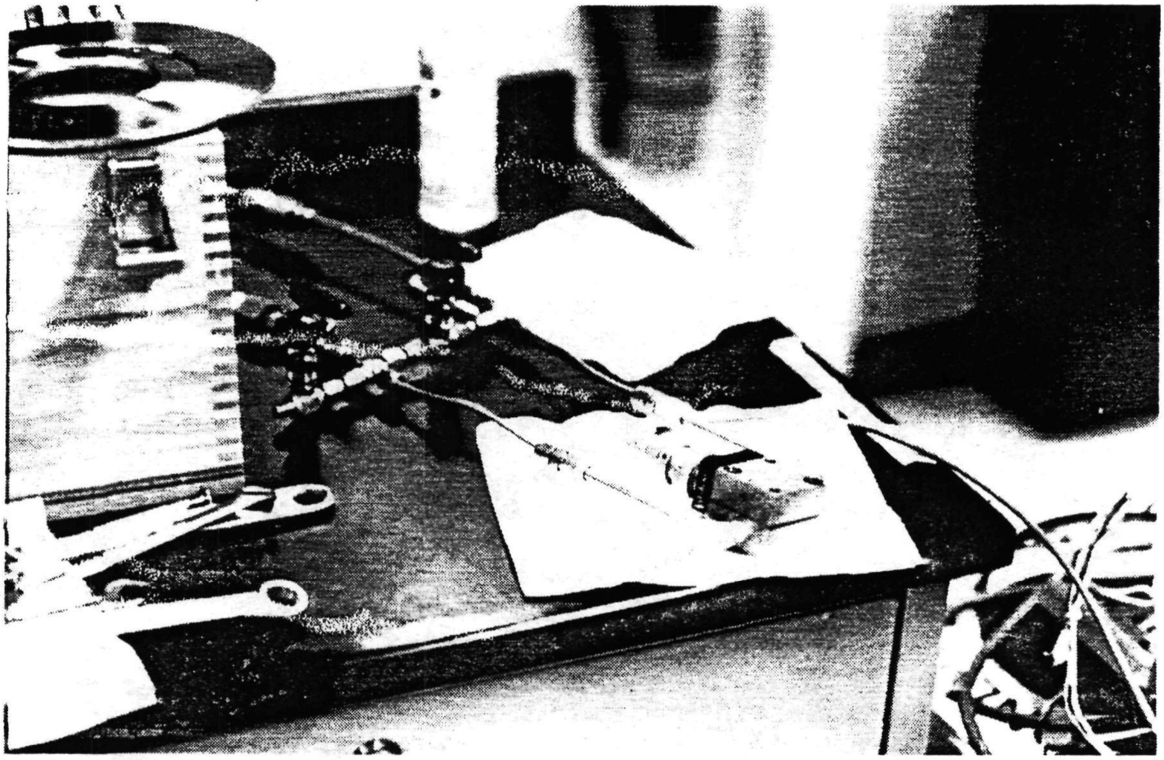


Figure E4. Differential-pressure transducer pressure-equalization network for calibration at Conoco, Inc.

Table E1. Calibrated Pressure Transducers

| TRANSDUCER NUMBER | CAL. ORDER | INTERCEPT | X COEFFICIENTS | | |
|---|---|---|---|---|---|
| PT032-25.CAL | Second | -15.0078 | 641.583 | 1.350509 | NA |
| PT038-30.CAL | Third | -817.835 | 858.0032 | -21.0604 | 0.90863 |
| PT136-10.CAL | Second | -255.822 | 264.2174 | -2.03393 | NA |
| PT137-10.CAL | Third | -257.688 | 266.8794 | -2.56352 | 0.061186 |
| PT138-30.CAL | Third | -809.03 | 837.715 | -16.9311 | 0.619525 |
| DP033-05.CAL | Third | 0.018025 | 0.958496 | 0.016785 | -0.00219 |
| DP033-15.CAL | Third | 0.180946 | 0.927259 | 0.024139 | -0.00358 |
| DP033-25.CAL | Third | 0.235349 | 0.808925 | 0.003119 | 0.000333 |
| DP034-15.CAL | Third | -0.00219 | 1.665724 | -0.02616 | 0.002819 |
| DP034-25.CAL | Third | -0.01134 | 1.783586 | -0.196 | 0.031635 |
| DP035-05.CAL | Second | -0.03383 | 2.531405 | -0.00869 | NA |
| DP035-15.CAL | Third | -0.01577 | 2.564948 | -0.02263 | 0.001539 |
| DP035-25.CAL | Third | -0.00181 | 2.584269 | -0.03398 | 0.002761 |
| DP036-05.CAL | Third | -0.00083 | 4.5565 | -0.18622 | 0.018681 |
| DP036-15.CAL | Second | 0.057773 | 4.082549 | 0.01175 | NA |
| DP036-25.CAL | Third | 0.001588 | 4.479852 | -0.15147 | 0.014939 |
| DP037-05.CAL | Third | -0.3012 | 4.193761 | -0.11797 | 0.017907 |
| DP037-15.CAL | Second | -0.46079 | 4.069449 | -0.02235 | NA |
| DP037-25.CAL | Third | -1.14542 | 4.638432 | -0.39268 | 0.058048 |
| DP139-04.CAL | Third | -0.03286 | 0.270412 | -0.0016 | 0.000353 |
| DP139-10.CAL | Third | -0.02798 | 0.254886 | -0.00143 | 0.000388 |
| DP139-15.CAL | Third | -0.01029 | 0.263378 | -0.01732 | 0.002552 |
| DP140-04.CAL | Third | -0.26747 | 10.2276 | -0.07129 | 0.006628 |
| DP140-10.CAL | Second | -0.40609 | 10.145 | -0.01623 | NA |
| DP140-15.CAL | Second | -0.45502 | 10.30998 | -0.03587 | NA |
| DP141-04.CAL | Third | -3.76935 | 53.49224 | -3.20371 | 0.52476 |
| DP141-10.CAL | Third | 0.005253 | 52.74301 | -1.0668 | 0.101462 |
| DP141-15.CAL | Third | 1.174866 | 50.38612 | -0.00372 | -0.02136 |
| DP142-04.CAL | Third | -7.47667 | 204.8533 | -3.57379 | 0.563824 |
| DP142-10.CAL | Third | -3.53824 | 202.6816 | -0.9419 | 0.09615 |
| DP142-15.CAL | Second | -1.88412 | 202.8089 | -0.44082 | NA |

operation but during calibration are connected. The flow meter that is for the mud column is connected to the Vindum valve going into the salt-water injection flow meter; from the output of the salt-water flow meter this is connected to the input to the reservoir-fluid flow meter. During calibration, the mud-column flow meter is filled with water and nitrogen pressure is imposed on this flow meter. Thus pressure and fluid are supplied in order to drive flow through the salt-water-injection flow meter. Fluid then moves to the reservoir-effluent flow meter; then the effluent goes into a vessel that is on a scale (Figure E5). The scale allows readings to a tenth of a gram. Output of this scale is fed to a computer (Figure E6) so that the digital data are recorded on the hard disk.

Each of the three flow meters has a Temposonics linear transducer that records the position of a magnet. The position of this magnet is measured precisely to 0.001 in.; with this the amount of flow that has gone from the flow meter to its destination can be determined. The conditioned electrical output of the Temposonics is fed through a multiplexer to the computer and stored on a hard disk. Because there are three of these Temposonics, the multiplexer will rotate the signals and record them serially.

Three pressure transducers also are mounted on the flow-meter network, as seen in Figure E7; these are mounted near the Vindum valves. The 1000-psi pressure transducer mounted on the downstream side of the salt-water-injection flow meter measures the pressure developed during operation of the flow meter. Two pressure transducers are mounted on either side of the Vindum valves on the reservoir-effluent flow meter. This allows determination of a pressure differential across the Vindum valves, during operation. Included in the console is a 1000-psi pressure gauge on the reservoir-effluent side, and a 1500-psi pressure gauge is on the salt-water side. All other outputs to the computer go to the multiplexer, so that the serial output is obtained; this cycles through at a rate of about 10 per second.

Before calibration starts, each of the flow meters must be prepared for operation. The reservoir-effluent flow meter and the salt-water-injection flow meter require that fluid be placed on both sides of the piston, which contains a magnet. Doing this requires that air be bled from the lines. In order to prepare the mud-column flow meter a hose must be connected to the vessel and filled with water. Once this is filled, nitrogen pressure (Figure E8) must be turned on and regulated to the particular pressure that will be used during calibration. Various ranges of pressures will be measured, so

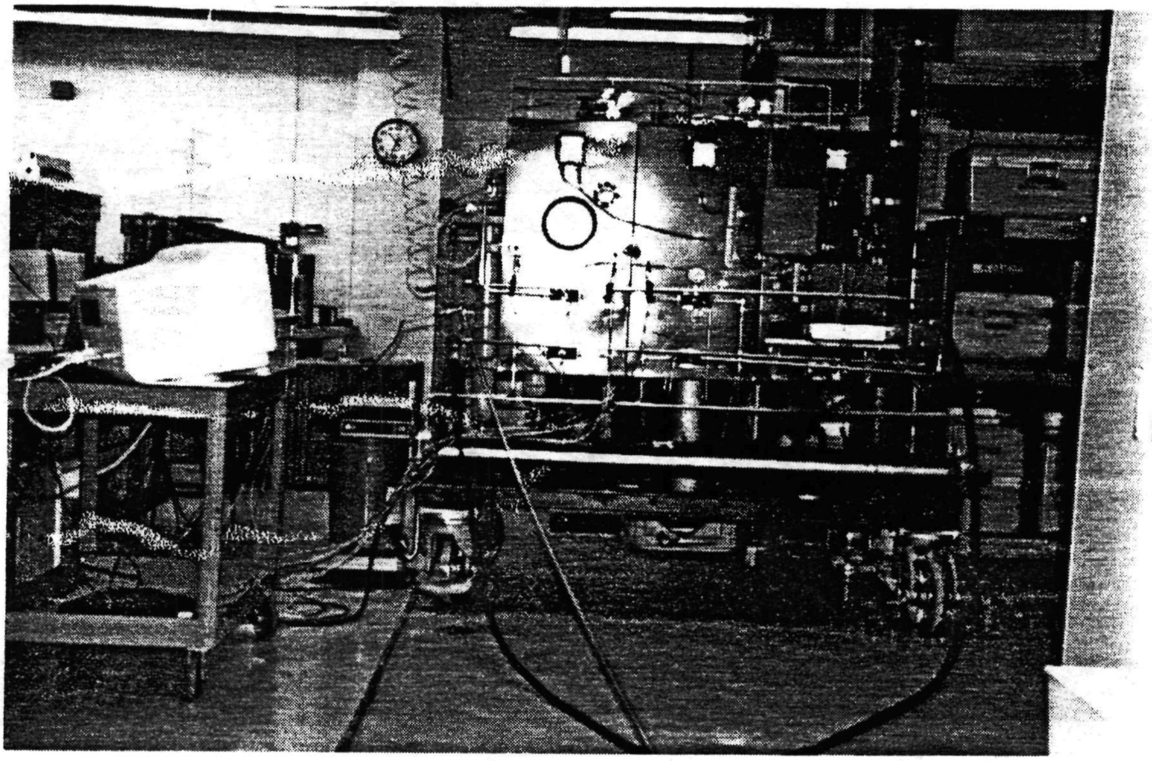


Figure E5. Overview of flow-meter calibration system with computer, scales and Instrumentation Console.

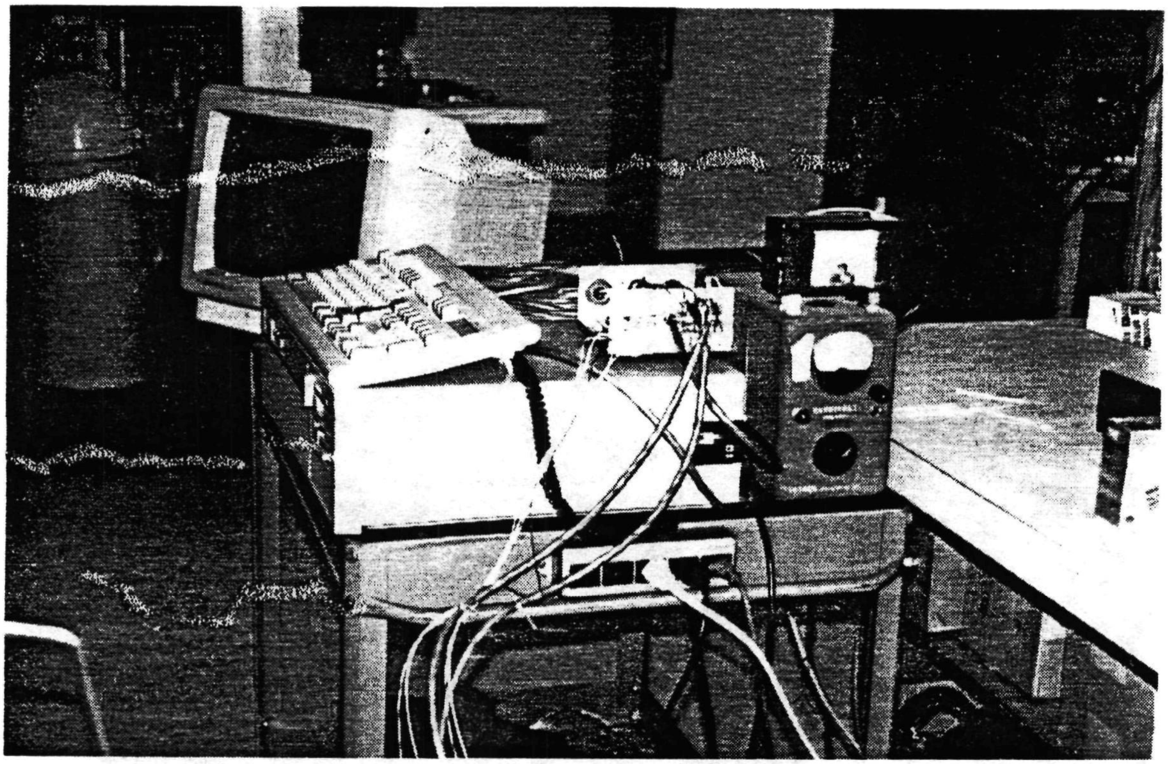


Figure E6. Computer, multiplexer for surface sensors, power supply and leads for calibrating flow meters on Instrumentation Console.

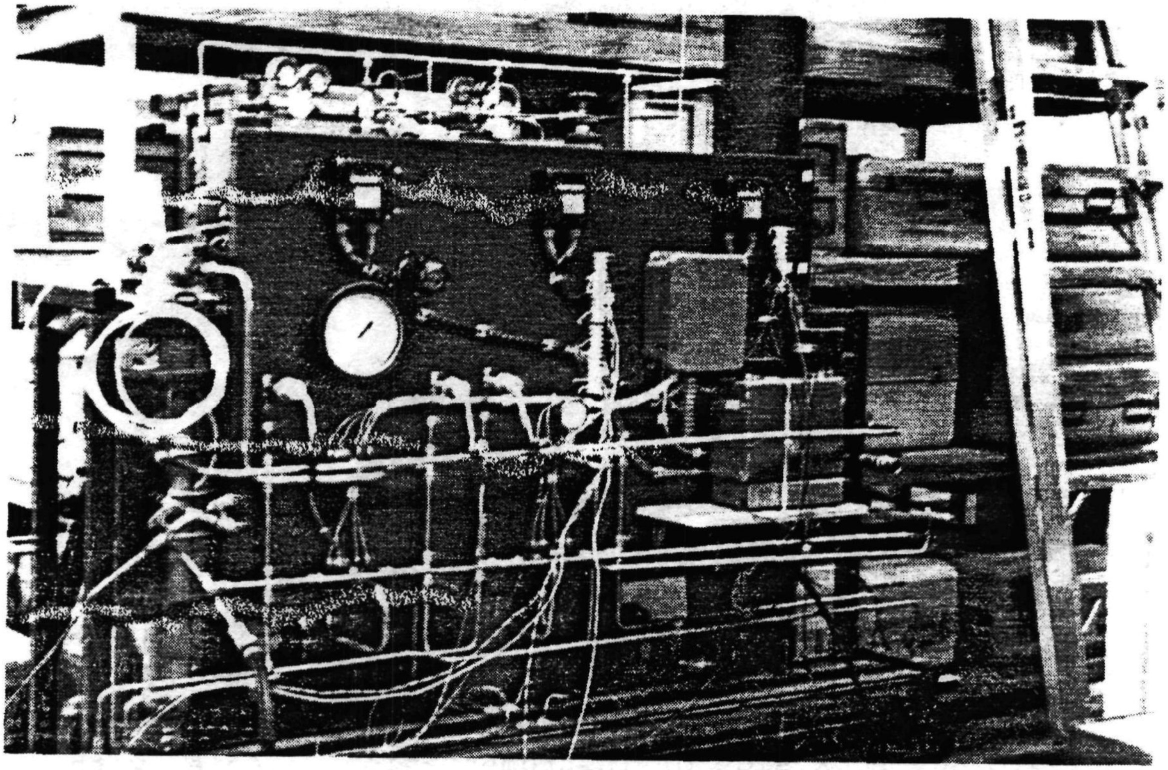


Figure E7. Front side of Instrumentation Console, with three flow meters.

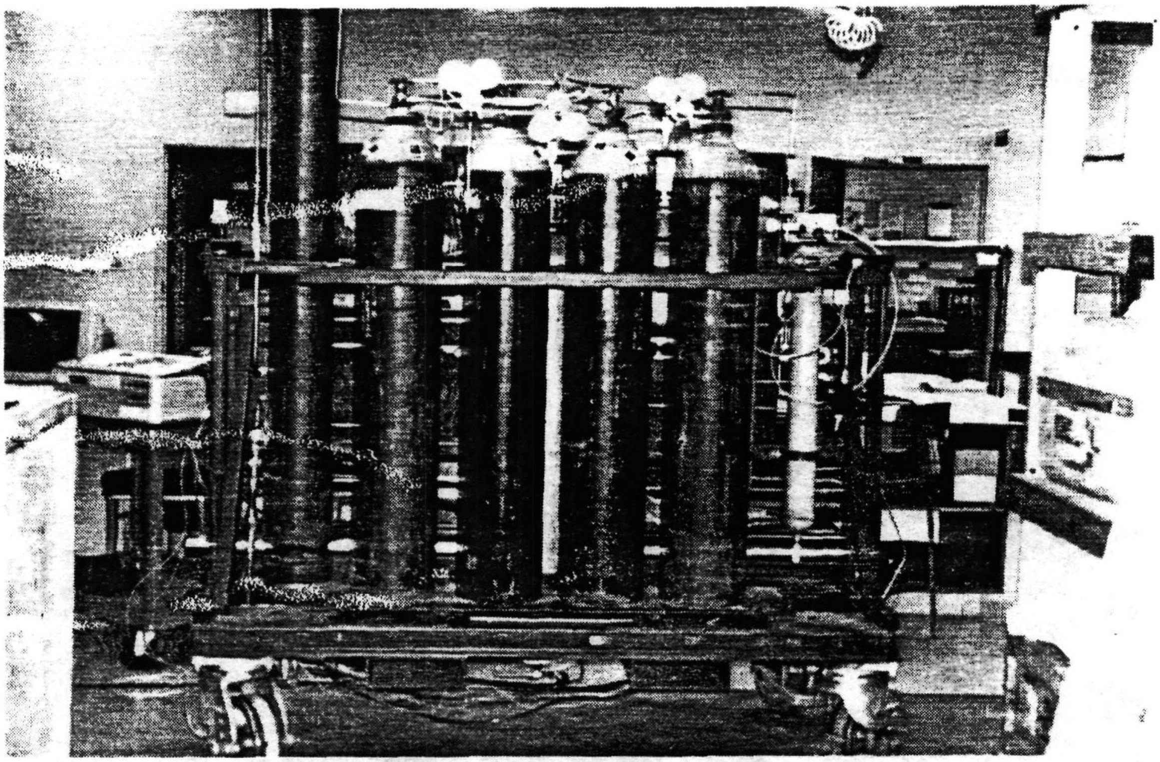


Figure E8. Back side of Instrumentation Console, with three flow meters.

that more than one calibration will be done for the flow meters.

It should be noted that calibration must end temporarily when the mud-column flow-meter vessel is emptied. Therefore, the amount of flow must be monitored and exposed during the process. In order to restart the process, nitrogen pressure must be blown down and the vessel refilled with water and pressurized with nitrogen.

The components of these three flow meters are divided into sections on the console, with some overlap. Basically, the mud-column flow meter is in the right-hand section of the console. Figures E9 and E10 are focused on these components. On the left-hand side is the effluent flow meter; some of its components are shown in Figure E11. Figure E12 is focused upon some of the components associated with the salt-water-injection flow meter; it is in the central section of the console.

The following definitions are used:

V1 = Vindum valve No. 1, which is the top control valve in the reservoir-effluent flow meter network.
V2 = Vindum valve No. 2, which is the control valve in the reservoir-effluent flow meter network.
V3 = Vindum valve No. 3, which is the top control valve in the salt-water flow meter network.
V4 = Vindum valve No. 4, which is the bottom control valve in the salt-water flow meter network.
PT = Pressure transducer.
BPV = Back-pressure valve.

CALIBRATION PROCEDURE FOR SIMULTANEOUS FLOW METER OPERATION

Note: Must have system bled prior to calibrating.

I. Set BPV pressure.
   1. Close all ports to V1 and V2 and close BPV (turn clockwise to increase pressure).
   2. Charge the 1-gal. accumulator with nitrogen to the desired back pressure.
   3. Turn BPV counterclockwise (decrease) until effluent just begins to seep out of the line.

II. Initialize the flow.
   1. Open all ports to Vindum valves V1, V2, V3, and V4.
   2. Increase nitrogen pressure to mud-column flow meter until pressures equal back pressure.
   3. Allow total system to equilibrate.
   4. Set Vindum valves V1, V2, V2, and V4 to their operating modes.
   5. Slowly increase nitrogen pressure until there is

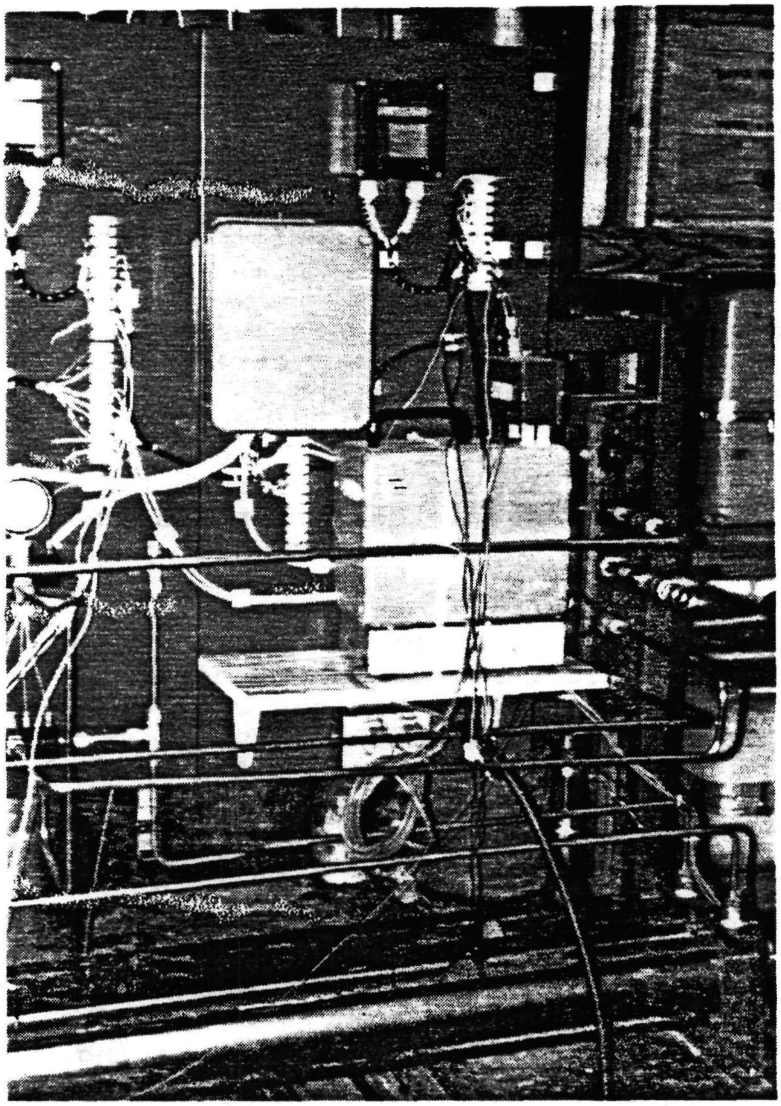


Figure E9. Electronics, flow-line connections and controls for mud-column flow meter.

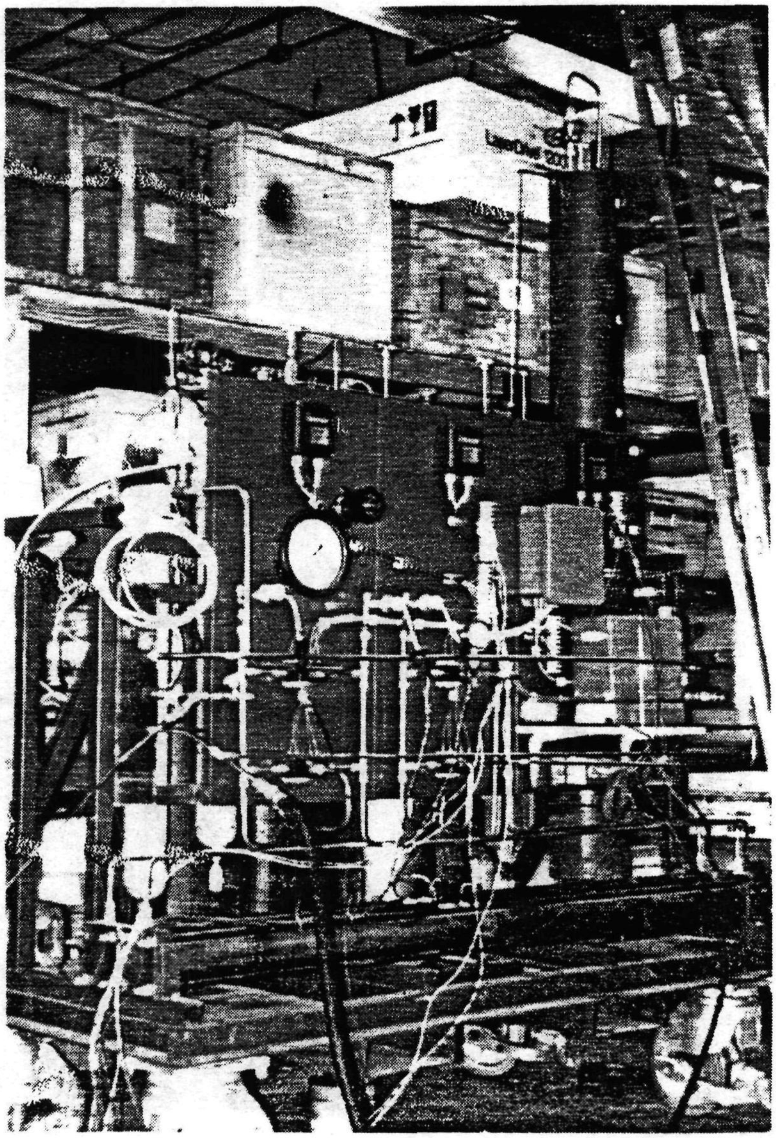


Figure E10. Simulated wellbore - mud column. Flow meter in right-hand side of photograph.

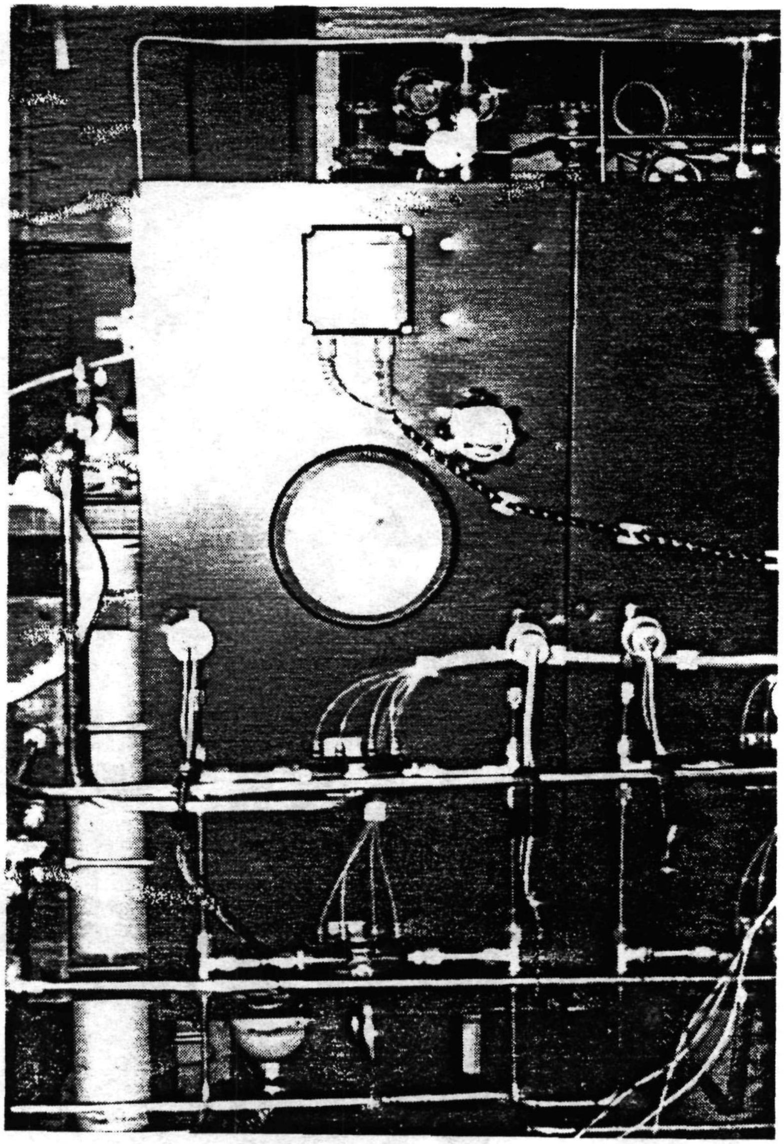


Figure E11. Electronics, flow lines, controls and line configuration for calibration of effluent flow meter.

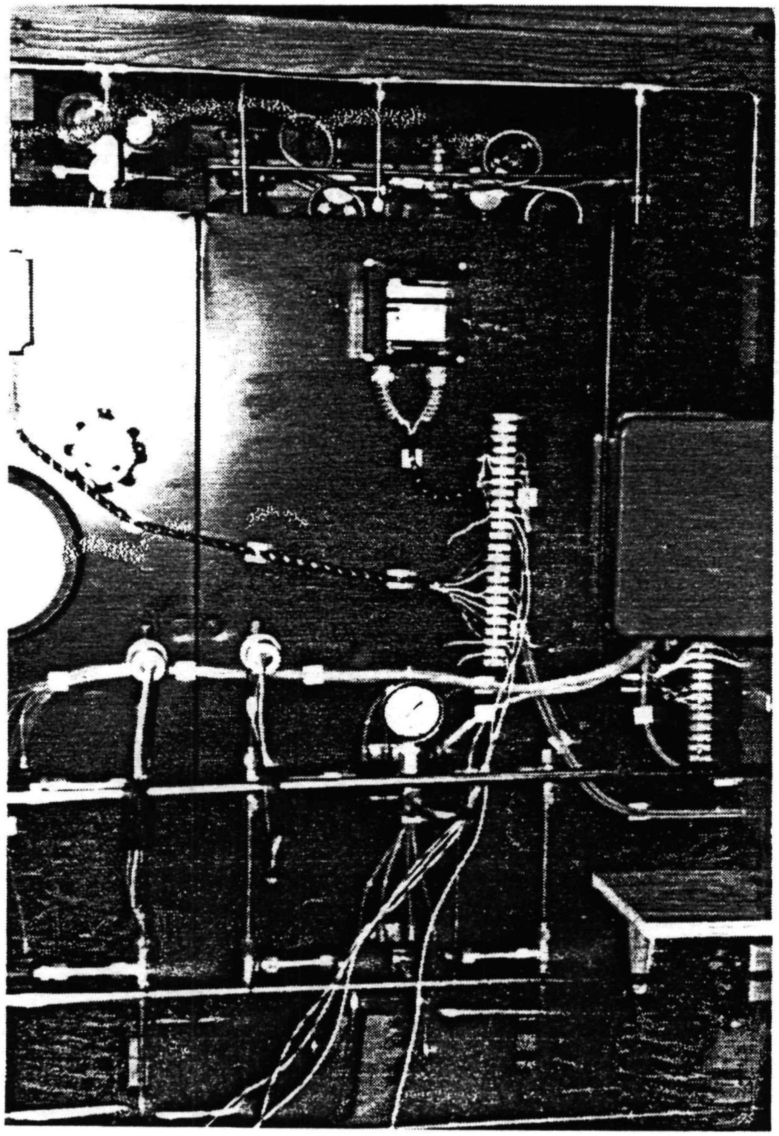


Figure E12. Electronics, flow lines with configuration for calibration of salt-water flow meter.

visible flow from reservoir-effluent line. This initial flow should be as slow as can be controlled -- just a drip or seep.

III. Record data.
  1. Set computer to cycle through all activated sensors.
  2. Manually record both gauge pressure and the scale output, as well as date and time. Do this periodically throughout the run.
  3. Allow enough time for pistons in flow meters to span their complete range of travel
  4. Allow enough time for the system to equilibrate before going to next flow rate.

IV. Span the flow range.
  1. Increase pressure until flow increases to rate desired.
  2. Proceed with Steps 3.1, 3.2, and 3.3.
  3. Repeat steps 4.1 and 4.2 until entire flow range has been spanned.

V. Span back-pressure range.
  1. Do steps I-IV for each back pressure desired.
  2. Choose back pressures coincident with test schedule.

# APPENDIX F

## DEVELOPMENT OF TEST FACILITY - OVERVIEW

### INTRODUCTION

Several items were originated with development of this project. These developments are discussed in the following paragraphs.

### ACCURATE DOWN-HOLE PRESSURE-GRADIENT MEASUREMENTS

Both a technique and hardware were developed to accurately measure down-hole pressure gradients. First a special technique to determine differential pressure with a combination of manometer principles, differential-pressure transducers and pressure transducers was developed. This technique requires simultaneous solutions of data from these three sources.

Also, a multiplexer was designed and built to transfer data from down-hole to the surface. This takes signals from each of a set of instruments, processes the information, and serially transfers it to a computer. A computer board was designed and built to accept and process data at the computer interface.

In addition, a data-acquisition software system was developed to interface with the multiplexers, sort the serial data, and store it.

A diaphragm-seal housing assembly was designed and built to interface between mud in the casing and water in the instrument lines, to provide accuracy and prevent plugging.

A temperature-sensor circuit was designed and built to enhance the accuracy of temperature measurements.

### SIMULATED RESERVOIR ROCK, FLOW AND PRESSURE CHARACTERISTICS

Several techniques were developed to simulate the significant conditions that occur in a reservoir while pressures are being imposed upon it, comprised of reservoir-fluid and mud-column pressure enhanced by injection pressures.

Associated with these techniques are several devices of hardware that were designed and constructed, including a cylindrical reservoir housing with blind flanges, for placement and removal of the artificial-reservoir material. Instrumentation and fluid-flow ports were included in the design and fabrication. Artificial-reservoir material was developed to yield a desired set of permeability values, based upon guidelines from Halliburton Services Company. This artificial reservoir has permeability barriers on the top and bottom of the formation to promote uniform radial flow between the ends, but to not allow flow around the ends. A high-permeability shell on the outer cylindrical surface provides vertical flow paths, to maintain uniform radial flow through the reservoir.

A flow-meter and flow-control system was designed, built and developed to accurately measure very low flow rates at high pressure and to maintain a constant back pressure, which simulates virgin reservoir encroachment. Also, an injection-pressure system and flow-meter system was designed, built and developed, to provide the ability to measure very low flow rates at high pressure and to control the system at various constant injection-pressure levels. A third flow meter was designed, built and developed. This is a mud-column pressure control and flow meter used to maintain a constant head of pressure on the mud column. This will simulate various depths and measure any flow that occurs going down-hole. It also acts as a solid plug when injection pressures control the flow potential.

A mud-mixing, mud-flow network and control system, to operate in conjunction with the mud-column flow meter system was designed and built, so that mud cake could be formed on the wellbore of the artificial reservoir.

We also designed and constructed a well system which provides a means of simulating conditions below the artificial reservoir to depths as great as 2000 ft. This system also is a means of controlled injection of fluids at any depth from 100 ft. to 2000 ft. This well system will provide the potential to investigate many phenomena, but some conditions can not be simulated accurately and the dynamic effects of a long mud column is one case.

## DEVELOPMENT OF SUBSURFACE FACILITIES

Jr.'s Rat Hole Drilling Company drilled a 60-in.-diameter rat hole 4 ft. deep. Because of wet weather, a bulldozer was used to pull the rig off location. Both a mud reserve pit and a working mud pit were dug. Grace Drilling was delayed from rigging up due to inclement weather, and when they began to drill they were hindered by mud-pump problems. They drilled to 333 ft. and then A-3 Casing crew set the casing and Dowell-Schlumberger cemented it. Drilling resumed for the 10 3/4-in. casing and total depth of 2110 ft. was reached four days later. Gearhart Inc. logged the well and then A-3 Casing crew set the casing and Dowell-Schlumberger cemented it bottom to top. Only the coupling on the 10 3/4-in. casing can be seen, near the edge of the concrete pad in the central foreground of Figure F1.

## DEVELOPMENT OF FACILITIES AT THE SURFACE

After the well was completed the concrete pad was formed, steel placed, tied and concrete was poured. This pad was designed to withstand the weight of the forklift, plus the artificial-reservoir housing and the artificial reservoir filled with water. It is 40 ft. by 30 ft.; it is shown in the central region of Figure F1. The size is based on the turning radius of the forklift and the equipment required to be placed on it.

The instrumentation building is the checkered building on the left side of Figure F1. A four-line plastic tubing ground loop was trenched and laid with an automated Ditch Witch machine. Use of the equipment was donated by Ditch Witch. This ground loop is coupled to a water-source heat pump in the instrumentation building, to supply proper temperatures for the computer and data acquisition system. The heat pump was also donated.

An electrical load requirement was designed for the facility. Trenches were dug, conduits placed in the trenches, wires were pulled and circuits were completed. Water and gas lines were laid prior to the electrical lines, because of the depth requirements.

A cinder pad was made for the tank battery and rock/gravel was put in the drive and parking area. Rock was also placed on the dirt road leading to the test site. The foreground in Figure F1 shows the parking area, and in the right-hand side is the tank-battery cinder pad.

Figure F2 shows the salt-water tank, pump and plumbing in the foreground. This facility is used for salt-water injection into the well. In the background is the tank that receives effluent from all the flow activities. These fluids are held in the tank for proper disposal.

The mud system is shown in Figure F3. The view is northeastward. Pipe racks are to the south of the mud system. The pipe network in the foreground is configured to allow bypass back to the tank under a given pressure, flow through the artificial reservoir, circulation through the calibration lines or just circulation back to the tank. The mud pump is

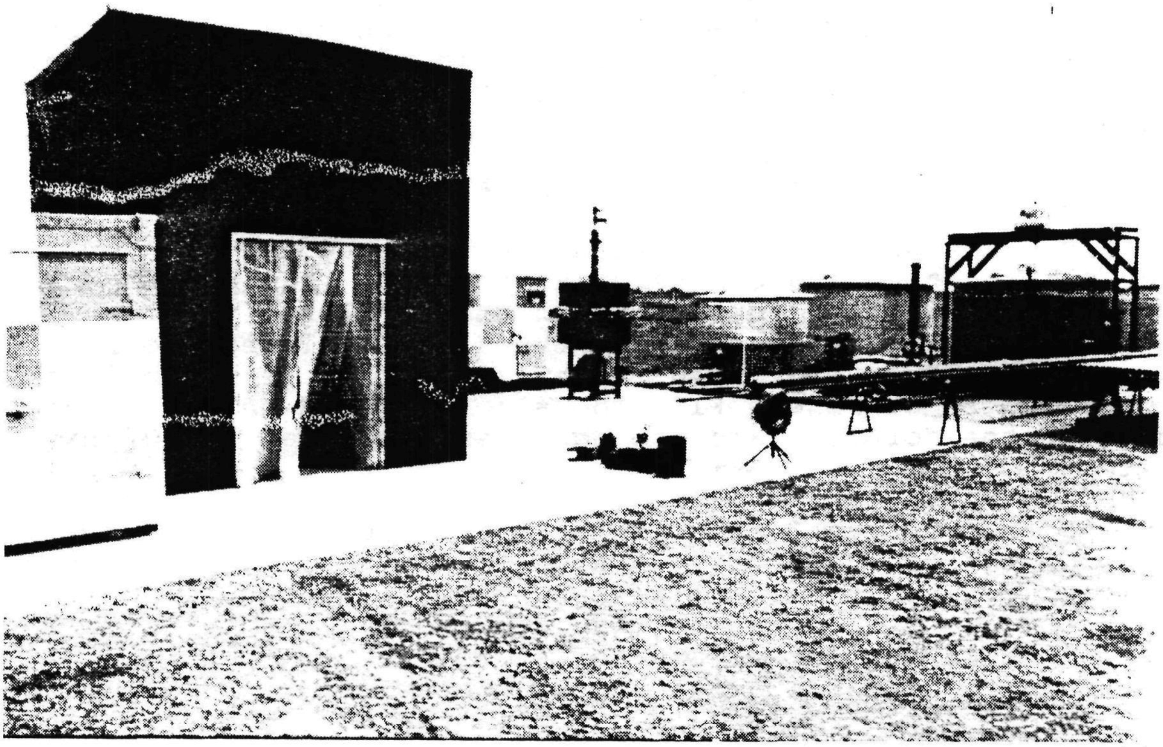


Figure F1. Mud-plug facility; view northeastward.

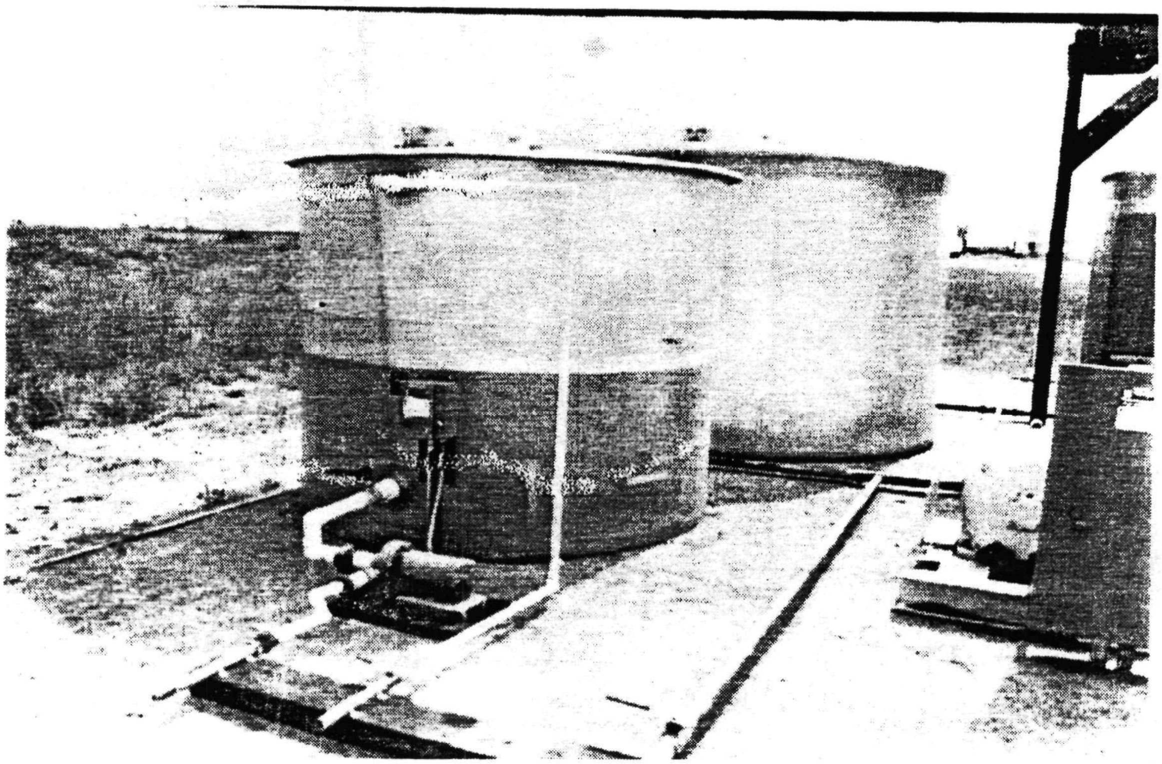


Figure F2. Salt-water tank in foreground; effluent tank behind.

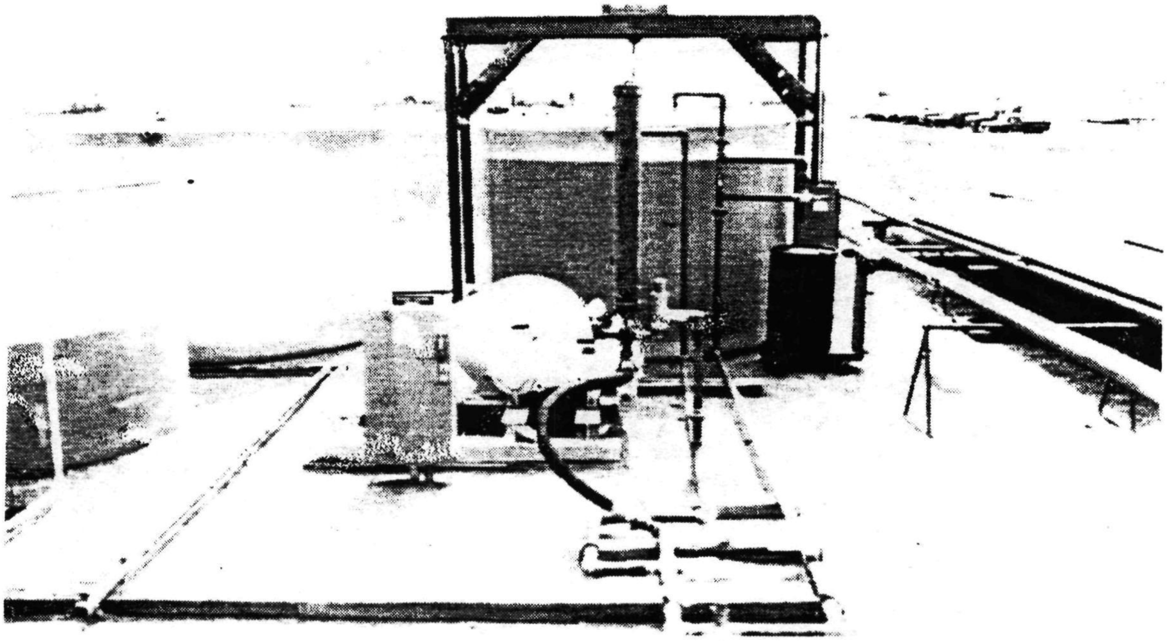


Figure F3. Mud pump, pipe network, tank and mixer system.

near the center of the figure, with a flex-hose discharge and a pulsation dampener, as well as a pressure-relief valve. Near the tank and on the right side is the calibration system, consisting of lines, control valves, sample container and scales for weighing the mud. Above the mud tank is the motor and drive for the mud-mixing impeller. The shaft is between the mud-mixer frame and the pulsation dampener. This system supplies mud to fill the wellbore and mud circulation to build a mud cake in the reservoir.

Figure F4 shows the v-door, attached to the pipe rack. On the pipe rack is the 5 1/2-in. casing for the simulated wellbore, the 1 1/4-in. tubing for injection of salt water, and 2 3/8-in. tubing for filling and jetting the well.

In Figure F5 the simulated wellbore-mud column section is lain on the pad prior to placing it on the tubing above the artificial reservoir. The artificial reservoir is shown in the environmental control building, as it would be placed while testing (Figure F6). The wellbore-mud column is inserted through the roof and attached to the tubing oh top of the artificial reservoir.

A part of the mud-column system is shown on the top of the artificial reservoir in Figure F7. This figure primarily is the artificial-reservoir housing assembly. The mid-section is the 36-in. pipe with an array of flow lines for the effluent from the reservoir. The flange and blind-flange pairs on the top and bottom are for reservoir-rock placement and removal. On the left side of the housing is a pressure transducer and a line going to the differential-pressure transducer, on the casing sub on top of the housing. A pressure transducer and two differential-pressure transducers are mounted on the casing above the top blind flange. The mud-inlet connection is under the housing, and sticking out to the left at an angle to the bottom casing sub. The artificial-reservoir housing is on the assembly stand. This is the location where the unit was hydrostatically pressure-tested and where the artificial-reservoir material is placed in the housing. Also, this is where the porosity and overall permeability of the rock are to be measured.

Figure F8 shows a closer view of the effluent lines from the reservoir housing, which are to come to a common point to discharge to the effluent tank. Also, the diaphragm-seal housing is placed to keep the instrument fluid separated from the effluent mud, but still to measure the pressure. The cross above it has one leg going to the pressure transducer, one to the pressure gauge, one from the diaphragm, and the vertical one extends to the radial differential-pressure transducer.

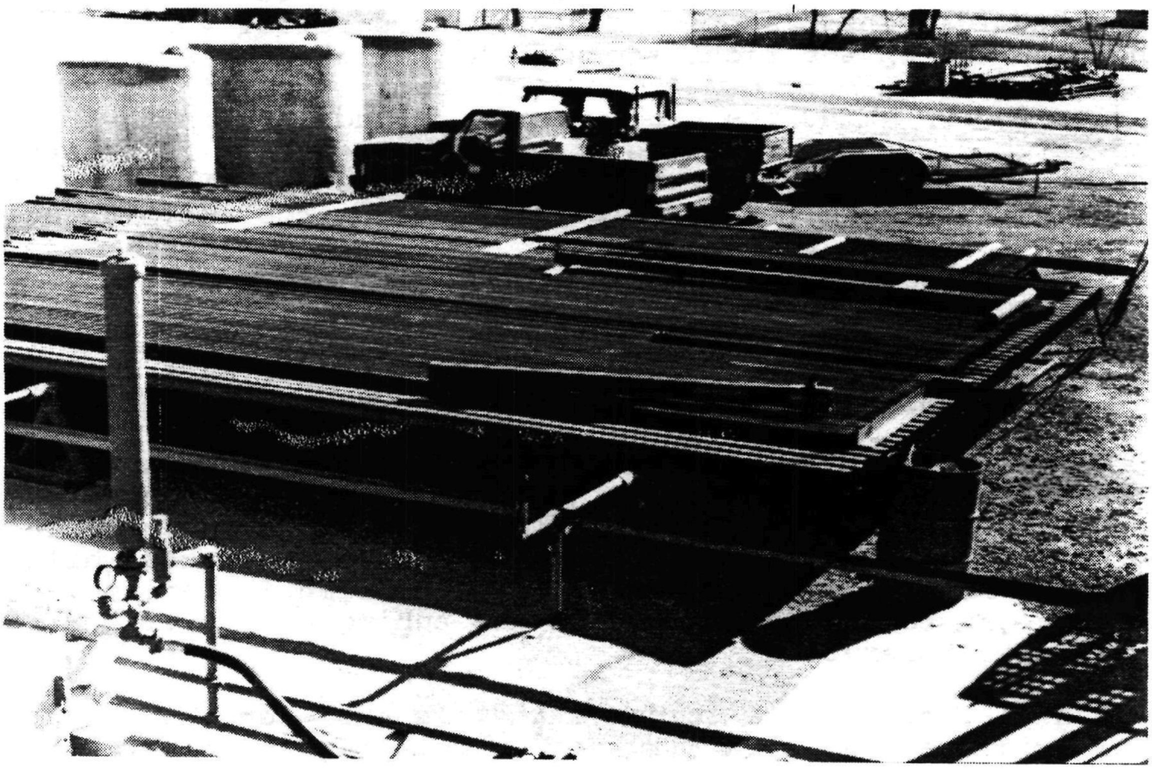


Figure F4. V-door attached to pipe rack; casing and turbine.

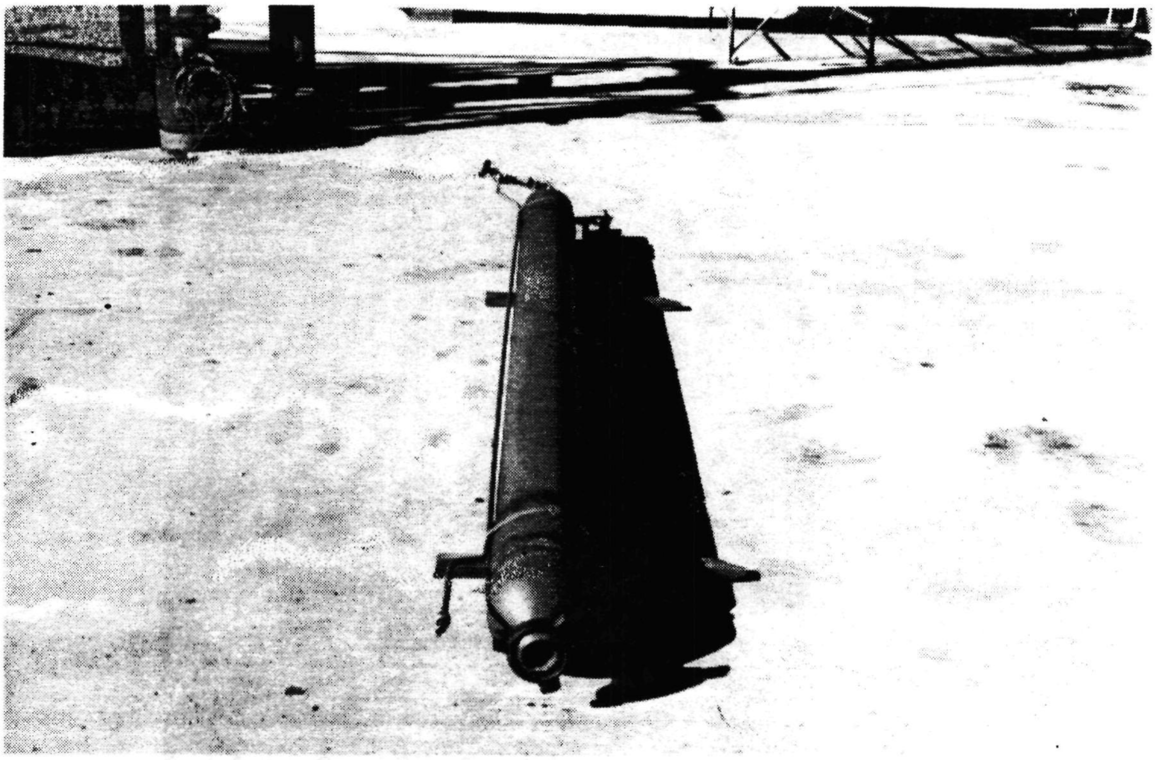


Figure F5. Simulated well-bore and mud-column section.

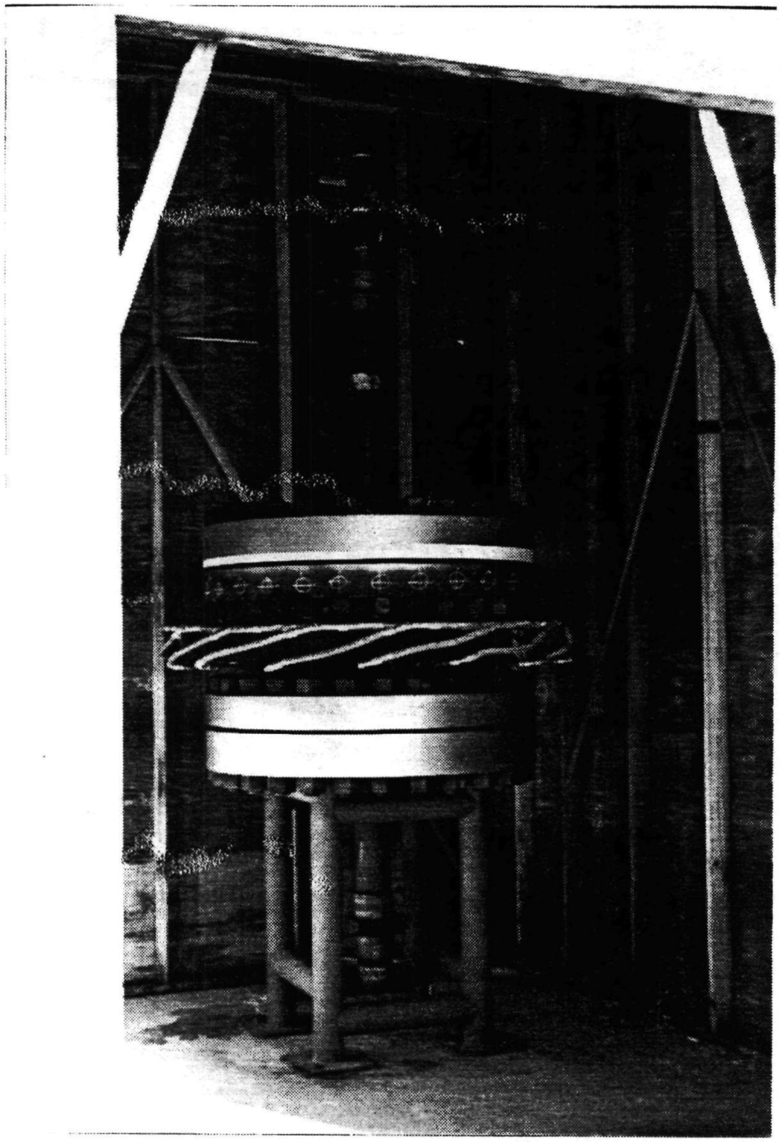


Figure F6. Artificial-reservoir system in environment-control building.

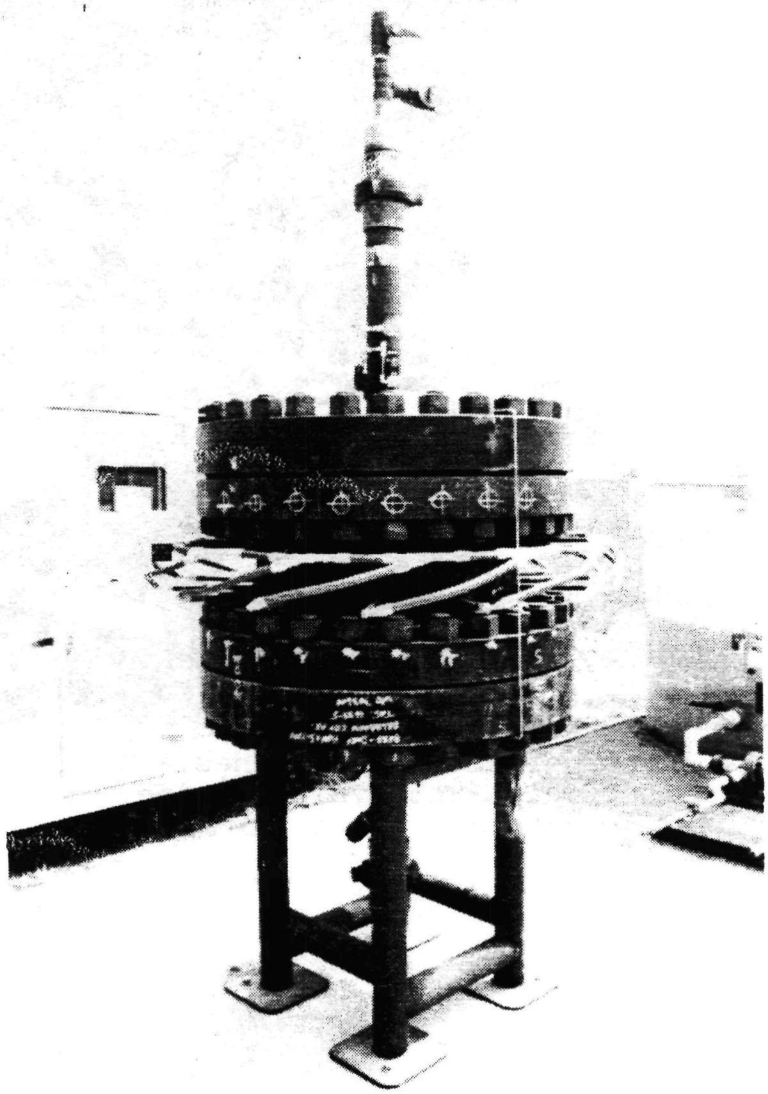


Figure F7. Artificial-reservoir housing assembly.

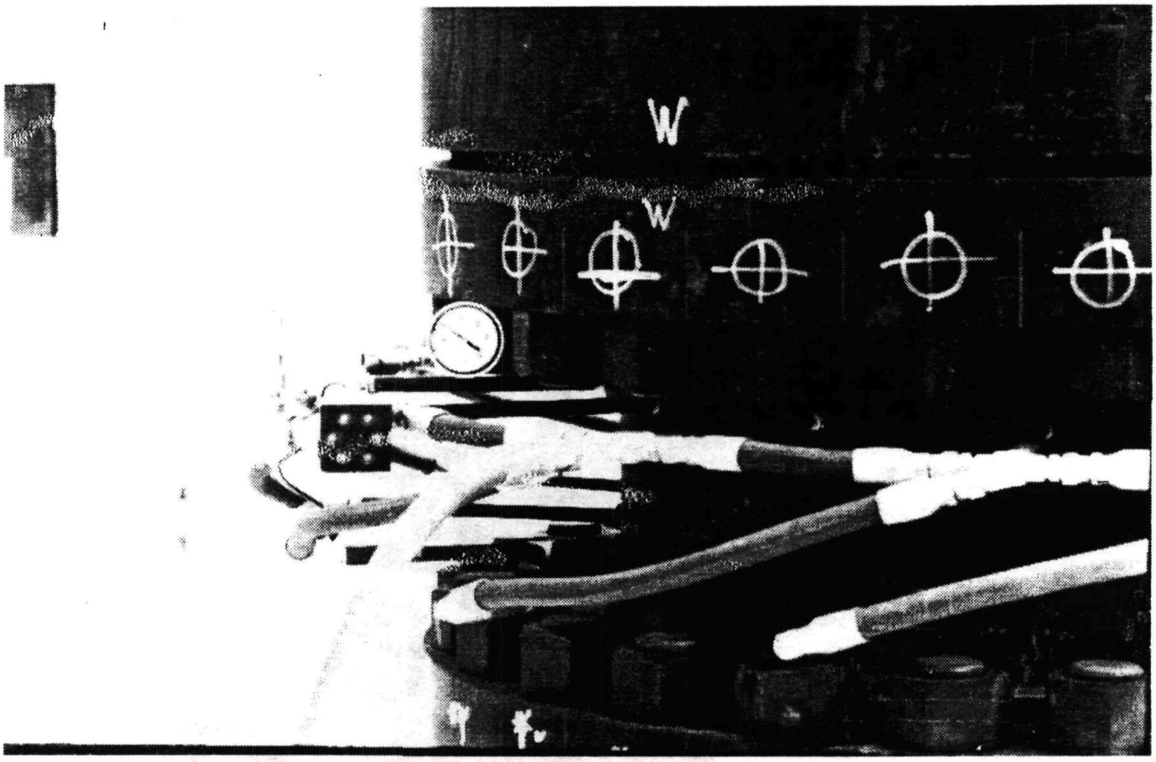



Figure F8. Peripheral effluent lines and instruments on artificial-reservoir housing.

In Figure F9 the centralizer is at the far end of the casing. This keeps the instruments protected while the casing is lowered in the hole. The end with the centralizer goes into the borehole first. Above the centralizer is where the first differential-pressure lead line, diaphragm and temperature sensor are located. Closer to the viewer's position is the location of the differential-pressure transducer, which connects the two diaphragm housings shown in the figure. The pressure transducer, temperature sensor and salt-water injection port are at the same nominal location. Figure F10 is a view up-hole from the salt-water injection port; it shows the salt-water injection tubing and the instrument wire and tubing, which extend to the next sensor.

The pulling unit is in the background of Figure F11, in position to run tubing and casing. Behind it are the well-head and the artificial-reservoir test stand. The reservoir is moved to this location after mud has been pumped into the 5 1/2-in. instrumented casing. On the left side is the end of the v-door. It is bolted to the pipe rack and the end section is removed after pipe has been run.

In Figure F11 the view is southward, whereas the view in Figure F12 is westward. In Figure F12 the well-head configuration is that of tubing in the hole ready to be used to run mud to the bottom. Wire sticking out of the casing head is composed of lead lines from the down-hole instruments. These will be connected to the multiplexer, shown in Figure F13 and then to the computer in the instrumentation building, shown in Figure F14.

The heart of the measuring system at the surface is shown in Figure E5. It is the flow-meter and pressure-control system, which is referred to as the instrumentation console. With it the observer will know whether mud cake is protecting the reservoir zone.

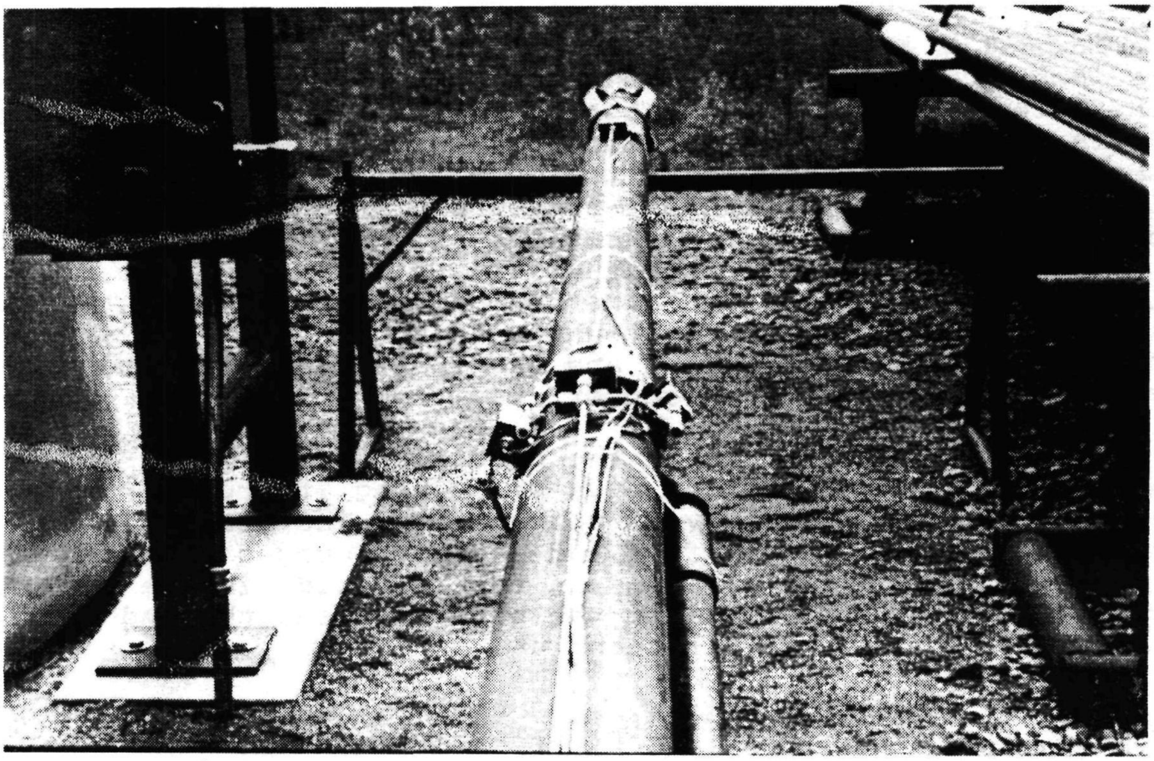


Figure F9. First (lowermost) joint of casing, with instrumentation.

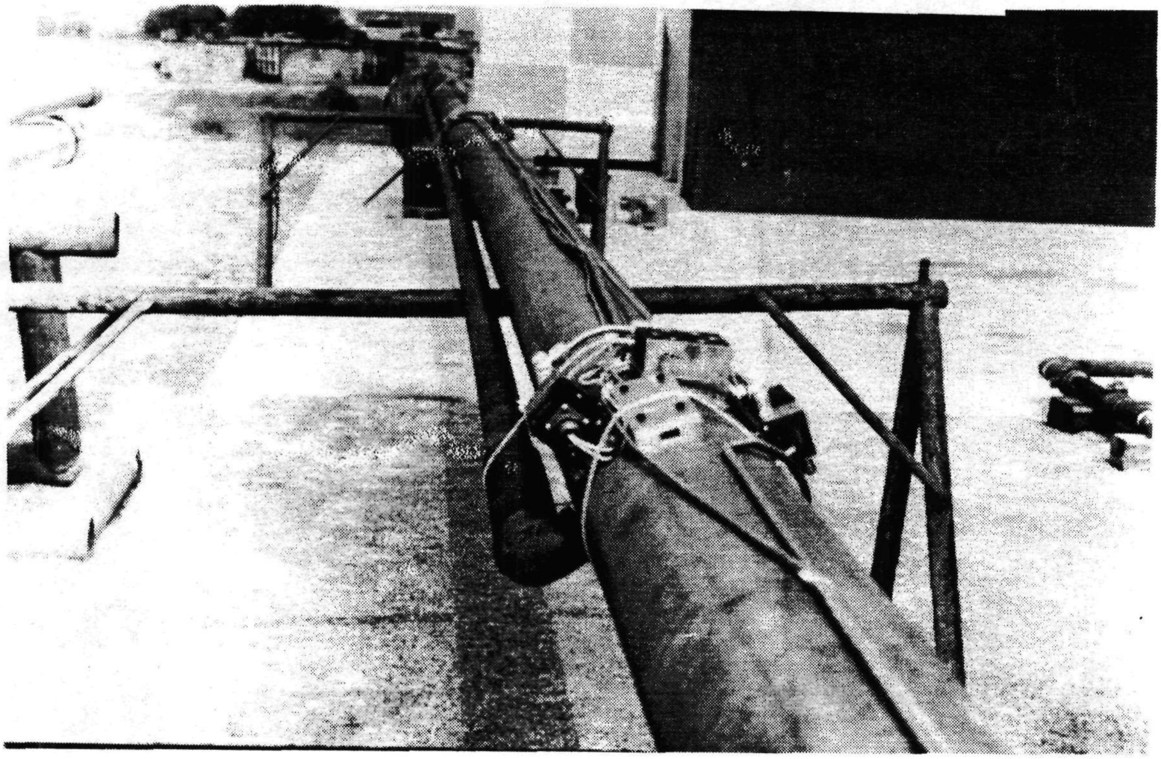


Figure F10. Bottom end of first (lowermost) joint of casing, as seen in the up-hole direction.

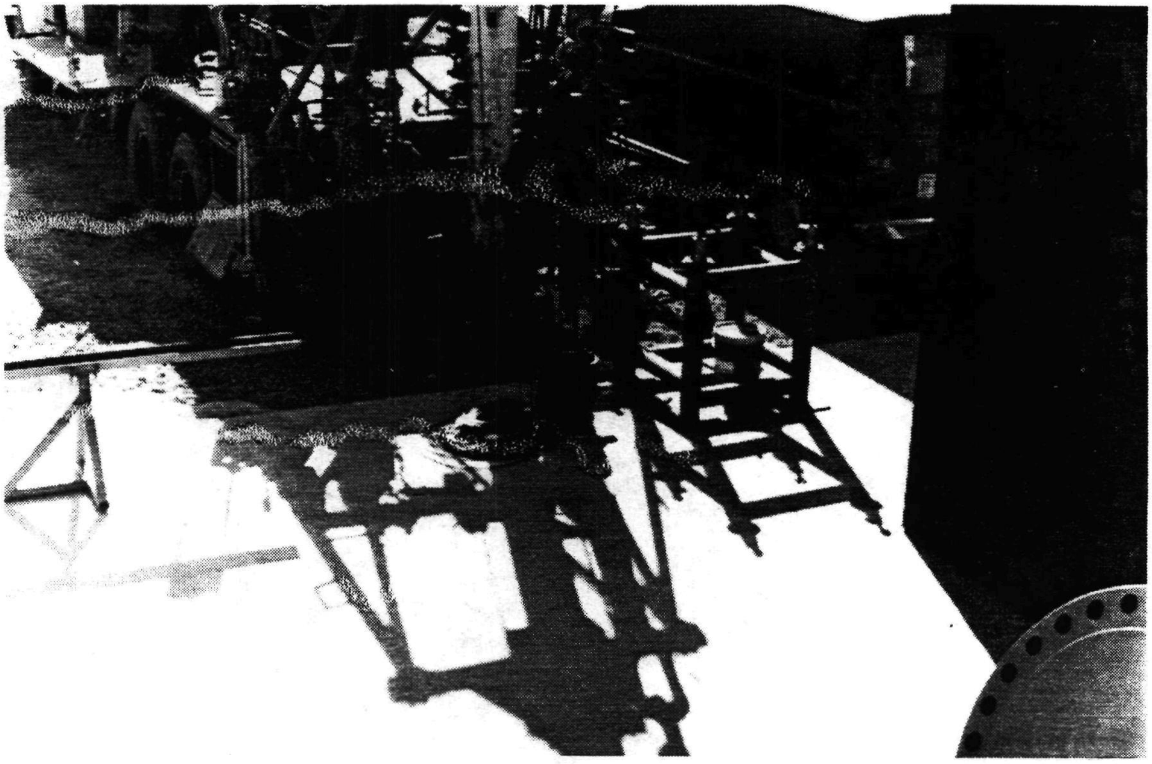


Figure F11. Pulling unit and well site.

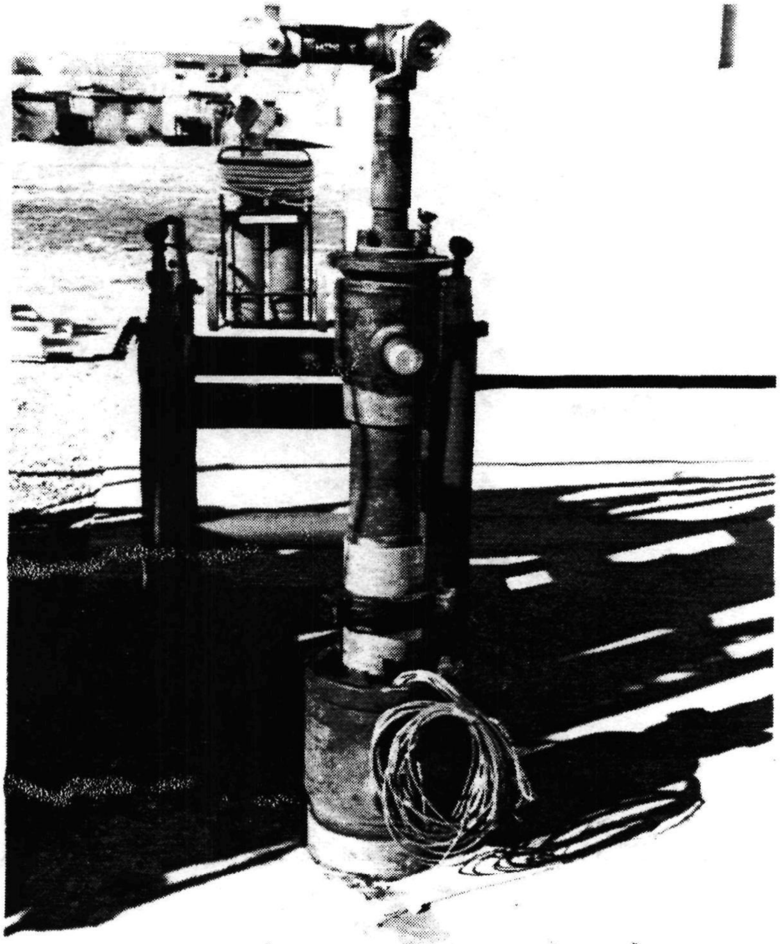


Figure F12. Well configuration for placement of water and mud in 5 1/2-in. casing, through 2 3/8-in. tubing.

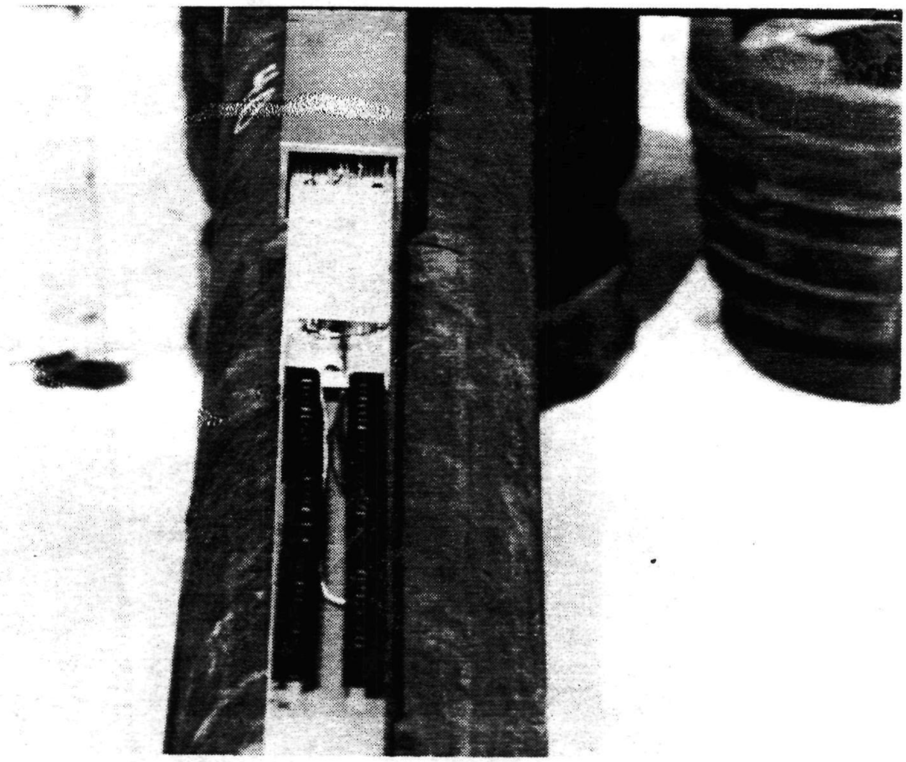


Figure F13. Multiplexer mounted on casing.

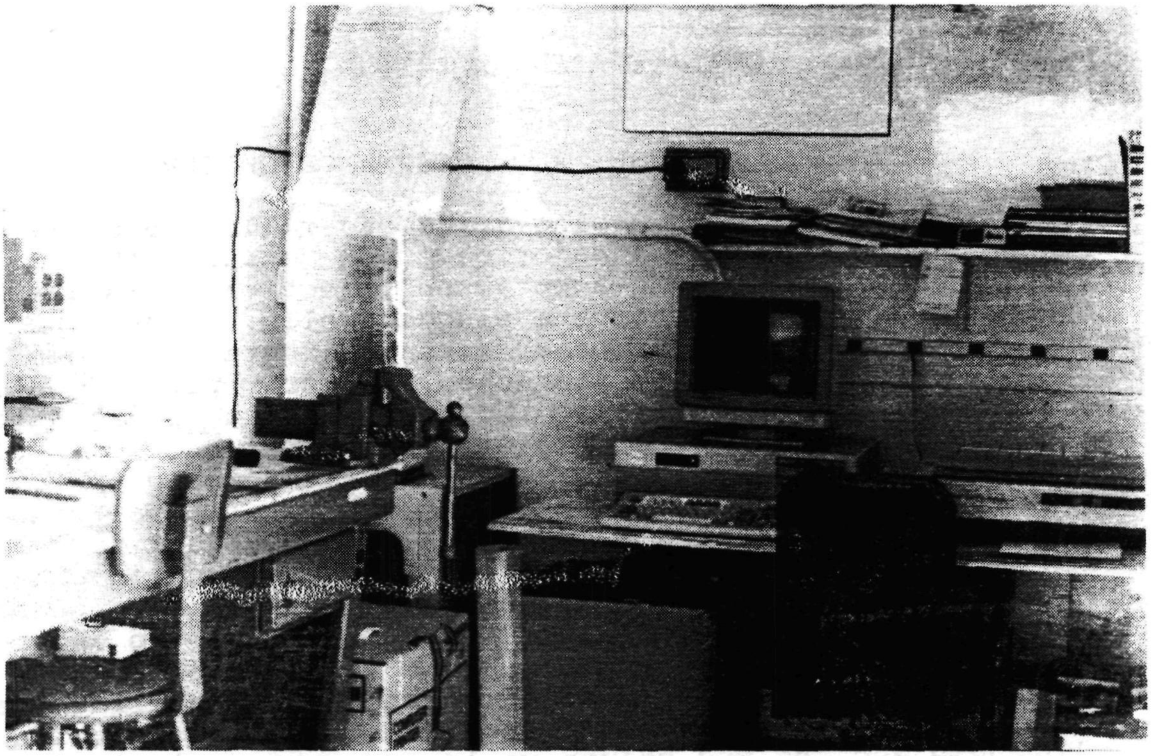


Figure F14. Heat pump and computer inside instrumentation building.

# APPENDIX G

# QUALITY ASSURANCE PLAN

## PROJECT OBJECTIVES, DATA USE, AND ACCEPTANCE CRITERIA

Current methods of plugging abandoned wells use drilling mud as a plugging agent. A major question concerns the performance of the plugging agent when injection wells are activated in the vicinity of the plugged wells. Thus, the primary objective of the proposed research is to test this hypothesis: Drilling mud in abandoned, properly plugged wells effectively seals the borehole. However, if fluids injected into reservoirs at depth were to migrate up the boreholes of such abandoned wells, filter cake nevertheless would prevent passage of these fluids into other reservoirs. The alternate hypotheses need no elaboration. A secondary objective is to obtain fundamental information on conditions of mud in the simulated well in order to provide guidelines for developing a technique and an associated instrumentation system to enter abandoned wells. These abandoned wells would be ones that were recorded as having been plugged properly. Entering these wells to obtain fundamental information about the condition of the borehole and the mud column would require specialized techniques and an instrumentation system to minimize altering downhole conditions and to provide proper interpretation of results.

One of the primary objectives of the project can be restated using performance variables. Results of the test will include values of low rates induced by particular injection pressures, along with other variables, as shown in Table G1. A plot of flow rate versus injection pressure, with other variables held constant, will generate a family of curves. This family of curves will define an envelope of performance characteristics. The envelope will show the combination of variables that potentially produces invasion of the reservoir -- or conversely, it will show the combination of variables under which the reservoir effectively would remain sealed. Thus, the results of the test will indicate the effectiveness of drilling mud as a plugging agent in accordance with a specific range of well conditions.

Mud properties as a function of time and depth are to be determined within a borehole, to establish characteristics of the mud as a plugging agent. Differential-pressure transducers will be placed on the casing to measure pressure gradients within the casing from above the simulated reservoir to the bottom of the casing. Similarly, temperature sensors will be

Table G1. Array of test variables for tests 1 through 6.

| CONTROLLED VARIABLE | TEST NUMBER | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| RESERVOIR DEPTH (FT) | 1000 | 1000 | 1000 | 1000 | 2000 | 2000 |
| MUD COLUMN PRESSURE AT RES. DEPTH (PSI) | 468 | 468 | 468 | 468 | 936 | 936 |
| RESERVOIR PRES.(PSI) | 450 | 450 | 450 | 450 | 900 | 900 |
| INJECTION DEPTH (FT) | 1168 | 1500 | 2000 | 2000 | 3000 | 4000 |
| MUD COLUMN PRESSURE AT INJ. DEPTH (PSI) | 547 | 702 | 936 | 936 | 1404 | 1872 |
| INJECTION PRES.(PSI) | 557 to | 712 to | 946 to | 946 to | 1414 to | 1882 to |
| INJ. FRAC. PRES. --- | 880 | 1200 | 1600 | 1600 | 2400 | 3200 |
| ** (MAX. ALLOWABLE --- | 1497 | 1684 | 1918 | 1918 | 1918 | 2386) |
| RESERVOIR PROPERTIES | | | | | | |
| PERMEABILITY (MD) | 100 | 100 | 100 | 150 | 150 | 150 |
| POROSITY (%) | 21 | 21 | 21 | 21 | 21 | 21 |
| FLUID PROPERTIES | | | | | | |
| MUD WEIGHT (LB/GAL) | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 | 9.0 |
| SALT H2O WT.(LB/GAL) | 8.7 | 8.7 | 8.7 | 8.7 | 8.7 | 8.7 |
| LEACHING | A minimum for all tests in the series. | | | | | |

** NOTE: 1450 PSI IS THE MAXIMUM WORKING PRESSURE THAT THE RESERVOIR CONTAINER WILL HOLD. IF FRACTURE PRESSURE EXCEEDS THE MAXIMUM ALLOWABLE THEN THE TEST IS LIMITED BY:

MAX. ALLOWABLE PRESSURE = MUD COL. PRES. AT INJ. DEPTH + ( 1450 PSI - MUD COL. PRES. AT RESER. DEPTH ) placed on the casing. If the density of the fluid that caps the total column of mud is known, then the average density between sensor-locations throughout the column of mud can be determined from the pressure and temperature gradients. Coupling these data with the mud properties and constituents (known from measurements made on the mud prior to circulation of it into the casing), the mixture of constituents at various depths can be calculated. Duplicates of these will be formulated at the surface and placed into aging-cells, to measure the shear properties at the time when injection into the well bore (casing) begins. Gel strength will also be measured with these samples. The shear stresses and gel strengths will be used to indicate the resistance to flow, and will be correlated with injection pressures required to invade a given reservoir. Other data will be obtained from the mud (prior to circulating it into the casing) such as Marsh Funnnel viscosity, plastic viscosity, apparent viscosity, yield point, shear strength, fluid loss, density, pH, and resistivity. This information will be used to correlate field data with results of experients.

A set of pressure-time history curves will be obtained for the period of time beginning with circulation of mud into the well and ending with stabilization of pressures in the static mud column. These pressures and their associated gradients will be used to estimate the change in potential for formation fluids to invade the well. Also, pressure-time histories during the period when fluid is injected into a lower formation will be recorded. Analysis of this information will allow estimates of the plugging capability of the mud under the controlled conditions.

The simulated reservoir will be evaluated for specific properties. These attributes will be correlated with field data to determine what field conditions would lead to invasion. These properties are porosity, permeability, reservoir pressure, and wellbore pressure. In addition, the amount and rate of fluid invasion into the reservoir will be mapped, along with a pattern of invasion. These data will also be used to correlate experimental data with field data to show potential invasion problems.

Flow rates of mud will be measured while circulating the mud through the simulated reservoir. Injection flow rates, cumulative flow, temperature and pressure will be measured during injection periods. Injection-fluid density and viscosity for each type of fluid will also be measured. All of these measured values will be included in the correlations of field conditions with experimental data.

Values from each of the variables measured will be reviewed for application in directing the development of a technique to insert tools into an abandoned, plugged well and measure the significant variables with minimal interference and error. Structural configuration, strength and sensitivity are some of the tool-attributes that would be sought.

To test the major working hypothesis, it is necessary to detect that second-stage invasion (i.e., invasion due to breaching of previously established mud cake) did or did not occur through the artificial reservoir. Moreover, it is necessary to know what the associated values of critical variables (discussed earlier) are, within a narrow error-band. The width of the error-band should be as small as that which the standard instrument can measure reliably for each variable. These same criteria will satisfy the secondary objective of the proposed research project.

## DATA-QUALITY OBJECTIVES

Successful detection of whether fluid enters the simulated wellbore during the injection period is essential to success of the project. Because fluid could enter at a rate too small for many of the standard flowmeters to detect accurately, or could come in at a very large rate, the design of a unique flowmeter is required to resolve both extreme situations. An error of 0.00017 barrel-per-day is sufficient in the low range (0.02 barrel-per-day); a 0.015 barrel-per-day in the higher range (15 barrel-per-day).

Pressure measurements are to confirm the flow data and assist in determining local properties of the mud. Pressure transducers with accuracy of plus or minus 1 percent of the full scale will be used. Full scale is 3000 psi. Also, an array of differential-pressure guages in the simulated reservoir area and at the bottom of 100 feet of casing will be used, to obtain greater sensitivity.

Temperature within the fluid system must be monitored and measured to assist in defining local properties of the mud and to assist in detecting fluid migration. Temperature sensors with accuracy of plus or minus 1 percent of full scale are readily available. Obtaining temperature within 0.5 to 1.0 degrees Fahrenheit will provide acceptable results.

## SELECTION OF SAMPLING LOCATIONS AND COLLECTION OF SAMPLES

The 2000-ft. casing that simulates a wellbore will be sampled for pressure at 100-ft. intervals, in general. However, at the bottom of the casing, pressures and differential pressures will be sampled at locations according to Figure C2. Temperature will be sampled at 300-ft. intervals except near the injection depth. At this position temperature will be sampled according to Figure C2.

Sampling of data from the simulated reservoir will come from locations at 16 positions on the periphery of the artificial-reservoir housing. Data will also be taken just above and below the 2-ft.-thick reservoir.

Cores of the simulated reservoir will be collected for laboratory analysis. Upon disassembly of the reservoir mold and inspection of the reservoir material, cores will be collected from it. These will be placed in containers, marked and stored in the analytical laboratory prior to evaluation.

Mud will be mixed according to the results of evaluating temperature-and-pressure data from the test well. These specific mixtures will be place in aging-cells, which will be marked according to depth and date. The aging-cells will be placed in an oven at the appropriate temperature, to age until injection in the well commences. At that time shear tests will be run on the samples of mud.

HANDLING, IDENTIFICATION AND STORAGE OF SAMPLES

Core samples from the simulated reservoirs will be collected. Each sample will be placed in a container and identified. The core will be marked with a date and index number. In addition, the container will be marked with the date and number. A data sheet showing the same date and number will also identify the location (radius, depth and azimuth) with respect to the simulated reservoir, the test number, test duration, simulated depth of core and injection point, mud pressure at the simulated reservoir, injection pressure, and type of injection fluid.

Data will be stored on computer disks and in bound notebooks. Core samples will be stored in the School of Geology.

METHODS OF MEASUREMENT, AND PERFORMANCE CHARACTERISTICS

For the most part, methods of measurement are considered to be standard. Data collection from temperature sensors, pressure sensors, and from flowmeters will be accomplished by a data-acquisition system developed by the Oklahoma State University Electronics Research and Development Laboratory. This method employs a down-hole remote-multiplexing scheme for selection of the sensor to be monitored. An interface card that plugs into an IBM PC-XT or compatible computer is used to address a multiplexer input, convert the analog data to digital data, and store the data on a disk, with other applicable information. System software is developed, using Microsoft "C".

An encoder on the interface board is controlled by the computer to select and hold the sensor addressed, until a value from the sensor is read. The binary address is encoded into a Bi-phase Level Pulse Code Modulated (PCM) signal that is transmitted by shielded twisted-pair wire to the remote multiplexer decoder. The decoder identifies the address and opens the corresponding multiplexer channel of the selected sensor. The output of the multiplexer containing the selected sensor voltage value is conditioned and fed to a voltage-to-current converter. The output of the converter is a 0-to-20 milliampere current loop that is sent up-hole through a shielded twisted-pair wire to the computer interface board. This current is converted to a precision voltage and fed into a 12-bit analog-to-digital converter. This digitized value is read by the computer, added to any applicable calibration offset, converted to an engineering unit (e.g., degrees Centigrade), and stored in memory. At midnight of each day, the data will be stored on disk with day and date, time, sensor number, and sensor value. Normally, data well be sampled at all sensors at 10-minute intervals.

A remote-multiplexing scheme was chosen because of the limited space for wiring in the borehole. Instead of a twisted-pair wire coming from each sensor, only three pairs of wires will extend upward from each multiplexer box. These wires will be for the address-data, returning-sensor-value, and for power. Sixteen to twenty-four inputs will be fed into each remote multiplexer. Data-loss will be minimized by this process: The computer will reboot automatically after a power failure, and will automatically resume the recording of data.

The test facility, as designed, has the capability to provide an array of independently controlled variables. These variables are listed below, with explanation of how they will differ and the ranges of expected values.

<u>Injection Depth</u>

The 5 1/2-in. casing has multiple perforations in the central portion of the bottom joint. As the casing is set in the well by hanging from the slips in the well head, the adjustment can be made so that the depth below the simulated reservoir is from 100 ft. to 2000 ft. Initial tests will begin at the 100-ft. depth and increase to the 2000-ft. depth below the reservoir by addition of casing joints to the string. Depths of 100, 500, 1000, 1500 and 2000 ft. below the simulated reservoir are planned, but the time required to run the test will dictate the number of depths that can be simulated. These depths are to be added to the simulated depth of the artificial reservoir.

Depth of Artificial Reservoir (Invaded Formation)

A column of mud in a 5 1/2-in. casing protruding above the artificial reservoir will be pressurized with a cylinder and a high-pressure nitrogen bottle, to achieve the pressure at the artificial reservoir commensurate with the mud in the well. This series of tests will be run only at the Oklahoma Corporation Commission's designated plugging mud weight of 9 lbs./gallon. Therefore, the mud weight is 0.468 psi/ft. or at a depth of 1000 ft., the pressure would be 468 psi. To simulate depth, a pressure would be applied at the artificial reservoir to be commensurate with the mud column at that depth. Depths of the invaded reservoir will range from 400 ft. to 3000 ft. Thus, the maximal simulated depth for injection will be 5000 ft.

Artificial-reservoir Pressure (Invaded Zone)

A large accumulator will accept effluent from the artificial reservoir and the pressure in the accumulator bladder will be maintained at the designated reservoir pressure with a high-pressure nitrogen bottle and both a regulating valve and a relief valve (see Figure 3). The fluid coming from the well bore to the reservoir would be working against a constant reservoir pressure. Reservoirs at different depths have different fluid-pressures, ranging from about 0.433 psi/ft. to about 0.471 psi/ft. of depth. In the case at hand, the chosen pressure-range will be from 0.433 psi/ft. to 0.45 psi/ft. Initial tests will begin at 0.45 psi/ft. and reduce to 0.44 psi/ft. and then 0.433 psi/ft., depending on available time. A new mud cake must be developed each time the reservoir pressure is changed because the change in pressure between the well pressure and the reservoir pressure would increase, thereby increasing the driving potential. This would result in deeper invasion of the mud into the reservoir.

Injection Pressure

Another bladder-type accumulator will be used to supply the fluid to be injected into the well bore full of mud. A high pressure nitrogen bottle will supply pressure to the bladder, which will force the injection fluid to the well bore. A tight-band-pressure control valve will meter the nitrogen into the bladder to maintain correct pressure. Pressures will range from 10 psi above the well pressure at the injection depth to a maximum of 0.8 psi/ft multiplied by the injection depth (unless significant invasion of the reservoir took place at a lower pressure). With all other variables remaining constant the injection pressure will be increased and time will be allowed for a reaction to occur. If nothing detectable happens, then the pressure will be increased and the process repeated until the reservoir is invaded or the maximum pressure (based on 0.8 psi/ft or 1450 psi at the simulated reservoir) is obtained.

## Reservoir Properties

A review of some Oklahoma formations that potentially would be invaded from the wellbore due to injection above or below the zone revealed a porosity range from about 18 percent to 24 percent. Initial tests will begin with about 21 percent porosity and depending on time available, the 18 and 24 percent runs will be made. Tentatively, permeabilities for these reservoirs will be in the range of 50 to 150 millidarcies. The initial reservoir will have permeability of about 100 millidarcies unless subsequent information supports a different value. Again, time will dictate the number of permeability cases which will be run.

## Fluid Properties

The two fluids involved in the initial test series are the 9.0 pound/gal mud and salt water. Mud in the simulated well is going to be placed at the one consistency for this test program. Salt water with a specific gravity that yields about 8.7 pound/gal would be the initial injection fluid. If time permits a 9.0 and a 9.3 pound/gal salt water would be tested. The salt water of least density is expected to have the greatest potential for invading a zone above the injection zone.

## Leaching

Movement of water out of mud in the well bore occurs if mud cake is not sufficient to effect a complete plug. Leaking would occur until a balance among the well-bore pressure, the reservoir pressure and the resistance to flow (mud cake) is achieved. It is anticipated that no substantial leaking will take place during the period between when the mud cake is formed and when injection commences for the current test program. Effluent will be detected. In the future,to create a situation that would cause substantial leaking to occur and to test for integrity under these conditions would be informative.

## Test Sequence

A maximum of six different simulated reservoirs is scheduled for this contract. This is tentative because the time to reach an equilibrium to simulate an abandoned plugged well is not known, and time limitations on the contract would dictate the number of tests. Measurements of mud-pressure gradients in the lower joints of casing will provide data to determine equilibrium conditions. Table G1 shows the test schedule.

## Standards for Measuring Mud and Reservoir Properties

A list of operating procedures is contained in Appendix H, and embedded in these are various standards. Examples of these are listed below.

| | |
|---|---|
| Mud Standards | API RP 13B (Second Edition)<br>STANDARD PROCEDURE FOR LABORATORY TESTING DRILLING FLUIDS |
| | API RP 13I (Eleventh Edition)<br>STANDARD PROCEDURE FOR FIELD TESTING DRILLING FLUIDS |
| Reservoir | API RP 27 (Third Edition)<br>RECOMMENDED PRACTICE FOR DETERMINING PERMEABILITY OF POROUS MEDIA |
| | API RP 40 (First Edition)<br>RECOMMENDED PRACTICE FOR CORE-ANALYSIS PROCEDURE |

# QUALITY CONTROL AND QUALITY ASSURANCE

Quality control and quality assurance are accomplished through the implementation of logical guidelines and operation procedures. In this document a series of steps to achieve the test-objectives is outlined. These steps are supported with specific operating procedures that are listed in Appendix H. Integrated into these procedures are the sampling methods, ways of storage and preparation of samples, and methods of analysis. Also included are measurement techniques, quality-control measures and methods of working with the data. Methods of minimizing down-time and ways to recover data if parts of the system fail are included in the specific procedures.

## DATA REDUCTION AND REPORTING

Field and laboratory data will be recorded on floppy disks and on forms that itemize each variable required, the data, and the assigned test-number. A "Comment" section will be provided for the recording of pertinent information. The hand-written documents will be completed in a periodic manner until an extraordinary event is detected; then a higher frequency of data-procurement could be desirable. The forms will be amenable to entry of data into the computer. Most of the data will be recorded electronically and continuously, with the data-collecting system, and will be stored on disks. With all this information, a data-base will be established to provide easy access for data-reduction programs.

Multivariate linear regression analysis will be used to determine significant statistical parameters. Nonlinear regression analysis will be applied to models to determine empirical correlation equations.

Data will be reported in tabular form and in graphical form, to enhance clarity of results. Preliminary data will be supplied in quarterly reports; data will be shown in completeness in the final report.

### Characteristics of Computer Data System

Most of the data will be processed directly into the computer and saved on the hard disk, and then a "back-up" floppy disk copy will be made. Periodic printouts will be made to allow review of the data in progress. A range of expected values for the variables will be used to compare with the computer output, to determine the validity of data. The pressure and temperature data will be processed down-hole and sent out as electrical current. A digital format and conversion to engineering units will be achieved at the surface. Hardware and software for these signals will be designed and built by personnel of Oklahoma State University who do this type of work for the Space Program's remote sensing. Each sensor will be calibrated while on the surface and the calibration curve programmed in the processor and digitized. A dead-weight tester will be the standard for pressure calibration and a precision thermometer and environmental chamber will provide the means of calibrating the temperature sensors. A calibration check will be made prior to each time fresh mud is put into the well. This will be done by flushing water through the well after displacing the old mud and having clean water in the well. Knowing the temperature and density of the water in the well and knowing the locations of the sensors, the pressures and temperatures can be computed and compared to the sensor outputs displayed on the computer screen or on a printout.

Software will be generated by faculty and staff at Oklahoma State University and it will be verified by using known inputs and comparing the output with hand-calculated or known results. Data-reduction software will be a combination of commercial software and that generated locally. Regression analysis will be accomplished using a commercial software package. The files to be read by the software for the regression analysis will be generated by our own software.

An empirical model will be developed using variables listed in Table G1 as injection depth, reservoir depth, injection pressure, reservoir pressure and permeability. These are independent variables with the dependent variable being the effluent flow rate from the simulated reservoir. Regression coefficients will be determined from the array of data and the regression-analysis program. An output of the program will list the estimated statistical parameters. Also provided will be an asymptotic correlation matrix of the parameters.

Uncertainties in Measured Values

Uncertainties or errors in the measured values will vary with each calibration curve and instrument. A list of the major values measured showing expected errors is shown in the following table.

| VARIABLE | MAXIMUM READING | ERROR (+/-) |
| --- | --- | --- |
| Pressure difference | 10 psi | 0.05 psi |
| Pressure | 3000 psi | 30 psi |
| Temperature | 90 deg.C | 0.3 deg.C |
| Flow rate - mud | 44 gpm | 1 gpm |
| Flow rate - salt water | 5 gpm | 0.5 gpm |
| Flow rate - inj. fluid & effluent | 25 gph | 0.0005 gph |
| Flow rate - mud column | 115 gph | 0.0002 gph |

## STRUCTURE OF THE GENERAL EXPERIMENT: STEPS WITHIN ONE CYCLE OF INJECTION

Figure G1 indicates the steps that can be done in parallel with others and those that must be done serially.

1. Build artificial reservoir of sand and epoxy. (See Operating Procedure (O. P. 1).

2. Calibrate instruments according to Operating Procedure 2.

3. At pipe rack, mount instruments on casing, according to design of test. (For example, see Figure C2, which shows design of casing instrumentation for Test 1.) (Also see O. P. 3).

4. Build casing string with pulling unit and run string into borehole, according to Operational Procedure 4.

5. First cycle of reservoir-testing only: Fill 5 1/2-in. casing string with water to clean out, and to double-check calibrations of instruments. (See O. P. 5).

6. Measure porosity and permeability of reservoir on Assembly Stand (Figure 2, Location A) by filling artificial reservoir with salt water and flowing water through reservoir. (O. P. 6).

7. Make artificial reservoir ready for placement over borehole, according to Operational Procedure 7.

8. Homogenize drilling mud. Place mud in 5 1/2-in. casing using tubing set to bottom of hole. Check instruments by measuring and recording gradient-effects of mud. (See Operational Procedures 8.1 through 8.4, and 5.3).

9. Place reservoir over borehole (Figure 2, Location B) and make all connections for flow-lines, instrumentation and back-pressure controls. (O. P. 9).

10. At Location B (Figure 2), build mud cake in reservoir section: To retain salt water in reservoir, make up hammer couple. Deflate packer. Displace packer out top with mud. Circulate mud through well bore in reservoir. When flow of mud filtrate radially through reservoir stops, then mud cake is built. Bring primary mud flow to zero, while maintaining well-bore pressure at simulated depth, according to Table 1. (See Operating Procedure 10).

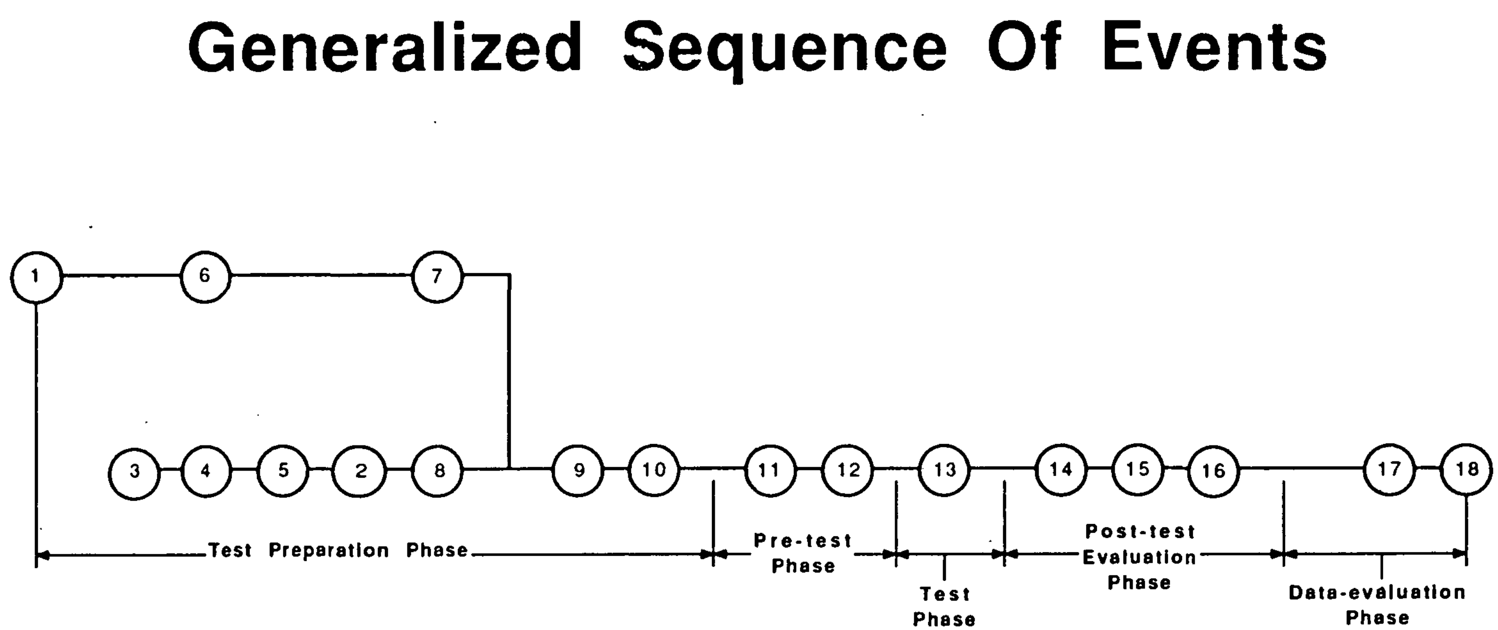



Figure G1. Sequence of events during one cycle of injection tests.

11. Let mud sit in column until equilibrium is reached, as measured by stabilization of temperature and pressure gradients across sensors. Monitor for displacement of fluid from column above reservoir, for detection of leakage in casing or migration through mud cake. (See Operating Procedure 11).

12. When mud equilibrates, begin injection of salt water at 10 psi above mud-column pressure, at injection point. Maintain for period of time judged to be sufficient for effect at reservoir. If flow from reservoir is undetectable, then increase injection pressure by increment specified in Operating Procedure 12.3. However, if flow from reservoir is detectable but less than 25 gpm, then increase pressure by the amount described in Operating Procedure 12.4. These steps would be repeated until (a) flow rate is equal to or greater than 25 gpm, or (b) the maximal injection pressure has been achieved.

13. Dismount artificial reservoir housing and move housing from Location B to Location A (Figure 2). (Operating Procedure 13).

14. Collect samples from reservoir according to sampling scheme prescribed for physical description of reservoir (Operating Procedure 14). Label and store as prescribed, in preparation for analysis.

15. Evacuate drilling mud in casing by water-displacement. Test calibration of down-hole sensors. Evacuate water with air, then swab dry. (O. P. 15).

16. Plot injection pressure against observed flow rates at reservoir-exit. Analyze these data to describe preservation or loss of reservoir integrity under experimental conditions. (O. P. 16).

17. Return to step 1.

## APPENDIX H

## OPERATING PROCEDURES: SUMMARY LISTING

1. Construction of artificial reservoir.

    1.1 Preparation of artificial-reservoir housing to receive sand mixture.

    1.2 Preparation of sand mixture.

    1.3 Filling of housing with sand mixture.

    1.4 Emplacement of top flange, artificial-reservoir housing.

2. Primary calibration of instruments.

    2.1 Calibration of pressure gauges.

    2.2 Calibration of pressure and differential-pressure transducers.

    2.3 Calibration of temperature-sensors.

    2.4 Calibration of flow meters.

    2.5 Calibration of mud-flow-rate system.

    2.6 Calibration of salt-water turbine meter.

3. Mounting of instruments.

    3.0 Mounting diaphragm-seal housings.

    3.1 Mounting of differential-pressure transducers.

    3.2 Mounting of pressure transducers.

    3.3 Mounting of temperature sensors.

    3.4 Mounting of multiplexers.

    3.5 Placing of flow meters.

    3.6 Mounting of pressure gauges.

4. Running instrumented casing string into borehole.

4.0 Pipe selection.

4.1 Positioning casing joint.

4.2 Connecting instrumentation lead-lines.

4.3 Mechanical installation of first joint.

4.4 Mechanical installation of second and all other joints.

4.5 Recording instrumentation position and location on casing string.

4.6 Securing top joint and lead-lines in wellhead.

5. Calibration-check of down-hole sensors and data-acquisition system.

5.1 Emplacement of water in casing string for calibration check of down-hole sensors.

5.2 Activation and check-out of computerized data-acquisition system.

5.3 Initial calibration-check of sensors.

6. Measurement of overall porosity and permeability.

6.1 Measuring porosity of artificial reservoir within housing.

6.2 Measuring permeability of artificial reservoir within housing.

7. Preparation of artificial reservoir for movement to position above borehole.

7.1 Containment of fluid within artificial reservoir during removal of instruments.

7.2 Installation of reservoir pick-up assembly.

8. Preparation of drilling mud, emplacement in casing and removal from casing string.

8.1 Mixing of mud according to Oklahoma Corporation Commission's standards for well-plugging.

8.2 Homogenization of drilling mud.

8.3 Sampling and testing of drilling mud.

8.4 Emplacement of drilling mud in casing string. (O.P. 11.1).

8.5 Removal of drilling mud from casing string. (O.P. 15.1)

9. Connection of artificial reservoir to casing string.

9.1 Placement of reservoir stand.

9.2 Placement of artificial reservoir on reservoir stand.

10. Building of mud cake.

10.1 Homogenization of drilling mud (O.P. 8.2).

10.2 Displacement of packer.

10.3 Adjustment of flow rate and back-pressure.

10.4 Monitoring of mud-filtrate flow rate.

10.5 Sampling and testing of drilling mud (O.P. 8.3).

10.6 Shut-down procedure and line removal.

10.7 Refined adjustment of pressure to prescribed magnitude.

11. Monitoring for equilibration of mud in casing string.

11.1 Monitoring of mud column (exposed to atmosphere) immediately after emplacement, for differential pressure, pressure and temperature.

11.2 Monitoring of mud column at simulated-depth conditions for differential pressure, pressure and temperature.

12. Monitoring effects of salt-water injection.

12.1 Activation of salt-water injection system.

12.2 Monitoring and recording comprehensive pressure differentials, pressures and flow rates.

12.3 Increasing injection pressure in response to undetectable flow from reservoir.

12.4 Increasing injection pressure in response to low rates of flow from reservoir.

12.5 Termination of injection in response to maximized flow or pressure.

13. Transfer of artificial-reservoir housing from test stand to assembly stand.

13.1 Removal of instrumentation from artificial-reservoir housing.

13.2 Disconnecting reservoir housing from casing string.

13.3 Installation of reservoir pick-up assembly and movement of reservoir housing.

14. Sampling of artificial reservoir.

14.1 Removal of artificial reservoir from housing.

14.2 Mapping and labeling of reservoir surface for random sampling.

14.3 Collection of random samples: channel samples, stratified samples and spot samples.

14.4 Labeling and storage of samples.

15. Evacuation of liquids from casing string.

15.1 Displacing drilling mud with water.

15.2 Calibration check of sensors (O.P. 5.3).

15.3 Displacing water with air.

15.4 Shut-down of computerized data-acquisition system.

16. Analysis of data and reporting of conclusions.

16.1 Documentation of software for reduction of data.

16.2 Documentation of software for analysis of data.

16.3 Methods for recording of data.

16.4 Methods for secure storage of data.

16.5 Methods for reducing data.

16.6 Methods for validating data.

16.7 Definition of data-quality indicators.

16.8 Methods for evaluating quality of data.

16.9 Methods for presenting data.

16.10 Reporting of conclusions.

## OPERATING PROCEDURE 1.1

## PREPARATION OF ARTIFICIAL-RESERVOIR HOUSING TO RECEIVE SAND MIXTURE

1.1.1 Install gasket between bottom blind flange and bottom flange.

1.1.2 Bolt flange halves together:

- o Insert bolts and screw nuts on, hand-tight.
- o Torque to 2500 ft.-lb. Tighten one nut; move to 180-deg. position; tighten that nut.
- o Move to next nut in clockwise direction and tighten it.
- o Move to 180-deg. position; tighten that nut.
- o Move to next nut in clockwise manner and tighten it.
- o Repeat this pattern until all nuts are torqued to 500 ft.-lb.
- o Repeat the same pattern at 1000 ft.-lb. and 2000 ft.-lb. torque, and finally at 2500 ft.-lb.

1.1.3 Clean surfaces on inside of artificial-reservoir housing.

1.1.4 Place form in housing to pour high-porosity outer shell.

1.1.4.1 Place HDPE liner on inside wall of artificial-reservoir housing and tape at butt joint.

1.1.4.2 Uniformly put parting compound on surface of sheet metal form, for making outer shell.

1.1.4.3 Place centering-device in form: Put sheet-metal-and-wood form in housing and secure form.

1.1.5 Place borehole form in 5 1/2-in. casing.

1.1.5.1 After outer shell has cured for 24 hr., remove form for making shell.

1.1.5.2 Roll a 3 ft.-by-20 in. sheet of HDPE so that it fits tightly on inside of casing. Place in lower casing so that top of rolled sheet is above top flange by about 1 in. Fill HDPE with sand to retain desired shape. Wrap fine woven screen around HDPE. Place movable screen clamps around screen, near pour-level. Move clamps up as number of lifts increases.

## OPERATING PROCEDURE 1.2

## PREPARATION OF SAND MIXTURE

1.2.1 Weight calculations.

1.2.1.1 Use Halliburton guidelines for weight of mixtures for sand and components of bonding agent. (See Appendix B, Attachment B1, letter from J. Murphey, Halliburton Co.)

1.2.1.2 Place scales under vented hood for weighing components of bonding agents. Wear protective clothing. Mix one lift at a time. One lift is 1/6 of total. Amount of bonding agent dependent on permeability and porosity desired.

1.2.1.3 Weigh sand components; place in 40-gal. containers and have divided to make six lifts.

1.2.1.4 Mix sand components in mortar-box with small roto-tiller.

1.2.1.5 Mix components of bonding agent in sequence and timing specified by Halliburton. Mix under fume hood and wear protective clothing.

1.2.1.6 Pour mixed bonding agent evenly over sand in 5-ft. mortar-box and mix with roto-tiller until sand is uniformly in "fluffy" state. (Note that this is an art.)

1.2.1.7 Immediately take to artificial-reservoir housing by forklift and begin placement.

## OPERATING PROCEDURE 1.3

## FILLING OF HOUSING WITH SAND MIXTURE

1.3.1 Outer shell mixture.

1.3.1.1 With forms in place and secured, pour high-porosity sand mixture evenly around periphery of mold at about 2-in. depth. Tamp mixture until a "bouncy" reaction takes place, suggesting a "dough-like" consistency. (Note, this is an art.)

1.3.1.2 Repeat Step 1.3.1.1 until the final compaction is even with top of reservoir housing.

1.3.2 Primary reservoir mixture.

1.3.2.1 Check to assure that movable screen clamp is just above height of lift to be poured. Each lift is about 4 in. high.

1.3.2.2 While two people are preparing mixture of sand, two people pour and tamp previously mixed batch.

1.3.2.3 With hand-compaction tools clean, the mixed sand and resin are placed in housing and spread evenly in a layer about 1 in. thick. Sand is tamped until "bouncy".

1.3.2.4 Steps 1.3.2.2 and 1.3.2.3 are repeated until entire reservoir-housing is filled to within 1/16 in. from top.

1.3.2.5 Place a layer of RTV 66 thicker than 1/16-in. on top surface of tamped sand mixture.

## OPERATING PROCEDURE 1.4

## EMPLACEMENT OF TOP FLANGE, ARTIFICIAL-RESERVOIR HOUSING

1.4.1 Place gasket over RTV 66 and center on housing.

1.4.2 Using forklift, place top flange carefully on housing, making sure that alignment allows the borehole form to fit on inside of upper 5 1/2-in. casing. Align bolt holes and place full weight of flange on housing.

1.4.3 Secure flange according to Operating Procedure 1.1.2.

1.4.4 After mixture has cured, remove bullplug at bottom of 5 1/2-in. casing and remove sand from mold. Remove the HDPE borehole mold and then screen.

## OPERATING PROCEDURE 2.1

## CALIBRATION OF PRESSURE GAUGES

2.1.1 Prepare deadweight tester for calibration of instruments.

- 2.1.1.1 Check level of oil in reservoir of deadweight tester.
- 2.1.1.2 Insure that weight mechanism spins freely.
- 2.1.1.3 Assemble weights necessary for desired range of tests.

2.1.2 Calibration of pressure gauges.

- 2.1.2.1 Mount gauge on deadweight tester.
- 2.1.2.2 Adjust needle on gauge face to be zero.
- 2.1.2.3 Assemble set of weights equal to mid-span of gauge and place on deadweight tester.
- 2.1.2.4 Adjust span of gauge so that needle on gauge face reads amount equal to weight load.
- 2.1.2.5 Remove weight load. Repeat steps 2.1.2.3 and 2.1.2.4 until registry at zero and midweight, respectively, are achieved.

2.1.2.6 Assemble set of weights appropriate for span and accuracy of gauge.

2.1.2.7 On gauge-calibration sheet, record sequence of weights.

2.1.2.8 Place weight on deadweight tester. Check weight shaft for free spin and free float. Record needle reading.

2.1.2.9 Add weight according to sequence specified in Step 2.1.2.7, and repeat Step 2.1.2.8, until maximal pressure is reached.

2.1.2.10 To determine gauge, remove weights one at a time. With each removal, record needle reading at proper place on gauge-calibration sheet.

2.1.2.11 If repeatability is outside range of accuracy for gauge under testing, then repeat 2.1 through 2.1.2.10.

2.1.2.12 If operations have been conducted as prescribed and observations repeatedly lie outside the range of accuracy, then reject gauge.

2.1.2.11 For an acceptable transducer, analyze calibration data and define a calibration equation for the given gauge.

OPERATING PROCEDURE 2.2

CALIBRATION OF PRESSURE AND DIFFERENTIAL-PRESSURE TRANSDUCERS

2.2.1 Preparation for Calibration.

2.2.1.1 Measure and cut all instrument lead-lines.

2.2.1.2 Connect instrument connectors to each lead-line.

2.2.1.3 Pre-plumb all pressure and differential pressure transducers with appropriate fittings and tubing. Refer to Figures D2 and D3.

2.2.1.4 Number all pressure and differential-pressure transducers according to location.

2.2.1.5 Gather all material, equipment, and tools for calibration.

2.2.2 Calibration of pressure and differential-pressure transducers.

2.2.2.1 A DESGRANGES et HUOT, deadweight pressure tester, type 5500 is used to calibrate.

2.2.2.2 Location of deadweight pressure tester for calibration of transducers is located at the Research and Development Complex, Conoco, Inc., Ponca City, Oklahoma.

2.2.2.3 All material, equipment, and tools are transported to Ponca City.

2.2.2.4 Calibration of pressure and differential-pressure transducer is accomplished using procedures outlined in:

DESGRANGES et HUOT PRESSURE STANDARDS
Deadweight Pressure Tester
Type 5500
Technical Manual

## OPERATING PROCEDURE 2.3

## CALIBRATION OF TEMPERATURE SENSORS

2.3.1 Activate Tenny Environmental Temperature Chamber.

2.3.1.1 Set controls to chill environmental chamber to 0 degrees C.

2.3.1.2 Put Analog Device 590 temperature sensor and the multiplexer box into environmental chamber. Connect entire assembly to electrical power outlet.

2.3.2 Check calibration references.

2.3.2.1 Calibrate Fluke Digital Thermometer and Precision Dial Thermometer by comparing values at ambient temperature and by submerging each sensor in ice water (0 deg. C.). Allow to stabilize for 10 minutes. Readings from these two points will define calibration of reference sensors.

2.3.2.1 Place both reference sensors into environmental chamber. Allow to chill and stabilize for 30 minutes.

2.3.2.2 On Temperature Sensor Calibration form, record temperatures shown on Fluke and Precision Dial thermometer. Record millivolt output from all AD 590s.

2.3.2.3 Set controls to elevate environmental chamber to 10 deg. C.

2.3.2.4 Allow chamber and contents to stabilize for 30 min.

2.3.2.5 Repeat Step 2.3.2.2.

2.3.2.6 Repeat Steps 2.3.2.3 through 2.3.2.5 at 20 deg. C., 30 deg. C., 40 deg. C. and 50 deg. C.

2.3.3 Analyze calibration data and define a calibration equation for each sensor.

## OPERATING PROCEDURE 2.4

## CALIBRATION OF FLOW METERS

The following definitions are used:

V1 = Vindum valve No. 1, which is top control valve in reservoir-effluent flow-meter network.
V2 = Vindum valve No. 2, which is control valve in reservoir-effluent flow-meter network.
V3 = Vindum valve No. 3, which is top control valve in salt-water flow-meter network.
V4 = Vindum valve No. 4, which is bottom control valve in salt-water flow-meter network.
PT = Pressure transducer.
BPV = Back-pressure valve.

2.4.1 Make Connection Changes

2.4.1.1 Attach hose adapter to inlet of mud-column flow-meter vessel.

2.4.1.2 Connect outlet of mud-column flow meter to V4 inlet with tubing.

2.4.1.3 Connect outlet of salt-water flow meter to inlet port of effluent flow meter.

2.4.1.4 Attach line and hose to the bleed and draw lines.

2.4.1.5 Connect outlet of effluent flow meter to tubing leading to vessel on scales.

2.4.2 Bleed the two piston flow meters.

2.4.2.1 Turn valves (vent and supply) to fill the mud-column flow meter with water. When full, shut off vent valve.

2.4.2.2 Circulate water through all flow meters with hydrant pressure.

2.4.2.3 Cycle pistons back and forth until no air comes out of the vent lines from the salt-water and effluent flow meters.

2.4.2.4 Shut off water supply and vent valves upon successful bleeding.

2.4.3 Activate computer/data acquisition system.

2.4.3.1 Connect all leads from flow meters, scales and pressure transducers to the multiplexer.

2.4.3.2 Connect control air to Vindum valves.

2.4.3.3 Activate software on selected instrument cycling.

2.4.4 Set BPV pressure.

2.4.4.1 Close all ports to V1 and V2 and close BPV (turn clockwise to increase pressure).

2.4.4.2 Charge the 1-gal. accumulator with N2 to the desired back pressure.

2.4.4.3 Turn the BPV counterclockwise (decrease) until the effluent just begins to seep out of the line.

2.4.5 Initialize the flow.

2.4.5.1 Open all ports to the Vindum valves V1, V2, V3 and V4.

2.4.5.2 Increase nitrogen pressure to the mud-column flow meter until the pressures equal the back pressure.

2.4.5.3 Allow the total system to equilibrate.

2.4.5.4 Set the Vindum valves V1, V2, V3 and V4 to their operating modes.

2.4.5.5 Slowly increase the nitrogen pressure until there is visible flow from reservoir-effluent line. This initial flow should be as slow as it can to be controlled; just a drip or a seep.

2.4.6 Record data.

2.4.6.1 Set computer to cycle through all activated sensors.

2.4.6.2 Manually record both gauge pressure and scale output as well as date and time. Do this periodically throughout the run.

2.4.6.3 Allow enough time for pistons in flow meters to span their complete range of travel.

2.4.6.4 Allow enough time for the piston to equilibrate before going to next flow rate.

2.4.7 Span the flow range.

2.4.7.1 Increase the pressure until the flow increases to the desired rate.

2.4.7.2 Proceed with Steps 2.4.6.1 through 2.4.6.4.

2.4.7.3 Repeat Steps 2.4.7.1 and 2.4.7.2 until the entire flow range has been spanned.

2.4.8 Span back-pressure range.

2.4.8.1 Do Steps 2.4.4 through 2.4.7 for each back pressure desired.

2.4.8.2 Choose back pressures coincident with the test schedule.

## OPERATING PROCEDURE 2.5

## CALIBRATION OF MUD FLOW-RATE SYSTEM

2.5.1 Circulate pre-mixed mud through recirculating lines for three cycles.

2.5.2 Fourth cycle: Sample mud at 6-min. intervals for 1 hr.

2.5.2.1 At time each sample is collected, measure viscosity by Marsh Funnel. Record measurement on Mud Flow-meter Calibration Sheet.

2.5.2.2 Measure weight/unit volume by precision scales. Record observations to hundredth of lb./gal. Record measurement on Mud Flow-meter Calibration Sheet.

2.5.2.3 Measure pH with pH meter. Record on Mud Flow-meter Calibration Sheet.

2.5.3 Calculate means and standard deviations.

2.5.4 Plot means and plus and minus two standard deviations on Mud-homogenization Quality-control Chart.

2.5.5 If plotted data lie outside rejection limits on Mud Homogenization Quality-control Chart, then repeat steps 2.5.2 through 2.5.4.

2.5.6 On Mud Flow-meter Calibration sheet record mean density of mud.

2.5.7 Activate computer and data-acquisition system for flow-rate calibration cycle.

2.5.7.1 Set back-pressure on mud pump at 400 psi.

2.5.7.2 Allow time for circulation system to equilibrate.

2.5.7.3 Set stop watch to zero. Set scales to zero.

2.5.7.4 Divert flexible hose from tank-return port into sample-collection funnel. Simultaneously start stop watch, according to standard countdown procedure.

2.5.7.5 Fill container to level-indicator.

2.5.7.6 Divert flow back to mud tank; simultaneously trip stop watch, according to standard countdown procedure.

2.5.7.7 Weigh fluid diverted into sample-container.

2.5.7.8 On Mud Flow-meter Calibration Sheet, record average millivolt output from tachometer, average pressure-gauge reading, and weight of sample.

2.5.7.9 Empty sample-container and clean same.

2.5.7.10 Repeat Steps 2.5.7.1 through 2.5.7.9 at back-pressures of 600 psi, 800 psi and 1000 psi.

2.5.7.11 Analyze data and define a calibration-equation for flow rate as function of back-pressure and revolutions per minute.

## OPERATING PROCEDURE 2.6

## CALIBRATION OF SALT-WATER TURBINE METER

2.6.1 Connect calibration system to salt-water line.

2.6.2 Connect turbine-meter electrical lead line to data-acquisition system and activate computer.

2.6.3 Open valves so that circulation can take place, and begin circulation of salt water from tank, and back to tank. Circulate for approximately 30 minutes. During circulation, check for leaks and other faults.

2.6.4 Adjust back-pressure valve to control flow at approximately 10 gpm, by using manufacturer's calibration factor.

2.6.5 Allow time for circulation system to equilibrate.

2.6.6 Set stop watch to zero. Set scales to zero.

2.6.7 Divert flexible hose from tank-return port into sample-collection funnel. Simultaneously start stop watch, according to standard countdown procedure.

2.6.8 Fill container to level-indicator.

2.6.9 Divert flow back to mud tank; simultaneously trip stop watch, according to standard countdown procedure.

2.6.10 Weigh fluid diverted into sample-container.

2.6.11 On Salt-water Turbine Meter Calibration Sheet record average reading from turbine meter and weight of sample measured during this time period.

2.6.12 Return salt water from calibration tank to salt-water tank, and clean calibration tank.

2.6.13 Repeat steps 2.6.5 through 2.6.12, for 8, 6, 4, 2, 1 and 0.5 gpm.

2.6.14 Analyze data according to Operating Procedure 16.5, and define calibration-equation for flow rates as function of millivolt output from turbine meter.

## OPERATING PROCEDURE 3.0

## MOUNTING DIAPHRAGM-SEAL HOUSINGS

3.0.1 Prepare all components of diaphragm-seal housing assembly for mounting.

3.0.1.1 Inspect diaphragm-housing valves for machining marks and burrs.

3.0.1.2 Check for weld preparation on half to be welded to 5-1/2-in. casing.

3.0.1.3 Clean surfaces to be welded, including removal of paint, thread compound, etc.

3.0.2 Mount bottom diaphragm-seal housing half to 5 1/2-in. casing.

3.0.2.1 Measure and mark position to mount diaphragm-seal housing.

3.0.2.2 Position bottom diaphragm-seal housing on 5 1/2-in. casing.

3.0.2.3 Weld bottom diaphragm-seal housing half to

5 1/2-in. casing using MIG welder with $CO_2$ gas shield and 0.035-in. mild steel wire.

3.0.2.4 Check all welds for possible pin holes or leaks.

3.0.2.5 If any visible flaws are apparent, grind out and reweld.

3.0.2.6 Welding should be done in such a way as to keep bending or warping at a minimum.

3.0.3 Assembly of diaphragm-seal housing.

3.0.3.1 Gather all parts and materials necessary to assemble diaphragm-seal housings:

- Top half, diaphragm-seal housing
- Diaphragm
- Six 8-32 x 1 1/4-in. grade-8 Allen cap screws
- One 1/4-in. NPT x 1/4-in. CPI fitting
- Allen wrench
- Masking tape
- Locktite safety solvent
- Locktite Fast Cure Epoxy 45
- PST teflon thread compound
- Paint

3.0.3.2 Gather all tools and equipment needed to assemble diaphragm-seal housing.

- Air compressor
- Sand blaster
- Sand-blast sand
- Torque wrench in inch-pounds
- End wrench, 9/16-in.
- Drill and drill bits

3.0.3.3 Sand blast both halves, diaphragm-seal housing to clean white metal.

3.0.3.4 Mask both faces, halves of diaphragm-seal housing with masking tape and paint inside and outside surfaces. Let paint dry for 24 hours.

3.0.3.5 Remove masking tape and clean faces with safety solvent.

3.0.3.6 Drill two 1/8-in. holes through 5 1/2-in. casing inside half of diaphragm-seal housing welded to 5 1/2-in. casing. One should go toward the top and one toward the bottom of the casing. Refer to Figure D1.

3.0.3.7 Mix Locktite Fast Cure Epoxy 45 according to instructions. Apply to housing half welded to 5 1/2-in. casing. Initial set-up time for Epoxy mixture is 5 min.

3.0.3.8 Install diaphragm with rubber side to 5 1/2-in. casing. Make sure holes in diaphragm are aligned with bolt holes in housing.

3.0.3.9 Apply Epoxy mixture to top-housing half and mate to bottom-housing half.

3.0.3.10 Apply small amount of PST thread compound on underside of the Allen cap screw head.

3.0.3.11 Insert Allen cap screw and make up finger tight with Allen wrench. The Epoxy mixture should flow only slightly out all four sides of housing.

3.0.3.12 Allow Epoxy to cure for a minimum of 24 hr.

3.0.3.13 Torque Allen cap screws to 60 in.-lb.

3.0.3.14 Apply PST thread compound to CPI fitting and make up into top of housing.

## OPERATING PROCEDURE 3.1

## MOUNTING OF DIFFERENTIAL-PRESSURE TRANSDUCERS

3.1.1 Prepare differential-pressure transducers for mounting.

3.1.1.1 Differential pressure transducers have been calibrated previously. Refer to Operating Procedure 2.2.

3.1.1.2 Locations 2, 3, 4, 5 and 6 are to have one differential-pressure transducer mounted to each; Location 7 has four each. See Figures C2, D2, and D3 for detail of locations.

3.1.1.3 Each differential-pressure transducer is to be filled with distilled water and bled of all air.

3.1.1.4 Mount differential pressure transducer to mounting plate and plumb to system with 1/4-in. stainless steel tubing.

3.1.1.5 All tubing is to be filled with distilled water and bled of air.

## OPERATING PROCEDURE 3.2

## MOUNTING OF PRESSURE TRANSDUCERS

3.2.1 Prepare pressure transducers for mounting.

3.2.1.1 Pressure transducers have been previously calibrated. Refer to Operating Procedure 2.1.

3.2.1.2 Locations 2, 6 and 7 are to have pressure transducers. See Figure C2 for detail of locations.

3.2.1.3 Each pressure transducer is to be filled with distilled water and bled of air.

3.2.1.4 Mount pressure transducer to mounting plate and plumb to system with 1/4 inch stainless steel tubing.

3.2.1.5 All tubing is to be filled with distilled water and bled of air.

## OPERATING PROCEDURE 3.3

## MOUNTING OF TEMPERATURE TRANSDUCERS

3.3.1 Preparation of temperature sensor for mounting.

3.3.1.1 Temperature sensor has been calibrated previously. Refer to Operating Procedure 2.3.

3.3.1.2 Temperature sensor is placed in a pre-prepared protective housing and potted for water resistance. Housing is made from a phenolic material and potted with hot glue.

3.3.2 Preparation of surface of 5 1/2-in. casing, where temperature sensor is to be mounted.

3.3.2.1 Surface of pipe must be clean of all grease, dirt, pipe-thread compound or paint.

3.3.2.2 Use of a wire brush or grinder with wire wheel would be suitable.

3.3.3 Mounting temperature sensor.

3.3.3.1 Apply a small amount of thermal-conductive silicone paste on temperature sensor.

3.3.3.2 Place the temperature sensor and housing on 5 1/2-in. casing at predetermined location.

3.3.3.3 Attach to 5 1/2-in. casing using large cable ties.

3.3.3.4 Integrate temperature-sensor lead-lines with other lead-lines up casing.

## OPERATING PROCEDURE 3.4

## MOUNTING OF MULTIPLEXERS

3.4.1 Attach dummy multiplexer-box to dummy shielding bracket.

3.4.2 Align this assembly so that axis of multiplexer and long axis of casing are superincumbent. Long axis of base of multiplexer must be the point of tangent to circumference of the casing.

3.4.3 Clamp assembly in proper place.

3.4.4 Weld shielding bracket to casing.

3.4.5 Remove dummy multiplexer; replace with actual multiplexer.

3.4.6 Attach instrumentation lead-lines according to wiring diagram.

## OPERATING PROCEDURE 3.5

## PLACING OF FLOW METERS

3.5.1 Move flow meters to location.

3.5.1.1 Flow meters will be utilized at reservoir assembly stand (Figure 2, Location A) and at well stand (Figure 2, Location B). Therefore, flow meters, associated instrumentation and equipment are mounted on a model platform.

3.5.2 Connecting flow meters to artificial reservoir.

3.5.2.1 Connect flow meters to artificial reservoir.

3.5.2.2 For Location A refer to Operating Procedures 6.1 and 6.2.

3.5.3 Connect instrumentation as required.

## OPERATING PROCEDURE 3.6

## MOUNTING OF PRESSURE GAUGES

3.6.1 Preparation of pressure gauges.

3.6.1.1 Pressure gauges have been calibrated previously according to Operating Procedure 2.1.

3.6.1.2 Pressure gauges are to be mounted at Location 7. One should be at top of artificial reservoir and one positioned for radial effluent of artificial reservoir.

3.6.2 Mounting pressure gauges.

3.6.2.1 Pressure gauges are to be plumbed into system with 1/4-in. stainless steel tubing. See Figure D3.

3.6.2.2 PST thread compound is to be used on all threads and tubing connections.

3.6.2.3 Tubing is to be filled with distilled water and bled of all air.

## OPERATING PROCEDURE 4.0

## PIPE SELECTION

4.0.1 Pipe tally and inspection.

4.0.1.1 All 5 1/2-in. and 1 1/4-in. pipe tallied. Each joint numbered, measured, and length recorded.

4.0.1.2 Each joint inspected for damage to pipe or

4.0.2 Selecting pipe for first test.

4.0.2.1 Four joints of 5 1/2-in. pipe were chosen.

| | |
|---|---|
| 1 - | 44.72 ft. |
| 2 - | 36.63 ft. |
| 3 - | 47.57 ft. |
| 4 - | 47.62 ft. |
| Total - | 176.53 ft. |

4.0.2.2 A 6.25-ft. was used to position string at precise depth and also to position top of casing at a precise elevation, to receive the artificial reservoir.

4.0.2.3 Five joints of 1 1/4-in. tubing were selected for salt-water injection string and are shown schematically in Figure C2. The 1 1/4-in. tubing is run alongside the 5 1/2-in. casing.

4.0.2.4 A transition fitting was designed and constructed to change from 1 1/4-in. tubing to 1/2-in. stainless steel tubing with 1/4-in. bleed line (see Figure C1-A and C1-B). This was done to accommodate filling of the 1 1/4-in. tubing string with salt water, to allow bleeding the system of air, and also to allow better passage through casing head.

## OPERATING PROCEDURE 4.1

## POSITIONING CASING JOINT

4.1.1 Moving pipe from rack to V-door.

4.1.1.1 Pipe is rolled from rack to V-door. Care should be taken, because diaphragm-seal housings and transducer mounting plates have been welded to casing.

4.1.1.2 A rope with hook connected to bottom end of casing is used to pull casing toward well head. Draw works of pulling unit are utilized.

## OPERATING PROCEDURE 4.2

## CONNECTING INSTRUMENTATION LEAD-LINES

4.2.1 Instrumentation lead-lines

4.2.1.1 All instrumentation lead-line lengths are calculated and cut.

4.2.1.2 Each lead-line instrument end is fitted with appropriate receptacle or plug, depending on the instrument.

4.2.1.3 Each fitting is potted with a waterproof material (hot glue) to provide water-tight fittings.

4.2.2 Instrumentation lead-line connections.

4.2.2.1 All instrument lead-line connections are of the form of plug twist-lock or plug with rubber seal.

4.2.2.2 Cable ties are used to secure lead-lines in place.

## OPERATING PROCEDURE 4.3

## MECHANICAL INSTALLATION OF FIRST JOINT

(Note: All location numbers refer to Figure C2.)

4.3.1 Preparation of first joint of casing.

4.3.1.1 Measurement rechecked and recorded as 44.72 ft.

4.3.1.2 Locations 1, 2, and 3 were measured, marked and recorded respectively as 39, 31, and 18 ft. from top of joint.

4.3.1.3 Bottom of the joint (40 ft.) was located.

4.3.1.4 Joint was cut off at 40.5 ft.

4.3.1.5 3/4-in. plate steel was cut to fit inside of 5 1/2-in. casing (bottom plug).

4.3.1.6 3/4-in. plate steel welded in place, top of plate to top of collar (40 ft.).

4.3.1.6.1 2-in. x 3/4-in. plate steel cut for cross brace for 3/4-in. plate steel bottom plug.

4.3.1.6.2 2-in. x 3/4-in. plate steel braces welded into place.

4.3.1.7 The remaining 4.22-ft. section was repositioned 5 1/2-in. casing and welded.

4.3.1.8 Retaining lugs were positioned and welded to the bottom 4.72 ft. of casing, to hold centralizer (center of centralizer 2 ft. from actual bottom).

4.3.1.9 Injection point is measure 9 ft. from bottom plug and marked. A 90-deg. elbow NPT schedule 160 was machined on one opening to fit flush with arc of 5 1/2-in. casing and weld-prepped on a bevel.

4.3.1.10 90-deg. elbow welded to 5 1/2-in. casing with 9-ft. mark at center of opening.

4.3.1.11 Change-over nipple collar made up with 90-deg. elbow (change-over from 11/12-in. thread to API 8rd thread).

4.3.1.12 Pressure-transducer mounting plates consisting of 6-in. x 2-in. x 1/4-in. steel plates, are positioned to 5 1/2-in. casing so as to position center of differential-pressure transducers parallel with center the diaphragm-seal housing.

4.3.1.13 Plate is welded top and bottom.

4.3.1.14 Two mounting plates positioned at Location 2, one on either side of diaphragm-seal housing.

4.3.1.15 One plate mounted at Locations 3,4,5 and 6.

4.3.2 Plumbing the pressure-measurement system.

4.3.2.1 Plumb a 1/4-in. tubing from Location 1 diaphragm-seal housing to positive side of differential-pressure transducers at Location 2.

4.3.2.2 Bleed port provided on both positive and negative sides of all differential-pressure transducers.

4.3.2.3 Bleed ports provided for pressure transducers.

4.3.2.4 A fill valve is placed just above diaphragm-seal housing at Locations 1, 2, 3, 4 and 5 and all tubing unions.

4.3.2.5 1/4-in. tubing from negative side of differential-pressure transducer at Location 2 to top side of diaphragm-seal housing at Location 2.

4.3.2.6 1/4-in. tubing from Location 2 diaphragm-seal housing to absolute-pressure transducer with bleed port.

4.3.2.7 1/4-in. tubing from Location 2 diaphragm-seal housing to positive side of differential-pressure transducer at Location 3.

4.3.2.8 1/4-in. tubing from negative side of differential-pressure transducer at Location 3 to top side of Location 3 seal housing.

4.3.2.9 1/4-in. tubing from Location 3 diaphragm-seal housing fill valve to top of first joint of casing and extended to point where Location 4 would be.

4.3.3 Hydrostatic-pressure testing of first joint.

4.3.3.1 Plugs for both the 5 1/2-in. casing and the 1 1/4-in. tubing were made and installed. The one for 5 1/2-in. casing had a bleed port; the one for 1 1/4-in. tubing had a fill port and a bleed port.

4.3.3.2 Pressure transducers and differential-pressure transducers are removed, to bleed individually by hand.

4.3.3.3 Absolute-pressure transducer is bled in the following manner: It is held down-side up and, with a syringe and needle, filled with distilled water.

4.3.3.4 Needle is inserted into tubing close to the bottom of absolute-pressure transducer and water injected, forcing all air up and out of pressure transducer toward top of the tubing.

4.3.3.5 Transducer is tapped gently to loosen all entrained air and more water is injected, assuring that all air is bled from system.

4.3.3.6 Absolute-pressure transducer is placed back onto its mounting plate and plumbed back into system.

4.3.3.7 Differential-pressure transducer has a diaphragm, and therefore both sides must be bled.

4.3.3.8 Differential-pressure transducer is turned on its side with diaphragm slightly higher than electronics end. A water-filled syringe-needle is inserted into tubing and water injected into pressure transducer until water comes out bleed port. Transducer is then tapped gently to make sure all the air is removed.

4.3.3.9 Bleed port is tightened to maintain the bled system while filling the opposite side.

4.3.3.10 Transducer is turned over and opposite side is treated in same manner.

4.3.3.11 When both sides are filled, differential-pressure transducer is mounted on mounting plate and plumbed back into system.

4.3.3.12 5 1/2-in. casing was picked up in vertical position, with all bleed ports open; starting with Location 1 fill valve, water was injected with syringe into tubing, which was tapped gently as water was injected, making sure air entrained would be loosed and go up with water. Water was injected until it discharged from bleed port at Location 2.

4.3.3.13 Casing is lowered until Location 2 is waist high.

4.3.3.14 Bleed port tightened on Location 2.

4.3.3.15 Water is injected into fill valve at Location 2, using same procedure as 4.3.3.12.

4.3.3.16 Fill valve at Location 2 was closed and casing lowered until Location 3 was waist high.

4.3.3.17 Bleed port tightened at Location 2.

4.3.3.18 Water injected at fill port and Location 3 using same procedure as 4.3.3.12.

4.3.3.19 Casing lowered and plug put on top of tubing and tightened to close system.

4.3.3.20 Regular tap water used to fill pipe and 1 1/4-in. tubing.

4.3.3.21 Air is bled out of the system and hydrostatic pressure pump connected.

4.3.3.22 System is pressured to 3000 psi.

4.3.3.23 All welds, connections, flanges pipe and tubing should be checked for leaks. Provided any leaks are found, system should be drained and leaks repaired. System is refilled and hydrostatic pressure-tested. Repeat as necessary until no leaks are detected.

4.3.3.24 Drain 5 1/2-in. casing and 1 1/4-in. tubing in preparation to lower pipe into well bore.

4.3.4 Installation of instrumented first joint.

4.3.4.1 Connect all instrumentation lead-lines as dictated in Operating Procedure 4.2.

4.3.4.2 Mount temperature sensor to casing. Refer to Operating Procedure 3.3.

4.3.4.3 Secure 1 1/4-in. tubing and all instrument lead-lines, using metal strapping and cable ties as needed.

4.3.4.4 Raise instrumented casing to vertical position above well base.

4.3.4.5 Attach centralizer to bottom of 5 1/2-in. casing.

4.3.4.6 Lower instrumented casing slowly into well, watching to insure that instruments remain clear of casing-walls.

4.3.4.7 After instrumented joint is lowered into well, set slips to hold casing and begin preparations to run remaining casing.

## OPERATING PROCEDURE 4.4

## MECHANICAL INSTALLATION OF SECOND AND ALL OTHER JOINTS

4.4.1 Casing Preparation.

4.4.1.1 Inspect casing and tubing for damage.

4.4.1.2 Place and weld diaphragm housings where needed. Refer to Operating Procedure 3.0.

4.4.2 Installation.

4.4.2.1 Raise casing to vertical position above wellbore.

4.4.2.2 Remove thread protector and apply thread compound to casing threads.

4.4.2.3 Lower casing to mate with casing in wellbore.

4.4.2.4 Make up casing joint to recommended torque of 2290 ft.-lbs.

4.4.2.5 Raise casing string to position to add 1 1/4-in. tubing.

4.4.2.6 Raise 1 1/4-in. tubing and mate with tubing in well. Make up to recommended torque of 570 ft.-lbs.

4.4.2.7 Add 1/4-in. tubing for instrumentation as needed.

4.4.2.8 Lower casing into well; stop at 3- to 5-ft. intervals. Place band to hold 1 1/4-in. tubing, instrumentation lead-lines, and instrumentation in place at each interval.

4.4.2.9 Lower casing string to appropriate location. Fill and bleed transducers. Refer to Operating Procedures 4.3.3.12 through 4.3.3.18.

4.4.2.10 Mount temperature sensor. Refer to Operating Procedure 3.3.

4.4.2.11 Connect instrument lead-lines. Refer to Operating Procedure 4.2.

4.4.2.12 Secure instrument tubing and lead-lines. See Operating Procedure 4.4.2.7.

4.4.2.13 Repeat Operating Procedures 4.4.2.6 through 4.4.2.10 to next casing joint.

4.4.2.14 Repeat Operating Procedures 4.4.2.1 through 4.4.2.11 until all casing is in well-bore.

## OPERATING PROCEDURE 4.5

## RECORDING INSTRUMENTATION POSITION AND LOCATION ON CASING STRING

4.5.1 Recording locations of instruments.

4.5.1.1 All locations of temperature sensors, pressure gauges, pressure transducers and differential-pressure transducers are to be measured and recorded.

4.5.1.2 Each joint of casing is measured and recorded.

4.5.1.3 Each down-hole instrumentation position is measured and recorded with respect to each casing joint.

4.5.1.4 All above-ground instrumentation positions are measured and recorded with respect to elevation.

4.5.1.5 Top of the casing well-head is base line for all measurements.

## OPERATING PROCEDURE 4.6

## SECURING TOP JOINT AND LEAD-LINES IN WELLHEAD

4.6.1 Securing lead-lines.

4.6.1.1 A cable hanger is attached to the instrumentation lead-lines approximately 3 ft. below the casing well-head and secured to the 5 1/2-in. casing.

4.6.2 Securing top casing joint in well-head.

4.6.2.1 Casing is secured in well-head by slips.

4.6.2.2 A segment (1/12th) of the slips is removed to allow passage of salt-water injection tubing and instrumentation lead-lines.

4.6.2.3 A seal bushing, retaining ring and lock ring are installed to secure the slips and casing at the desired location.

## OPERATING PROCEDURE 5.1

## EMPLACEMENT OF WATER IN CASING STRING FOR CALIBRATION CHECK OF DOWN-HOLE SENSORS

5.1.1 Place 2 3/8-in. tubing in casing string.

5.1.1.1 Attach 5 1/2-in. x 2 3/8-in. tubing head to casing string with 5 1/2-in. sub and hammer union.

5.1.1.1 Using pulling unit, run 2 3/8-in. tubing to bottom of casing string. Lift off bottom no more than 10 in.

5.1.1.3 Set tubing to desired depth.

5.1.2 Fill casing string with water.

5.1.2.1 Plumb water supply to tubing.

5.1.2.2 Plumb discharge piping to 5 1/2-in. tubing head.

5.1.2.3 Fill casing string with water.

5.1.2.4 Leave tubing in casing for placement of mud. Refer to Operating Procedure 8.4.

## OPERATING PROCEDURE 5.2

## ACTIVATION AND CHECK-OUT OF COMPUTERIZED DATA-ACQUISITION SYSTEM.

5.2.1 Connection of instrumentation lead-lines.

5.2.1.1 Make all connections of down-hole sensors to multiplexer.

5.2.1.2 Connect multiplexer to computer.

5.2.2 Activation of data-acquisition system.

5.2.2.1 Power-up computer and all related equipment.

5.2.2.2 Install software and activate control program.

5.2.2.3 Collect enough data to check out-put of all down-hole sensors.

## OPERATING PROCEDURE 5.3

## INITIAL CALIBRATION CHECK OF SENSORS

5.3.1 Calculated values.

5.3.1.1 Calculate down-hole pressure at appropriate location.

5.3.1.2 Calculate down-hole temperatures.

5.3.1.3 Adjust for atmospheric and climatic conditions.

5.3.2 Comparison of calculated values with sensor readings.

5.3.2.1 Compare calculated pressures with pressure-transducer readings.

5.3.2.2 Compare calculated temperatures with temperature-sensor readings.

5.3.2.3 Compare differential-pressure transducer readings with zero-calibration point.

5.3.2.4 Record all findings.

## OPERATING PROCEDURE 6.1

## MEASURING POROSITY OF ARTIFICIAL RESERVOIR WITHIN HOUSING

6.1.1 Determine bulk volume.

6.1.1.1 Artificial reservoir is assembled on reservoir-assembly stand. Assembly would include bottom flange and 5 1/2-in. casing sub with appropriate valves and bull plug, reservoir housing with radial flow lines and plug, top blind flange with 5 1/2-in. casing sub and 5 1/2-in. hammer-union half, and gaskets for artificial-reservoir housing.

6.1.1.2 Artificial reservoir is filled with water from a 4000-ml. graduated cylinder, to a point horizontal with top 5 1/2-in. casing sub, just inside 5 1/2-in. hammer-union half.

6.1.1.3 Volume of water to fill reservoir to pre-determined point is recorded for porosity calculation and is referred to as "bulk volume."

6.1.2 Determination of pore volume.

6.1.2.1 Place reservoir media in artificial reservoir housing. Refer to Operating Procedure 1 (Construction of artificial reservoir).

6.1.2.2 Void space is filled with water through the reservoir radial-flow lines and salt-water-injection flow-meter assembly.

6.1.2.3 Record volume of water to fill reservoir to pre-determined point with reservoir medium in place.

6.1.2.4 Determine volume of reservoir medium placed in reservoir housing.

6.1.2.5 Determine porosity of the outer shell, of coarse grained reservoir rock. (Appendix B, Attachment B2.)

6.1.2.6 Calculate pore volume from predetermined values.

6.1.2.7 Determine reservoir-medium porosity using volume of reservoir medium and calculated value of pore volume of reservoir medium.

## OPERATING PROCEDURE 6.2

## MEASURING PERMEABILITY OF ARTIFICIAL RESERVOIR WITHIN HOUSING

6.2.1 Place and connect instrumentation console.

6.2.1.1 Fill reservoir with water. Refer to Operating Procedure 6.1.

6.2.1.2 Place instrumentation console next to artificial reservoir at assembly stand.

6.2.1.3 Connect a line from a water supply to salt-water-injection flow meter.

6.2.1.4 Connect a line from salt-water-injection flow meter to 1/2-in. fitting welded to bottom bottom 5 1/2-in. casing sub.

6.2.1.5 Connect a line from reservoir radial flow line to effluent flow meter and back-pressure valve.

6.2.1.6 Connect line from back-pressure control valve to effluent tank. Fill and bleed all lines.

6.2.2 Determine permeability of reservoir media.

6.2.2.1 With all valves closed, set back pressure control valve to predetermined pressure.

6.2.2.2 Set salt-water injection pressure to test pressure above that of the back pressure.

6.2.2.3 Open valve to wellbore.

6.2.2.4 Open valve to effluent flow meter.

6.2.2.5 Let flow stabilize. Salt-water injection and effluent flow rate should be equal.

6.2.2.6 Record stabilized flow rate.

6.2.2.7 Record pressures of injection and effluent.

6.2.2.8 Determine all other parameters, such as porosity, viscosity of the fluid, etc.

6.2.2.9 Calculate permeability.

## OPERATING PROCEDURE 7.1

## CONTAINMENT OF FLUID WITHIN ARTIFICIAL RESERVOIR DURING REMOVAL OF INSTRUMENTS

7.1.1 Containment of Fluid.

7.1.1.1 After permeability test all valves are closed.

7.1.1.2 Relieve pressure from system, both the instrumentation console and artificial reservoir.

7.1.1.3 Disconnect all lines to and from instrumentation console.

7.1.1.4 Move or place instrumentation console away from reservoir assembly stand.

7.1.1.5 Remove tee assembly from top of reservoir.

7.1.1.6 Insert bladder to a position between drilling-mud supply port and water-injection port on bottom 5 1/2-in. casing sub.

7.1.1.7 Inflate bladder.

7.1.1.8 Remove 5 1/2-in. bull plug from bottom 5 1/2-in. casing sub.

## OPERATING PROCEDURE 7.2

## INSTALLATION OF RESERVOIR PICK-UP ASSEMBLY

7.2.1 Reservoir pick-up assembly.

7.2.1.1 The 5 1/2-in. casing elevators with appropriate cable chokers are used for pick-up assembly.

7.2.1.2 A crane is scheduled to move reservoir from assembly stand to reservoir stand.

7.2.1.3 Elevators are connected to top 5 1/2-in. casing sub welded to artificial reservoir.

## OPERATING PROCEDURE 8.1

## MIXING OF MUD ACCORDING TO OKLAHOMA CORPORATION COMMISSION'S STANDARDS FOR WELL-PLUGGING

8.1.1 Mud must weigh at least 9.0 lb./gal.

8.1.2 Mud must have funnel viscosity of 36 sec./qt. or more.

8.1.3 For fresh mud of these properties, the proportions are 42.0 gal. of water, 1.17 gal of bentonite, and 0.614 gal. of barite.

## OPERATING PROCEDURE 8.2

## HOMOGENIZATION OF DRILLING MUD

8.2.1 Homogenization of drilling mud.

8.2.1.1 Activate mud pump with appropriate valves opened.

8.2.1.2 Set back-pressure valve to approximately 200 psi.

8.2.1.3 Circulate mud to and from mud tank.

8.2.1.4 Activate mud mixer in mud tank.

8.2.1.5 Operate for sufficient time, with mud pump and mud mixer activated, to mix mud thoroughly.

8.2.1.6 Terminate mixing when mud becomes a homogeneous mixture. Refer to Operating Procedure 8.3.

## OPERATING PROCEDURE 8.3

## SAMPLING AND TESTING OF DRILLING MUD

8.3.1 Mud is sampled during circulation, while performing Operating Procedures 8.2, 8.4, and 10.5.

8.3.2 Obtain a 2-qt. sample each time. Sample at the beginning and end of the operation, and at one-fourth the way, one-half the way, and three-quarters the way through the operation.

8.3.3 Test mud according to API RP 13B, pages 4, 6, 8, 9, 19, 42 and 43.

## OPERATING PROCEDURE 8.4

## EMPLACEMENT OF DRILLING MUD IN CASING STRING

8.4.1 This procedure described in Operating Procedure 11.1.

## OPERATING PROCEDURE 8.5

## REMOVAL OF DRILLING MUD FROM CASING STRING

8.5.1 This procedure described in Operating Procedure 15.1.

## OPERATING PROCEDURE 9.1

## PLACEMENT OF RESERVOIR STAND

9.1.1 Removal of 2 3/8-in. tubing from casing.

9.1.1.1 Remove tubing fittings used to fill casing.

9.1.1.2 Pull 2 3/8-in. tubing with pulling unit.

9.1.1.3 Stack 2 3/8-in. tubing on rack.

9.1.2 Disassembly of 5 1/2-in. casing head.

9.1.2.1 Disconnect 5 1/2-in. casing-head assembly at 5 1/2-in. hammer union.

9.1.2.2 Place 5 1/2-in. casing-head assembly under pipe on rack.

9.1.3 Placement of reservoir stand.

9.1.3.1 Lift reservoir stand over well bore.

9.1.3.2 Align anchor bolt holes with pre-drilled Red Head anchors.

9.1.3.3 Make up anchor bolts.

9.1.3.4 Adjust screw jacks to receive artificial reservoir.

## OPERATING PROCEDURE 9.2

## PLACEMENT OF ARTIFICIAL RESERVOIR ON RESERVOIR STAND

9.2.1 Preparation of reservoir stand and casing string.

9.2.1.1 Place reservoir stand. Refer to Operating Procedure 9.1.

9.2.1.2 Fill casing string with drilling mud. Refer to Operating Procedure 8.4.

9.2.1.3 Check hammer union to mate with artificial reservoir.

9.2.1.4 Schedule crane to move artificial reservoir.

9.2.2 Preparation of reservoir for moving.

9.2.2.1 Disconnect instrumentation console and associated lines while maintaining fluid in artificial reservoir.

9.2.2.2 Move environmental building to northeast corner of slab.

9.2.2.3 Place bladder in artificial reservoir between drilling-mud supply port and water-injection test port and inflate.

9.2.2.4 Remove bull plug from bottom of artificial reservoir.

9.2.2.5 Move artificial reservoir to reservoir stand.

9.2.3 Moving artificial reservoir to reservoir stand.

9.2.3.1 Attach 5 1/2-in. casing elevators to crane.

9.2.3.2 Connect elevators to 5 1/2-in. casing on top of artificial reservoir.

9.2.3.3 Pick up and move artificial reservoir to reservoir stand.

9.2.3.4 Pay particular attention to alignment of reservoir with casing string.

9.2.3.5 After alignment is obtained, screw hammer union together hand-tight.

9.2.3.6 Adjust screw jacks on reservoir stand to level artificial reservoir.

9.2.3.7 Tighten hammer union with sledge hammer.

9.2.3.8 Loosen and release crane from artificial reservoir.

9.2.3.9 Retrieve elevators from crane.

9.2.3.10 Re-check level of artificial reservoir.

## OPERATING PROCEDURE 10.1

## HOMOGENIZATION OF DRILLING MUD

10.1.1 This procedure described in Operating Procedure 8.2.

## OPERATING PROCEDURE 10.2

## DISPLACEMENT OF PACKER

10.2.1 Connect mud supply to bottom of reservoir.

10.2.2 Connect return line to horizontal leg of tee on top of reservoir.

10.2.3 Open all valves on upper tee.

10.2.4 Adjust bypass valve to place low-pressure mud supply in supply line. Open supply valve below reservoir and allow mud to force packer slowly up wellbore. Watch packer arrive at top by viewing through top valve. Screw fixture in packer to hold in place.

10.2.5 Hold packer in place; shut off supply valve and mud pump.

10.2.6 Use packer to swab out the mud above it. Remove hammer union and then remove packer.

## OPERATING PROCEDURE 10.3

## ADJUSTMENT OF FLOW RATE AND BACK-PRESSURE

10.3.1 See page 16 of report for details.

## OPERATING PROCEDURE 10.4

## MONITORING OF MUD-FILTRATE FLOW RATE

10.4.1 See page 16 of report for details.

## OPERATING PROCEDURE 10.5

## SAMPLING AND TESTING OF DRILLING MUD

10.5.1 This procedure described in Operating Procedure 8.3.

## OPERATING PROCEDURE 10.6

### SHUT-DOWN PROCEDURE AND LINE REMOVAL

10.6.1 See pages 16 and 17 of report for details.

10.6.2 Shut all valves in vIcinity of mud pump -- in both supply and return lines. Shut valve in line connecting supply to reservoir and valve in line connecting return to reservoir.

10.6.3 Remove upper line (return line) first and drain into buckets. Then pour into effluent tank for disposal.

10.6.4 Repeat 10.6.3 for lower line.

## OPERATING PROCEDURE 10.7

### REFINED ADJUSTMENT OF PRESSURE TO PRESCRIBED MAGNITUDE

10.7.1 Check pressure in casing above artificial reservoir; if pressure is less that desired under conditions of testing, increase regulator setting for mud-column flow meter to desired value.

10.7.2 If pressure is more than desired under conditions of testing, use bleed-line valve connecting line from top of mud column to effluent tank, to reduce to desired pressure.

## OPERATING PROCEDURE 11.1

### MONITORING OF MUD COLUMN FOR DIFFERENTIAL PRESSURE, PRESSURE AND TEMPERATURE

11.1.1 Data-acquisition system is activated during time mud is placed in well. System is to continue monitoring mud from time well is full until equilibration is recorded.

11.1.2 Data are recorded continuously on computer hard disk, but computer screen is to be viewed during the first hour and each hour thereafter for 6 hr., then periodically until there is no apparent change in output of differential-pressure transducer.

## OPERATING PROCEDURE 11.2

### MONITORING OF MUD COLUMN AT SIMULATED-DEPTH CONDITIONS, FOR DIFFERENTIAL PRESSURE, PRESSURE, AND TEMPERATURE

11.2.1 After reservoir is placed over well, and all systems are connected, and mud is put under simulated well pressure, the effect of pressure on equilibration will be monitored.

11.2.2 Use Operating Procedure 11.1.2 to monitor well under pressure.

## OPERATING PROCEDURE 12.1

### ACTIVATION OF SALT-WATER INJECTION SYSTEM

12.1.1 Salt water is placed in the two salt-water accumulators, using salt-water tank and transfer pump.

12.1.2 Adjust regulator on instrument console to supply salt-water accumulators with desired injection pressure.

## OPERATING PROCEDURE 12.2

### MONITORING AND RECORDING COMPREHENSIVE PRESSURE DIFFERENTIALS, PRESSURES AND FLOW RATES.

12.2.1 Data are recorded on hard disk of computer; screen is to be monitored several times each day. If a significant event occurs, then floppy-disk file will be used to investigate the activity.

12.2.2 If a 0.3-gpm flow rate is detected, test is complete. If a low rate or no rate is detected, then a higher injection pressure is set.

## OPERATING PROCEDURE 12.3

### INCREASING INJECTION PRESSURE IN RESPONSE TO UNDETECTABLE FLOW FROM RESERVOIR

12.3.1 If no flow into reservoir is detected, and no gradient change is detected in transducers just above injection zone, then injection pressure is increased.

12.3.2 If a gradient change occurs in pressure transducers above injection zone, then movement of gradient change is to be monitored. Time required for gradient change to get to top will be determined. If time has expired and no flow rate is detected, then injection pressure will be increased.

## OPERATING PROCEDURE 12.4

## INCREASING INJECTION PRESSURE IN RESPONSE TO LOW RATES OF FLOW FROM RESERVOIR

12.4.1 If a low flow rate is detected, this rate will be monitored for 24 hr., to determine the time history. After that time, injection pressure will be increased and monitoring will continue.

12.4.2 Procedure 12.4.1 will be repeated until flow rate attains a level of 0.3 gpm.

## OPERATING PROCEDURE 12.5

## TERMINATION OF INJECTION IN RESPONSE TO MAXIMIZED FLOW OR PRESSURE

12.5.1 When the flow rate is 0.3 gpm or greater, tests are considered to be complete; pressures are relieved from the system. Computer-data acquisition is terminated after pressures are relieved.

## OPERATING PROCEDURE 13.1.1

## REMOVAL OF INSTRUMENTATION FROM ARTIFICIAL-RESERVOIR HOUSING

13.1.1 Only the instrumentation that is not securely attached to housing must be removed -- such as the two differential-pressure processing units on top of housing.

13.1.2 Remove all electrical connections from multiplexers to instrumentation and from multiplexers to computer.

## OPERATING PROCEDURE 13.2

### DISCONNECTING RESERVOIR HOUSING FROM CASING STRING

13.2.1 Pump mud from supply line located under reservoir-housing and place it in effluent tank.

13.2.2 Disconnect effluent line from reservoir. Also, remove the mud column from above reservoir-housing, using forklift boom and hook; bring it out through roof of building.

13.2.3 Remove lean-to from building and take instrument console out of building.

13.2.4 Lift building off reservoir-housing with forklift and boom. Hook into four lifting eyes attached to building.

13.2.5 Knock off the hammer union connecting casing and reservoir housing.

## OPERATING PROCEDURE 13.3

### INSTALLATION OF RESERVOIR PICK-UP ASSEMBLY AND MOVEMENT OF RESERVOIR HOUSING

13.3.1 Call for crane services to move artificial reservoir.

13.3.2 Place crane on concrete pad so that it can just swing boom to pick-up and replace housing.

13.3.3 Pick reservoir housing up using 5 1/2-in. casing tongs.

13.3.4 Place housing on assembly stand and secure.

## OPERATING PROCEDURE 14.1

### REMOVAL OF ARTIFICIAL RESERVOIR FROM HOUSING

14.1.1 Remove all vertical flow lines that connect from top of housing to bottom of housing and that would hinder removal of top flange.

14.1.2 Remove all bolts connecting the two top flanges.

14.1.3 Use forklift to remove top flange, being careful to not disturb gasket.

14.1.4 Remove all bolts connecting the two bottom flanges.

14.1.5 Attach cables to top of flange and to forklift.

14.1.6 Lift flange; artificial reservoir should remain on bottom blind flange. If not, a set of rail ties, of dimensions that will fit on inside of housing, will be placed on the ground. Housing will be dropped strategically on ties, to force artificial reservoir out of housing.

## OPERATING PROCEDURE 14.2

## MAPPING AND LABELING OF RESERVOIR SURFACE FOR RANDOM SAMPLING

14.2.1 Divide artificial reservoir into pie sections; label each according to radial position, depth into reservoir and azimuth. Assign a code number for each section.

14.2.2 Sample reservoir by random-number coding. Sample size equal to or more than 30.

14.3.1 Take channel samples at specified locations, from top to bottom on periphery of artificial reservoir. Mix and sample randomly.

14.3.2 Take stratified samples (according to lifts) at periphery, coring toward the borehole.

14.3.3 Spot samples will be taken from any location that can give suitable access.

## OPERATING PROCEDURE 14.3

## COLLECTION OF RANDOM SAMPLES

14.3.1 This procedure described in Operating Procedure 14.2.

## OPERATING PROCEDURE 14.4

### LABELING AND STORAGE OF SAMPLES

14.4.1 Reservoir samples are to be labeled with the following information:

- Location (radius, depth and azimuth)
- Code number
- Date
- Test number
- Test duration
- Simulated reservoir depth
- Simulated injection depth
- Mud pressure at reservoir depth
- Injection pressure at injection depth
- Type of injection fluid

14.4.2 Samples will be stored in the School of Geology.

## OPERATING PROCEDURE 15.1

### DISPLACING DRILLING MUD WITH WATER

15.1.1 Run 2 3/8-in. tubing into 5 1/2-in. casing and set it on bottom. Make sure seating nipple is placed on bottom joint.

15.1.2 Connect water pump to 2 3/8-in. tubing. Connect well-head annulus to effluent tank.

15.1.3 Pump water through tubing to force mud out of casing into tank. Continue pumping until clean water comes out of line.

## OPERATING PROCEDURE 15.2

### CALIBRATION CHECK OF SENSORS

15.2.1 This procedure described in Operating Procedure 5.3.

## OPERATING PROCEDURE 15.3

## DISPLACING WATER WITH AIR

15.3.1 Disconnect water line and line to tank. Connect high-volume air compressor to annulus of well head. Connect plastic flow line to 2 3/8-in. tubing and run flow line to ditch.

15.3.2 Shut valve on top of 2 3/8-in. tubing and pressure annulus with air, sufficient to lift water from maximum depth. Operate until all water is out of the casing (detectable when air flows from the line).

15.3.3 Pull tubing, making sure that if some of joints are still "wet," water is kept from going back into casing.

## OPERATING PROCEDURE 15.4

## SHUT-DOWN OF COMPUTERIZED DATA-ACQUISITION SYSTEM

15.4.1 Deactivate sensors; stop computer data-acquisition program.

15.4.2 Transfer data from hard-disk data file to a 3 1/2-in. floppy disk. Shut computer off.

## OPERATING PROCEDURE 16.1

## DOCUMENTATION OF SOFTWARE FOR REDUCTION OF DATA

16.1.1 Document software for reduction of data by defining all variables used in program.

16.1.2 Use comment statements to guide users through source program, to identify pertinent steps.

16.1.3 Describe reduction steps and show by example.

## OPERATING PROCEDURE 16.2

## DOCUMENTATION OF SOFTWARE FOR ANALYSIS OF DATA

16.2.1 Show software documentation for Quattro and Timeslab.

16.2.2 Itemize the particular sections of these software packages used to analyze the data and show an example.

## OPERATING PROCEDURE 16.3

## METHODS FOR RECORDING OF DATA

16.3.1 Make appropriate forms for type of test being conducted and record data by hand to spot-check computer results.

16.3.2 Record data on hard disk and at end of each day transfer data to 3 1/2-in. floppy disk.

## OPERATING PROCEDURE 16.4

## METHODS FOR SECURE STORAGE OF DATA

16.4.1 Store all important data in safe, in Development Engineer's office.

16.4.2 Duplicates of data in safe will be placed in file in Project Director's.

## OPERATING PROCEDURE 16.5

## METHODS OF REDUCING DATA

16.5.1 Raw data from each sensor will require a calibration curve to reduce data to engineering units.

16.5.2 Sub-programs for Quattro are one means that will be used to reduce data to usable terms.

16.5.3 Programs to be written in "C" and basic languages for those cases in which Quattro software requires too much storage for size of file used.

16.5.4 Average values over a period of time (determined by viewing segments of data plotted on screen of the computer monitor) are to be used in place of single values, when slope of data string is zero and data variations are not greater than estimated error.

16.5.5 Data analysis will be done using regression techniques. Time-series analysis will be used to determine correlation of different events occurring simultaneously or with time-lag. Regression coefficients will be determined from the data shown in Table G1.

## OPERATING PROCEDURE 16.6

## METHODS FOR VALIDATING DATA

16.6.1 Total flow from injection flow meter and mud-column flow meter must equal that from effluent flow meter. If not, suspicion of a leak is in order.

16.6.2 Water in system before testing and after testing provides check on calibration of instruments for data-validation.

16.6.3 Readings from pressure-transducers mounted down-hole are to be used to validate differential-pressure transducer readings. These are for only the differential-pressure transducers that are bounded by pressure transducers on both ends.

16.6.4 Theoretical calculations are to be made, to be compared with measured pressure and differential-pressure values, to determine whether data are within the range of expected values.

16.6.5 Pressure gauges are placed in the system, to be used for comparison with those pressure transducers associated with the gauges.

16.6.6 Pressure gradients of mud will be plotted. The curve interpolated curve will be used to determine the amount of mud required to be mixed in water, to achieve the gradient. These calculations will be compared with amounts of mud actually put into the system. These values should be equal.

## OPERATING PROCEDURE 16.7

### DEFINITION OF DATA-QUALITY INDICATORS

16.7.1 If continuity from flow-meter measurements shows total volume within 1 percent error, data are considered to be of acceptable quality.

16.7.2 If values from calibration with water (a) prior to the test and (b) subsequent to the test compare within 1 percent, data are considered to be of acceptable quality.

16.7.3 If those values from Operating Procedure 16.6.6 are within 2 percent, data are considered to be of acceptable quality.

16.7.4 If those values from Operating Procedure 16.6.4 are within the range of calculated limits, then the data are acceptable.

## OPERATING PROCEDURE 16.8

### METHODS FOR EVALUATING QUALITY OF DATA

16.8.1 Compare flow volume from effluent flow meter with sum of values from injection flow meter and mud-column flow meter, to determine percent variation. Compare to the percent error allowed in Operating Procedure 16.7.1.

16.8.2 Reduce data from (a) prior to test and compare to (b) data subsequent to test with water in the system, to determine percent variation. Compare to the criteria in Operating Procedures 16.7.2.

16.8.3 Calculate mud required to give pressure gradient measured during the test and compare calculation with total mud placed in system, to determine percent variation. Compare percent variation to criteria shown in Operating Procedure 16.7.3.

16.8.4 Where possible, make theoretical calculations using an upper and lower limit of expected data and compare calculations to actual data. Use Operating Procedure 16.7.4 to judge results.

## OPERATING PROCEDURE 16.9

## METHODS FOR PRESENTING DATA

16.9.1 Data will be provided in data files, ASCII format, for viewing on monitor.

16.9.2 Pertinent data will be presented in tabular format.

16.9.3 Dependent variables will be plotted with respect to independent variables, to show their relationships.

16.9.4 Statistical parameters will be presented in tabular format.

## OPERATING PROCEDURE 16.10

## REPORTING OF CONCLUSIONS

16.10.1 Define as much of the performance envelope as data allow, to show effects of injection on plugged wells.

16.10.2 Provide lists of developments and knowledge, which will be guidelines for future activities.