EFFECTIVENESS OF DRILLING MUD
AS A PLUGGING AGENT

By
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CHAPTER I

FOREWORD

The data collected for this thesis were obtained during a period of time when I was working for Dr. Marvin Smith, Department Head, Oklahoma State University Mechanical Power Technology Department and Dr. Gary Stewart, Professor, School of Geology. The problem under investigation concerned the effectiveness of drilling mud as a plugging agent in abandoned oil and gas wells. The research was funded by the Environmental Protection Agency; I was employed as a research assistant on the project. My direct supervisor was Randy Perry. The experiments were conducted at the OSU Petroleum Laboratory. My involvement with this project started in approximately December, 1993, and lasted until July, 1994.

The experiment was designed ultimately to build drilling-mud filter-cake on specimens of artificial rock. The rock was cut into core-plugs 1 inch in diameter, circular in cross section, and 1.375 inches in length (Figure 1). The cores were placed in a permeameter assembly where drilling mud was circulated across the core and mud cake was built on the core. After a sufficient layer of mud cake was built, the circulated drilling mud was replaced with fresh water, and the system was shut in under pressure to simulate a plugged well. This situation would be analogous to a plugged and abandoned mud-plugged well in which clay and other solid particles in the drilling mud had settled

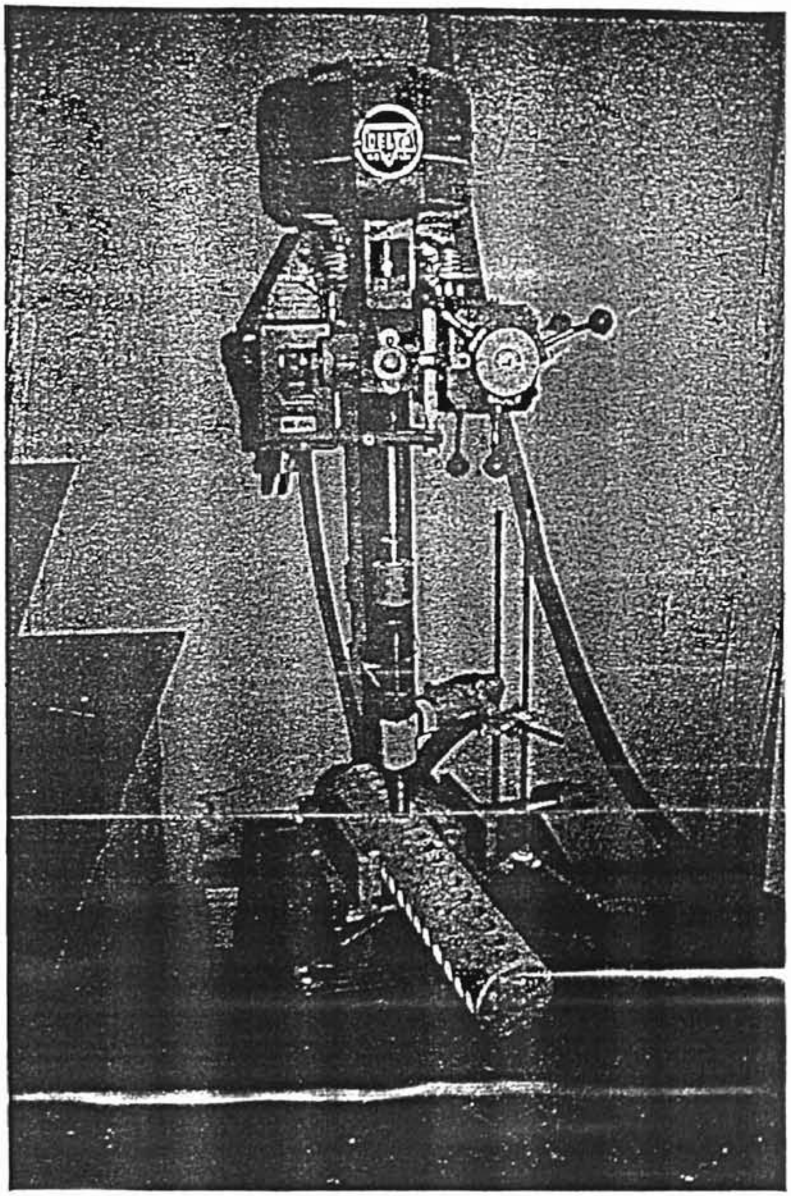


Figure 1. The small core-boring machine, cutting plugs from core of artificial reservoir.

out, leaving dense mud in the lower part of the well and fresh water in the upper portion of the well. In this situation it is possible to estimate the effectiveness of mud cake to protect fresh-water aquifers from intrusion of saltwater driven into the borehole from deeper formations under high pressure.

Figures 2 through 14 show mostly schematic drawings and photographs of the test facility and of mud-cake build-up test equipment. Equipment included a small coring machine, a small tamper with a hydraulic system and controller, a Ruska permeameter, a mud-cake-and- permeability test system, and computerized data-acquisition instruments of the mud-cake-and- permeability system (Figures 1, 3, 4, 5, 6, 7, and 8). A jet mud mixer, a mud-holding tank, and mud-pumping equipment were installed outside the laboratory building on a crushed-rock pad (Figures 9 and 10).

My duties were as follows (for details see chapter VI):

(1) Mix synthetic sandstone of specific mixtures of resin and sand, to produce artificial sandstone of a specified range of permeability.

(2) Tamp the sand-and-resin mixtures with a hydraulic tamping machine to produce rock of predictable permeability (Figure 3). The cores were made in a steel mold 5 inches in diameter, and 6 inches long (see Figure 4).

(3) Cut core-plugs 1 inch in diameter by 1.375 inches long from the large cores described under (2) above. The core-plugs were cut by the core-boring machine shown in Figure 1

(4) Measure permeability of core-plugs using the Ruska nitrogen-permeameter (Figure 5).

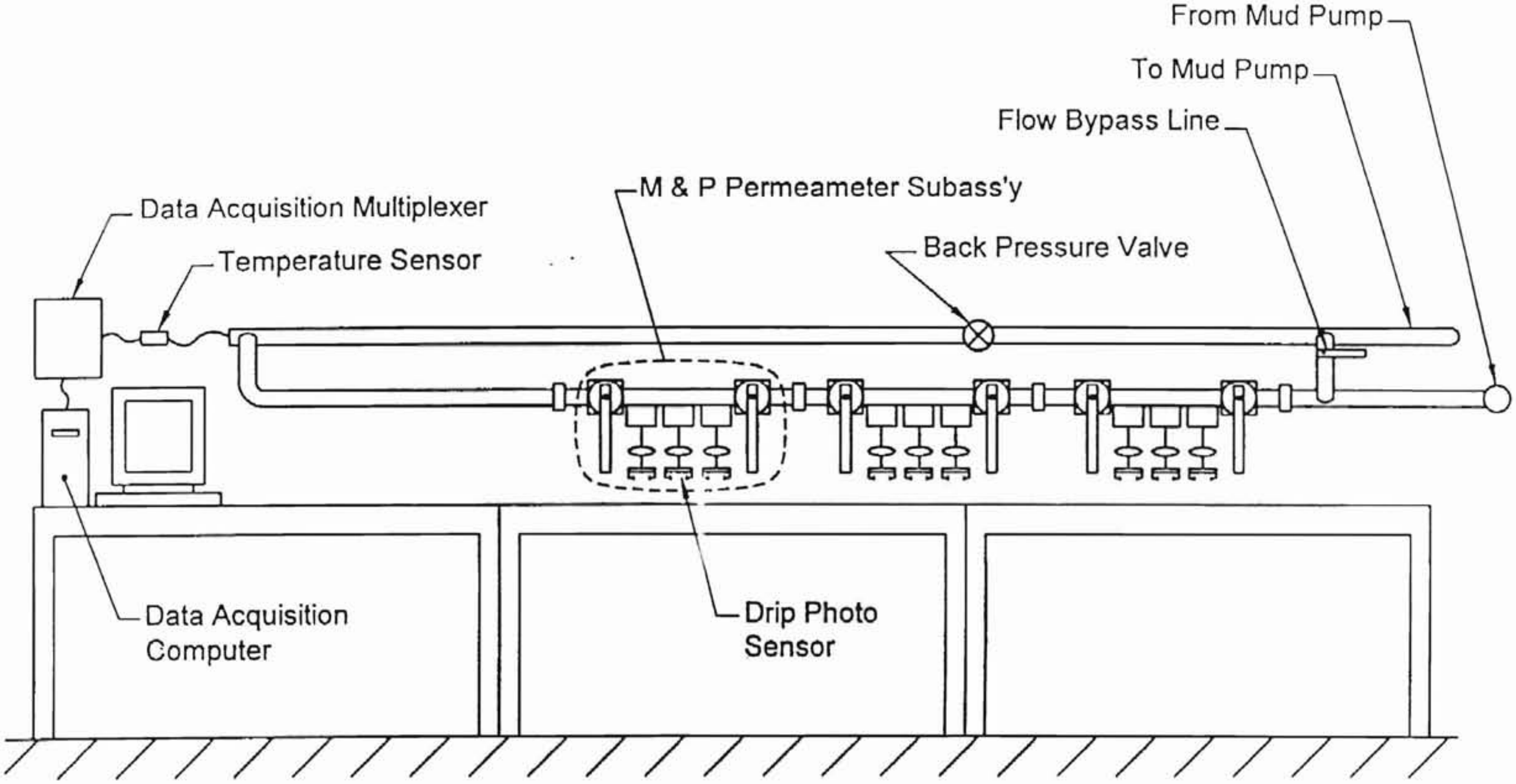


Figure 2. **Functional Schematic drawing,** mud-cake-and-permeameter system.

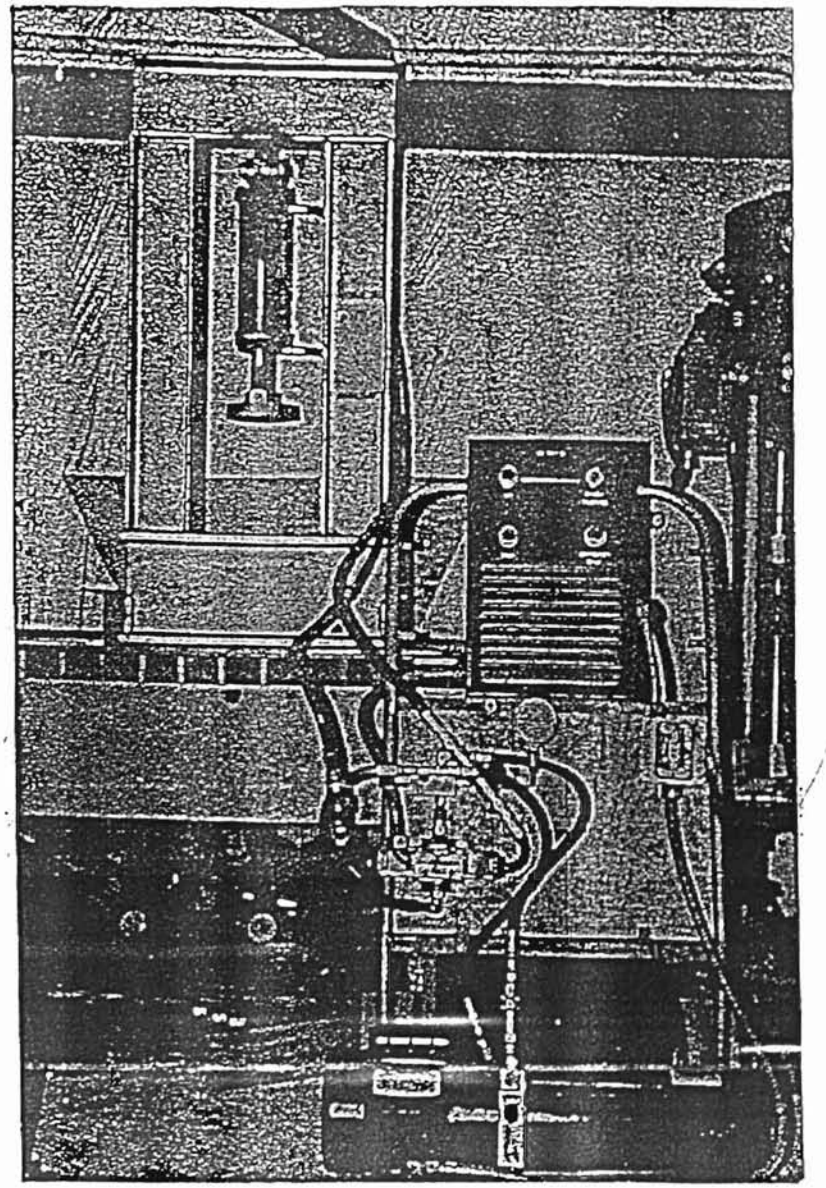
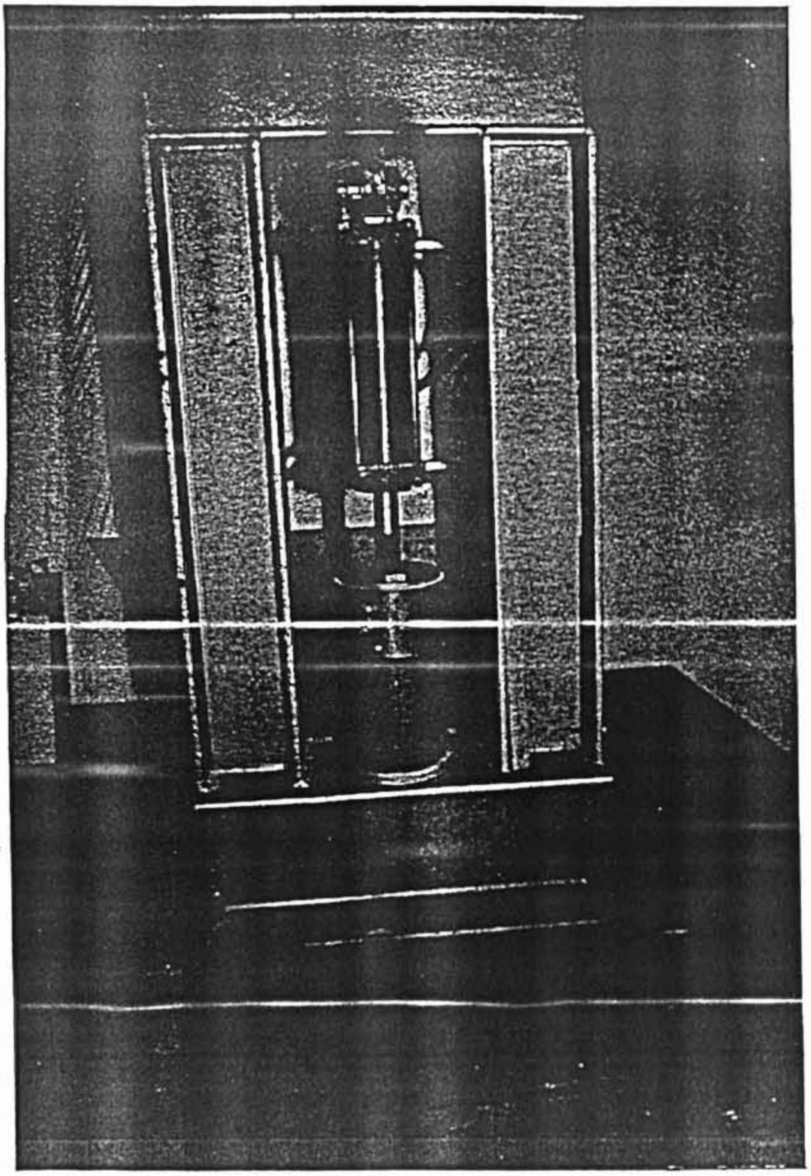


Figure 3. Small tamper (background), with hydraulic system and controller (foreground). The tamper was used to compact the mixtures of resin and sand.



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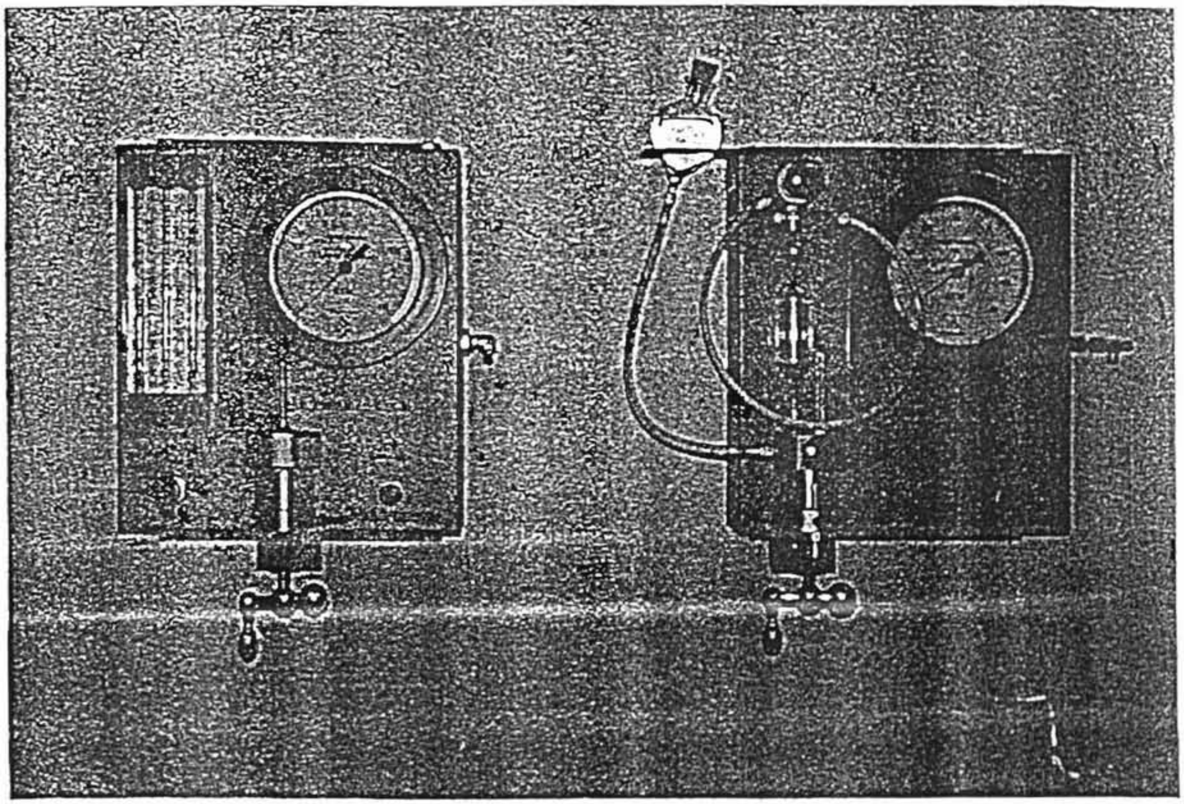

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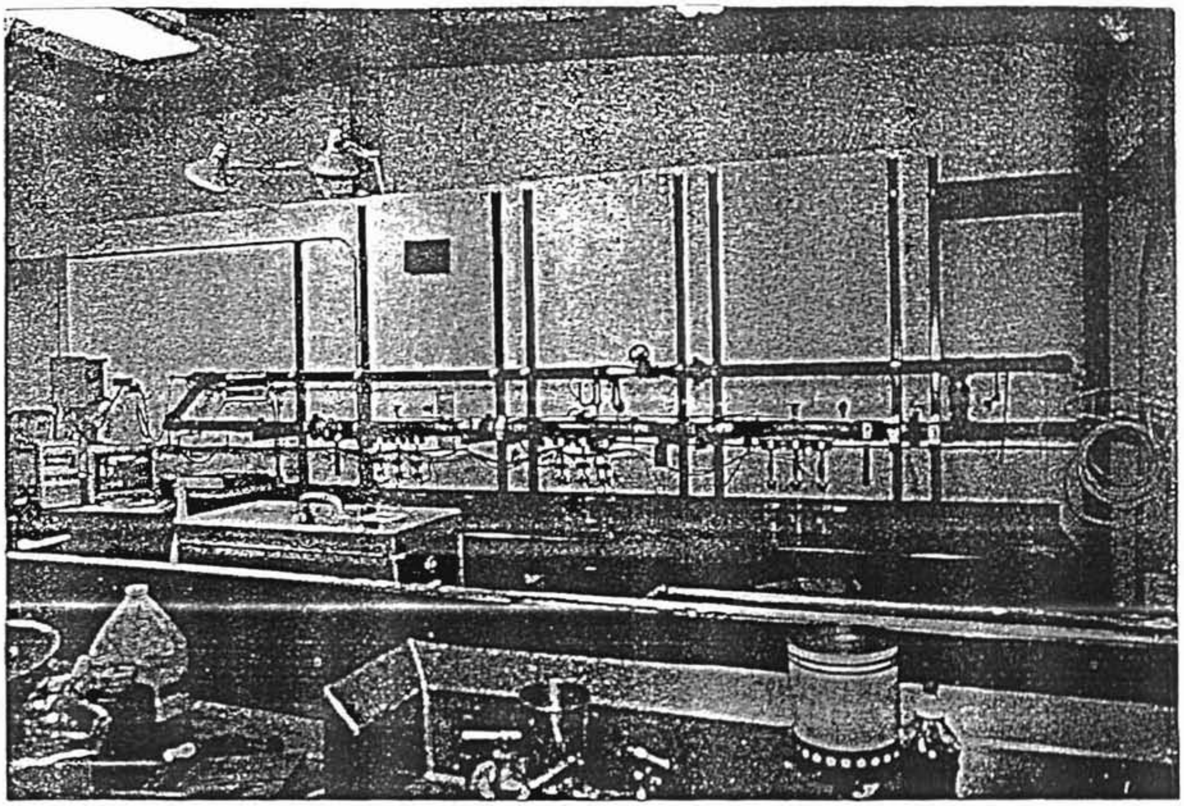

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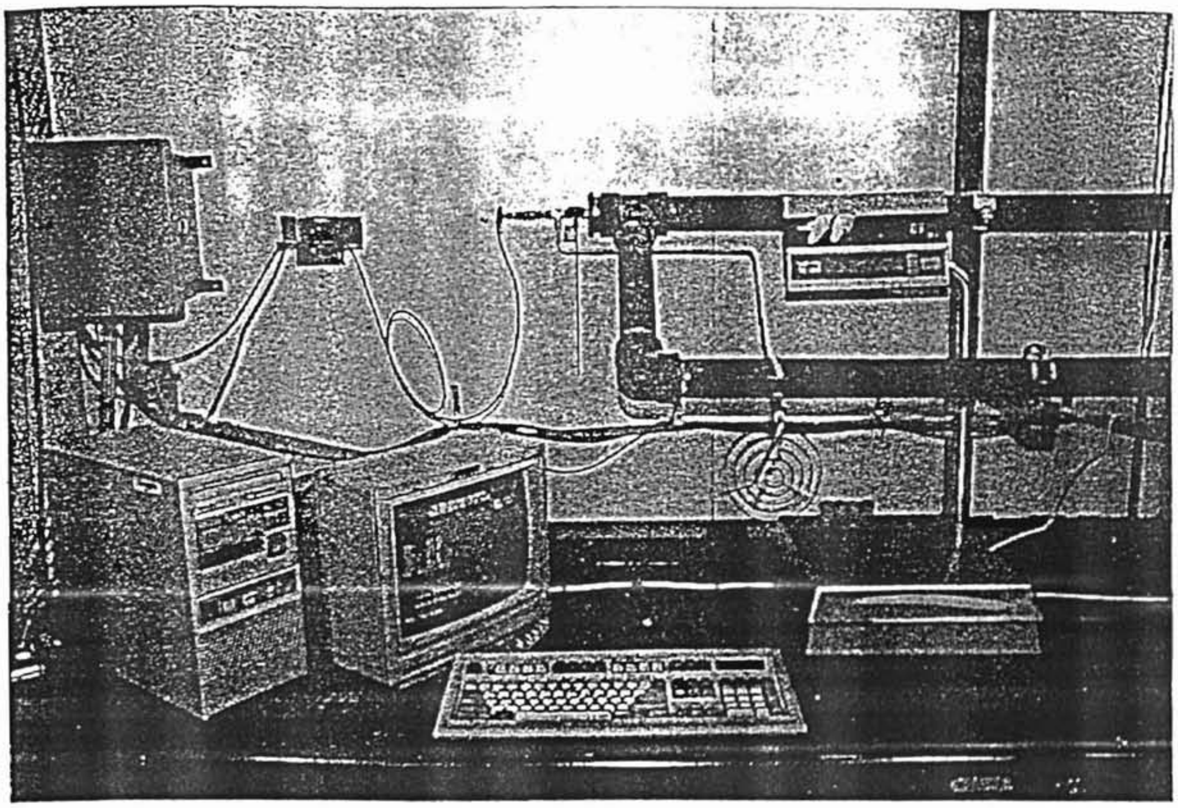

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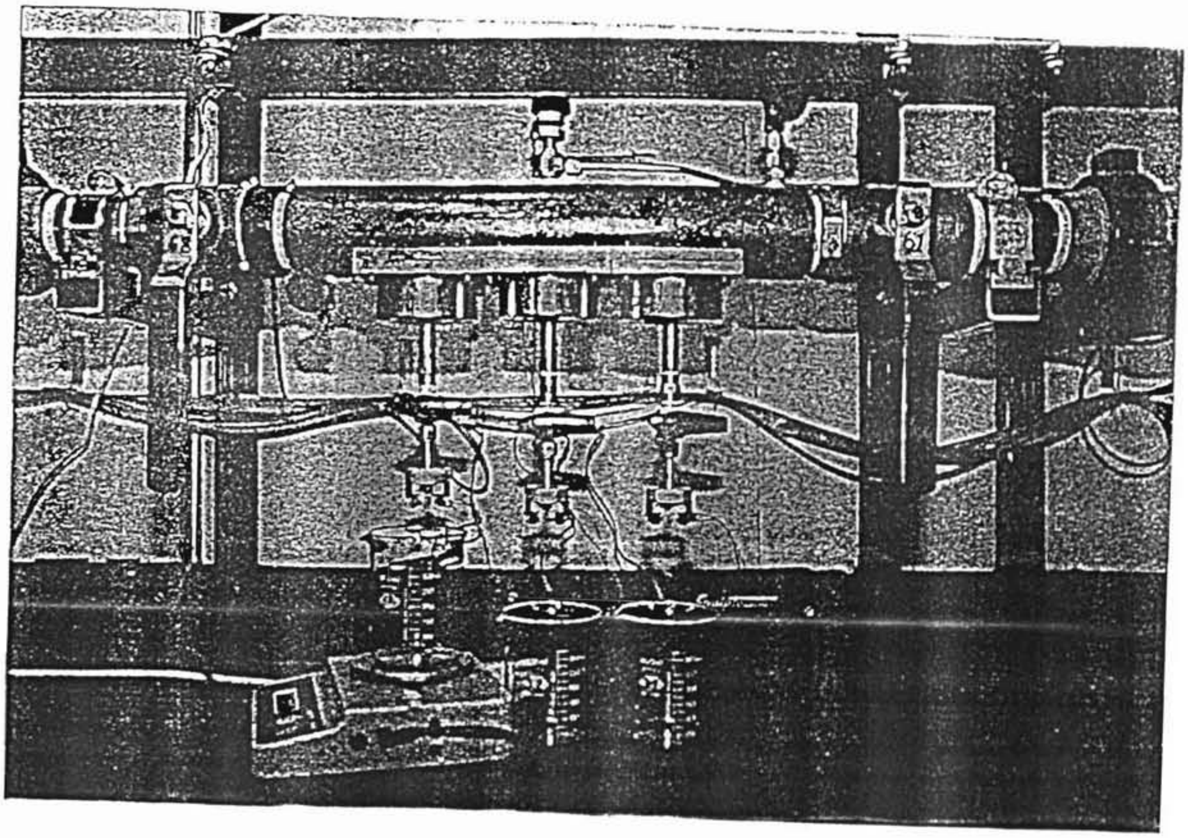

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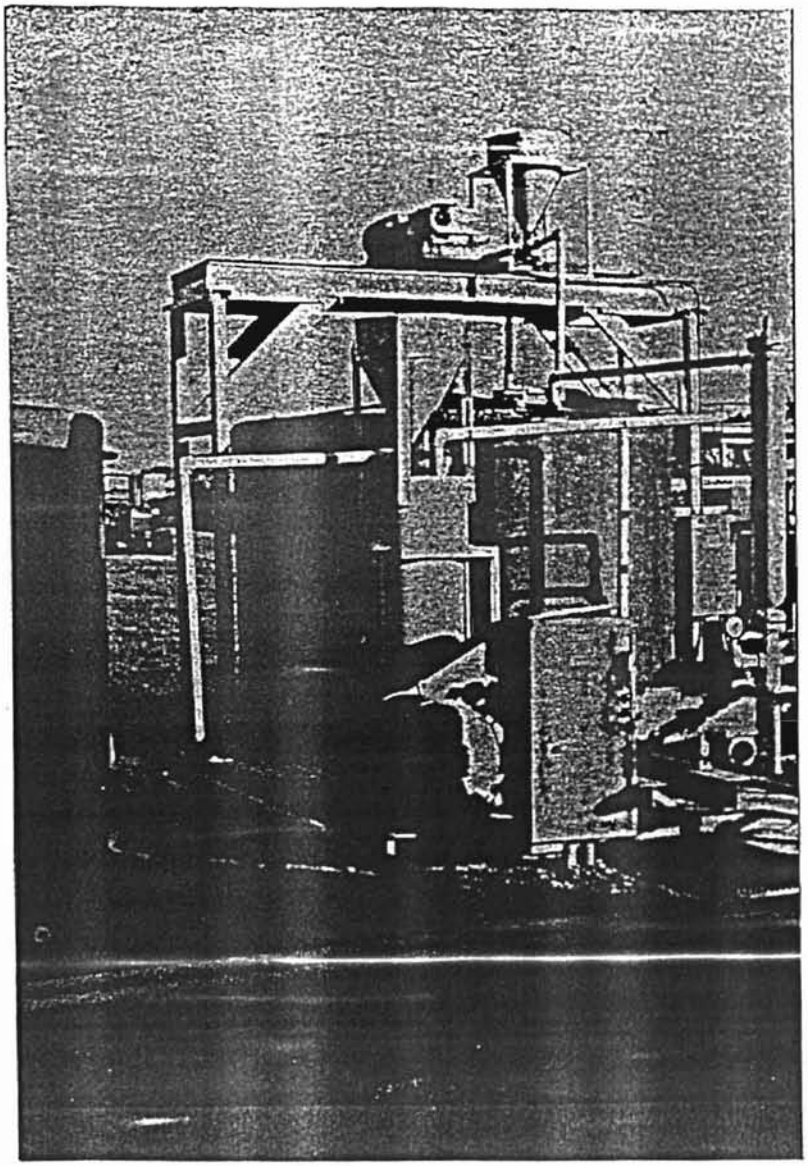

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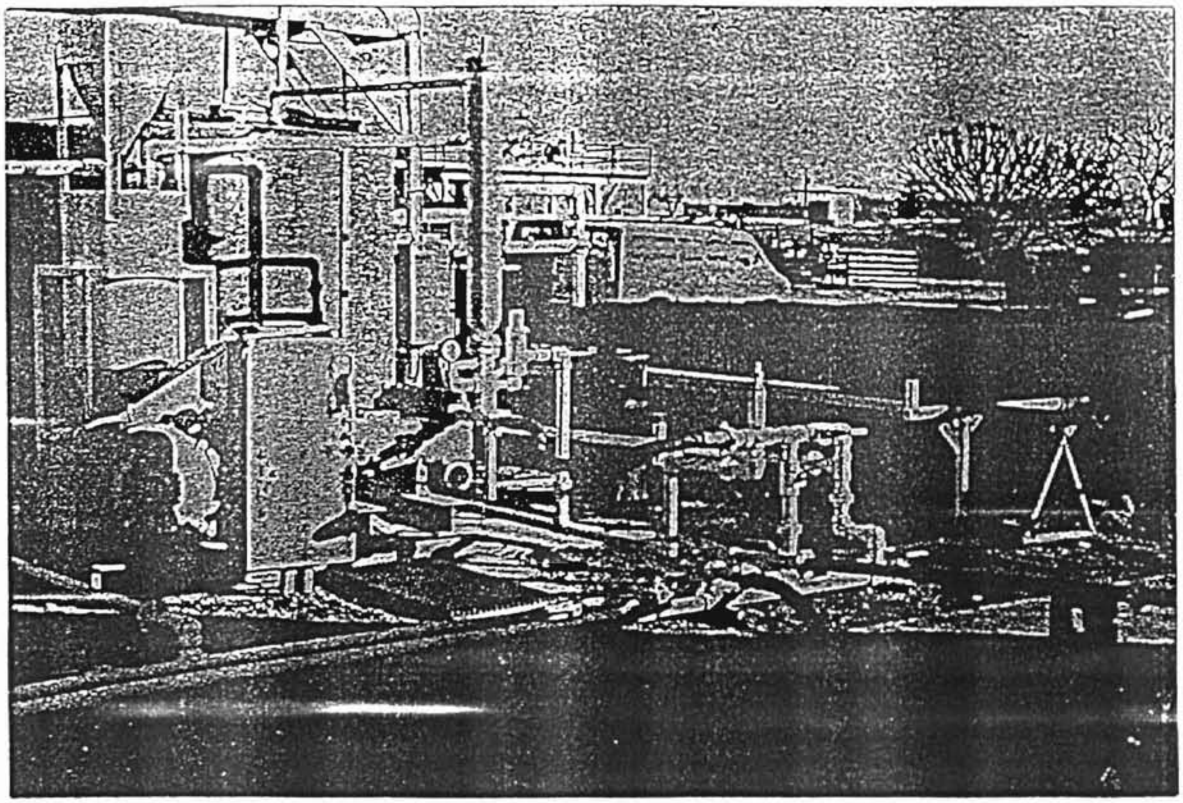
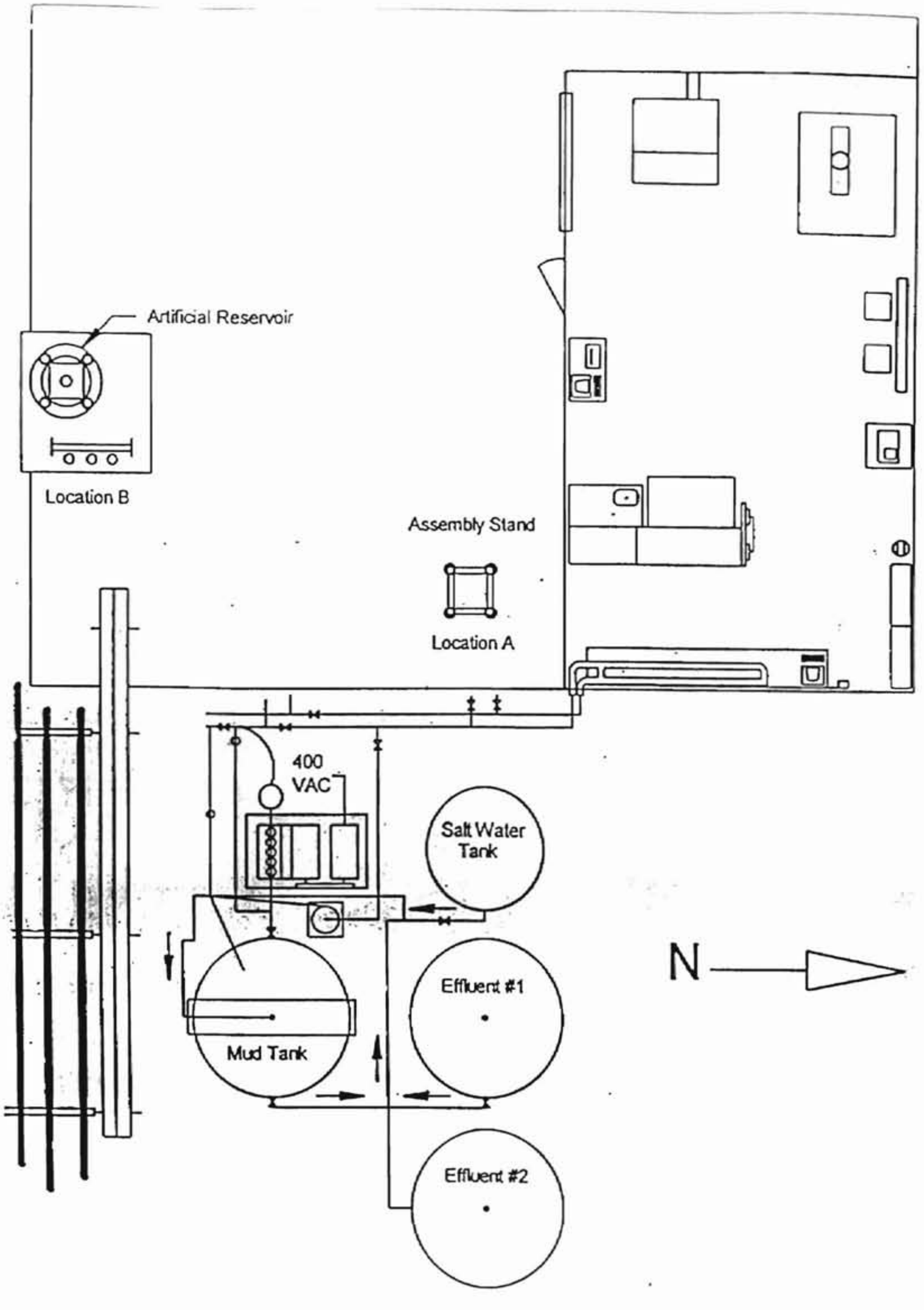


Figure 10. Mud-pipe network (center) with casing and tubing on pipe rack behind.



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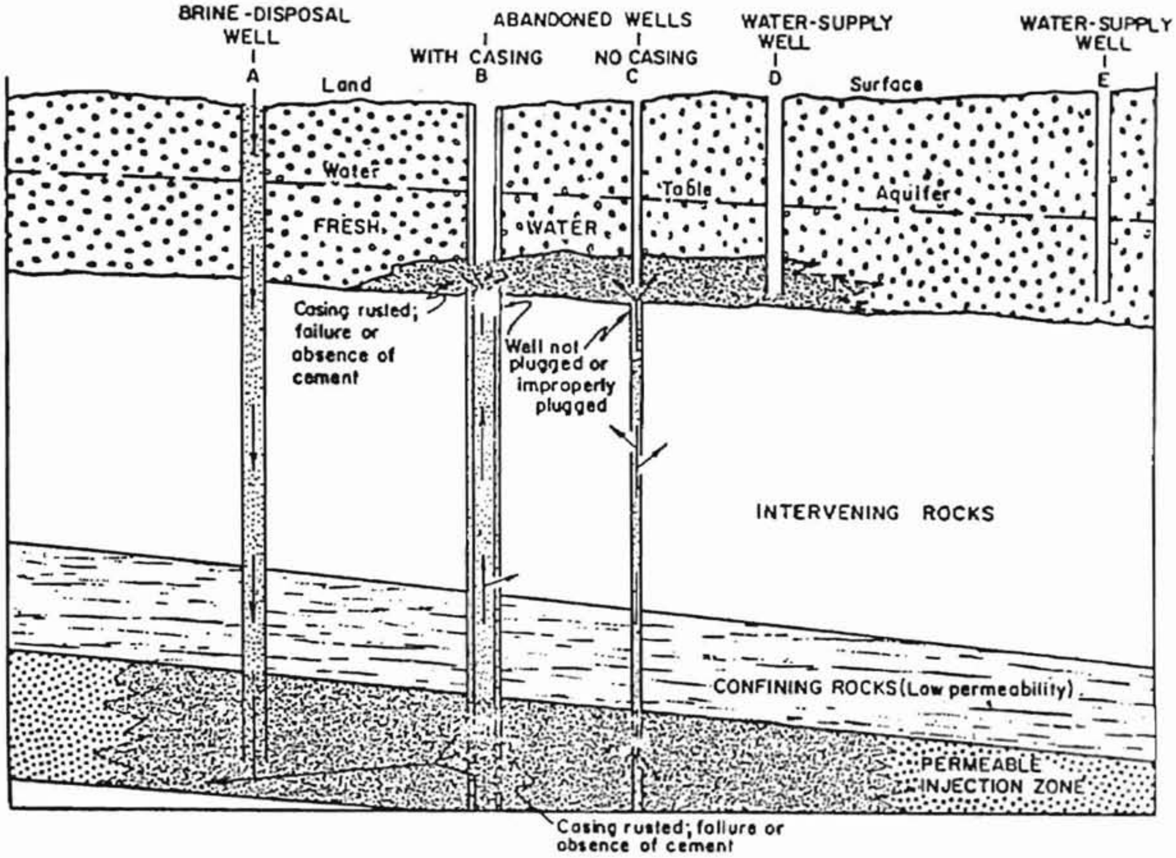

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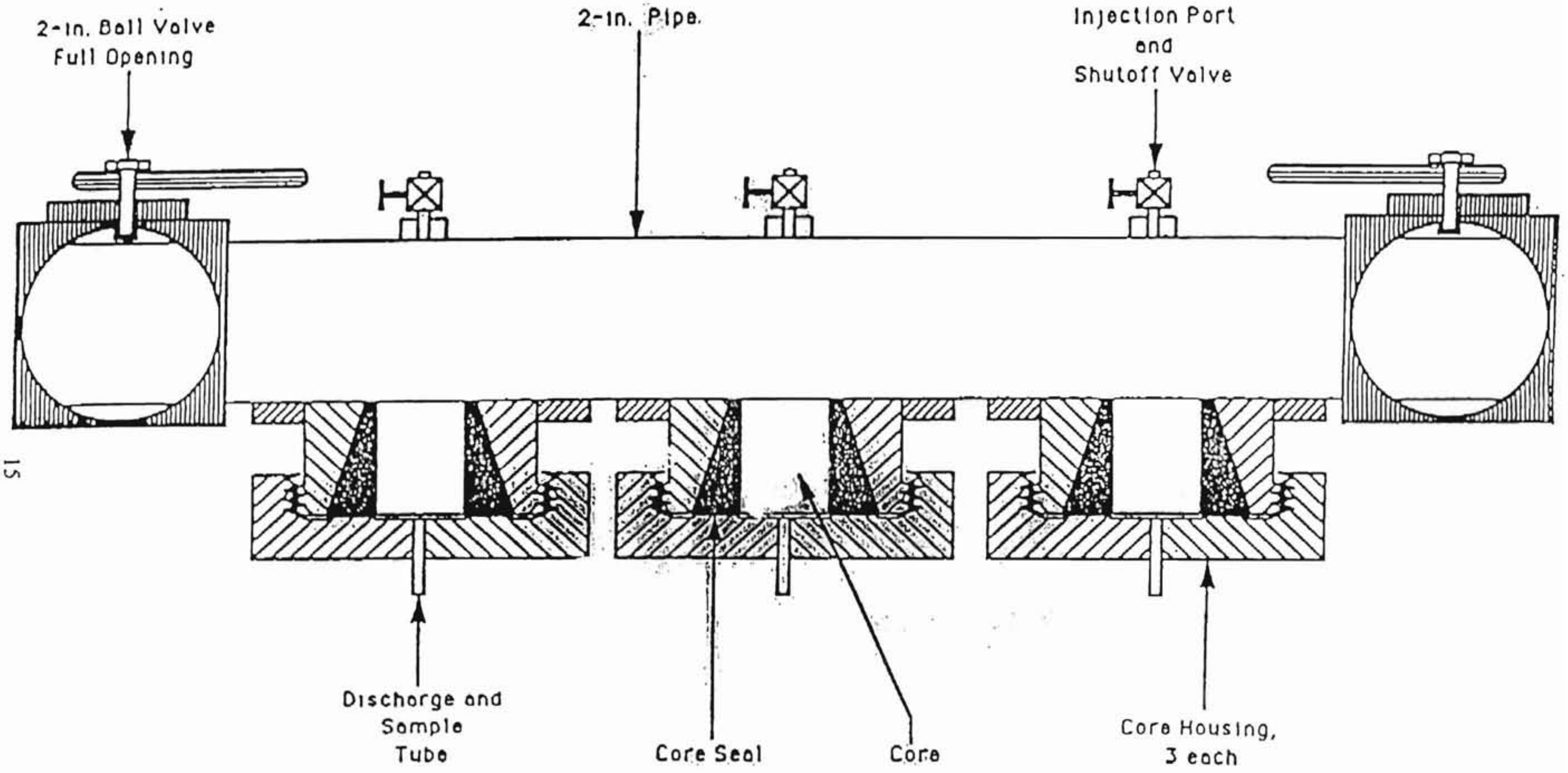

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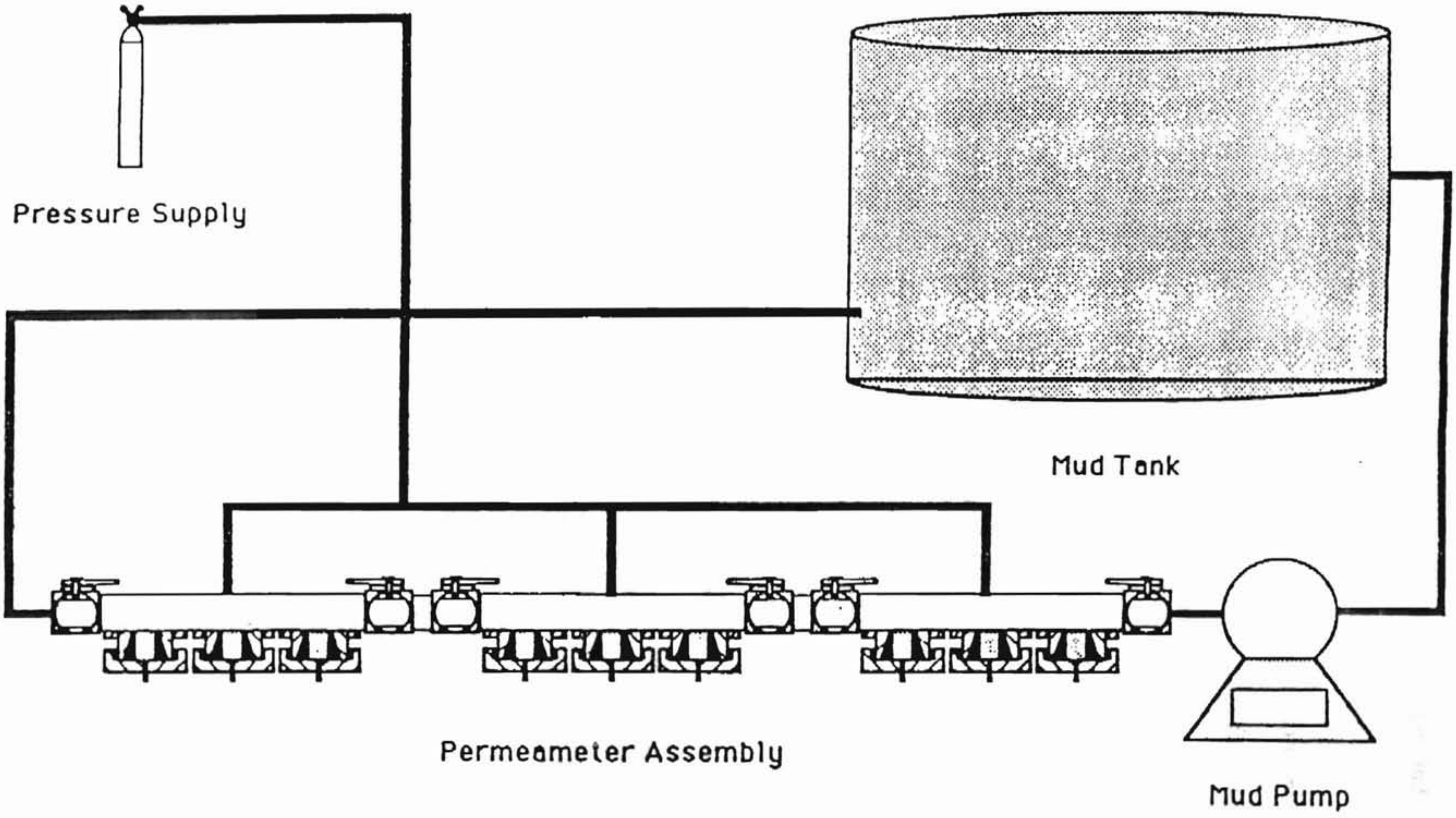


Figure 14. Functional schematic drawing of test facility.

(5) Place cores in a large beaker, cover with distilled water and, in an altitude chamber, evacuate cores at altitude-equivalent of 90,000 feet for 30 minutes. By this method air was removed from the core-plugs.

(6) Load cores into the 9-core permeameter for the mud-plugging test.

(7) Mix drilling mud of 36-second Marsh Funnel viscosity at 9.0 pounds per gallon.

(8) Operate the system to circulate drilling mud through the mud-cake-and-permeameter (M&P) test equipment, for the mud-plugging test (Figures 2, 6, 8, 9, 10, and 11).

(9) Run the mud-cake build-up test to simulate drilling, and collect the data.

(10) Construct curves with data collected from the mud-cake build-up test.

(11) Run the *in-situ* test to simulate a plugged well, and collect the data.

(12) Construct curves with data collected from the *in-situ* test.

(13) Shut down the test equipment, and clean the test equipment.

CHAPTER I

INTRODUCTION

Problems Associated with Abandoned Oil and Gas Wells

Some abandoned oil and gas wells are potential conduits for salt-water pollution of shallow, fresh-water aquifers. Abandoned wells are of two general types: unsuccessful wells, or wells that have reached economic limits; in either case, the wells are plugged. In the past -- particularly early in the history of oil and gas exploration -- procedures for plugging were not stringent; consequently, many wells that were plugged improperly are conduits or potential conduits for movement of salt water into sources of drinking water.

Abandoned wells are of particular concern in the underground injection of oil-field brine, such as in a disposal well or in a water-flood project. In the United States, since the first oil well was drilled 125 years ago, approximately 2 million oil and gas wells have been abandoned (Canter, 1984, p.1). Figure 12 illustrates one way in which an abandoned well could transmit brine to fresh-water aquifers. A well with no cement plugs across permeable zones can permit fluids to migrate from high-pressure zones to low-pressure zones.

Many of the older abandoned wells have no cement plugs, or if a well does have such a plug, the plug is at or near the surface, above the fresh-water aquifers; the borehole is filled with drilling mud. Wells plugged in this fashion are called "mud-plugged wells".

This procedure was a common practice before down-hole cementing and associated methods were developed. Modern technology permits cement plugs to be set, to seal permeable zones. Furthermore, government regulations require strict plugging procedures. In some instances however, enforcement of these procedures is left up to the operator of a well due to inadequate manpower and other resources in regulatory agencies.

Plugging: Compliance In Oklahoma

In many instances data necessary to determine the status of a well are insufficient. The Oklahoma Corporation Commission (OCC) refers to such wells as being of "unknown status". If the well in question had been plugged, then written records would have been filed with the OCC. Many wells that have not been plugged have been declared by the OCC as having been "abandoned". A study of extensive records indicates that in central Oklahoma, more than 3,200 wells in the terrain of the Garber-Wellington aquifer alone have not been plugged (Fairchild, 1984, p.233). Records of more than 8,000 plugged oil wells, gas wells and dry holes were compared to regulations in effect at the dates of plugging; about 72% of plugged oil wells in the Garber-Wellington aquifer were plugged improperly (Fairchild, 1984, p.233). However, to plug all unplugged and improperly plugged wells is neither technically nor economically feasible.

The general public is becoming increasingly aware of the abandoned-well problem, and greater pressure is being felt by regulatory agencies to address problems of ground-water pollution caused by abandoned wells; consequently, methods to protect drinking-water aquifers, without locating and properly plugging these wells, should be studied and developed for areas that include wells of unknown status, unplugged wells, or improperly plugged wells.

Case Studies

In the south-central United States alone, many thousands of abandoned wells have penetrated aquifers that contain water ranging in quality from good to bad. Although the states have plugging regulations to isolate zones -- and thus to isolate fresh-water aquifers from oil and gas zones -- thousands of abandoned unmarked wells exist. These wells might become conduits for migration of fluids between aquifers.

Abandoned wells that date from the frantic wildcat drilling during the 1920's and 1930's in Taylor County, Kentucky are numerous; some began to flow brine when water-flood injection wells were installed from March 1959 to March 1960. When brine was injected under pressure, the abandoned wells that had penetrated the injection formation started flowing. Brines changed the chloride concentration of drinking-water aquifers from less than 60 mg/l on the average before injection to as much as 51,000 mg/l after injection (U.S. Environmental Protection Agency, 1977, as referenced by Canter, 1984, p.1-11).

In 1968, an oil well in west central Colorado, drilled to 1,837 feet in 1915, was discovered flowing 1,350 gallons per minute (gpm) of water with a total-dissolved-solids (TDS) concentration of 19,200 mg/l. This well has contributed perhaps as much as

57,000 tons of dissolved solids per year to the White River. The well was plugged, but hydrostatic pressure caused other wells in the area to flow, which resulted in saline seeps (U.S. Environmental Protection Agency, 1977, as referenced by Canter, 1964, p.10).

An abandoned, unplugged well in Glynn County, Georgia, yielded salt water with a chloride concentration of 7,780 mg/l. The 4,615 foot well penetrated both fresh-water and salt-water aquifers and the well served as a conduit between them. Because pressure in the salt-water formations was greater, it flowed upward into the fresh-water aquifer. Elevated chloride concentrations appeared to extend 1.5 miles along the hydraulic gradient (Wait and McCollum, 1963, as referenced by Canter, 1984, p.11).

CHAPTER III

DRILLING FLUIDS

Introduction

In rotary drilling, continuous circulation of drilling fluid (mud) is important. In fact, the development and application of drilling mud is the principal reason why rotary drilling became so successful in areas underlain by soft rock or unconsolidated sediments, which had been considered undrillable by cable-tool methods.

According to Gatlin (1960, p. 70-74), drilling mud has five basic functions:

1. To cool and lubricate the drill bit and drill string.
2. To remove and transport cuttings from the bottom of the hole.
3. To control subsurface pressure.
4. To hold cuttings in suspension when circulation is stopped.
5. To line the hole with an "impermeable" filter cake.

Basic Ingredients of Fresh-water Drilling Mud

The basic ingredients of fresh-water drilling muds are fresh water and suspended clays. Desirable properties for specific down-hole conditions are obtained by adding various materials to this basic mixture. Certain clay materials hydrate readily to form stable colloids. Sodium bentonite, composed of the clay montmorillonite, has the highest fresh-water "yield" of all clays; "yield" is defined as the number of 42-gallon barrels of

15-centipoise mud obtained per ton of clay. For bentonite, this yield is approx-imately 100 barrels. Wyoming is the principal source of sodium bentonite, in which Na^+ is the dominant ion. (This material was drawn from the work of Gatlin, 1960, p.79-80.)

General Functions of Drilling Mud

The first drilling muds were composed only of pulverized rock and water. However, during the drilling of the famous Spindletop well, "quicksand" threatened loss of the well. A muddy solution was mixed by driving cattle through a shallow pit of water. When the muddy water was used for drilling, the borehole was lined with mud cake, which prevented the sand from caving. From this crude beginning drilling-mud technology began to develop (Gatlin, 1960, p.77).

The building of filter cake and the control of subsurface pressure are the most important functions of drilling mud used as a plugging agent. In order to control subsurface pressure -- or hold back formation fluids and stop them from entering the wellbore -- the mud must have hydrostatic pressure greater than pressure within the formation. In Oklahoma, mud of 9 lb/gal commonly is used. Filter cake is an aggregate of clay that bridges small pores in the rock, the clay being deposited as pressure of the mud-column forces mud-filtrate into the rock. Eventually, a filter cake is impermeable, for all practical purposes (Gatlin, 1960, p.77). Consequently, after a well is mud-plugged, migration of fluids from the borehole to formations, or the opposite, should not occur. If formation fluids do migrate toward the well bore, they should not penetrate the filter cake; thus, shallower fresh-water aquifers should remain protected. However, this assertion would hold true only if pressures in the brine-bearing formations were not to exceed the natural, original conditions.

CHAPTER IV

OVERVIEW OF THE UNDERGROUND INJECTION CONTROL PROGRAM

Authority for the Underground Injection Control (UIC) program was generated through the Safe Drinking Water Act, 42 U.S.C. 300(f) *et seq*. The regulation is 49 CFR 144-149. One purpose of the Act is to protect underground sources of drinking water (USDWs) from adverse effects from the injection of fluids; "fluids" are defined as any material or substance that flows or moves, whether semisolid, liquid, sludge, gas or in any other state.

Area of Review

The "area of review" is defined as the area surrounding an injection well into which fluids are to be injected, the radius of which is delimited by the zone where the injection pressure would be equal to the natural formation pressure (zero injection head). Generally, this radius must not extend to within one-quarter mile of an USDW. For class 1 wells this radius must be 2 miles.

Classification of Injection Wells

The information below was compiled from CFR Parts 144-149.

Class I

Wells used to inject hazardous waste, and other industrial and municipal waste.

Class II

(1) Wells into which fluids are injected that were brought to the surface in connection with natural-gas storage operations or conventional oil or natural gas production; these fluids may be commingled with waste waters from gas plants that are integral parts of production operations, unless these waste waters are classified as hazardous waste at the time of injection. (2) Wells into which fluids are injected for the enhanced recovery of oil or natural gas. (3) Wells used for the storage of hydrocarbons (products derived from crude oil) that are liquid at standard temperature (60°F) and pressure (29.92 Hg).

Class III

Wells into which fluids are injected for extraction of minerals, including (1) mining of sulfur, (2) *in-situ* production of uranium or other metals, and (3) solution mining of salts or potash.

Class IV

Wells used to dispose of hazardous or radioactive waste into or above a formation that within one quarter-mile of the well bore contains an underground source of drinking water.

Class V

All other injection wells, e.g., heat pumps, cesspools, cooling-water return flows, storm-water drainage wells, ground-water recharge wells, salt-water intrusion-barrier wells, septic-system wells, and several others. (See 40 Code of Federal Regulation 146.5.) (The classification described is from Focht, 1993, p.131.)

National Ground-water Protection Strategy

The national ground-water protection strategy recognizes that aquifers should be protected differentially, based on importance, use and vulnerability. The basis for this philosophy is to designate certain aquifers, or portions of aquifers, for differential protection, according to the classification of the aquifer. The portion of an aquifer so classified is termed the Classification Review Area (CRA)--generally a 2-mile-radius delineation (Focht,1993, p.126). Classification of aquifers is as follows:

Class I Special Drinking Water

The class has these attributes: (1). Highly vulnerable, sole or irreplaceable source, or ecologically vital, such as recharge areas, islands, and unique habitats. (2). Protection level is (a) maximum contaminant level (maximum contaminant level that will not harm human health or the environment), (b) maximum contaminant level goal (a contaminant level not to be exceeded if at all possible), or (c) background (contaminant level is set to the levels already existing in the aquifer in surrounding areas). (3). No alternate-concentration limits (ACLs). (An alternate-concentration limit may be allowed if proven that the alternate level will not harm human health and the environment).

Class II Current and Potential Source of Drinking Water

Class II-A: Current Source of Drinking Water One or more drinking-water wells, or an aquifer designated by a state or local agency as a drinking-water source.

Class II-B: Potential Source of Drinking Water Yields at least 150 gallons per day per family, with total-dissolved-solids concentration of less than 10,000 mg/l, and of quality sufficient to drink after treatment by methods reasonably employed by public water- treatment systems. Protection levels allow alternate concentration limits, if justified.

Class III: Not a Potential Source of Drinking Water Aquifers with total-dissolved-solids concentrations greater than 10,000 mg/l, or of a quality not sufficient to drink after treatment by methods reasonably employed by public water-treatment systems due to natural or broad-scale human activity.

Class III-A High to Intermediate Connection to Class I or II Aquifers Protection level allows alternate concentration limits, if justified.

Class III-B Low Connection to Class I or II Aquifers Protection level allows no treatment.

(All the discussion of classification of aquifers was drawn from Focht (1993, p. 126)).

CHAPTER V

OBJECTIVE

The Environmental Protection Agency is required by the Hazardous and Solid Waste Amendment of 1984 to assess the environmental suitability of injection of liquid waste 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 injection waste, the formation, and the formation fluids (OSU EPA study, p. 1).

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 vicinities of the plugged wells. Thus, the primary objective of the proposed experiment was to test this hypothesis: Drilling mud in abandoned, properly plugged wells effectively seals the borehole, but 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.

To insure the effectiveness of drilling mud as a plugging agent, "mud-plug" and "*in-situ*" tests were conducted on core plugs of various permeabilities. The mud-plug and *in-situ* tests were designed to indicate the potential of invasion of the reservoir -- or conversely, to indicate that reservoir effectively would remain sealed. Thus, results of the tests were to indicate the effectiveness of drilling mud as a plugging agent.

CHAPTER VI

DESIGN OF THE EXPERIMENT

The following was modified from the Draft OSU EPA report dated July 1994, p4.10, Appendix A1-A10:

Development of Artificial Rock

An artificial rock 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 to 20 percent and permeability near 200 millidarcies would be close to the average properties of injection zones. 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. Experimentation with composition and methods of compaction of the artificial rock stemmed from suggestions given by Mr. J. Murphy.

Principal components of the artificial rock were 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. 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 inches. 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 rock was made according to recommendations by Halliburton Services. Its appearance and heft indicated strongly that the rock would have porosity and permeability in amounts smaller than required for the overall purposes of the experiment. 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.

The artificial rock used in the experiments was composed of about 3 parts (by weight) of fine-grained quartzose sand to one part 12-20 mesh frac sand, cemented by epoxy resin. As described above, at the outset of this research, Halliburton Services recommended 150 lb. of fine-grained quartzose sand, 50 lb. of frac sand and 19 lb. of resin for 2.3 cu. ft. of artificial rock. Proportionally smaller batches, called "1.0 Halliburton," produced artificial rock with about 5% to 10% porosity and 10 to 20 millidarcies of permeability -- a substance too "tight" for the intended experiments. Therefore, samples were mixed with reduced volumes of resin; amounts of resin tested were in proportions of 0.5, 0.75, 0.8 and so on, which were named "0.5 Halliburton, 0.75 Halliburton," and so forth. These fractional mixes produced rock with porosity in the range of about 13% to 20%, and permeability in the range of 0.1 to 7 darcies.

Because the artificial rock was intended to function in testing as an analog to actual rock, the desirable range of permeability (for equivalent range of porosity) was between 100 and 1000 millidarcies. Thus, considerable effort was expended to determine a method of compaction and to produce amounts of compaction that would reduce permeability but preserve the general range of porosity. First, by combining drill-press parts, platform scales, compactor-foot, and molds, a method was developed for compaction with results expected to be more predictable than those attained previously by hand-tamping. A 0.5-Halliburton recipe was used as the test case; the mixture was compacted into molds with axial loads of 1000, 750 and 500 pounds. A plot of permeability showed a steep gradient in permeability with respect to axial force in the interval between 500 and 750 pounds of force, but a much smaller gradient between 750 and 1000 pounds of force. At the 1000-pound force, permeability was about 5800 millidarcies -- which was too great for the pertinent experiments. Extrapolation of this curve dictated an axial force much greater than the capability of the modified drill-press-and-scales device that was being used. Consequently, a hydraulic system was developed to tamp the Halliburton mix.

Core-plugs for Mud-cake-and-permeability Tests

Samples of artificial rock were constructed in molds of 5-in. diameter. Core plugs cut from the 5-in. diameter, 6-in. high samples were cut normal to the direction of the tamping force. Tests showed that significant difference exists in permeability, depending on whether the core is taken perpendicular or parallel to direction of the tamping force. This is consistent with conditions in natural rocks; permeability commonly varies with the bedding of strata.

Core-plugs were drilled, cleaned, and evacuated in a vacuum chamber to 0.24 psia, and stored in water. Permeability of the plugs was measured, using both nitrogen and water. In the initial sets of tests, from trial to longer spans of time were required for 10 ml. of test fluid to flow through each plug. In one instance, the transit time varied from 1 minute and 44.39 seconds to 4 minutes and 12.65 seconds. Of course this increase cannot be attributed entirely to instrument error or to operator error, owing to the magnitude of variation. By removing the cores from the permeameter holder, turning the opposite ends up, and re-running the tests, the transit times were essentially the same. Increase of transit time was attributed to migration and "stacking" of "rock flour" from cutting of the cores. A change in procedure was made and a device was built to clean the cut core from the central part outward to the ends, with air pressure. Other steps in the procedure involved various cut-off procedures, use of detergent on core plugs, and use of a shop vacuum while drilling the core plugs and when removing plugs from the core. Vacuum was used to clean core plugs after they were trimmed to proper length.

Extrapolation of the permeability and tamping-force data indicated that tamping alone would not provide the range of permeability and porosity required for the mud-cake-and-permeability tests. Thus, a series of tests was run on resin mixtures and tamping forces. The maximum foot-pressure that the hydraulic system could provide was 140 psi. Resins of 0.6, 0.7, 0.8, 0.9, and 1.0 "Halliburton" mix were tested. All the cores were done with the relief valve set so that a foot-pressure of 125 psi was achieved.

Test results showed that permeability decreased as the mix increased from 0.6 to 1.0 Halliburton. Permeability ranged from 50 millidarcies to more than 5000 millidarcies. In fact, some of the 1.0-mix core plugs had permeability of zero. One of the 0.9-mix core plugs separated at the lift (layer) interface, and one of the 1.0-Halliburton plugs sheared into two parts during the coring. The separation and shearing phenomena had not occurred before and permeabilities in some cases were lower than the desired values; so a test was devised to use the 0.9-Halliburton mix and foot-pressures ranging from 105 psi to 145 psi. Results of these tests were that gas permeability was in the range of the desired values of 100 to 1000 millidarcies.

Core plugs analyzed by this system were 1 inch in diameter and 1.375 inches long. They were emplaced in sleeves of hard rubber and mounted in cylinders that permitted the introduction of water or drilling mud at tops of cylinders. Permeability of rock and rate of buildup of mud cake could be evaluated by the amount and time-distribution of flow through the plug. Pressure transducers were installed in the mud-conditioning flow lines. A set of miniature scales was connected to the data-acquisition system, to monitor weights of volumes of mud filtrate or drilling mud transmitted through core plugs; weights could be measured as functions of time, to within approximately one-tenth of a gram. Information from the miniature scales could be transmitted to the data-recording computer on a real-time basis during operation of the permeameter.

Mud-cake Build-up System

A mud-cake build-up system was constructed such that nine cores could be tested at the same time. Furthermore, the core-holder system was set up with three subassemblies; each subassembly was constructed to hold three cores. Valves were installed on both the upstream and downstream sides of the subassemblies. This valve arrangement allowed for isolation of each subassembly (Figures 2, 8, and 13). A computer data-acquisition system was developed to record continuously the data created by this system (Figure 7). However, because first-hand evaluation of data was necessary, this paper refers strictly to hand-recorded data.

Cores were placed in sleeves of hard rubber; the sleeves were mounted into steel cylinders that permitted water or mud to flow into and through the cores from the top. At the bottom of each core holder was a discharge tube, from which water or mud filtrate dripped into a beaker. The beaker was placed on an OHAUS scale that recorded the weight of the accumulated fluid (Figure 8). As mudcake was being built on the top of a core plug, filtrate flowed through the core plug and dripped through the discharge tube; time-between-drips was recorded by a personal computer. Pressure and temperature sensors were integrated into the system.

The system was connected to a mud-mixing hopper and a mud-supply pump. Valve assemblies were arranged such that flow rates could be determined by bucket-and-stop-watch method. Valves also allowed mud to be diverted to mud tanks, mud hopper, or to the mud-cake build-up system.

System pressure was supplied either by a plunger pump (during the mud-cake build-up test) or by a nitrogen supply-system (for the *in-situ* portion of the test). Pressure supplied by the plunger pump was regulated with a restriction-type choke valve; a by-pass valve was used to adjust mud flow rate. Nitrogen pressure was regulated with a standard compressed gas-regulator.

Drilling Mud

The drilling mud used in the experiment was designed to conform to standard oil-field practices. A drilling mud made of fresh-water, bentonite and barite was prepared for each mud-cake build-up test. Barite was added to fresh water to increase the weight to 9.0 pounds per gallon. Bentonite was added to increase the mud viscosity to funnel viscosity of 36 seconds. Fifty-six gallons of mud were mixed for each test. Mud properties were tested periodically as a quality-control check. Description of the standard operating procedure follows, shown as it was defined for use in the laboratory.

Multiple-core Mud-cake-and-permeability Test Procedure

Test for permeability to water.

1. Select cores by defined criteria.
2. Put cores in 100-ml. beaker; cover cores with distilled water.
3. Place beaker with cores in altitude chamber; evacuate chamber to 90,000 ft. altitude equivalent for approximately 1 hour. (Caution: Do not let the water freeze).
4. Take wet-weights of cores using OHAUS scale; record in M&P data book.

5. Place cores in rubber core-holders. Make sure that bottoms of cores are flush with bottoms of rubber holders.
6. Coat outsides of rubber core-holders with light coat of white grease. Hold core-holder cap assembly right-side-up and fill drip tube with water.
7. Open drip valve until bottom of drip tube is full of water; then shut valve.
8. Refill assembly with water.
9. Slide core rubber (with core inside) into subassembly.
10. Screw core-holder caps onto subassembly to hold core.
11. Tighten caps with cap wrench.
12. Record core locations in subassemblies, in M&P data book.
13. Take dry-weights of 400-ml. beakers; record in M&P data book.
14. Place 400-ml. beaker under each drip tube.
15. Place 400-ml. beaker under drip tube 3.3 directly on the OHAUS scale; tare the scale.
16. Close valves 42, 49, 50, 60, 61, 68.
17. Fill subassemblies with water using 1/4-in. flexible hose.
18. Open nitrogen-inlet valves 46, 56, 65.
19. Open pressure-gauge valves 54 and 57.

Mud-cake Buildup Procedures

1. To weigh constituents for 9-16 lb./gal., 36-sec.-viscosity mud (Marsh Funnel test):
    - Zero scale with 5-gal. bucket on scale.

- Weigh 30 lbs. of bentonite into 5-gal. bucket.
- Weigh 60 lbs. of barite into 5-gal. bucket.

2. Valves in EPA Building: valve 42 closed; valve 41 open; valve 51 closed.
3. Valves on mud-pump plumbing:
    - Valve on bottom of hopper closed.
    - Suction valve for pump open.
    - Valve to large mud tank closed.
    - Drain-valves to system drain closed.
    - Discharge straight-through valve on Baird pressure-relief valve closed; down valve open.
    - System-line valve at "B" open.
    - Jet-system mixer-valve open.
    - Down side of jet-mixer valve closed.
    - Main throttle valve all the way open.
    - Effluent valve closed.
    - Drain side of effluent valve closed.
    - Calibration-line valve open.
    - Valve on 80-bbl. mud tank closed.
    - Mud-hopper return valve open.
4. Fill hopper with 67.7 gal. of water, using water hose and flow meter.
5. Start circulating through hopper and jet-mixer. Make sure the valves are set, so mud will not circulate through multi-core permeameter in EPA Building.

6. Pour bentonite and barite into jet-mixer.
7. Circulate for 30 minutes.
8. Divert flow into EPA Building.
9. Open line-valve to EPA Building.
10. Close jet-mixer valve about halfway.
11. Take mud samples for mud properties, through sample-port Valve 40 in EPA Building (flush port tube into separate container).
12. If mud is 9.0 lb./gal and 36-viscosity, continue; if not add enough bentonite and barite to reach these standards.
13. Open valve 51 (throttling valve).
14. Close valve 54 (nitrogen-inlet valve).
15. Adjust nitrogen to 50 psi. with subassembly valves closed.
16. Adjust primary choke valve to 50 psi at gauge on mud pump.
17. Set mud-bypass valve (valve to jet-mixer) for a flow rate to range from 14.7 gpm to 19.5 gpm.
18. Check pressure at pump.
19. Divert flow through M&P system.
    - Throttling-valve 51 full open.
    - Open ball valves 68, 61, 60, 50, 49, 42.
    - Close crossover-valve 54.
    - Turn off nitrogen valve 54
    - Open nitrogen-inlet valve 65 to subassembly 3.
    - Close nitrogen bottle.

20. (At this point, mud will circulate through subassemblies). Open drip-tube valves 44, 45, 47, 53, 58, 63, 64, 66.

21. Run mud-cake build-up for 24 hours; keeping pressure at 50 psi by adjusting choke valve. Attendant must be on duty throughout mud-cake build-up.

22. Manually record mud-cake build-up data every hour as follows:

    - Start-up time.
    - General permeability of cores.
    - Mud temperature.
    - Computer time.
    - Drip time.
    - Pressure.
    - Weight on OHAUS Scale.

23. Create QUATTRO PRO spreadsheet with manually recorded data.

24. Create QUATTRO PRO graph with manual data. (Note: Computer time must be divided by 3600 to convert it to hours!) Graph should have run-time in hours on X-axis, and drip-time in seconds on Y-axis. Legend should be on upper-right-side of plot, identifying each curve. File name and permeability should be on both spreadsheet and graph.

25. Fill 1-gal. jug with mud from mud-port in EPA Building; record data and time on jug.

26. Run water-loss test, using mud kit. Record water loss and mud-cake thickness on data sheet, with data taken manually at drip-tube 3.3.

27. Run Fann Viscometer test on mud and record data in M&P data book.

28. After 24 hours, divert mud from subassemblies and flush with clean water.

29. At least 3 hours before terminating mud-cake build-up test, fill the fresh-water tank to at least 1 ft. above suction valve.

30. Adjust nitrogen pressure to 50 psi, with valve 54 closed.

31. Open effluent line.

32. Close mud-return line (not mud-mixing valve!).

33. Draw mud down to top of cone in mud hopper.

34. Open fresh-water inlet valve to pump.

35. Close suction valve on mud hopper.

36. Circulate water through subassemblies until mud hopper is almost full, or until clean water returns to hopper.

37. Open by-pass valve 41.

38. Close ball valves 42, 49, 50, 60, 61, 63.

39. Close throttle valve 51.

40. Close drip valves 44, 45, 47, 53, 55, 58, 63, 64, 66. Clean drips off drip-tubes.

41. Open choke-valve fully.

42. Close jet-mixing valve before hopper overflows.

43. Take wet-weight of 400-ml. beakers; record with the manually-recorded data.

44. Record pH of filtrate water that is in beakers.

45. Clean and dry 400-ml. beakers.

46. Flush mud pump with fresh water and pump mud into the effluent tank and clean equipment.

Procedure for Water *In-situ* Test

1. Place 400-ml. beakers under drip-tubes.
2. Set time and date on data-acquisition computer.
3. Check time and date on data-acquisition computer.
4. Open nitrogen valve 54.
5. Adjust nitrogen pressure to 50 psi -- the P-500 reading on the computer.
6. Open nitrogen-supply valves 46, 56, 65 to each subassembly. (The L,M,R indicators on the computer should now have 1's, indicating that the valves are open).
7. Open drip-valves 44, 45, 47, 53, 55, 58, 63, 64, 66.
8. Run *in-situ* test for 72 hours, keeping pressure at 50 psi by adjusting the nitrogen regulator.
9. Record data manually every hour, as follows:
   - Start-up time.
   - Temperature of Subassembly 3.3.
   - Computer time.
   - Drip time.
   - Pressure.
   - Weight on OHAUS Scale.
10. Create QUATTRO PRO spreadsheet with manually recorded data.

11. Create QUATTRO PRO graph with manual data. (Computer time in secondsmust be divided by 3600 to convert it to hours!) Graph should have run-time in hours on X-axis, and drip-time in seconds on Y-axis. Legend should be on upper-right-side of plot, to identify each curve. File name and permeability should be on both spreadsheet and graph.
12. To end the *in-situ* test, close nitrogen inlet.
13. Close drip valves 44, 45, 47, 53, 55, 58, 63, 64, 66. Clean drips off drip tubes.
14. Close valve on nitrogen bottle.
15. Slowly open bleed valve at nitrogen regulator on nitrogen bottle, to relieve pressure on nitrogen-supply line.
16. Slowly open valves 43, 52, 62, the top ports on each subassembly, to relieve pressure on subassemblies.
17. Slowly open valves 48, 59, 67, to drain water from subassemblies.

Procedure for Removing Cores and Making Photographs

1. Remove drip-tube and photocell.
2. Remove core-holder cap.
3. Remove rubber core-holder, using knife.
4. Place core (still in core-rubber) on clean white sheet of paper that is marked with core drip-tube number and M&P test date. Take photograph of core in the core-holder rubber from horizontal position, with ruler marked in thirty-seconds of an inch lying against core-rubber.

5. Remove core from rubber core-holder. Place core back on the paper and take photograph from above the core, with ruler lying flat.
6. Take photograph from horizontal position. Make sure angle is 90 degrees to core. Ruler should be in vertical position, so mud-cake thickness can be observed clearly, by comparison with 32's-of-an-inch scale.
7. Place cores in plastic film containers with test date and corresponding core-holder number marked on lid.
8. Place unusable cores in core-rubbers and install in subassembly.
9. Install core-holder caps.
10. Close mud-hopper suction valve.
11. Open fresh-water suction valve on fresh-water tank.
12. Close valve 41 and open valves 42, 49, 50, 60, 61, 68 and 51.
13. Open discharge valve to effluent tank.
14. Start mud pump.
15. Circulate fresh water through subassemblies.
16. Clean mud pump, and mud hopper and equipment.
17. Stop pump.
18. Open mud-system drain valves.
19. Remove core-holders.
20. Clean insides of subassemblies with brush.

Operating Procedure for Preparation for Mud-cake-and-permeability Test

1. Measure dry weight of each test core.

2. Measure volume of each test core.
3. Complete gas-permeameter test for each core.
4. Measure wet-weight of each core.
5. Complete liquid-permeameter test for each core.

End of operating procedure.

CHAPTER VII

RESULTS AND CONCLUSIONS

The first mud-cake build-up test was run on May 12, 1994. Core permeability on this first test was approximately 1.5 darcys. Permeability for the entire set of tests (six in all) ranged from approximately 2.0 darcys in synthetic rock to approximately 0.3 darcys in sandstone of the Hughes Creek Shale (natural rock).

As previously mentioned, a batch of 9-pound-per-gallon, 36-second Marsh Funnel mud was mixed for each experiment. Mud was circulated through the system at a rate such that laminar flow would occur (drilling fluids commonly are circulated at velocities that produce laminar flow). The mud-cake build-up portion of the test lasted for 24 hours. As mud flowed through the core a layer of filter cake was deposited on top of the core; as filter cake built on the core, filtrate dripped into a beaker. A scale under the beaker measured the weight of the filtrate water. Time between drips, mud temperature, run-time, and mud pressure were recorded by hand and then plotted (in Quattro Pro) with run-time in hours on the X-axis and drip-time, mud temperature, weight on the scale, and mud pressure on the Y-axis.

After the 24-hour mud-cake-build-up test, the *in-situ* portion of the test was begun. For the *in-situ* test mud was replaced with fresh water to simulate migration of brine into a plugged-and-abandoned well. Much care was taken to hold the pressure at a constant 50 psi while the mud was being circulated out of the system and replaced with fresh water. This method would insure that the mud cake would not be disturbed. Fresh water was used for the *in-situ* portion of the test, because fresh-water drilling mud tends to permit settling of solids, leaving a column with fresh water in the upper part of the well bore and a very dense mud column in the lower part.

The *in-situ* tests were run from a minimum of 49.5 hours (on the 0.5-darcy synthetic rock) to a maximum of 95.5 hours (on the 1.5-darcy synthetic rock). The *in-situ* tests were terminated after it was estimated that sufficient data were generated. Again time between drips, temperature, run-time, and pressure were recorded by hand and plotted (in Quattro Pro) with run-time in hours on the X-axis and drip-time, temperature, weight on the scale, and pressure on the Y-axis. During the mud-cake build-up portion of the test, the system was manned for the entire 24 hours to adjust the pressure manually and keep the choke clear of solids-build-up, and to lubricate and adjust the plunger-pump packing. Consequently, during the mud-cake build-up part of the test, it was possible to collect data points on a more-frequent basis.

During the *in-situ* portion of the test the nitrogen pressure system required practically no manual adjustments; therefore, the system was manned only during the day and spot-checked during the late-night hours. Consequently, fewer data points were taken during the *in-situ* tests.

Six sets of mud-cake build-up and *in-situ* tests were run starting on May 12, 1994, with the last test having been run on June 22, 1994.

Using Quattro Pro's advanced math function, linear regression was used to predict how well the core (for the *in-situ* portion of the tests) would remain sealed after one, five, ten, twenty, and fifty years. Drip-time was plotted on the "Y" axis and run-time was plotted on the "X" axis.

Discussion of Test Data

The first mud-cake-build-up test was 51294MCB, which was run on May 12, 1994. The core used in this test was a synthetic core with permeability of 1.5 darcy. Tabulated data and the graph of them (Table 1 and Figure 15) show that the test was run for 28.61 hours. During the test, pressure was about constant, at about 50 psi, with a maximum pressure of 54.2 psi and a minimum of 48.6 psi. These small fluctuations would have negligible effects on the drip-time data.

At the beginning of the test the mud temperature was 88°F. As the test proceeded, temperature increased, due to friction and the sun's energy (Table 1 and Figure 15) (the mud pump and holding tank are outside the EPA Laboratory building). Temperature of the mud rose to 98°F after about 3 hours of run-time (Table 1 and Figure 15), then began to decrease as evening approached and night fell. Minimal temperature was 77°F. On the second day, maximal temperature was 97°F. In general, figure 15 shows that the longer the test was run, the longer the time between drips. Between 10 and 15 hours into the test, time between drips declined as temperature declined.

Run Time	Drip Time	Mud Temp.	Pressure
0.10	23.24	88	54.2
0.22	32.36	88	52.0
0.36	37.89	88	52.2
0.41	41.43	89	52.0
0.47	44.25	89	50.7
0.61	48.91	89	50.8
0.71	52.41	90	50.7
0.88	56.52	91	50.5
0.88	60.18	92	50.0
1.31	58.06	93	50.5
1.57	59.76	95	50.3
1.81	60.84	95	49.5
2.05		96	50.5
2.30	59.85	96	49.5
2.66	58.98	97	50.0
2.81	57.31	97	50.7
3.05	54.56	97	50.5
3.55	62.12	98	50.2
3.81	65.77	98	50.7
4.06	65.30	98	50.8
4.30	67.49	97	50.7
4.55	69.75	95	50.2
4.80	69.80	95	50.5
5.06	69.27	95	50.8
5.31	71.27	95	50.0
5.55	71.55	95	49.7
6.54	73.76	95	51.7
7.71	83.05	92	51.2
8.60	88.95	89	49.3
9.63	88.81	86	49.5
10.64	81.56	84	48.6
11.66	76.64	82	49.0
12.65	83.00	81	50.0
13.56	77.31	80	50.3
14.56	76.74	79	51.2
15.55	97.81	79	51.5
16.55	100.25	79	50.0
17.54	104.52	78	50.3
18.57	111.75	78	52.0
19.62	120.69	77	51.7
20.64	118.63	77	52.2
21.52	121.67	78	50.3
22.61	130.85	80	52.7
23.55	133.84	82	51.2
24.59	131.77	86	51.3
25.78	118.32	92	52.7
26.58	114.62	95	52.0
27.53	117.89	97	49.8
28.61	119.30	94	50.0

Table 1. Summary of data for mud-cake-build-up test 51294MCB. Run time is in hours; drip time is in seconds. Temperature is in degrees farenheit. Pressure is in pounds per square inch.

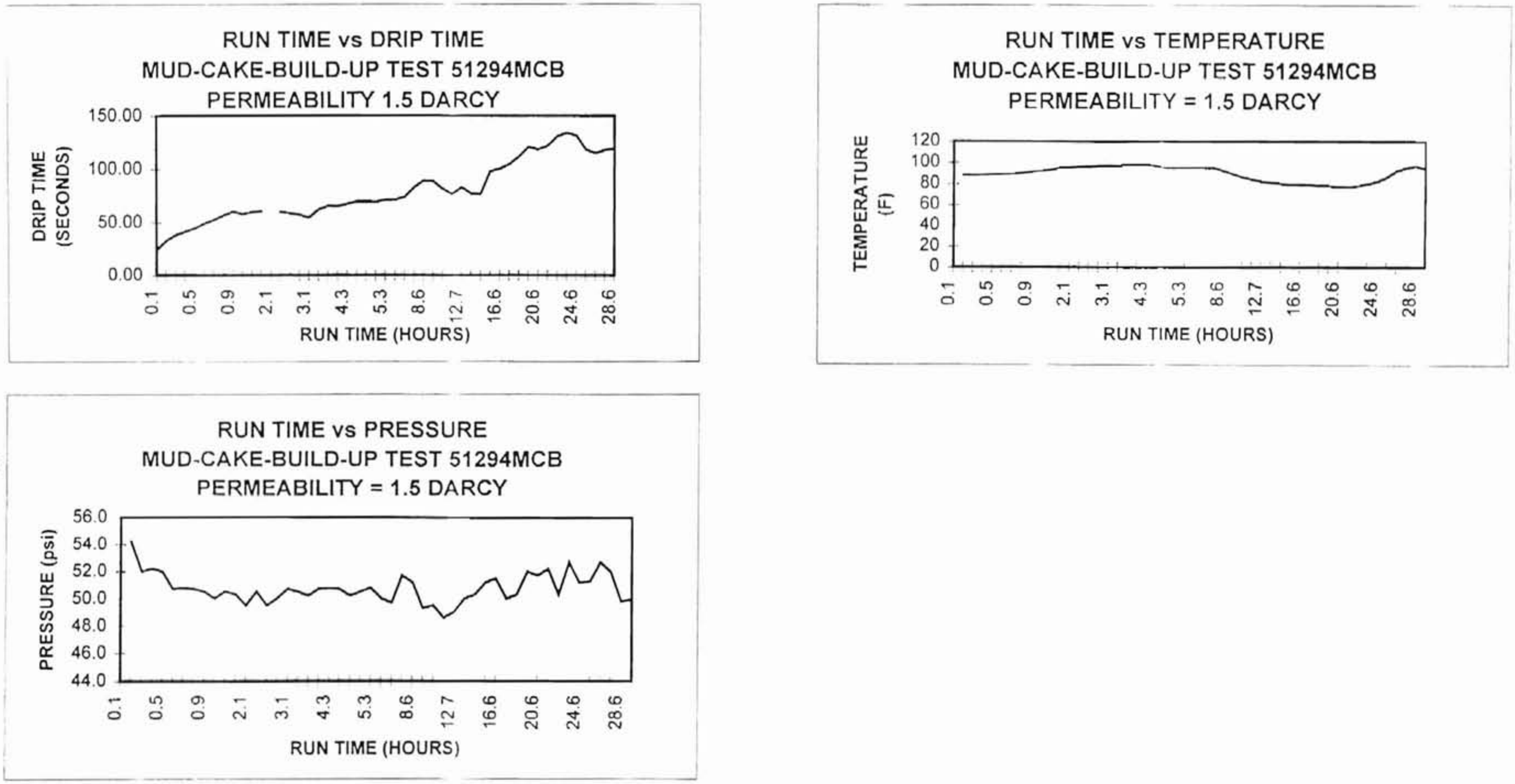


Figure 15. Graph of summary of data for mud-cake-build-up test 51294MCCB. Run time is in hours. Drip time is in seconds. Temperature is in degrees farenheit. Pressure is in pounds per square inch.

However, no apparent correlation exists between direction of variation in temperature and time between drips.

Time between drips started at about 23 seconds and increased to more than 56 seconds between drips after about 1 hour. The increased time between drips indicates that mud filter cake was being built successfully. As run-time increased, filter cake on the core became thicker and the solids in the filter cake packed tighter and tighter, a valid inference drawn from the general increase in time-between-drips. The period between drips was reduced on several occasions: first after 1.81 hours, then at 2.66 through 3.05 hours, at 4.06 hours, and at 12.65 hours into the test (Table 1 and Figure 15). On the average, the time between drips increased through the mud-cake buildup test. The data show no anomalous variations in temperature or pressure that would explain the events when the time between drips was reduced. The conclusion drawn from the data is that the core would continue to seal-off as test time continued and the core would eventually have a negligible amount of filtrate water drip through it.

The test denoted 51395INS.PRM is the *in-situ* portion of 51294MCB; it was run immediately after the mud-cake build-up test (each *in-situ* test was run immediately after the mud-cake build-up test of each core). The test was conducted on May 13, 1995. Tabulated data and the graph for 51395INS.PRM are shown as Figure 16 and Table 2. The graph and tabulated data show that the time between drips began at 91 seconds. The time between drips increased with minor instances of regression to 86.9 hours, then the time between drips began to increase and decrease significantly. However, a curve representing average period-between-drips would still have been on an upward trend.

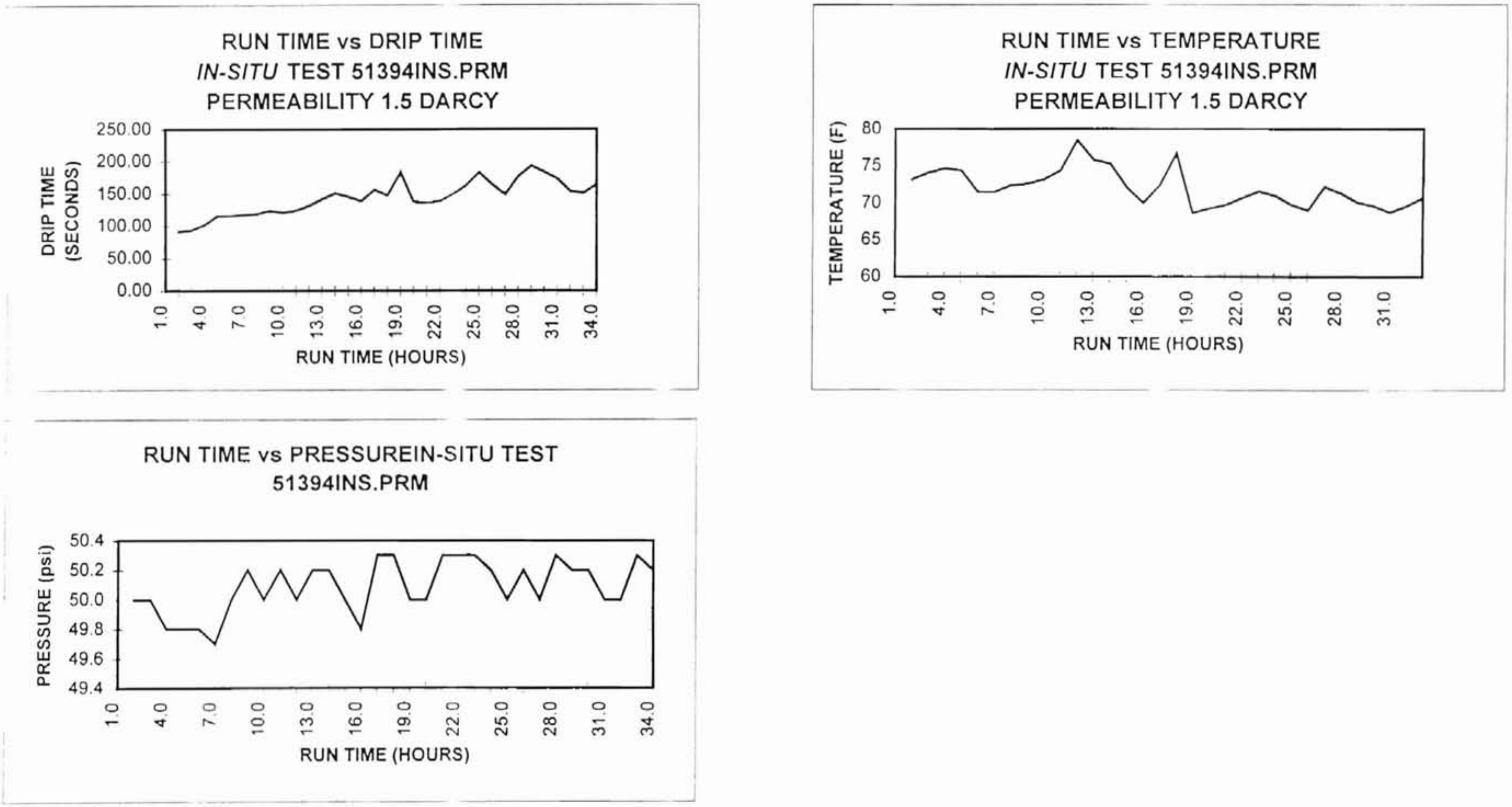


Figure 16. Graph of summary of data for *in-situ* test 51394INS.PRM. Run time is in hours. Drip time is in seconds. Temperature is in degrees Farenheit. Pressure is in pounds per square inch.

Run Time	Drip Time	Mud Temp.	Pressure
0.06111	91.14		50.0
0.35000	93.56	73.2	50.0
1.92500	101.68	74.1	49.8
6.16944	115.69	74.7	49.8
6.97222	115.67	74.4	49.8
13.93060	117.07	71.5	49.7
15.33330	118.07	71.5	50.0
16.98580	123.19	72.4	50.2
17.56670	120.49	72.6	50.0
18.40830	123.69	73.2	50.2
20.54440	131.10	74.4	50.0
23.61670	141.06	78.5	50.2
30.00000	150.79	75.8	50.2
30.70560	145.10	75.3	50.0
48.01000	138.40	72.1	49.8
64.75830	155.97	70.0	50.3
66.33610	147.42	72.4	50.3
78.70560	182.75	70.7	50.0
86.96110	137.41	68.6	50.0
87.64720	135.45	69.2	50.3
88.07500	138.47	69.7	50.3
88.67220	149.46	70.6	50.3
89.10830	162.25	71.5	50.2
90.11940	182.76	70.9	50.0
90.59440	163.96	69.7	50.2
91.08220	148.45	68.9	50.0
92.43610	176.50	72.1	50.3
93.11640	192.56	71.2	50.2
93.63670	183.20	70.0	50.2
94.13000	172.66	69.5	50.0
94.62940	153.76	68.6	50.0
95 07580	150.76	69.5	50.3
95.54920	164.09	70.6	50.2

Table 2. Summary of data *in-situ* test 51397INS.PRM. Run time is in hours; drip-time is in seconds. Temperature is in degrees Farenheit. Pressure in in pounds per square inch.

Pressure was steady throughout the test, staying within a few tenths of 50 psi. Temperature ranged from 68.6°F to 78.5°F. Consequently, variation of temperature and pressure were not considered to be the cause of the drip-period fluctuations in the later stages of the *in-situ* test. When these data were entered into the regression program and time-between-drips was predicted at the ends of one year, five years, ten years, and twenty years, the drip-periods increased to about 7 hours, 12 hours, 24 hours, and 49 hours respectively (Table 3). The data indicate that if this core were to have remained at these conditions, it would have continued to be sealed.

Experiment 51894.PRM was a mud-cake build-up test on a synthetic core with permeability of 1.0 darcy. This test was run on May 18, 1993. Table 4 and Figure show that temperature of the mud followed the general pattern as that of test 51394.INS.PRM, discussed above. The maximal temperature of 102°F occurred 4.3 hours into the test. The minimal temperature of 70°F occurred first at 18.6 hours into the test. However, periods between drips did not increase at a general steady rate. In fact, the only steady increases in drip-periods were near the beginning and the end of the test; moreover, drip-periods varied significantly during the last two hours of the test. Pressure was nearly constant at about 50 psi. Minimal pressure occurred 1.1 hours into the test; maximal pressure of 52.9 psi developed 4.3 hours into the test. Figure 17 shows that the drip-period increased during these two large fluctuations in pressure. After about 6 hours, pressure varied less, but drip-periods varied from about 28 seconds to about 67 seconds. Additionally, Figure 17 shows rather long intervals of decrease in drip-periods. However, variation of pressure was not considered to be the reason for variation in drip-

B = Constant	23.6137
Std Err of Y Est	16.5668
R Squared	0.14247
No. of Observations	20
Degrees of Freedom	18
M = X Coefficient(s)	0.37313
Std. Err of Coef.	0.21577

Drip time vs. extrapolated run time.
Y = MX + B

Run Time = X = 1 year.
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
1	365	24	23.6137	0.37313	23413.7	6.50379

Run Time = X = 5 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
5	365	24	23.6137	0.37313	43736.7	12.1491

Run Time = X = 10 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
10	365	24	23.6137	0.37313	87536.7	24.3158

Run Time = X = 20 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
20	365	24	23.6137	0.37313	175137	48.6491

Table 3. Summary of regression output, test 51394INS.PRM

Run Time	Drip Time	Mud Temp.	Pressure
0.19250	26.25	84	52.2
0.70333	39.45	89	48.8
1.16972	39.14	93	47.8
1.71111	36.51	96	52.0
2.17472	43.21	97	49.5
2.68333	41.96	99	51.0
3.18806	44.22	100	49.7
3.66389	42.72	100	51.9
4.33333	43.73	102	52.9
4.69806	48.59	101	48.1
5.14222	49.25	101	48.0
5.81972	32.03	100	50.0
5.67250	32.16	100	52.0
6.70278	32.53	99	50.0
7.70528	34.79	96	49.3
8.80639	33.56	91	49.3
9.67417	30.48	86	51.3
10.68670	31.74	83	50.2
11.68890	41.66	80	52.2
12.66330	47.10	78	50.3
13.88890	34.29	76	50.8
14.67220	33.17	75	49.0
15.67190	28.81	73	49.0
16.70190	27.83	72	49.0
17.68530	28.16	71	50.2
18.67610	27.59	70	51.9
19.67690	29.69	70	51.3
20.68610	33.24	72	50.0
21.68890	38.48	76	49.0
22.66390	51.71	80	50.5
23.68530	59.31	82	51.5
24.69640	67.41	87	49.3
25.69580	56.74	92	49.5
26.67780	59.48	97	48.3

Table 4. Summary of data for mud-cake-build-up test 51894MCB. Run time is in hours; drip time is in seconds. Temperature is in degrees Farenheit. Pressure is in pounds per square inch.

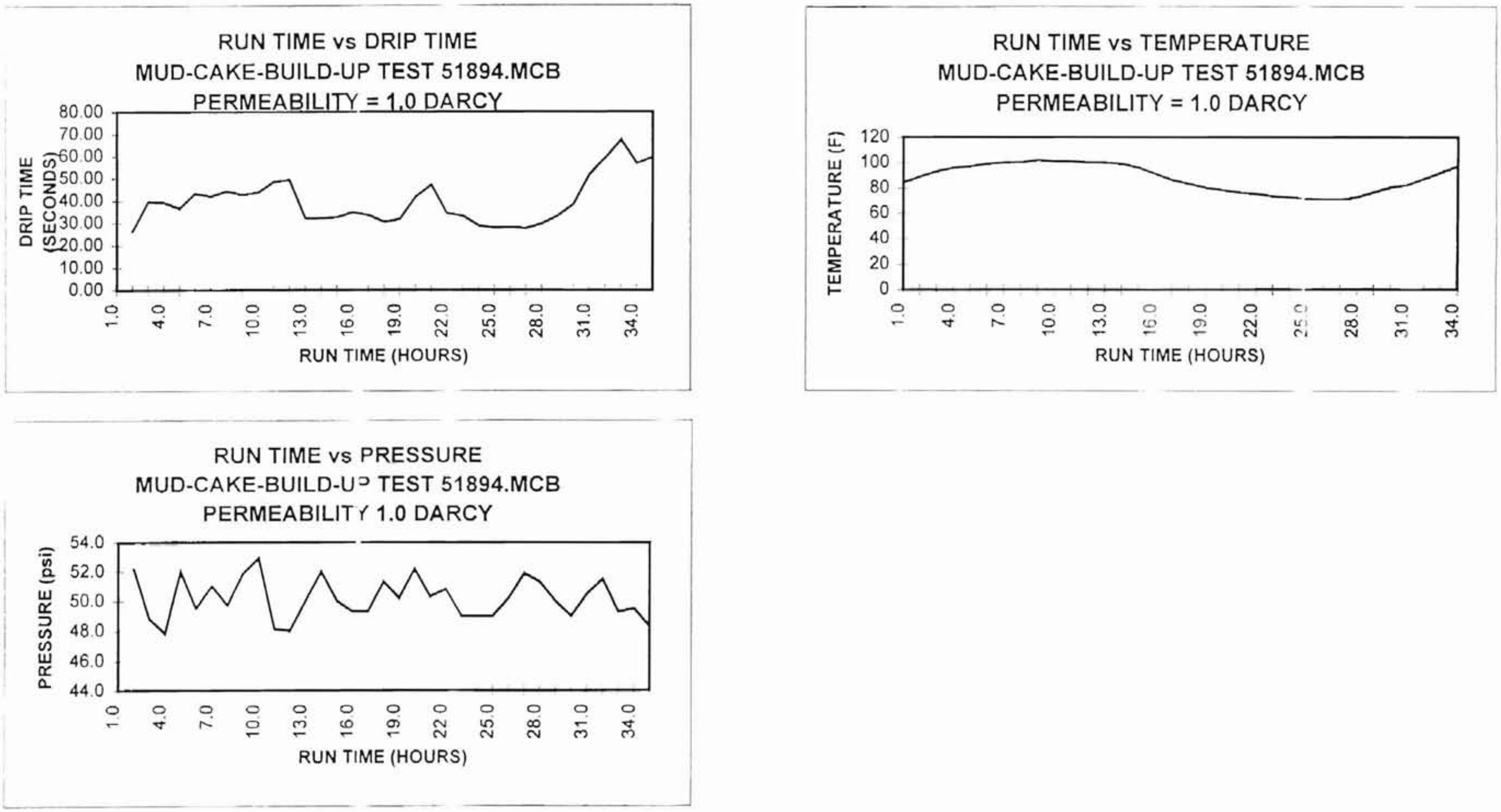


Figure 17. Graph of summary of data for mud-cake-build-up test 51894.MCB. Run time is in hours. Drip time is in seconds. Temperature is in degrees Farenheit. Pressure is in pounds per square inch.

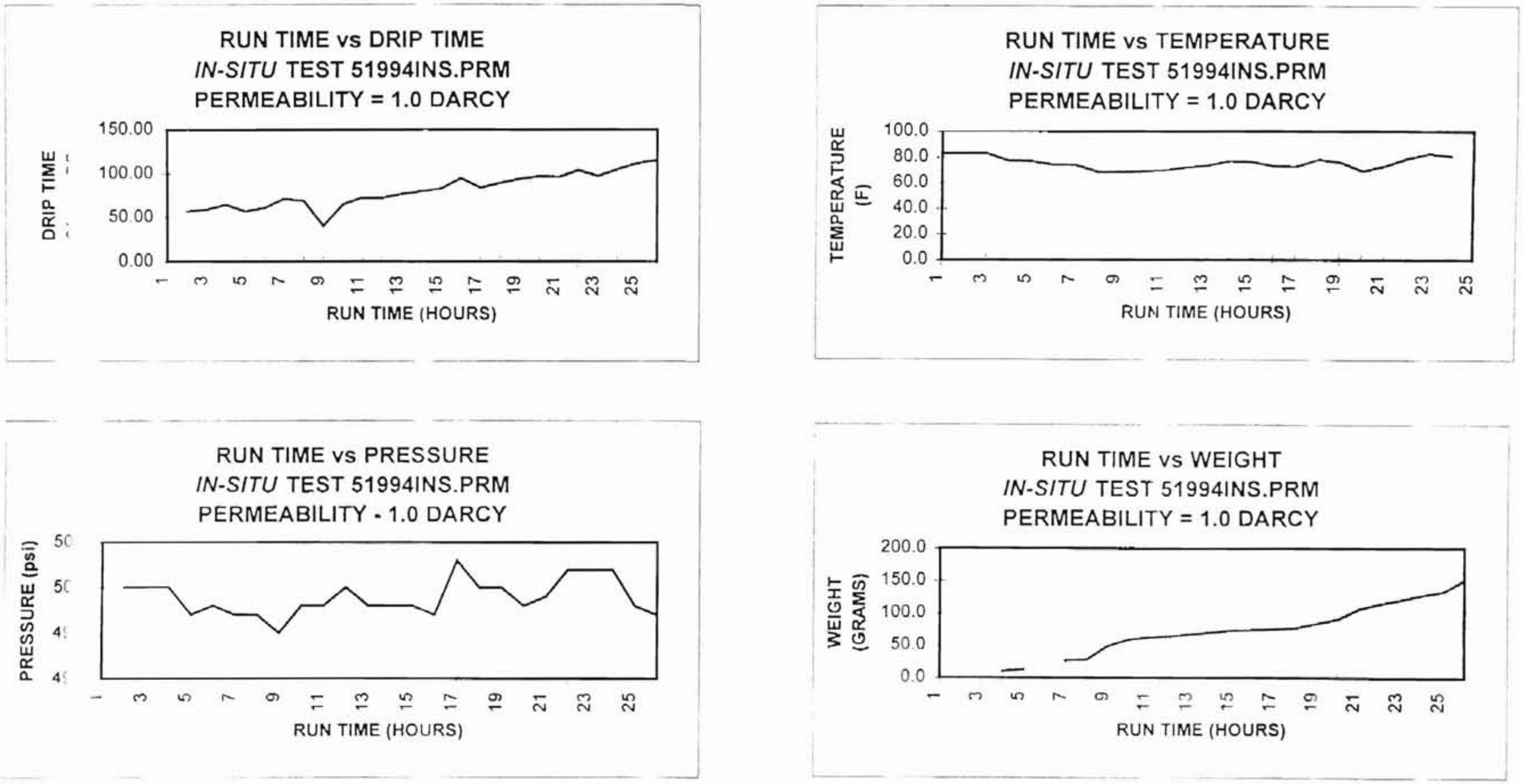
periods. One possible explanation for decrease in drip-periods was leakage between the core and the rubber core-holder. If mud particles were to bridge over a apace that was leaking between the core and the core holder, then break-through before re-sealing the space, then drip-periods surely would vary.

The *in-situ* portion of the 51894.MCB test was run immediately after the mud-cake build-up test. A scale was placed under the beaker for the filtrate water to drip into. Cumulative weight of the collected water in the beaker was plotted with run time, drip time, temperature and pressure (Table 5 and Figure 18). Drip-periods increased, on average, throughout the test except for one major decrease, which occurred at about 14.7 hours into the test. The period decreased abruptly from 68.49 seconds between drips to 40.04 seconds between drips. This decrease in time between drips was neither caused by nor correlated with fluctuation in pressure, because pressure remained very close to 50 psi throughout the test. Furthermore, the temperature remained between 68.0°F and 82.8°F. Figure 18 shows that weight on the scale increased almost linearly throughout the test except for one change in slope of the line, which developed between about 18 and 24 hours. At the end of the test the time between drips had increased to 115.49 seconds. Moreover, the test data indicate that if the test were to have continued, the core would have continued to be sealed.

Time between drips predicted by regression analysis at the end of one year, five years, ten years, and twenty years increased from about 2 hours, to about 9, 18, and 37 hours respectively (Table 6).

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.75833	56.62	82.5	50.0	
1.76389	58.47	82.5	50.0	
3.04444	64.25	82.8	50.0	10.2
4.04167	56.76	77.3	49.7	12.6
5.06806	60.42	76.7	49.8	
8.59722	70.99	74.1	49.7	27.0
8.92778	68.49	73.8	49.7	27.9
14.77390	40.04	68.6	49.5	48.6
17.13890	64.51	68.0	49.8	58.9
18.30000	72.40	68.9	49.8	62.3
19.01390	72.33	69.7	50.0	64.3
20.06580	76.46	71.8	49.8	67.2
21.08720	79.63	73.5	49.8	69.8
22.71110	82.63	77.0	49.8	73.4
23.04720	94.74	76.4	49.7	73.9
24.09940	83.75	72.9	50.3	75.3
24.97000	89.05	72.6	50.0	76.9
28.36670	94.16	78.2	50.0	83.9
32.02920	97.09	75.8	49.8	90.7
39.81500	96.12	68.9	49.9	105.8
44.22610	103.69	72.9	50.2	114.5
47.31810	97.27	79.0	50.2	120.3
51.25890	105.04	82.8	50.2	127.4
54.42060	111.95	80.8	49.8	132.6
65.60390	115.49		49.7	150.6

Table 5. Summary of data for *in-situ* test 51994INS.PRM. Run time is drip time is in seconds. Temperature is in degrees Farenheit. Pressure i pounds per square inch. Weight is in grams.


RUN TIME vs DRIP TIME
IN-SITU TEST 51994INS.PRM
PERMEABILITY = 1.0 DARCY

RUN TIME vs TEMPERATURE
IN-SITU TEST 51994INS.PRM
PERMEABILITY = 1.0 DARCY

RUN TIME vs PRESSURE
IN-SITU TEST 51994INS.PRM
PERMEABILITY - 1.0 DARCY

RUN TIME vs WEIGHT
IN-SITU TEST 51994INS.PRM
PERMEABILITY = 1.0 DARCY

Figure 18. Graphs of summary data *in-situ* test 51994INS.PRM. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

During the mud-cake-buildup test of May 25, 1994, sealing of the artificial core plug began immediately and continued for about 2 hours (Figure 19). Then drip-periods decreased slightly but remained about the same for approximately 8 more hours; afterward, time between drips decreased, indicating that the core had begun to transmit mud filtrate at greater rates. Times between drips increased from 18.81 seconds at 20 hours into the test to 26.52 seconds when the test ended at about 25 hours (Table 7). At the end of the test, the drip-periods had not slowed to 41.1 seconds between drips, the rate that occurred at 1.9 minutes into the test. Figure 19 indicates that pressure was maintained very near 50 psi. Therefore, the effect of variation in pressure is dismissed as an explanation for the decline in drip-period after 10 hours.

Because the mud pump and holding tank were outdoors, temperature of the mud rose in response to outside temperature. Figure 19 shows that mud temperature rose from about 80° F to more than 100° F. Did the temperature fluctuation affect time between drips? In Figure 19, curves of drip-period and mud-temperature are of strongly similar shapes. But what effect of temperature would logically tend to be expected? As the artificial sandstone increased in temperature, the resin cement would tend to expand, an effect which should tend to reduce permeability and cause time between drips to increase; but just the opposite happened. Did resin swell with temperature, push the sand grains apart, and increase permeability? If temperature caused the core to transmit mud filtrate faster, then all the cores should have shown the same effect; however, this was not observed. However, in this case the configurations of drip-period and temperature curves are so similar (Figure 19) that the hypothesis of a cause-and-effect relationship cannot be

B = Constant	-89.9191
Std Err of Y Est	5.18526
R Squared	0.87528
No. of Observations	10
Degrees of Freedom	8
M = X Coefficient(s)	1.31973
Std. Err of Coef.	0.17613

Drip time vs. extrapolated run time.
$Y = MX + B$

Run Time = X = 1 year.
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
1	365	24	-89.9191	1.31973	6705.85	1.86274

Run Time = X = 5 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
5	365	24	-89.9191	1.31973	33256.7	9.23797

Run Time = X = 10 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
10	365	24	-89.9191	1.31973	66445.3	18.457

Run Time = X = 20 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
20	365	24	-89.9191	1.31973	132822	36.8951
						(1.5373 Days)

Run Time = X = 50 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
50	365	24	-89.9191	1.31973	339154	92.2094
						(3.84206 Days)

Table 6. Summary of regression output, test 51994.INS

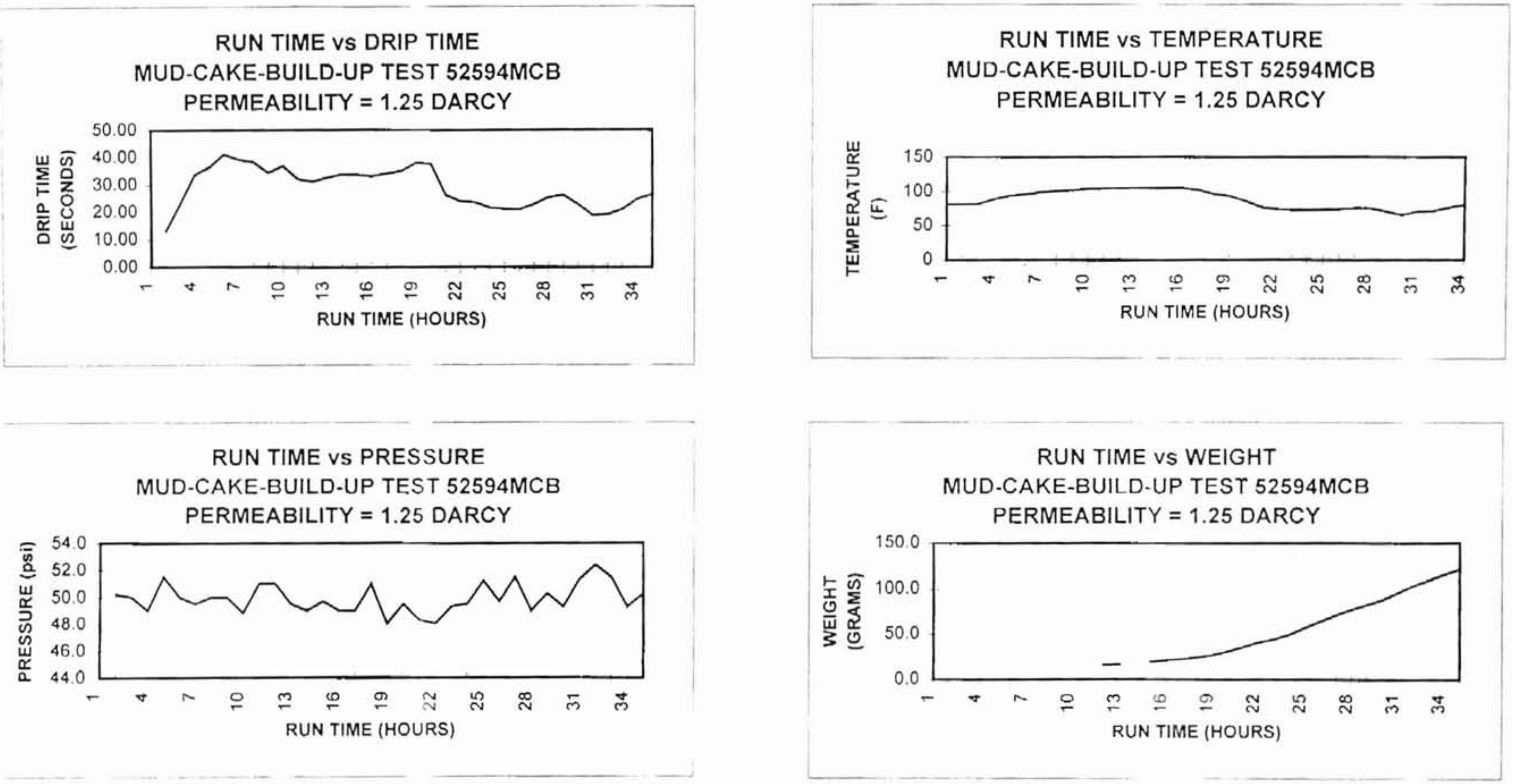


Figure 19. Graphs of summary data mud-cake-build-up test 52594MCB. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.00800	13.12	81	50.2	
0.26278	23.16	81	50.0	
0.76944	33.76	82	49.0	
1.08056	36.38	89	51.5	
1.85833	41.10	94	50.0	
2.37472	39.26	96	49.5	
2.82306	38.27	99	50.0	
3.50694	34.43	101	50.0	
3.81361	36.98	102	48.8	
4.31250	32.14	104	51.0	
5.11670	31.09	105	51.0	15.9
5.35000	32.67	106	49.5	16.6
5.81444	33.79	106	49.0	
6.31361	33.74	105	49.7	19.4
6.89444	33.16	105	49.0	21.0
7.30556	34.13	105	49.0	22.2
8.14167	35.06	102	51.0	24.2
8.83278	38.02	96	48.0	26.6
10.07500	37.63	93	49.5	30.8
11.26670	26.20	86	48.3	35.6
12.19170	24.05	77	48.0	40.7
12.75000	23.60	74	49.3	44.0
13.66390	21.56	73	49.5	49.7
14.54170	21.24	73	51.2	57.1
15.80830	20.95	73	49.7	64.2
16.88690	22.94	74	51.5	71.2
17.81940	25.50	75	49.0	76.9
18.81060	26.20	75	50.3	82.4
19.80970	22.81	70	49.3	87.7
20.80560	18.81	65	51.3	95.6
21.84080	19.16	70	52.4	103.2
22.75110	21.13	71	51.5	109.2
23.80560	24.84	76	49.3	115.6
24.81250	26.52	80	50.3	121.4

Table 7. Summary of data for mud-cake-build-up test 52594MCB. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

dismissed.

The *in-situ* portion of the May 25 test was run on May 26, 1994. Although the mud-cake buildup test did not result in sealing of the core, the *in-situ* test showed evidence of plugging of the core. The test lasted 50 hours (Table 8). The time between drips increased from about 27 seconds to about 44 seconds. However, the drip-period line (Figure 20) suggests that mud cake might not have sealed the core. (Note the small positive slope of the curve, and the suggestion of a negative slope near the right-hand end to the curve.) Because pressure was nearly uniform at 50 psi, variation in drip-period is not attributed to variation in pressure.

Temperature ranged only about 10° F (Table 8); fluids were confined to the laboratory throughout the test. Thus, effects of temperature were diminished beyond recognition or were none at all. Regression analysis (Table 9) predicted drip-periods of 1, 5, 10, 20, and 51 hours between drips at intervals of 1, 5, 10, 20, and 50 years, respectively.

The mud-cake build-up test 6194 MCB. evaluated 0.5-darcy synthetic sandstone. The test was run on June 1, 1994. As shown in Figure 21 and Table 10 initial temperature was 100°F; the maximum was 104°F after 2.7 hours. This occurred when the outside air temperature was at its peak for the day. Temperature declined as evening approached. The minimal temperature was 75°F, just before sunrise, after which the temperature rose (Table 10). Drip time began at 23.2 seconds between drips. Drip-periods increased for the first 6.3 hours. Thereafter, drip-periods started decreasing.

Time between drips varied, but tended to decrease, until 20 hours had elapsed (Table 10; Figure 21). Figure 21 shows that as temperature increased, the time between drips increased; when the temperature decreased, time between drips decreased. The drip-period curve is not as "smooth" as the temperature curve, but the two curves have the same general shape (Figure 21). Did temperature increase cause resin in the core to expand and thereby reduce the permeability? If expansion of resin is the reason for this behavior, then continued elevation of temperatures should have had a more definite effect on drip-periods. Mud-cake build-up tests 51894.PRM and 52594.MCB indicate similar relationships between temperature and drip-period; however, all three tests were under operating temperatures that were relatively the same. Without a means of heating the circulation drilling mud it was not possible to test the explanation that increase of temperature causes reduction of permeability. This problem remains to be solved.

Pressure ranged only about 5 psi, and departed only 3.9 psi from the 50 psi of the experiment's design (Figure 21).

Results of the *in-situ* portion of the 6194. MCB test are shown as Table 11, Figure 22, and Table 12. Drip-periods increased almost constantly throughout the *in-situ* test (Table 11). However, in two instances -- one at 18.78 hours and one at 26.8 hours -- drip-period declined (Table 11). Pressure and temperature varied only slightly during the anomaly at 18.78 hours into the test; consequently, change in pressure and temperature are considered not to have caused the slightly increased drip rate for this period. However the anomaly at 26.8 hours occurred when temperature declined from 70.9°F at 25.78 hours to 69.5°F at 26.8 hours, then rose to 76.4°F at 42.7 hours (Table

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.10000	26.71	81.4	50.5	1.0
0.94000	26.90	81.1	50.3	5.2
1.25583	27.69	82.0	50.5	6.8
3.12472	31.72	84.0	50.3	15.2
8.57083	30.37	79.0	50.2	36.5
10.45500	26.25	76.7	50.0	45.4
18.26670	32.17	73.0	50.0	85.4
19.25000	32.08	70.9	50.2	89.6
20.24720	34.41	71.5	50.2	93.6
21.96110	35.83	74.1	50.2	100.4
24.47610	28.87	69.2	50.0	109.8
25.27220	34.30	69.5	50.0	113.1
27.27780	38.06	74.1	49.8	120.8
43.26390	44.16	72.4	49.8	174.4
45.50560	44.16	74.1	50.0	181.1
50.23560	42.98	80.8	50.0	195.1

Table 8. Summary of data for *in-situ* test 52694INS.PRM. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

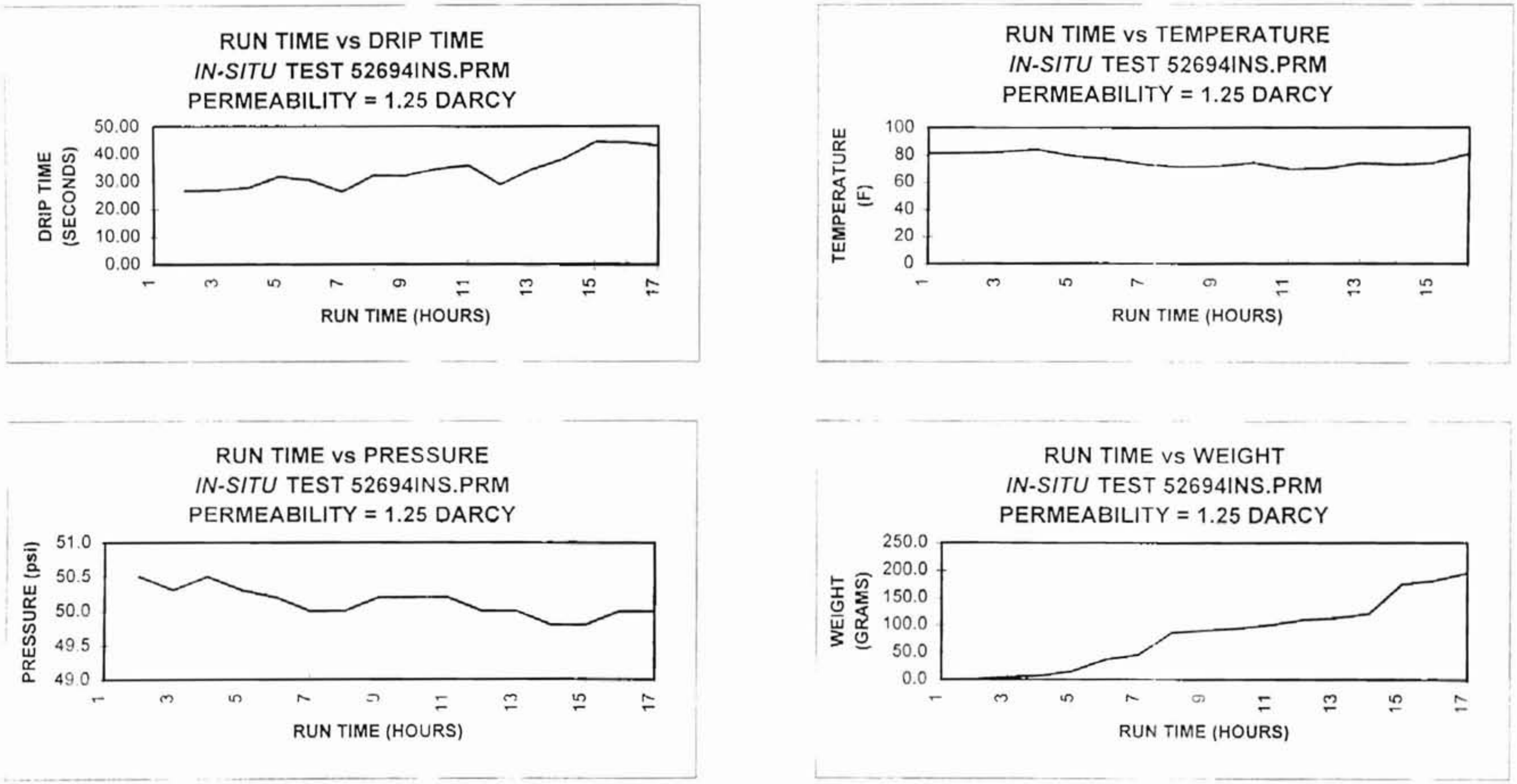


Figure 20. Graphs of summary data *in-situ* test 52694INS.PRM. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

B = Constant	-60.165
Std Err of Y Est	6.74698
R Squared	0.83366
No. of Observations	16
Degrees of Freedom	14
M = X Coefficient(s)	2.39042
Std. Err of Coef.	0.28537

Drip time vs. extrapolated run time.
$Y = MX + B$

Run Time = X = 1 year.
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M		
1	365	24	-60.165	2.39042	3689.8	1.02494

Run Time = X = 5 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
5	365	24	-60.165	2.39042	18348.3	5.09675

Run Time = X = 10 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
10	365	24	-60.165	2.39042	36671.5	10.1865

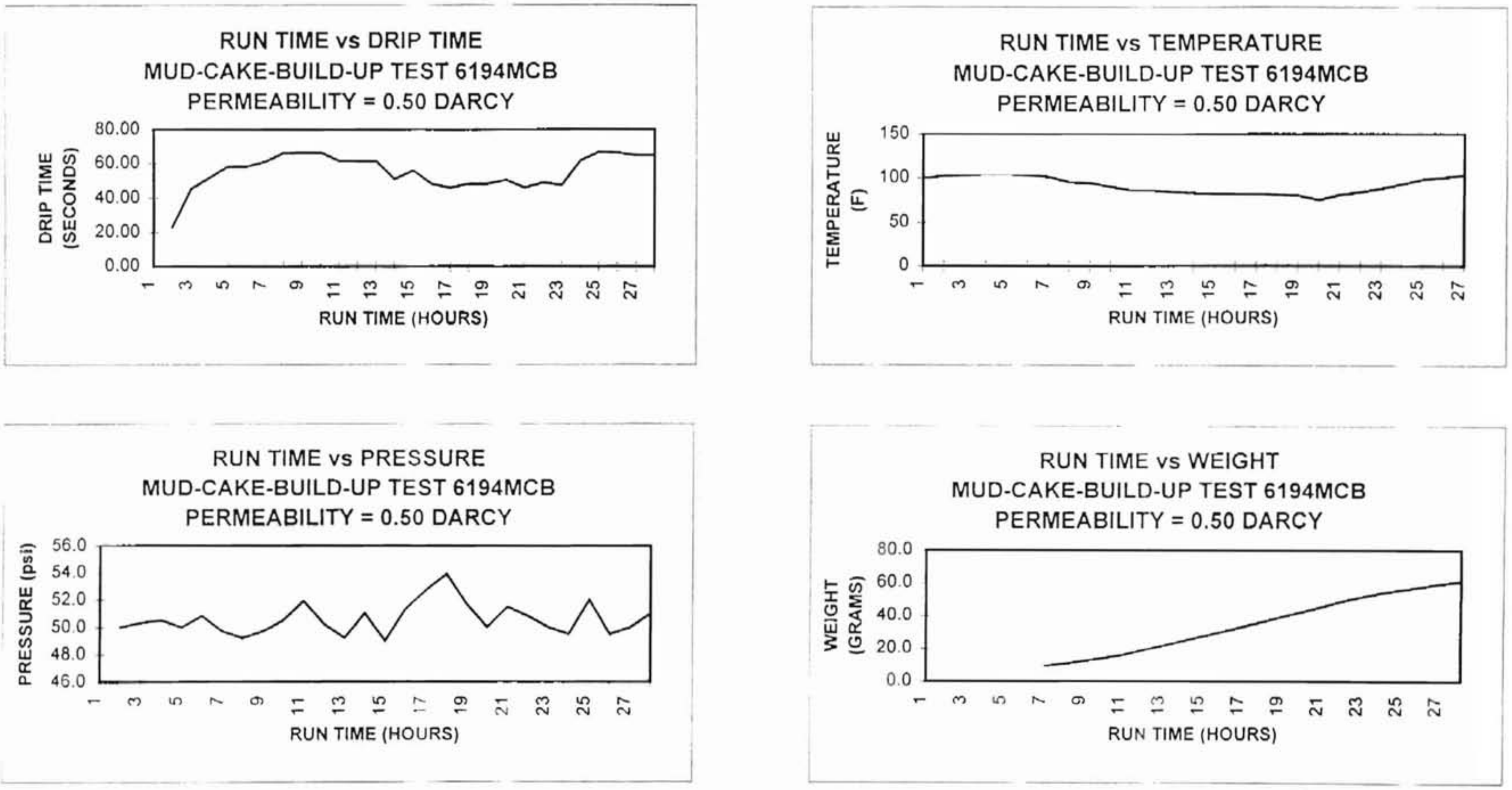
Run Time = X = 20 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
20	365	24	-60.165	2.39042	73317.8	20.366
					(0.84859 Days)	

Run Time = X = 50 years
$X = (Y - B) / M$

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
50	365	24	-60.165	2.39042	183257	50.9046
					(2.12103 Days)	

Table 9. Summary of regression output, test 52694INS.PRM.



RUN TIME vs DRIP TIME
MUD-CAKE-BUILD-UP TEST 6194MCB
PERMEABILITY = 0.50 DARCY

RUN TIME vs TEMPERATURE
MUD-CAKE-BUILD-UP TEST 6194MCB
PERMEABILITY = 0.50 DARCY

RUN TIME vs PRESSURE
MUD-CAKE-BUILD-UP TEST 6194MCB
PERMEABILITY = 0.50 DARCY

RUN TIME vs WEIGHT
MUD-CAKE-BUILD-UP TEST 6194MCB
PERMEABILITY = 0.50 DARCY

Figure 21. Graphs of summary data mud-cake-build-up test 6194MCB. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.12083	23.16	100	50.0	
0.75889	45.17	102	50.3	
1.22639	51.54	103	50.5	
2.31000	58.09	104	50.0	7.4
2.74778	58.06	104	50.8	
3.43056	60.86	103	49.7	9.4
4.24444	66.02	101	49.2	10.8
5.24722	66.23	95	49.7	12.5
6.33333	66.25	94	50.5	14.3
7.23611	61.47	90	51.9	16.2
8.43611	61.16	86	50.2	19.2
9.38056	61.43	86	49.2	21.8
10.30000	50.85	84	51.0	24.6
11.41940	55.86	83	49.0	27.5
12.31110	48.07	82	51.3	30.2
13.28360	45.77	82	52.7	33.2
14.25060	48.15	82	53.9	36.3
15.24440	48.13	81	51.7	39.3
16.22780	50.39	80	50.0	42.3
17.24170	46.02	75	51.5	45.6
18.21940	48.88	81	50.8	48.8
19.27780	47.45	84	50	51.5
20.31110	61.70	88	49.5	54.0
21.21580	66.63	93	52.0	55.8
22.24080	66.34	98	49.5	57.5
23.20280	64.81	100	50.0	59.4
24.02610	64.84	103	51.0	60.6

Table 10. Summary of data for mud-cake-build-up test 6194MCB. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

11). Fluctuation of temperature is a possible cause of the decreased rate of dripping. Cumulative weight on the OHAUS scale increased almost linearly from 18 hours to about 27 hours into the test (Figure 22).

Regression analysis of the data from the *in-situ* test (Table 12) indicated that the core would continue to seal and that time between drips would increase from 2.8 hours between drips at the end of one year, to 55.2 hours or 2.3 days between drips after 20 years. The "R- squared" value was 0.96 (Table 12) which indicates that the data fit the straight-line regression model well.

Mud-cake-build-up test 6794MCB.PRM was run using a core plug taken from the Pony Creek Sandstone (a natural rock). The core had a permeability of 1.25 darcys, which is the same as that of synthetic rock evaluated by the 52594MCB test. The graph of data from 6794MCB (Figure 23) shows evidence of strong increase in time between drips for the first ten hours; however, thereafter time between drips stopped increasing and fluctuated between 199 and 249 seconds (Table 13). Temperature declined through the first 21 hours but rose during the final two hours of the test; however, variation of temperature showed no obvious relationship to variation of drip-period (Figure 23). Pressure was effectively constant (within 2 psi of the intended pressure of 50 psi). Fluctuation in the time between drips is judged to not have been caused by the fluctuations of pressure. (The curve representing increase in weight is suppressed in Figure 23, because of the scale required to accommodate the larger numbers in times between drips.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.08056	23.90	76.700	49.800	0.900
1.03750	24.98	74.400	49.800	6.800
1.78333	26.92	72.600	49.500	11.200
6.10556	35.60	79.000	49.700	32.900
17.90560	41.20	76.100	49.500	83.400
18.77780	38.84	75.800	50.200	87.100
19.86110	41.08	76.100	50.300	91.600
20.75280	41.33	76.700	50.300	95.100
21.85830	43.64	78.200	50.200	99.300
23.77500	48.73	73.800	50.300	104.500
24.82530	52.22	71.800	50.300	107.100
25.77800	53.38	70.900	50.300	109.300
26.79890	50.63	69.500	50.000	111.400
42.71110	74.59	76.400	50.200	147.500
53.32780	82.13	66.500	49.500	159.300

Table 11. Summary of data for *in-situ* test 6294INS.PRM. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

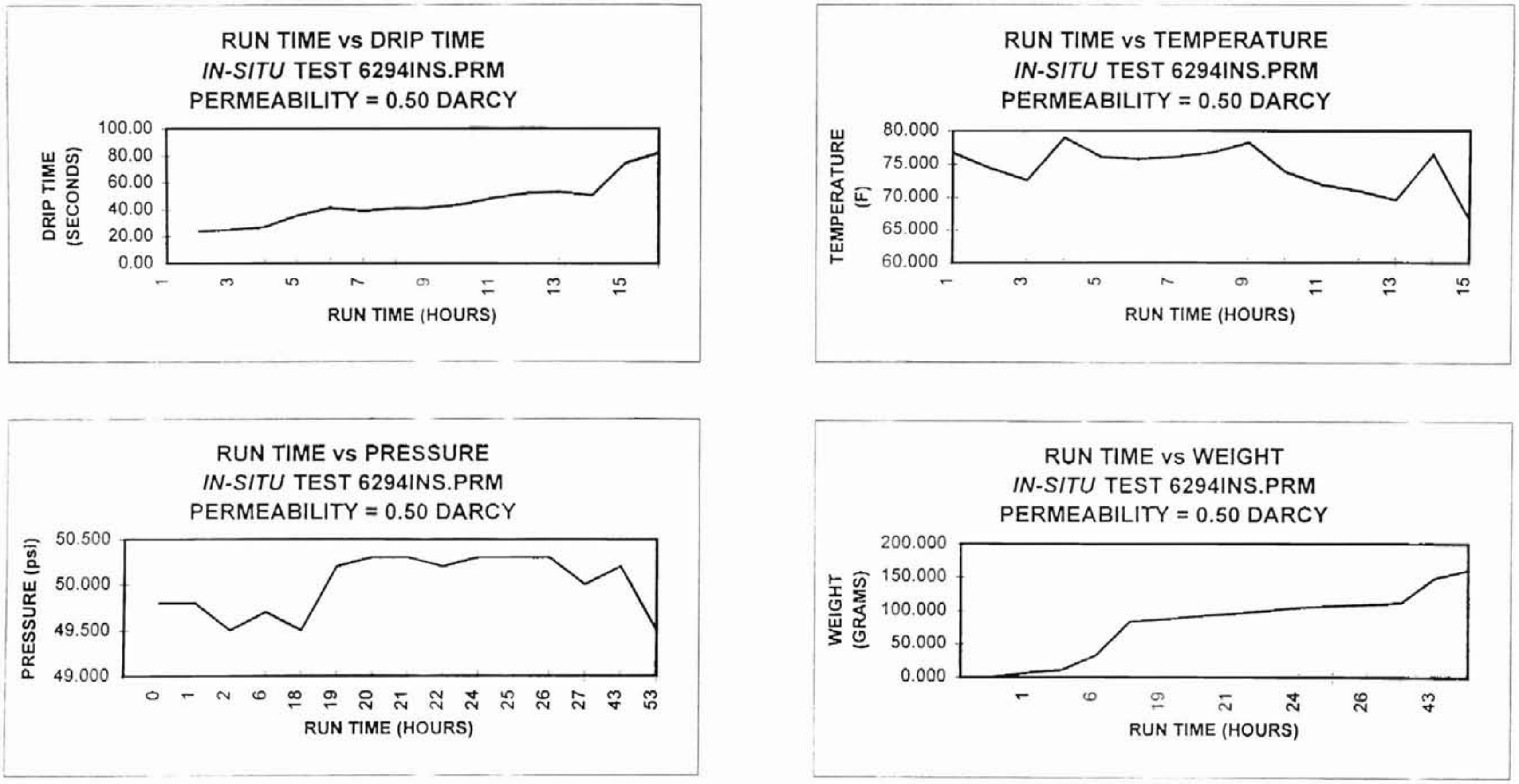


Figure 22. Graphs of summary data *in-situ* test 6294INS.PRM. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

B = Constant	-19.495
Std Err of Y Est	2.9839
R Squared	0.96184
No. of Observations	15
Degrees of Freedom	13
M = X Coefficient(s)	0.8802
Std. Err of Coef.	0.04863

Drip time vs. extrapolated run time.

Y = MX + B

Run Time = X = 1 year.

X = (Y - B) / M

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**	**X**	
1	365	24	-19.495	0.8802	9947.46	2.77068

Run Time = X = 5 years

X = (Y - B) / M

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**	**X**	
5	365	24	-19.495	0.8802	49783.7	13.8288

Run Time = X = 10 years

X = (Y - B) / M

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**	**X**	
10	365	24	-19.495	0.8802	99545.3	27.6515

Run Time = X = 20 years

X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
20	365	24	-19.495	0.8802	199068	55.2968
					(2.30403 Days)	

Table 12. Summary of regression output, test 6294INS.PRM.

The *in-situ* portion of the 6794MCB test was 6894.INS.PRM. The time between drips began at 162 seconds on the *in-situ* test (Table 14), built to 202 seconds at 16.6 hours, and declined for approximatel the next 4 hours. Drip-periods increased between 20 hours and 24 hours of testing, then decreased for the remainder of the test (Table 14 and Figure 24). Temperature and pressure varied slightly; temperature ranged from 74.4°F to 77.9°F and pressure ranged between 49.7 and 50.3 psi (Table 14). Variation of temperature and pressure probably had no effect on the times between dips.

Results of regression analysis (Table 15) suggest that the core would have continued to be sealed and that time between drips would have increased to 5.7 hours between drips at the end of one year, and 4.7 days between drips at the end of 20 years. However, the "R- squared" measurement of these data was 0.697, which indicates that the behavior of the sandstone was not approximated well by the regression model. Figure 24 shows data scattered so as to not "appear" as being distinctly linear. Accordingly, the prediction of drip-periods over long periods of time should be considered with appropriate questioning.

The mud-cake-build-up test 62194MCB was evaluation of a core from the Hughes Creek Sandstone (a natural rock). The core plug permeability of 0.3 darcy was the lowest permeability of any sample tested. Figure 25 shows evidence of abrupt increase in time between drips for the first two hours of the test. Thereafter, increase in time between drips was slower, until 17.7 hours (Table 16), when time between drips was 122 seconds. Thereafter time between drips decreased throughout the remainder of the test. At the end of 23.8 hours, drip-period had decreased to 88.7 seconds (Table 16).

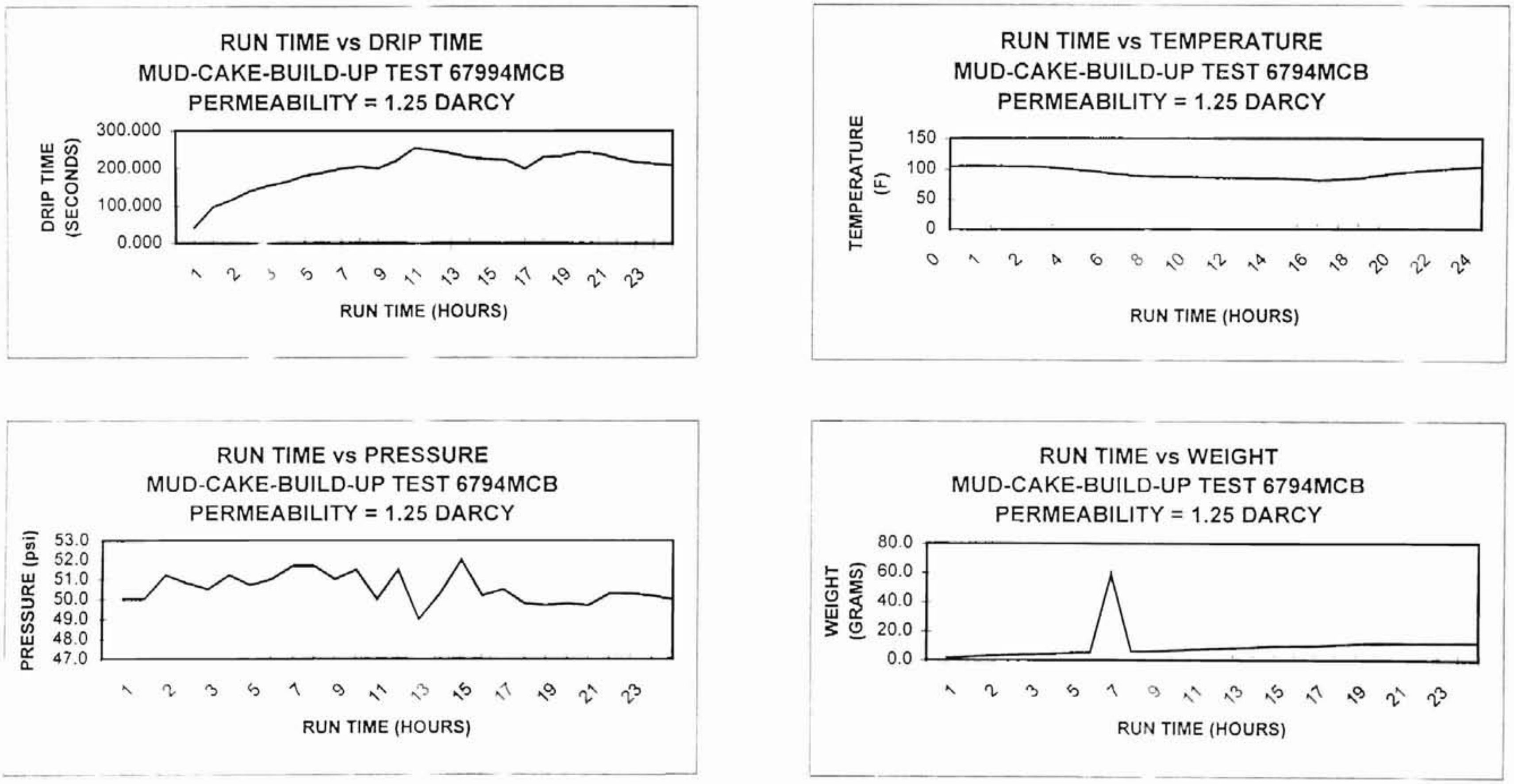


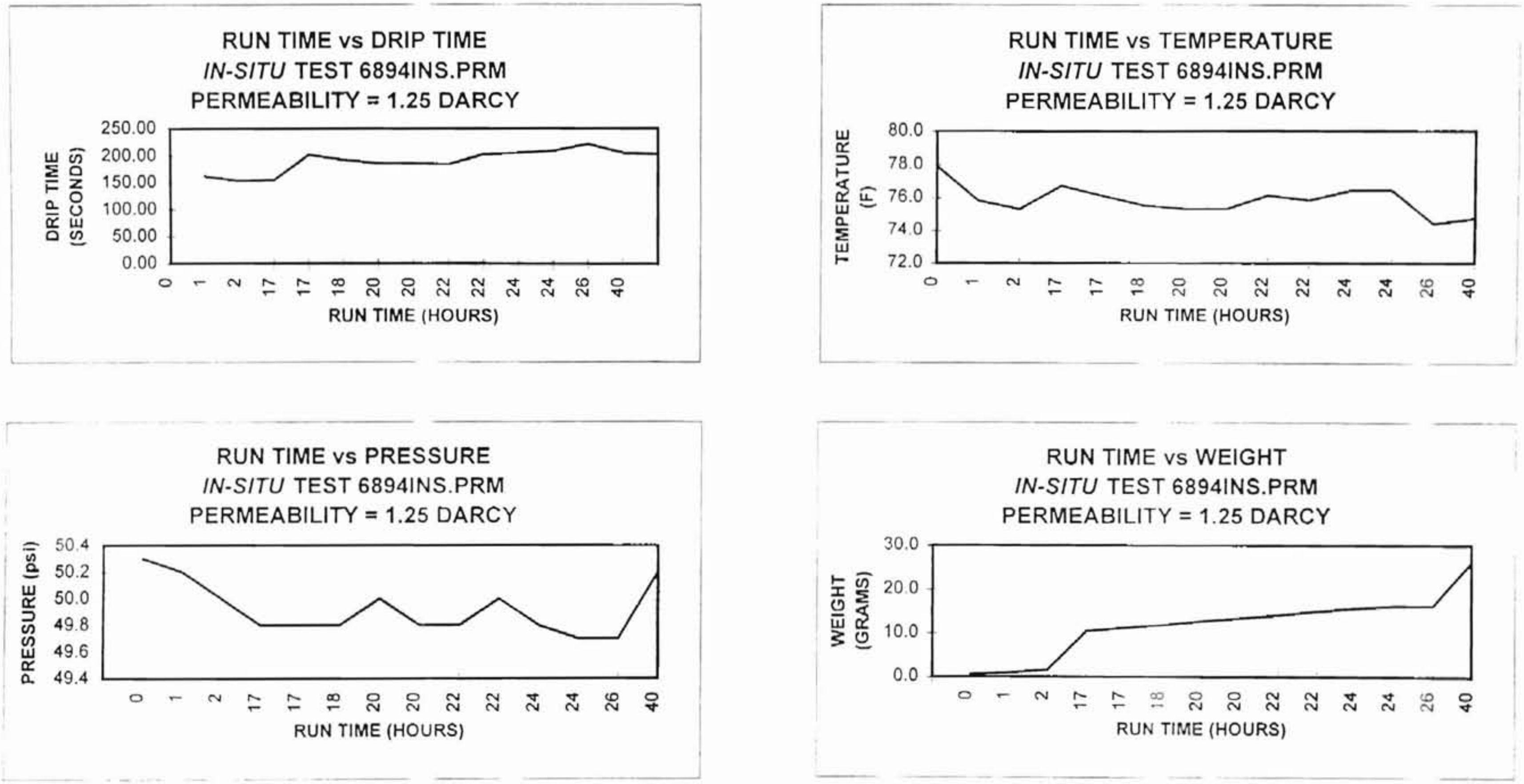
Figure 23. Graphs of summary data mud-cake-build-up test 6794MCB. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.22333	41.910	104	50.0	1.3
0.85000	96.440	105	50.0	2.4
1.32500	114.810	105	51.2	3.0
1.88056	138.740	104	50.8	3.5
2.44167	153.270	104	50.5	3.9
2.88056	163.350	102	51.2	4.2
4.02500	180.270	99	50.7	4.8
4.93889	188.490	96	51.0	5.1
5.85833	199.520	92	51.7	58.5
6.92778	205.230	89	51.7	5.9
8.23889	200.180	87	51.0	6.3
8.81111	220.660	87	51.5	6.7
9.71111	253.820	86	50.0	7.3
10.91389	248.630	85	51.5	8.0
11.72222	239.860	85	49.0	8.4
12.69444	228.630	84	50.3	8.8
13.75972	224.840	84	52.0	9.5
14.77222	221.800	83	50.2	9.8
15.75556	198.950	81	50.5	9.8
16.80278	229.950	82	49.8	10.7
17.76389	233.140	84	49.7	11.4
18.84167	244.174	89	49.8	11.7
19.84167	239.020	93	49.7	11.7
20.74444	226.840	96	50.3	11.7
21.91667	216.950	99	50.3	11.8
22.74444	213.200	101	50.2	11.9
23.80556	208.840	103	50.0	12.0

Table 13. Summary of data for mud-cake-build-up test 6794MCB. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.46944	161.83	77.9	50.3	0.6
0.91250	153.30	75.8	50.2	1.0
1.52778	154.84	75.3	50.0	1.6
16.61110	202.03	76.7	49.8	10.5
17.49170	192.27	76.1	49.8	11.2
18.48190	185.81	75.5	49.8	11.9
19.55560	185.96	75.3	50.0	12.7
20.32780	184.46	75.3	49.8	13.4
21.75560	202.95	76 1	49.8	14 1
22.49440	205.56	75.8	50.0	15.0
23.58890	209.23	76.4	49.8	15.7
24.47220	221.98	76.4	49.7	16.2
25.93720	205.84	74.4	49.7	16.2
40.38610	202.99	74.7	50.2	26.1

Table 14. Summary of data for *in-situ* test 6894INS.PRM. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.



RUN TIME vs DRIP TIME
IN-SITU TEST 6894INS.PRM
PERMEABILITY = 1.25 DARCY

RUN TIME vs TEMPERATURE
IN-SITU TEST 6894INS.PRM
PERMEABILITY = 1.25 DARCY

RUN TIME vs PRESSURE
IN-SITU TEST 6894INS.PRM
PERMEABILITY = 1.25 DARCY

RUN TIME vs WEIGHT
IN-SITU TEST 6894INS.PRM
PERMEABILITY = 1.25 DARCY

Figure 24. Graphs of summary data *in-situ* test 6894INS.PRM. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

B = Constant	-64.0034
Std Err of Y Est	6.23729
R Squared	0.69764
No. of Observations	14
Degrees of Freedom	12
M = X Coefficient(s)	0.43069
Std. Err of Coef.	0.08185

Drip time vs. extrapolater run time.
Y = MX + B

Run Time = X = 1 year.
X = (Y - B) / **M**

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**		
1	365	24	-64.0034	0.043069	20488.3	5.69119

Run Time = X = 5 years
X = (Y - B) / **M**

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**	**X**	
5	365	24	-64.0034	0.043069	101847	28.2908

Run Time = X = 10 years
X = (Y - B) / **M**

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**	**X**	
10	365	24	-64.0034	0.043069	203545	56.5404

Run Time = X = 20 years
X = (Y - **B**) / **M**

# of Years	**# of Days In One Year**	**# of Hours In One Day**	**Constant**	**X Coefficient**	**Drip Time (Seconds)**	**Drip Time (Hours)**
Years * Days * Hours = Y			**B**	**M**	**X**	
20	365	24	-64.0034	0.043069	406942	113.04
					(4.70998 Days)	

Table 15. Summary of regression output, test 6894INS.PRM

Temperature of the mud was 104°F at the start of the test, increased to 107°F at the end of the first 2.8 hours, decreased to 83°F at 16.8 hours, then rose to 107°F (Table 16). Because mud temperature was 107°F near the beginning and at the end of the test, and because drip-periods were different at these stages, the conclusion is drawn that variations of the temperature did not affect the times between drips. Pressure ranged between 47.5 and 53 psi, which indicates that the decrease in drip-periods was not an effect of increase in pressure. Loss of seal between the core and the rubber core-holder was suspected; however visual inspection of the core and holder produced no evidence of a broken seal.

The *in-situ* portion of the 62194MCB test was 62294INS.PRM. As the *in-situ* test proceeded, time between drips decreased for the first 1.2 hours of the test (Table 17), but then the trend reversed. Drip-periods lengthened, indicating that the core was sealing off. The core continued to seal for the first 19.2 hours of the test, wherein the time between drips increased to 104 seconds between drips. Figure 26 and Table 17 show two data points where time between drips decreased (1.2 and 3.8 hours); the drip-periods were longer time throughout the remainder of the test, with the exception of one point at 41.4 hours. Time between drips decreased abruptly to 94.2 seconds, but increased to 104.9 seconds between drips at the end of the test, at 42.3 hours.

Mud temperature at the start of the test was 89.5°F, but decreased to 61°F after 17.3 hours. Temperature fluctuated within the range of 15°F throughout the remainder of the test. Although the temperature and drip curves have similar shapes (Figure 26)

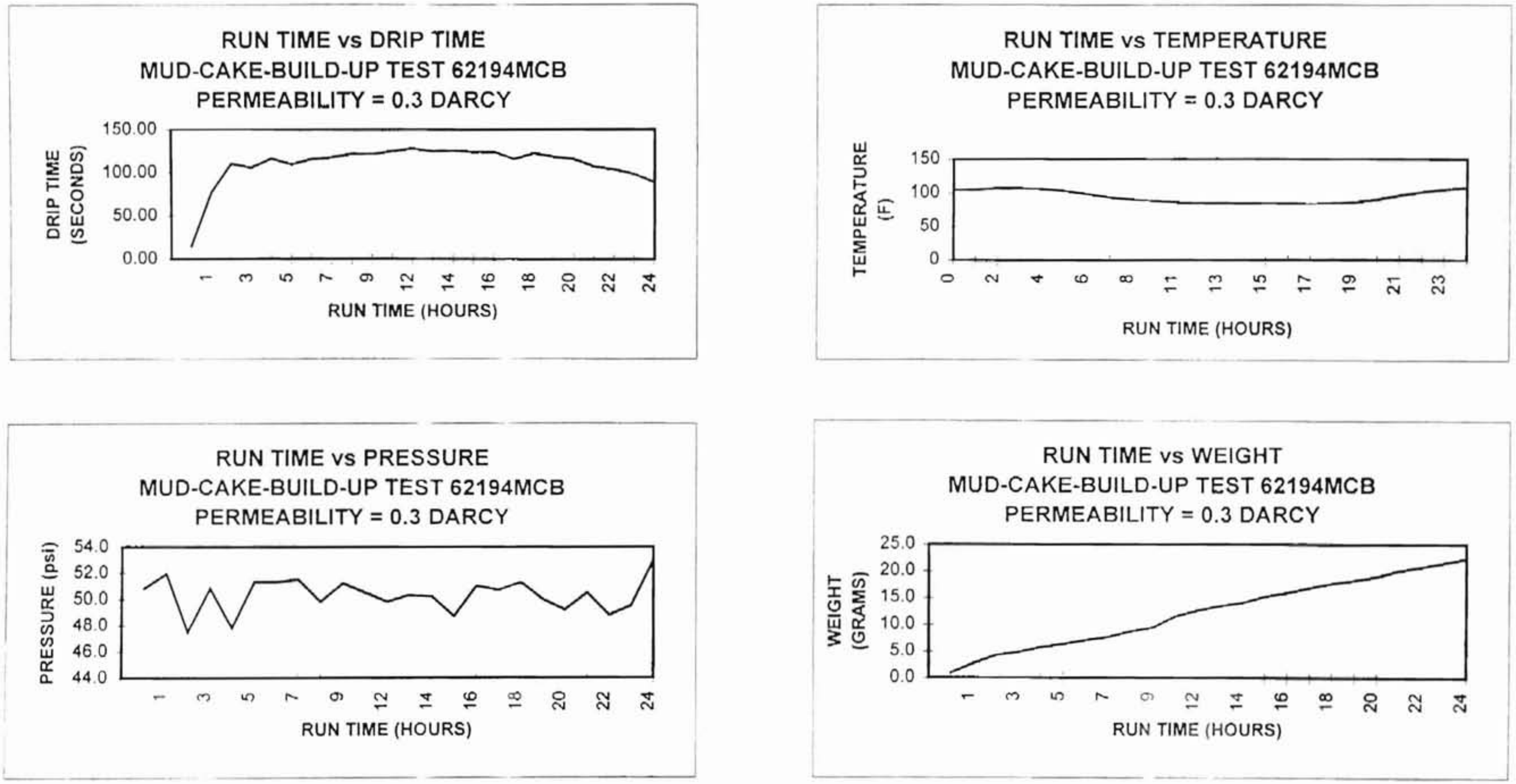


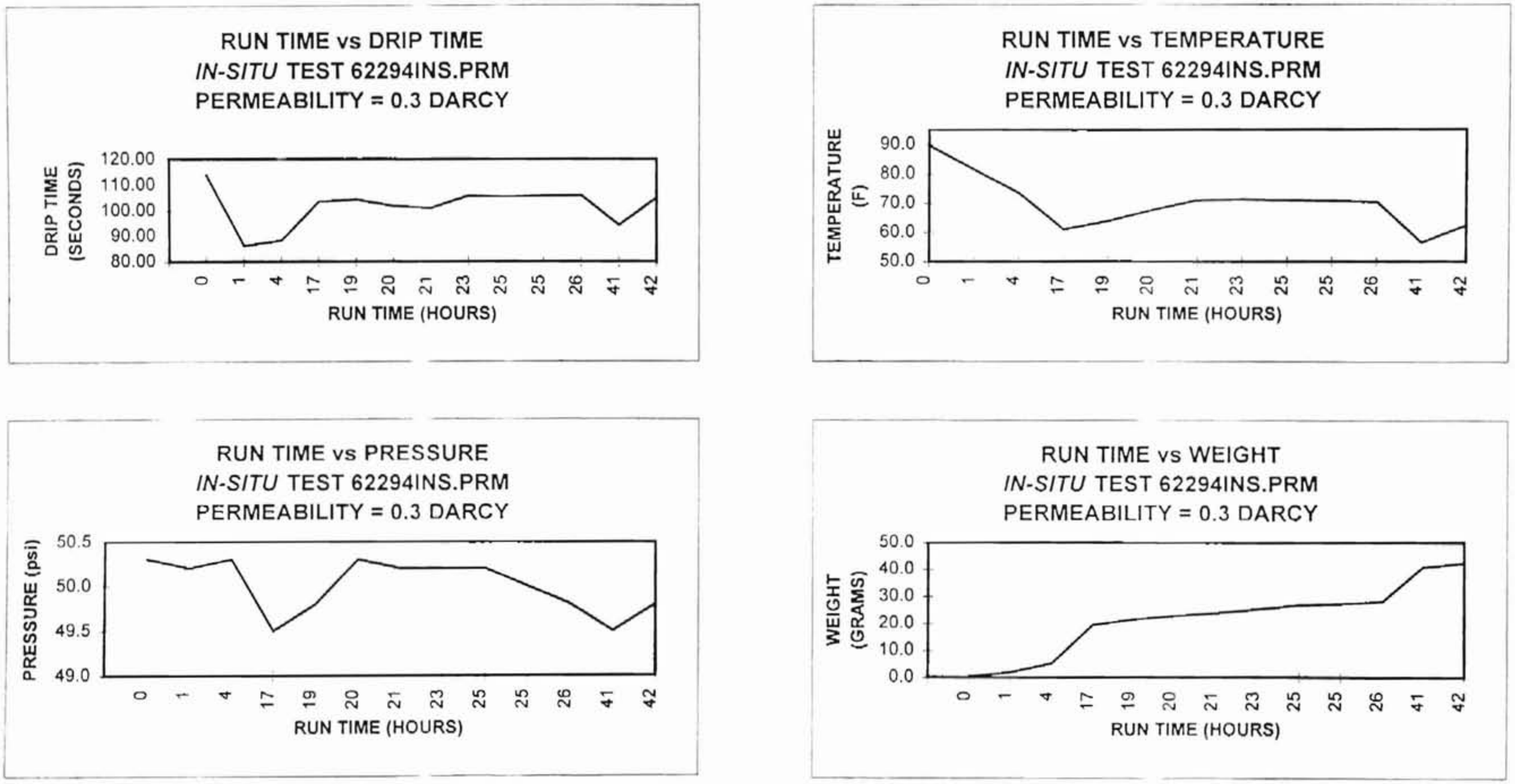
Figure 25. Graphs of summary data mud-cake-build-up test 62194MCB. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.10000	15.11	104	50.8	0.9
0.83472	76.82	105	51.9	2.7
2.18611	109.95	107	47.5	4.2
2.81667	105.64	107	50.8	4.8
3.96667	116.25	106	47.8	5.7
4.90417	109.51	103	51.3	6.3
5.91806	115.67	98	51.3	7.0
6.84167	117.56	93	51.5	7.6
7.85556	121.78	90	49.8	8.7
8.86944	121.38	88	51.2	9.4
11.00560	124.59	86	50.5	11.5
12.13330	127.81	85	49.8	12.6
12.88610	124.13	85	50.3	13.4
14.05280	125.45	84	50.2	14.0
14.74720	123.55	85	48.7	15.2
15.82220	124.04	84	51.0	15.9
16.85000	115.75	83	50.7	16.8
17.75830	122.24	84	51.3	17.6
18.69440	118.40	86	50.0	18.2
19.81810	115.83	90	49.2	18.9
20.85830	106.79	96	50.5	20.0
21.83750	103.56	101	48.8	20.7
22.86110	98.34	105	49.5	21.5
23.76390	88.68	107	53.0	22.3

Table 16. Summary of data for mud-cake-build-up test 62194MCB. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

Run Time	Drip Time	Mud Temp.	Pressure	Weight
0.05083	113.72	89.5	50.3	0.3
1.23028	86.11	81.4	50.2	1.9
3.77778	88.27	73.5	50.3	5.1
17.29440	103.37	61.0	49.5	19.3
19.17500	104.28	63.9	49.8	21.4
20.13890	101.70	67.7	50.3	22.7
20.93060	100.88	70.9	50.2	23.8
22.75830	105.76	71.2	50.2	25.2
24.61670	105.14	70.9	50.2	26.7
25.23060	105.81	70.6	50.0	27.2
26.14440	105.95	70.3	49.8	27.9
41.45000	94.25	56.4	49.5	40.8
42.33330	104.91	62.2	49.8	42.2

Table 17. Summary of data for *in-situ* test 62294INS.PRM. Run time is in hours; drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.



RUN TIME vs DRIP TIME
IN-SITU TEST 62294INS.PRM
PERMEABILITY = 0.3 DARCY

RUN TIME vs TEMPERATURE
IN-SITU TEST 62294INS.PRM
PERMEABILITY = 0.3 DARCY

RUN TIME vs PRESSURE
IN-SITU TEST 62294INS.PRM
PERMEABILITY = 0.3 DARCY

RUN TIME vs WEIGHT
IN-SITU TEST 62294INS.PRM
PERMEABILITY = 0.3 DARCY

Figure 26. Graphs of summary data *in-situ* test 62294INS.PRM. Run time is in hours. Drip time is in seconds. Temperature is in degrees Fahrenheit. Pressure is in pounds per square inch. Weight is in grams.

temperature of mud is not believed to have been the cause of variation in drip-periods. The third, fourth and fifth data points on the graph trend in opposite directions. However, the temperature and drip curves of the last half of the test do seem to covary. do seem to reflect each other. If mud temperature were directly affecting the drip times, the two curves should be consistently of similar trend, or of opposite trend, but not both. As in other *in-situ tests*, pressure was steady at about 50 psi, neither less than 49.5 psi nor more than 50.3 psi. Variation of pressure is not regarded as the cause of variation in drip-periods.

Regression analysis of data yielded an "R-squared" value of 0.30, indicating that the regression model is inefficient as a predictor of drip-periods (Table 18). If the predictions were accepted, then after one year the time between drips would be 2.5 hours. As time progressed to 50 years the time between drips would increase to 5.3 days.

Conclusions

As mud temperature increased, drip-period tended to increase. This phenomenon occurred with all synthetic rock cores tested, except the core plug evaluated on May 12, 1994. Cores of natural sandstone did not show this characteristic. Perhaps the resin used to cement the sand grains in the synthetic sandstone expanded from increased temperature and thus reduced permeability.

Three mud-cake build-up tests had negative drip-period slopes entirely or partly -- synthetic rock with 1.25-darcy permeability, Pony Creek sandstone with 1.25-darcy permeability, and Hughes Creek sandstone with 0.3-darcy permeability (Figures 19, 23

B = Constant	-73.3864
Std Err of Y Est	10.64
R Squared	0.30325
No. of Observations	12
Degrees of Freedom	10
M = X Coefficient(s)	0.94968
Std. Err of Coef.	0.45521

Drip time vs. extrapolated run time.
Y = MX + B

Run Time = X = 1 year.
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M		
1	365	24	-73.3864	0.094968	9301.47	2.58374

Run Time = X = 5 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
5	365	24	-73.3864	0.094968	46198.3	12.8329

Run Time = X = 10 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
10	365	24	-73.3864	0.094968	92319.3	125.6442

Run Time = X = 20 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
20	365	24	-73.3864	0.094968	184561	51.267
					(2.13613 Days)	

Run Time = X = 50 years
X = (Y - B) / M

# of Years	# of Days In One Year	# of Hours In One Day	Constant	X Coefficient	Drip Time (Seconds)	Drip Time (Hours)
Years * Days * Hours = Y			B	M	X	
50	365	24	-73.3864	0.094968	461287	128.135
					(5.33897 Days)	

Table 18. Summary of regression output, test 62294INS.PRM.

and 25). Although graphs of the synthetic rock and the Pony Creek sandstone had negative drip-time slopes, the plotted data suggest that drip-intervals would vary with time, would remain within some range, but that the permeability would not be ended; nevertheless water loss would be controlled. However, the 0.3-darcy Hughes Creek sandstone was not as variable as were rocks of the other two mud-cake build-up tests with negative drip-period slopes. The Hughes Creek sandstone's mud-cake-build-up drip interval became more frequent after 15 hours, with no indication of slowing down. If a core plug were continuing to seal, then the slope of the drip-period curve would be positive (for example see Figure 15). Conversely, if the slope of the line were negative, then the core would not be sealing and would allow water to pass through the core faster and faster with time. Consequently, a regression equation with negative slope indicates that the core was not continuing to seal; it was being "broken through." None of the *in-situ* tests showed regression equations with negative slopes (see Tables 3, 6, 9, 12, 15 and 18; note the coefficients labelled "M"); therefore, during all *in-situ* tests the cores continued to be sealed with time.

Figures 19, 23, and 25 show that each core started plugging early in the test, but that the cores started transmitting drops faster after some elapse of time. This could have been caused by leakage between the core and the rubber core-holder; however, after each test, each core was removed from the core holder and inspected. No sign of leakage between any core and its rubber core-holder was observed. Furthermore, if a core had lost its seal, one would assume that the small annular space between the core and the holder would plug-off in the same manner as did pores in the core.

To gain a better understanding of the effectiveness of drilling mud as an oil-well plugging agent, mud-cake build-up tests and *in-situ* tests with an extremely long test periods should be run. Data that appear in this report were taken from tests run with mud-cake having been deposited on tops of cores. In an oil well, mud cake is built on the side wall of the well bore, making the mud cake susceptible to sliding. Tests with mud cake on vertical surfaces of rock with *in-situ* tests of several months duration may lead to better understanding of how well a mud-plugged oil well is sealed.

The principal hypothesis to be tested by this endeavor was 'Drilling mud in abandoned, properly plugged wells effectively sealing the boreholes, and if fluids injected into reservoirs at depth were to migrate up the boreholes of such abandoned wells, filter cake would prevent the passage of the fluids into other reservoirs.' Results of experiments described here (particularly results of the *in-situ* tests) indicate that is a positive pressure gradient exists, invasion of formations by water from boreholes may not be stopped, but probably would be diminished to levels that would not be harmful to freshwater aquifers.

SELECTED REFERENCES

Canter, L.W., 1984, The problem of abandoned wells ,in Fairchild, D.M., ed., Proceedings of the First National Conference on Abandoned Wells: Problems and Solutions: Environmental and Ground Water Institute, Univ. Okla., U.S. Environmental. Protection Agency, and National Water Well Assoc., p. 1-16 and 227-236.

U.S. Environmental Protection Agency, 1977., Impact of Abandoned Wells on Ground Water: EPA-600/3-77-095, Mar., Washington, D.C.

Wait, R.L. and McCollum, M.J., 1963., Contamination of fresh water aquifers through an unplugged oil test well in Glynn County, Georgia: Georgia Geological Survey Mineral Newsletter, v. 16, no. 3-4, p. 74-80.

Gatlin, Carl, 1960, Petroleum Engineering; Drilling and Well Completions: Prentice-Hall, Inc., p. 70-92.

Focht, W,1993,GEOL 5710 class notes, p.126-131.

Code Of Federal Regulation Parts 144-149.

APPENDIX A

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.

A Halliburton Company

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

VITA

Bill T. Novotny

Candidate for the Degree of
Master of Science

Thesis: EFFECTIVENESS OF DRILLING MUD AS A PLUGGING AGENT

Major Field: Environmental Science

Biographical:

Personal Data: Born in Chickasha, Oklahoma, August 23, 1955, the third child of Mr. and Mrs. Thomas W. Novotny.

Education: Graduated from Chickasha High School, Chickasha, Oklahoma, in May, 1974; received Bachelor of Science degree in Petroleum Engineering Technology from Oklahoma State University in May, 1984; Completed requirements for Master of Science degree at Oklahoma State University in July, 1998.

Professional Experience: The Wil-Mc Oil Corporation/Harbert Energy corporation, 1984-91; Production engineer, Managed over 300 oil and gas wells in Oklahoma, Texas, and New Mexico; Self employed and attended Graduate School at Oklahoma State University 1991-94; State of Oklahoma, 1994-95, Staff Hydrologist; Brown and Root Environmental Co., 1995 to present, State Manager.