THE DESIGN AND CONSTRUCTION OF AN ABSOLUTE PERMEAMETER TO MEASURE THE EFFECT OF ELEVATED TFERATURE ON THE ABSOLUTE PERMEABILITY TO DISTILLED WATER OF UNCONSOLIDATED SAND CORES

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By
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To Michal

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Many thanks are due to my friends and the department staff who helped me finish this work.

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Abstract

A new absolute permeameter was designed and constructed in order to investigate the effect of temperature on absolute permeability. The main goal of this work was to improve the controls of the permeameter and to investigate the flow of distilled water through unconsolidated silica sand cores. No significant change in the absolute permeability with a change in temperature was observed. This result is different than results reported in previous work done at Stanford. It is believed that system problems, such as converging flow in the core plugs, caused the observation of permeability reduction with an increase in temperature.

This work will be extended to consolidated sandstones and will aid in the design of relative permeability experiments.

Table of Contents

Table of Contents, cont.

Table of Contents, cont.

List of Illustrations

List of Tables

1. Introduction

Absolute permeability is an important parameter in the evaluation and performance of geothermal or hydrocarbon reservoirs. Primary production of oil and gas reservoirs does not change the temperature of the system. This is not the case in geothermal reservoirs or in many of the EOR* projects. In these reservoirs the temperatures of the formations change and, along with this, many of the formation properties change. Absolute permeability is an essential parameter and there is a great need to study the effect of temperature on absolute permeability.

A grid of experiments investigating the effect of temperature on absolute permeability has been carried out throughout the last decade. These experiments covered a range of rock types, fluids, confining pressures and several other system characteristics. It is evident that not all the results are in agreement. In some cases the observations in the laboratory yielded different interpretations by the researchers. Cassé (1974) interpreted a decrease of absolute permeability to distilled water of Berea sandstone with an increase in temperature as a temperature effect. Other observers, including Sydansk (1980) claim a permeability reduction is due to fines migration and not temperature effects.

Upon searching the literature, another disagreement surfaces that is somewhat easier to settle. There are different laboratory observations for the same experiments. Most of these disagreements can be settled by taking a close look at the "control" the experimenter has of the system. Runs have to be repeated with improved systems that will give maximum

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* EOR means "Enhanced Oil Recovery"

information about the parameters included in the experiment.

This is the point at which this work is introduced. Out of the grid of possible experiments, one configuration of rock, confining and pore pressures, and fluid was chosen. This work studied the effect of temperature on the absolute permeability to distilled water of unconsolidated sand cores. Work done at Stanford University, primarily by Cassé and Aruna (1976), produced a decrease in permeability with an increase in temperature. This decrease in permeability could not be explained by thermal expansion, porosity changes, or other explanations that were suggested, such as silica-water attraction. This work was set up to design and construct an absolute permeameter with improved system controls in order to take a close look at the change of permeability with temperature.

2. Apparatus Description

Figure 1 is a rough 60° axonometric view of the apparatus while Figure 2 is a schematic of the system. Later in this chapter all the components will be described in detail. Most of the equipment (air bath, recorders, pumps) was used in other experiments. The valves, the tubing, and the core holder are new.

2.1 Air Bath Set-up

Air Bath Specifications: "Blue M" by Blue M Electric Company, Blue Island, IL.

Model #: POM - 1406C-1
Serial #: CD - 10690
Line Voltage: 240V/1 PH/60 Hz
Temperature Range: To 343°C/650°F
Line Currents: L_1 - 40A, L_2 - 40A

The air bath houses the following:

- The heating coils before the core
- The core holder
- Four (4) thermocouples
- Flow lines
- Pressure recording lines
- Confining pressure line

To minimize vibration the core holder hangs from the ceiling of the bath and sits on a rubber cushion. The tubing in the bath is tied together in various places with thermal tape to further dampen vibration.

The bath maintains a .constant temperature. It has a variable' heating capacity and small temperature oscillations. The temperature bath will heat up an increment of 100°F in about fifteen minutes. The core heating requires about two to three hours.

The bath is equipped with a vent which makes controlled cooling possible. The bath had 100 hours of use when this project began. The project used another 370 hours.

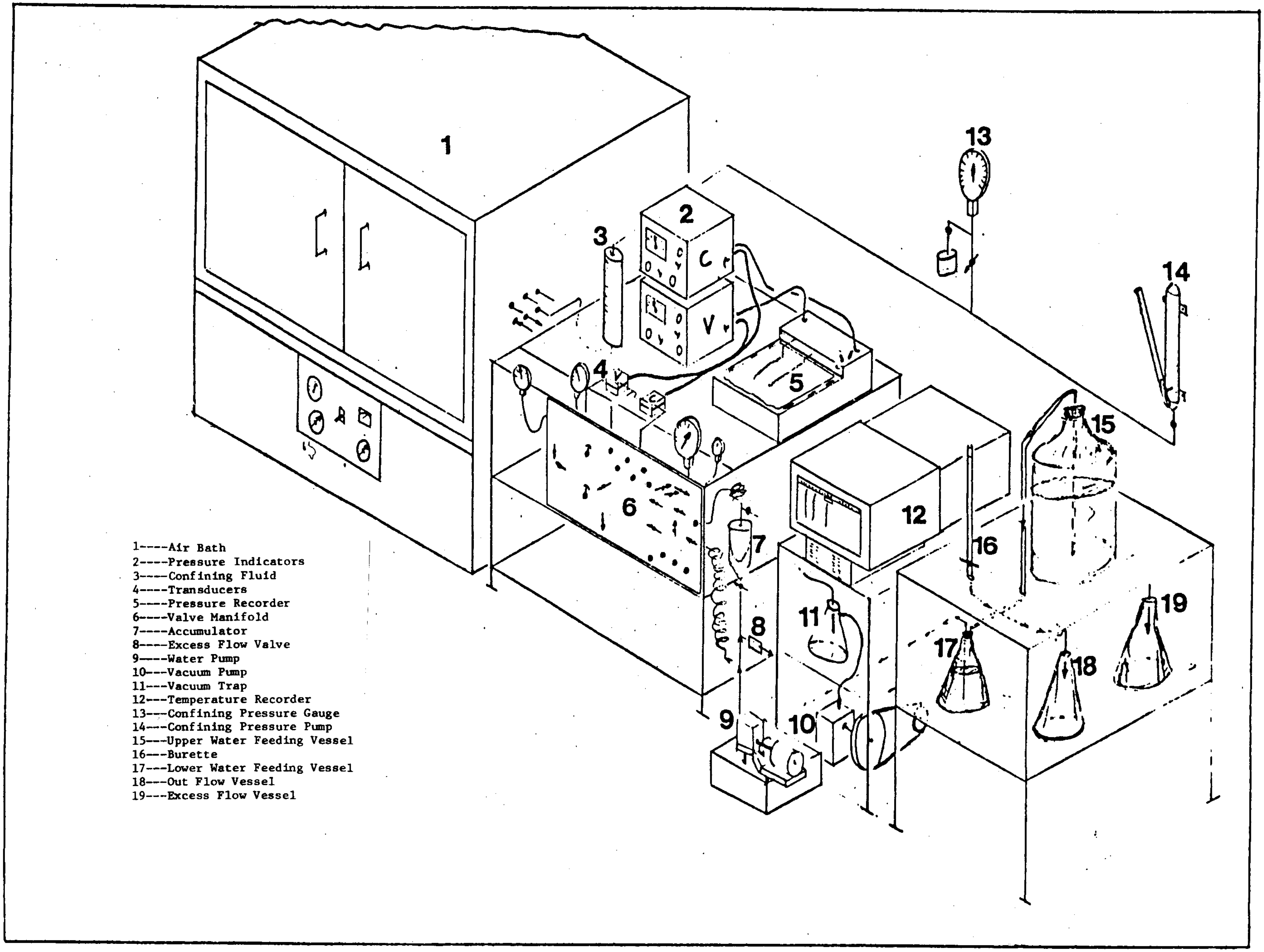


Fig. 1: General View of the Apparatus

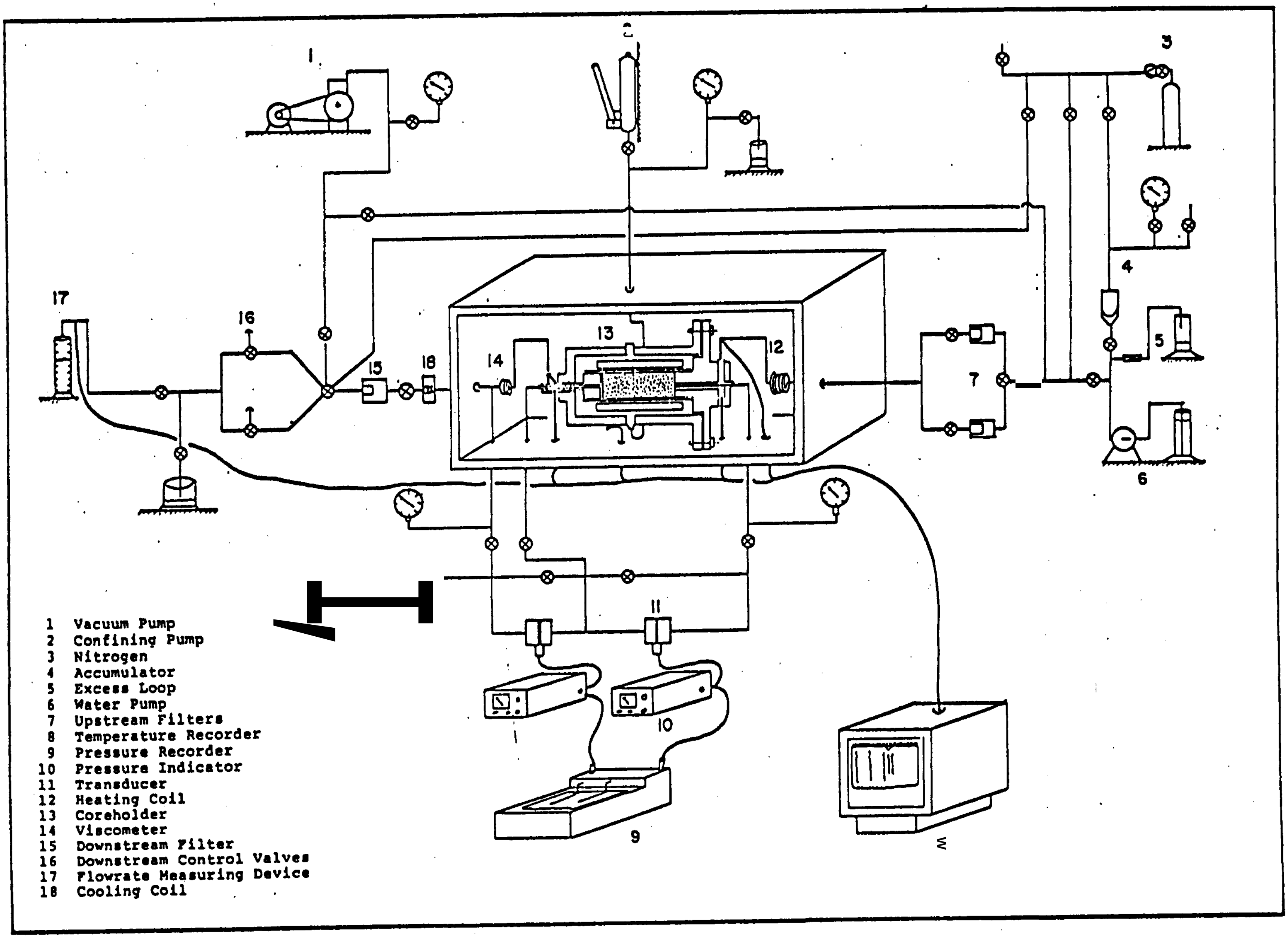


FIG. 2 : SCHEMATIC DIAGRAM OF THE APPARATUS-WATER FLOW

2.2 Water Pump and Accumulator

Water pump specifications:

Lapp Pulsafeeder
Model #LS.20
Serial no. X-7704
Process Equipment
Lapp Industries Company, Inc. Leroy, NY

Accumulator specifications:

Greerolator Model f20-30 TMR 5 1/2 WS
Serial #14008
30 cubic inches
A division of Greer Hydraulics, Inc. Los Angeles, CA

Figure 3 presents the pump and the accumulator. The tubing and valves between "A" and "D" are 1/4". (See section 3.2 for other details). The gas line coil and the flow line coil separate the pump from the recording elements. The coils reduce vibrations that are caused by the pump and transfered to the transducers. The pump is set directly on the floor so no vibrations are transferred to the recording tables. The pump can produce a maximum flow of about 1150 cc/hour at room conditions. This arrangement produced a good dampening of the pulses, leaving them almost negligible. In other words, as can be seen in Figure 18, the thickness of the 1 psi plate line is practically the thickness the pen produces.

2.3 Excess Flow Loop

Figure 3 presents the excess flow loop or the overflow loop. This flow system accepts the difference of flow between the pump's output and the flow in the core.

The pressure relief valve is a 1/4" "Nupro" valve with swagelock fittings. The operating pressure can be manually set at a range of 150 psig

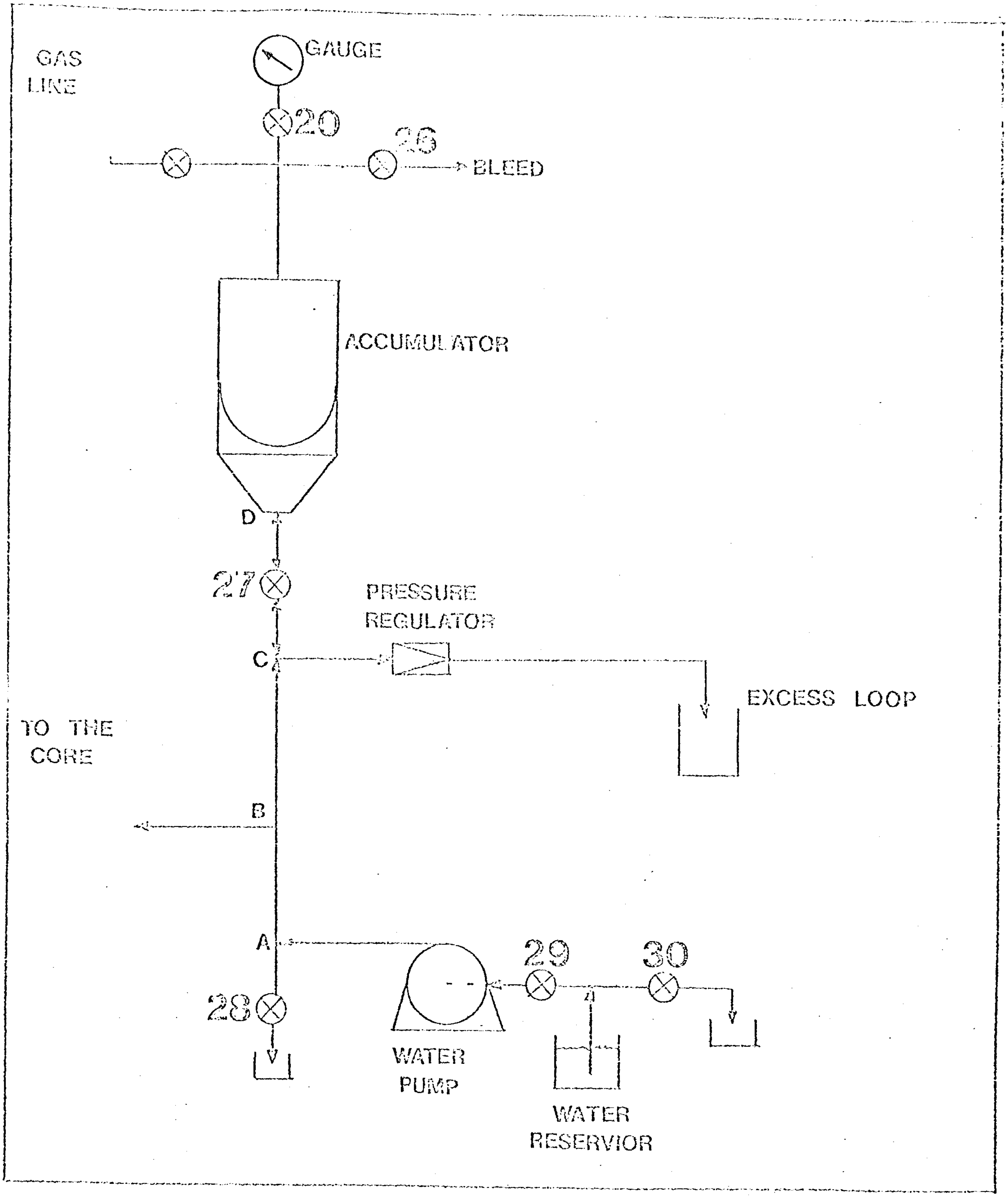


Figure 3 - A SCHEMATIC DIAGRAM OF THE WATER PUMP, THE ACCUMULATOR, AND THE OVER FLOW LOOP

to 350 psig. The valve is set horizontally in order to get a constant behavior of both the spring and the travelling seat. In addition to the improvement in the flow control described in section 3.3, the loop provides a safety valve for the whole system. Most importantly, it protects the accumulator from a 25% increase in the line pressure. This high pressure would blow the diaphragm in the accumulator.

2.4 Filters

There are two parallel up stream filters and one down stream filter. Seven micron filters were used although other types of filter elements (60µ) can be used.

The up stream filters cannot be changed during the run. Some air would be driven into the core. But'the flow can be directed through either one of them. This doubles the time for plugging. The down stream filter can be changed in the middle of a run. Figure 2 shows the location of the filters.

2.5 Confining Pressure System

Figure 4 presents a schematic diagram of the confining pressure system. Water .was used instead of oil in the confining chamber of the core holder. This eliminates contamination of the down stream if a failure should happen. Furthermore, a spill of oil in the bath at 300°F can be dangerous. The pressure is applied by an "Enerpac" hand pump rated at 10,000 psig. The pump is oil operated. The converting vertical vessel (see Figure 4) is not in the bath. The oil inlet is on the top and the water outlet is on the lower part. The volume of the vessel is larger than the confining chamber in the core holder so that no

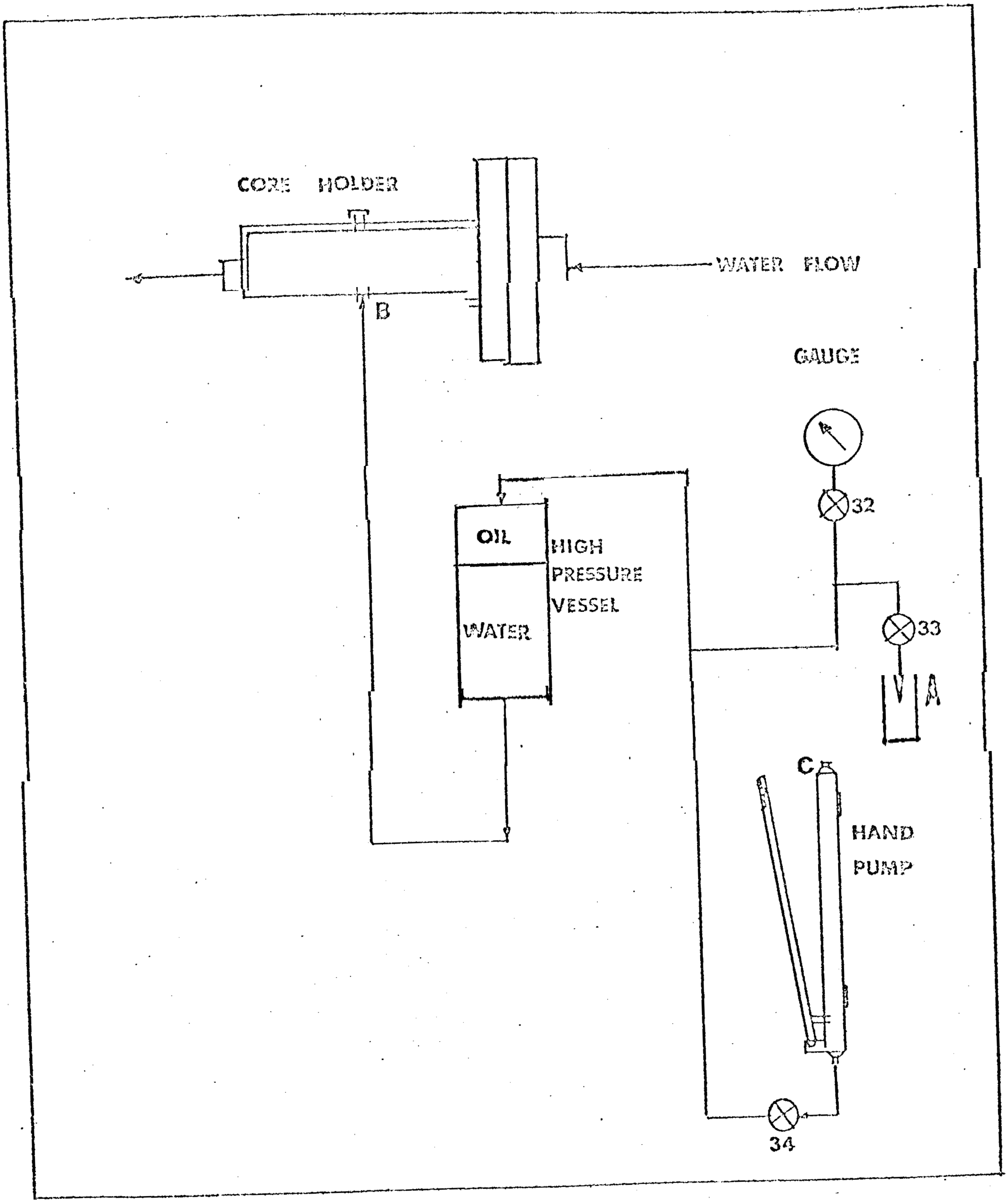


Figure 4 - A SCHEMATIC OF THE CONFINING PRESSURE SYSTEM

oil can get into the bath.

The pressure gauge is a "Helicoid" gage U.S.A., 8 1/2 W, 10,000, 50 libs., subd. ±1/4% accuracy.

2.6 Core Holder

The core holder consists of three parts: (1) The core holder body, Figure 5; (2) The up stream core plug, Figure 6: and (3) The down stream core plug, Figure 7.

It is rated at about 4000 psig confining pressure. The core plugs are sealed by "o" rings at both ends. The viton sleeve supporting the sand is held in an aluminum perforated sleeve. The assembled core holder is presented in Figure 8. This core holder was redesigned by Mr. A. Sufi, and, to date, has been performing very well.

2.7 Temperature Recording

Five (5) thermocouples are scanned about once in ten (10) seconds by a Leeds and Northrup Speedomax Recorder. The recorder has twenty-four channels and a range of 0°F to 600°F. Figure 8 shows the location of the five thermocouples: (1) in stream, up stream of the core; (2) in stream, down stream of the core; (3) up stream core plug metal; *(4)* core holder body surface; and (5) out flow temperature entering the flowrate metering burette. All thermocouples were checked and the recorder calibrated prior to the runs and during the runs. The resolution of the recorder is about ± 1°F.

2.8 Pressure Differences Recording and Calibrating

The pressure recording system includes the following: (1) pressure taps, 1/16" lines open at the sand faces, Figure 8; (2) pressure lines

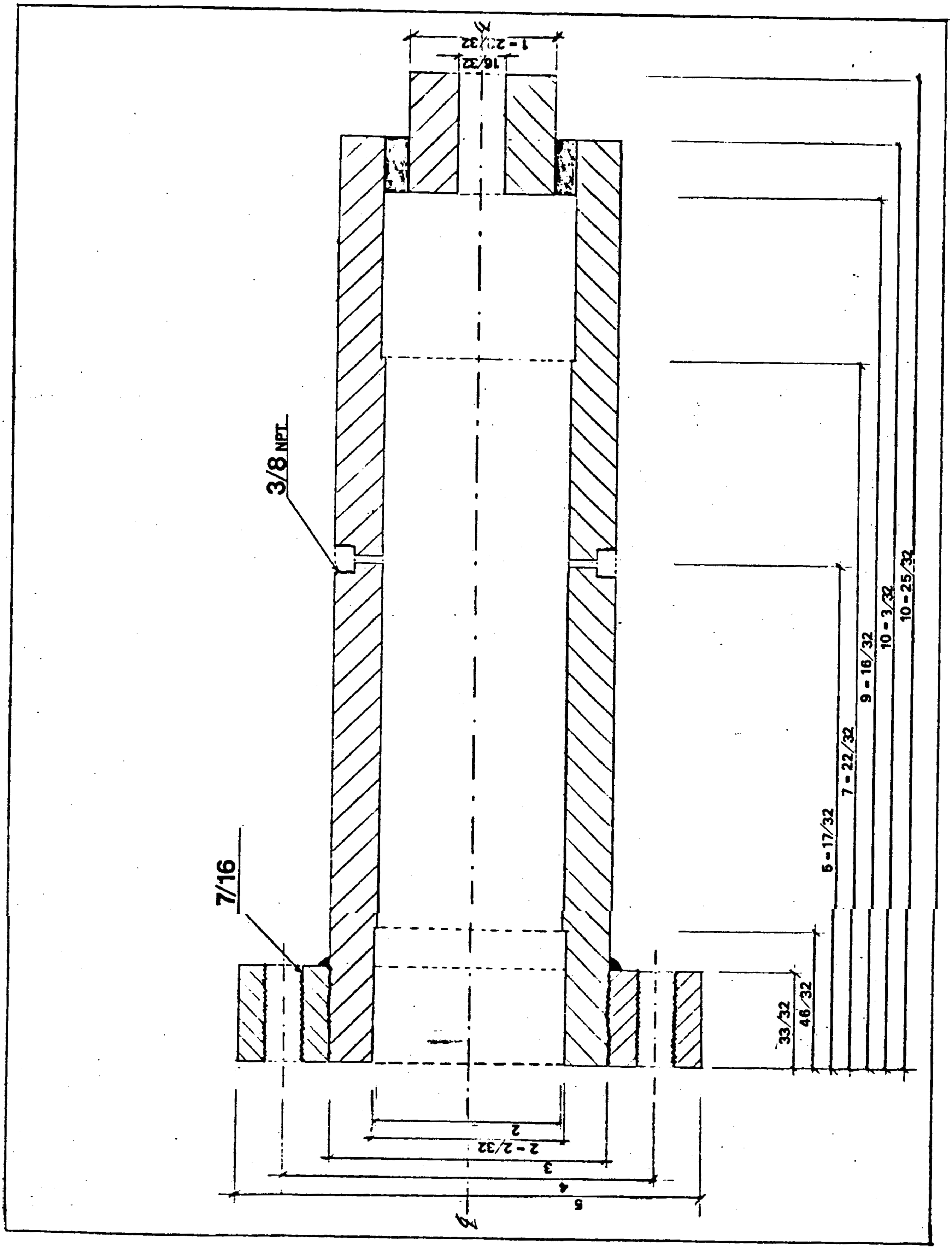


Figure *5* - CORE HOLDER BODY

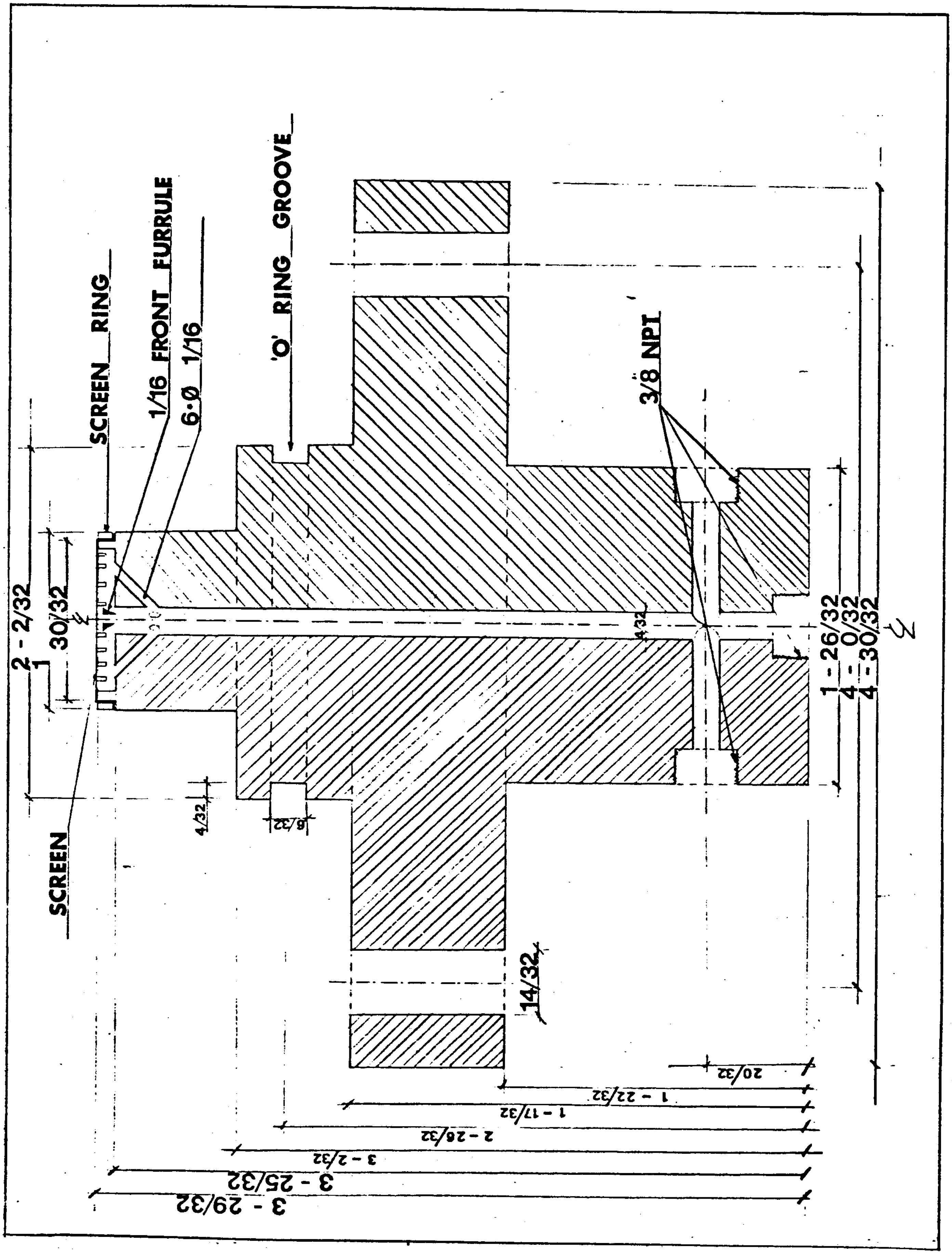


Figure 6 - UP STREAM CORE PLUG

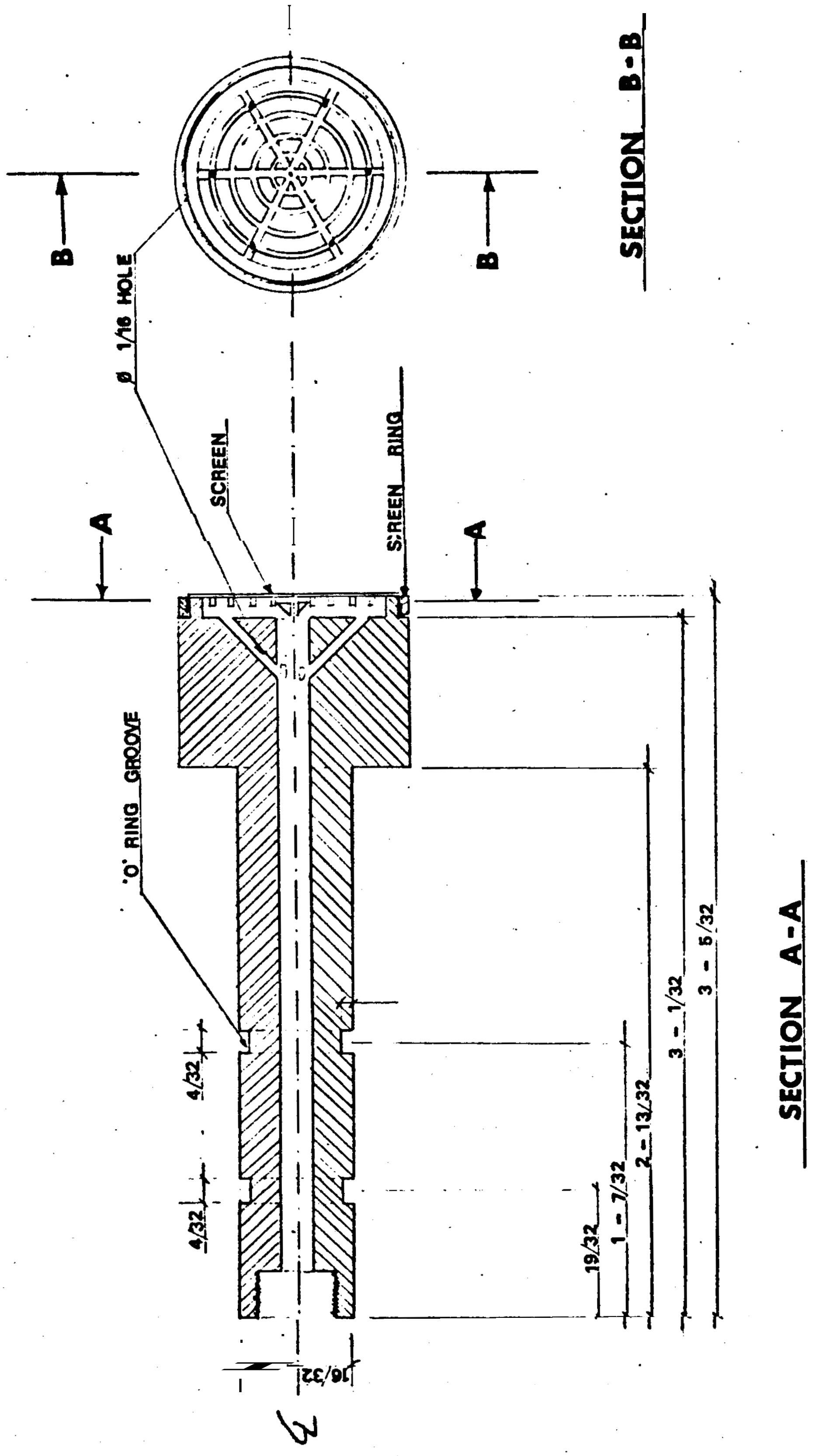


Figure 7 - DOWN STREAM CORE PLUG

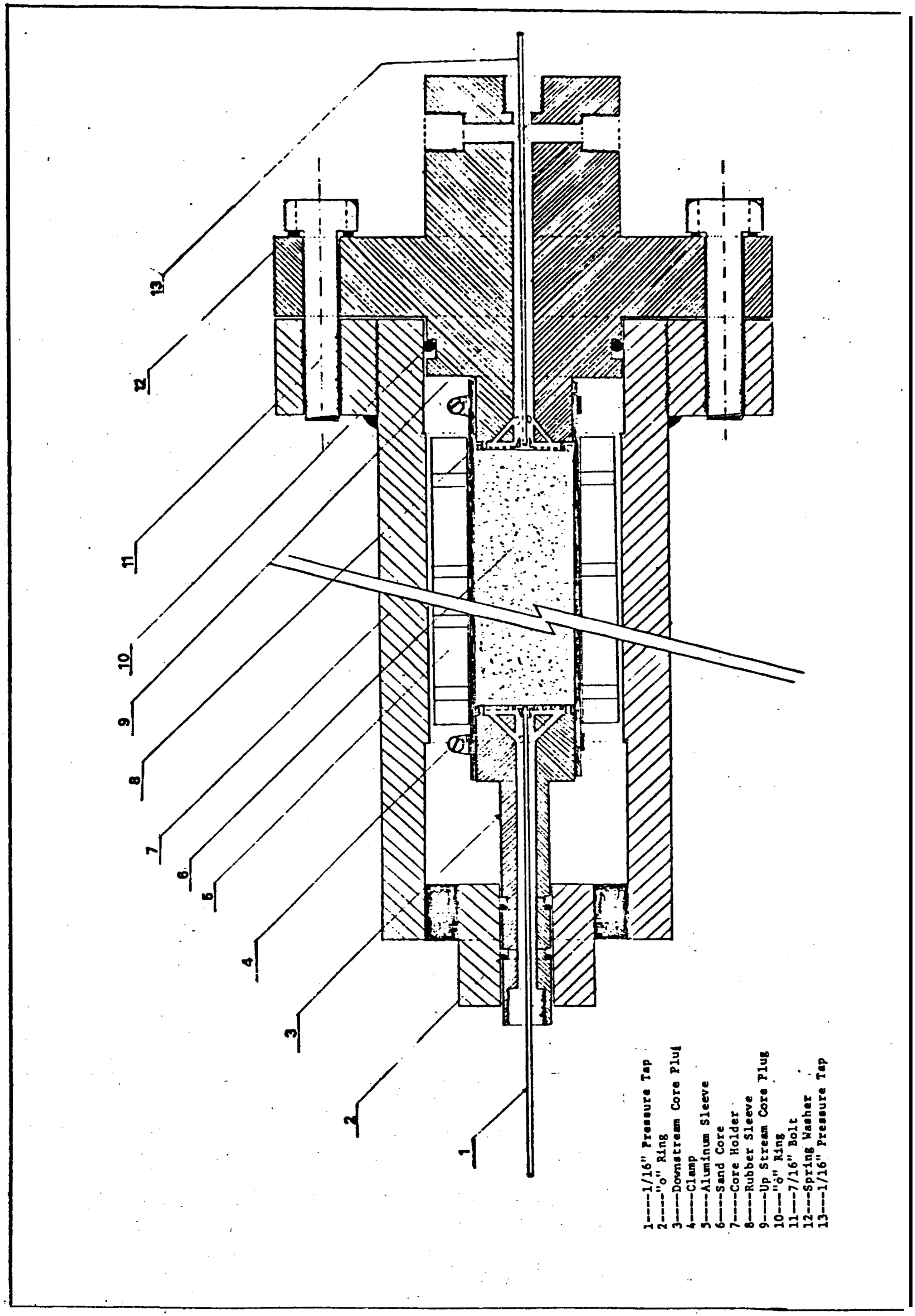


Figure 8 - A SCHEMATIC OF THE CORE HOLDER

and valve manifold, Figure 2; (3) transducers, Figure 2; (4) pressure indicators, Figure 2; and (5) recorder, Figure 2.

Pressure gauges read the pressures up stream of the core and down stream of the viscometer, Figure 2.

The sensitivity of the readings to the location of the pressure taps is presented in section 3.4. The core transducer has a 1 psi plate model KP 15. The viscometer transducer has a 5 psi plate. The pressure indicators (one for each transducer) are model "CD 25" by Dynasciences Corporation. The recorder is a two (2) channel "Chessell BD9" Recorder.

The up stream pressure gauge is a "Duragauge AISI 3/6 tube and socket, 0-600 psi, 5 psi subd." The down Stream gauges are a "U.S. Gauge" make, 0-600 and 0-1000 psi range. The accuracy of the transducers is ±1% of the plate value.

Calibration is done by a manometer. A water manometer is used for the 1 psi plate and a mercury one is used for the 5 psi plate. The mercury calibration is done with a nitrogen cushion while the water column is applied directly to the transducer.

The transducer plates can be changed during a run. They are located high above the valve manifold and can be bled after reinstalling. They can be recalibrated during a run as well.

2.9 Cooling system

Figure 9 presents the cooling system. The first goal is to cool the outflow from the bath to room temperature. This is done by running a coil of the flow line through a vessel with tap water circulating in it.

The second goal is to keep the water flowing through the fine needle

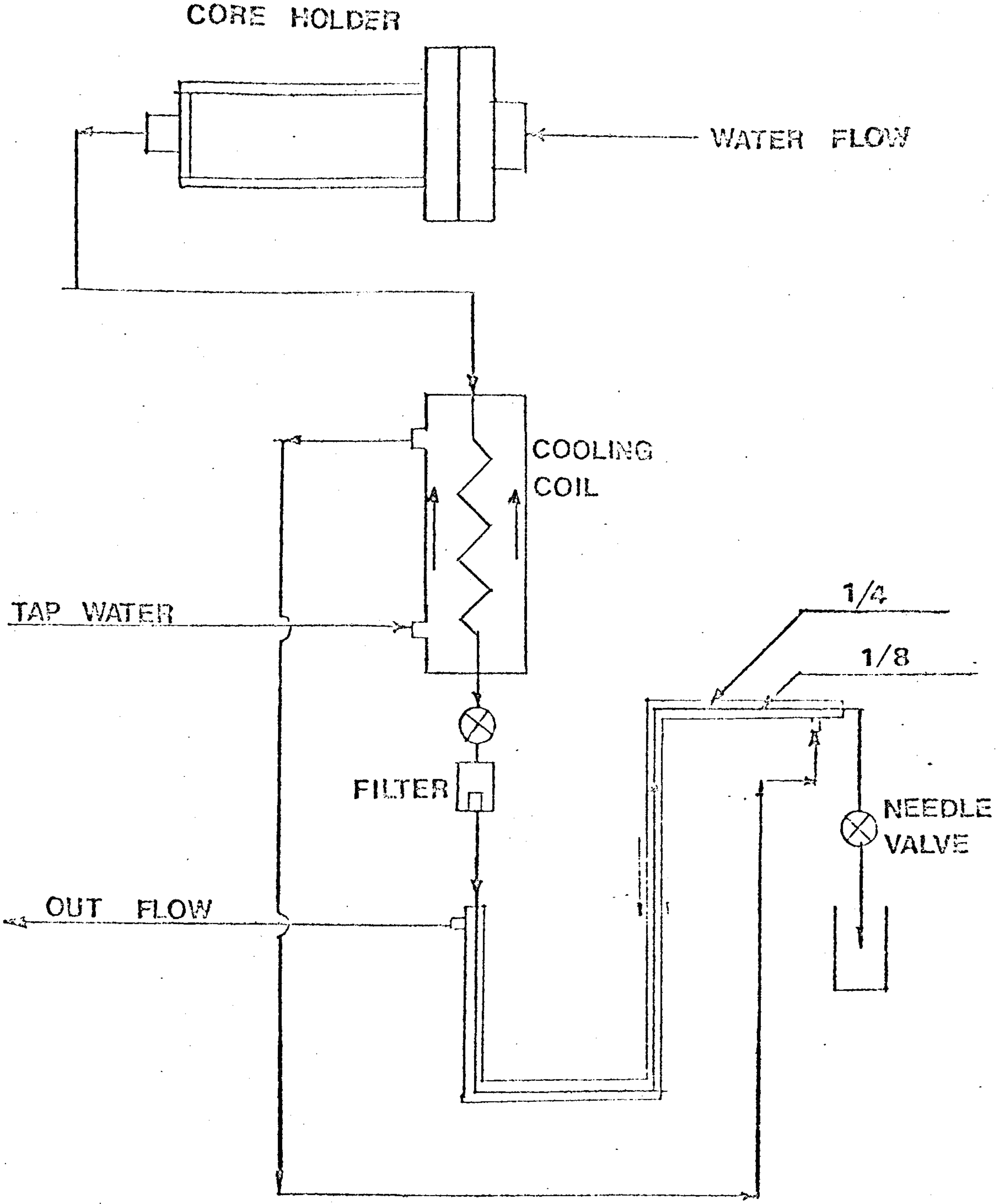


Figure 9 - A SCHEMATIC OF THE COOLING SYSTEM

valve at a constant room temperature. The performance of the valve is very sensitive to changes in room temperature. The temperature is kept constant by surrounding the 1/8" flow lines with a 1/4" flow line and letting tap water run in the annular space. This cooling exchanger is located before the needle valve.

2.10 Flowrate Measuring

Figure 10 shows the simple system theat was used to measure flowrate.

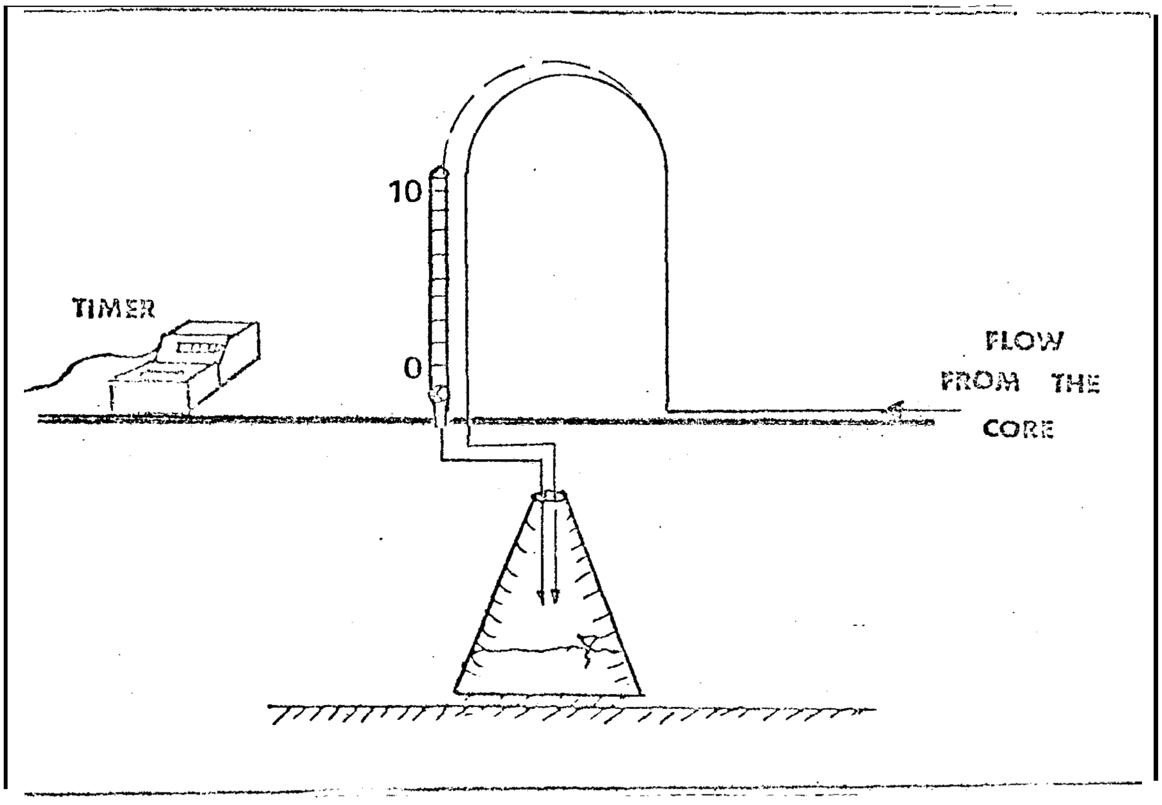


Figure 10 - Flowrate Measuring System

A very important point must be made here and it will be stressed in other places throughout the report. It is said that 10 cc are measured for all flowrates. Perhaps due to a thin layer of water, only 9.8 cc are actually measured. This will introduce an error in the absolute value of k, but as long as the measuring procedure is followed in the same way every time, an error in the relative changes in k is not introduced.

The time needed to produce the given volume in the burette is measured by a "Precision Scientific Com." timer, which is good to about 0.05 seconds, cat. #69230, 120V - 60 cycles.

2.11 Intake Water System

In order to be able to change the intake water reservoir without shutting down the pump and without getting air into the suction, a two stage feeding system was built (Figure 1). The larger reservoir, #15, is a five gallon glass bottle that can be replaced. Water is syphoned to the primary reservoir, #17, a *4000* cc glass bottle. This lower primary reservoir is not touched during the run and the pump's suction end is never above water level. An adjusting valve is located on the syphon between the two reservoirs and it is set in such a way that the level of water in the low reservoir is constant (around the *4000* cc mark).

2.12 Vacuum System

Vacuum is applied by the vacuum pump. A liquid trap is located between the pump and the flow lines. The vacuum is measured with a "Labconco" mercury gauge which is good to 5 microtorr. The gauge is disconnected before flow is initiated *to* protect it.

2.13 Gas System

A 2200 psig nitrogen bottle supplies gas to charge the gas chamber in the accumulator. It also supplies gas to the up stream or down stream ends of the core if gas flood is desired (Figure 2).

2.14 Valve Manifold

Figure 11 presents a schematic diagram of the valve manifold. All the gas valves and the transducer valves are needle valves, installed to prevent shocks. The down stream control valve' and auxiliary valve (7 and 6 in Figure 11) are fine needle valves.

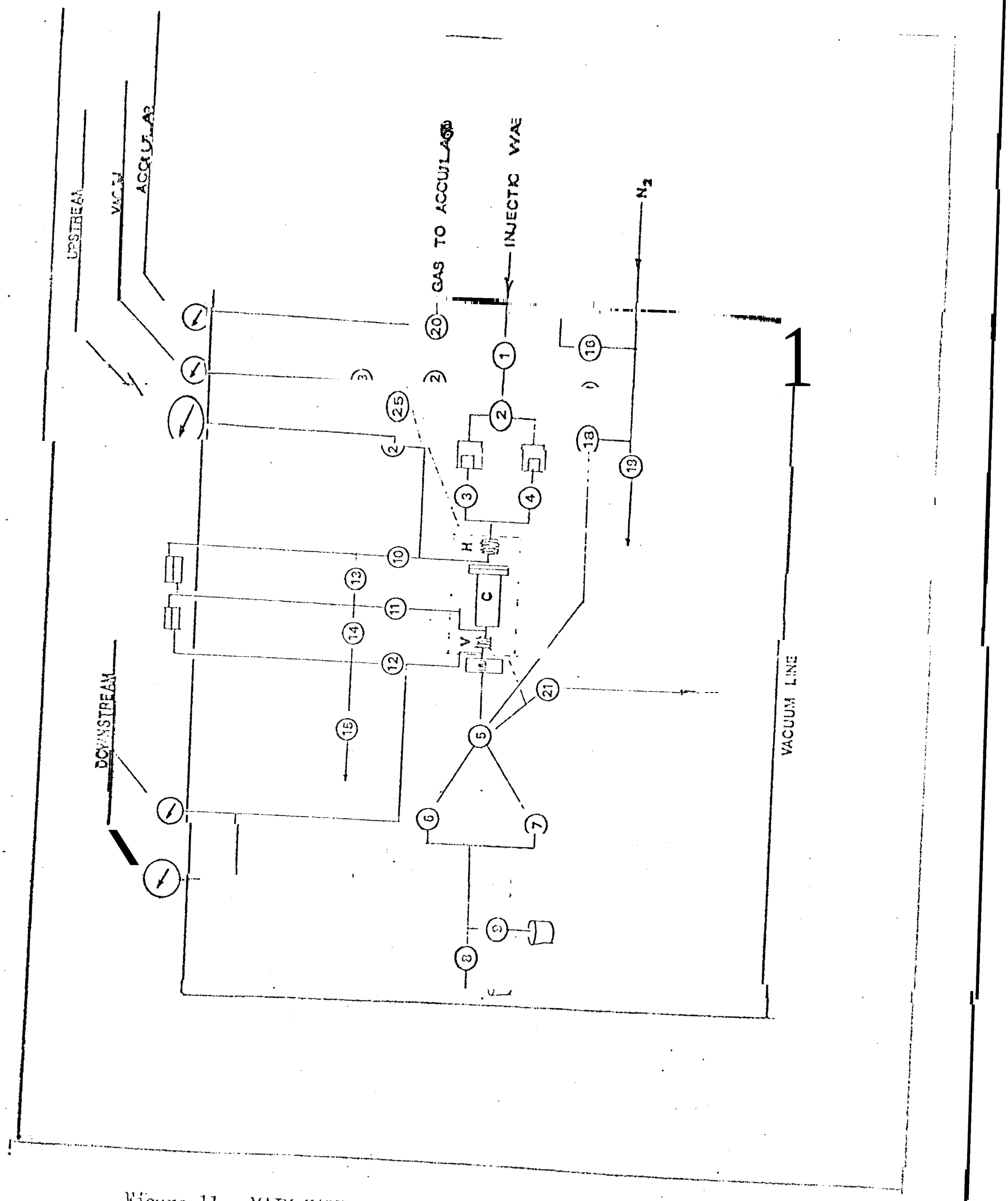


Figure 11 - MAIN VALVE MANIFOLD

3. Apparatus Improvements

Four major problems that arose during the first run were: (1) Noise and pump pulsations affecting the transducer's performance; (2) Control of the average pore pressure with varying flowrates; (3) A calculated permeability that was flowrate dependent; and (4) Plugging of the down stream needle valve. These problems were studied in order during the next seven runs. Actually, this procedure yielded a sensitivity analysis of the behavior of the apparatus. The magnitude of the problems and the ways for improving the apparatus are described in the following sections.

3.1 Vibrations in the Air Bath

The flow was initiated at room temperature. For a given accumulator setting and a constant flow the core transducer (1 psi plate) had a certain magnitude of oscillation. When the bath was turned on, the oscillation magnitude doubled. The main cause was the fact that the core holder sat on the bath floor and the vents' vibration was picked up by the pressure taps. The problem was solved by hanging the core from the main ceiling frame of the bath. A rubber lining separated the core holder from the frame to further dampen the vibratons.

3.2 Accumulator

The two following changes cut the pump pulsation effect on the core transducer by 50% each time.

The first accumulator piping was the 1/8" tubing shown in Figure 12.

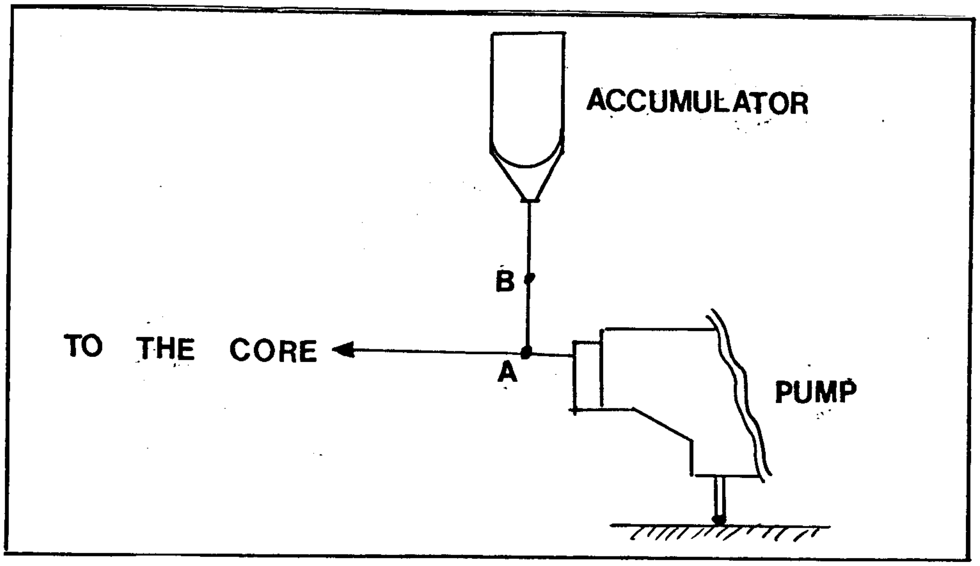


Figure 12 - "Old" Accumulator Arrangement

The connection to the core at point "A" was moved to point "B" as is shown in Figure 13. This put the accumulator in the direct line of the pulsations and 'helped the accumulator absorb the pulses.

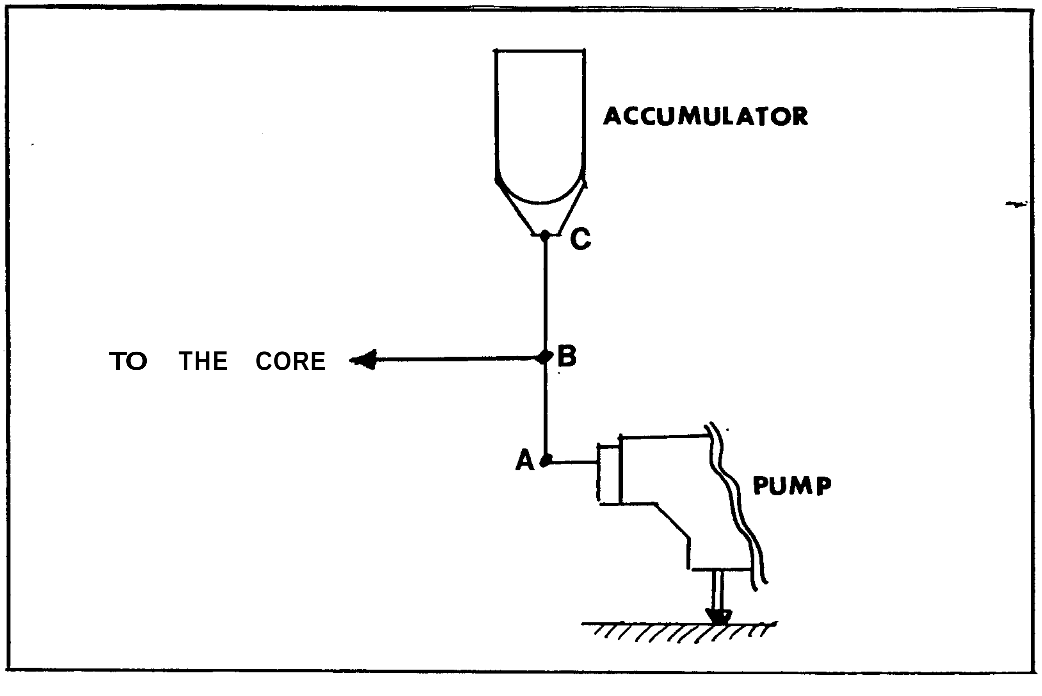


Figure 13 - "New" Accumulator Piping

The second change was the replacement of the section of 1/8" tubing

"ABC" by a 1/4" tubing. The improvements, as was mentioned before, were significant.

3.3 Excess Flow Loop

A serious problem arises when a pulsating pump, an accumulator, and a back pressure needle valve are used. One must adjust the outlet flow to be exactly the same as the pump output. If the flows are not the same, the accumulator either loads or unloads, hence varying the pressure. The problem was magnified when the accumulator unloaded into the flowing system. Rust and gum (orange in color) would build in the accumulator. When unloading would occur, the rust and gum would plug the filters and accumulate in the upper section of the core.

The two problems were solved by introducing the excess flow loop presented in Figure 3. The pressure regulator maintained a good average up stream pressure, and as long as the output of the pump was larger than the flow in the core, the extra flow exited through the excess loop. The volume of the tubing between point "A" and point "B" (Figure 3) is larger than the maximum pulse of the pump. So no fluid that went by point "B" towards the accumulator could find its way back to the core. This completely isolates contamination in the accumulator from the core. All up stream sand faces of the cores were inspected and showed no evidence of contamination after the excess loop was introduced.

3.4 Pressure Taps

Naturally, in the initial construction of the apparatus the pressure taps were as in Figure 14.

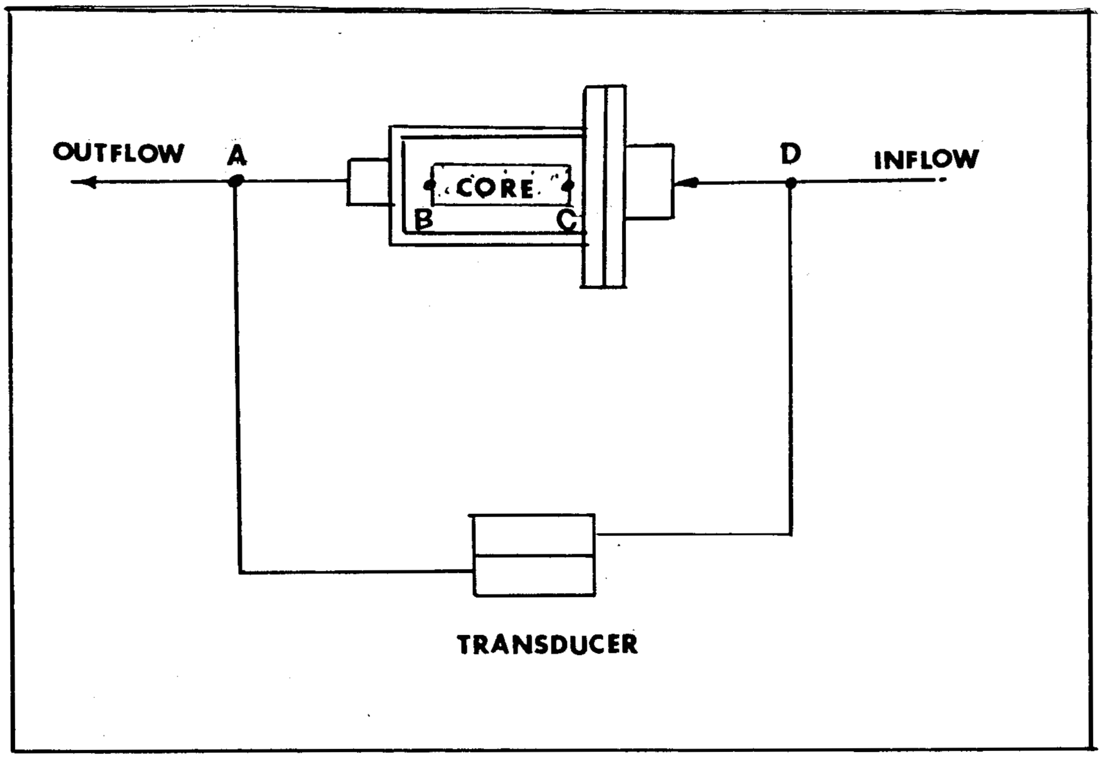


FIGURE 14 - "Old" Pressure Taps

At this point a serious flowrate dependency of the permeability was experienced. By all means the flow is laminar, as shown in section 5, hence there should not be flow rate dependency. It is obvious that the Δp measured is not only the Δp of the core but includes the Δp in the tubing sections A–B and C–D. Simplified we have the following condition:

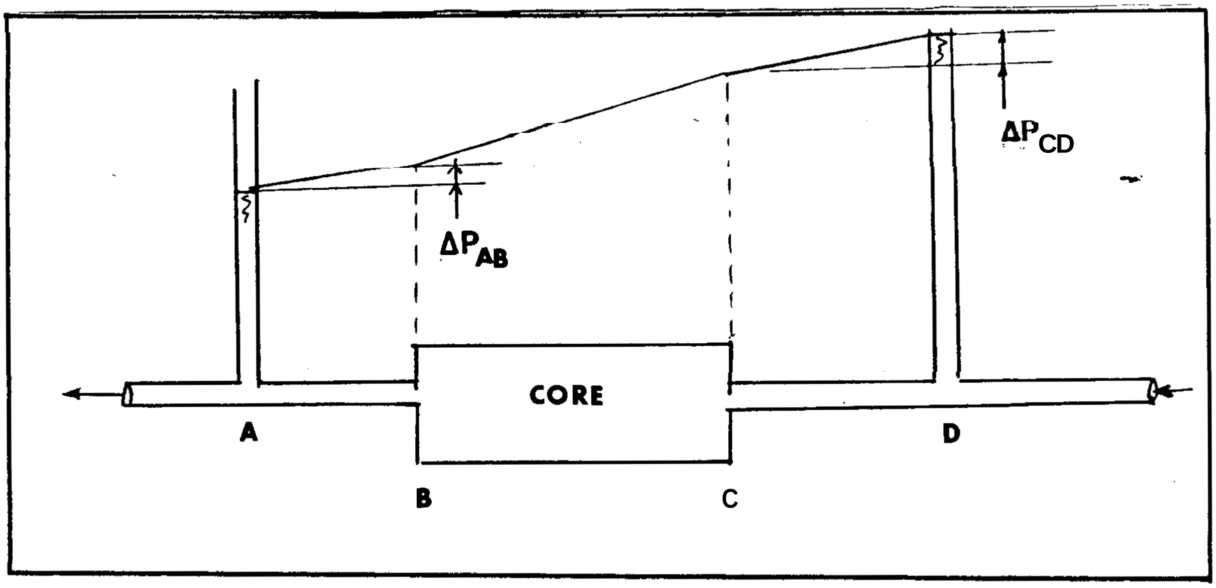
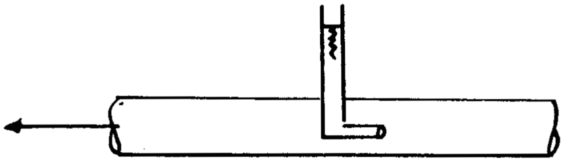


Figure 15 - "Old" Head Loss on the Core

Δp_{AB} and Δp_{CD} are mostly a function of V but some of the "T" and elbows and other irregularities are a function of V^2 and hence are not linear with **q** as Darcy's law is. This yielded part of the permeability (k) dependence upon the flowrate (q). Varying the flowrate (q) from 200 cc/hour to 300 cc/hour caused a drop in k of about 100 md from a level of 3500 md.

Figure 8 presents the solution to this problem. The pressure taps were made of 1/16" tubing and put into the 1/8" flow lines at the sand face. This cut the flow rate dependency of the permeability by 50%. This pressure tap measures the kinetic potential of the flow:



A sample calculation shows that the extra Ap due to the flow is negligible:

$$Ap = \frac{14.7\ \gamma\ V^2}{2g}$$

Where:

Ap ≡ psi

$\gamma \equiv kg/cm^3 = 10^{-3}$

$V \equiv cm/sec \simeq 0.3$ (Maximum flow)

$g \quad cm/sec^2 = 981$

so:

$$\Delta p = \frac{14.7 \text{ x } 10^{-3} \text{ x } 0.3^2}{2 \text{ x } 981} = 687 \text{ x } 10^{-9} \text{ psi}$$

3.5 Core plugs

As presented in section 3.4, the rate dependency remained. It was reduced by half but something was still wrong. A closer look at the core plugs is presented in Figure 17. As they were, there was a serious end effect in the sand due to converging of flow. The receiving channels were simply not big enough. This caused the Δp to look as presented in Figure 16:

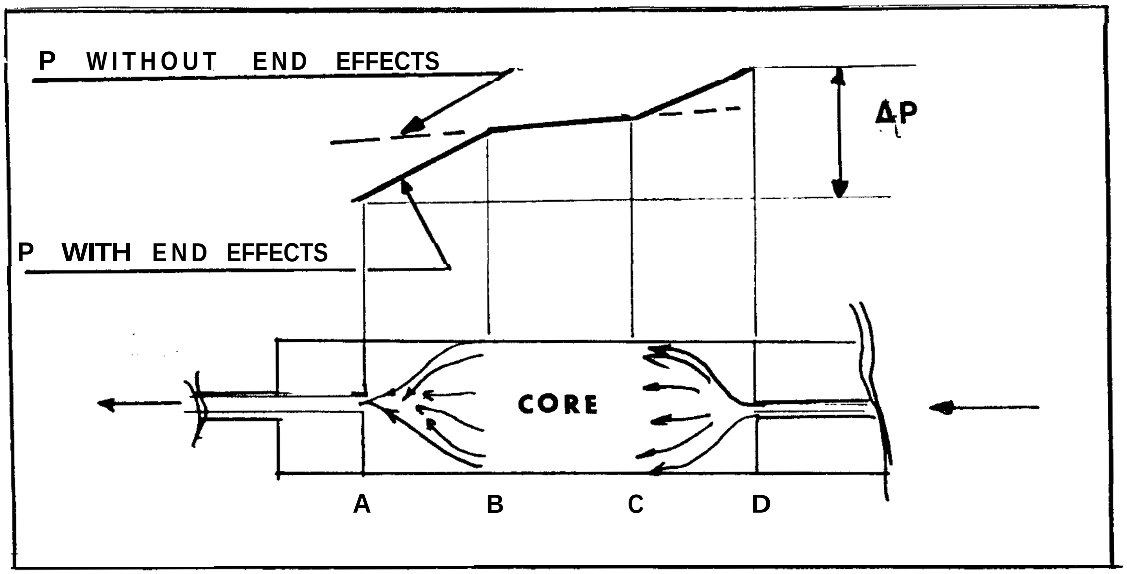


FIGURE 16 - End Effects Pressure Losses

Δp_{AB} and Δp_{CD} are a function of the flow. This was a key factor once improved. The improved core plugs are presented in Figures 6 and 7. Once improved, not only did the k dependency on q vanish, but k increased by as much as 30%. That is logical since Δp decreased by a large amount for the same flow.

3.6 Sand Sieving and Cleaning

Finally, to complete this section, one more problem was solved: the plugging of the needle valve that sets the flow in the core. The sand was sifted about five times, and then washed with distilled water and dried at 70°C. That improved the flowing stability a great deal. The particles plugging the needle valve were smaller than seven microns since a seven micron filter is up stream of the valve. The sand sand sizes are about

130 to 180 microns so probably the flow of fines did not affect the permeability. 'Furthermore, after the first heating cycle to 300°F, the plugging effect practically disappeared.

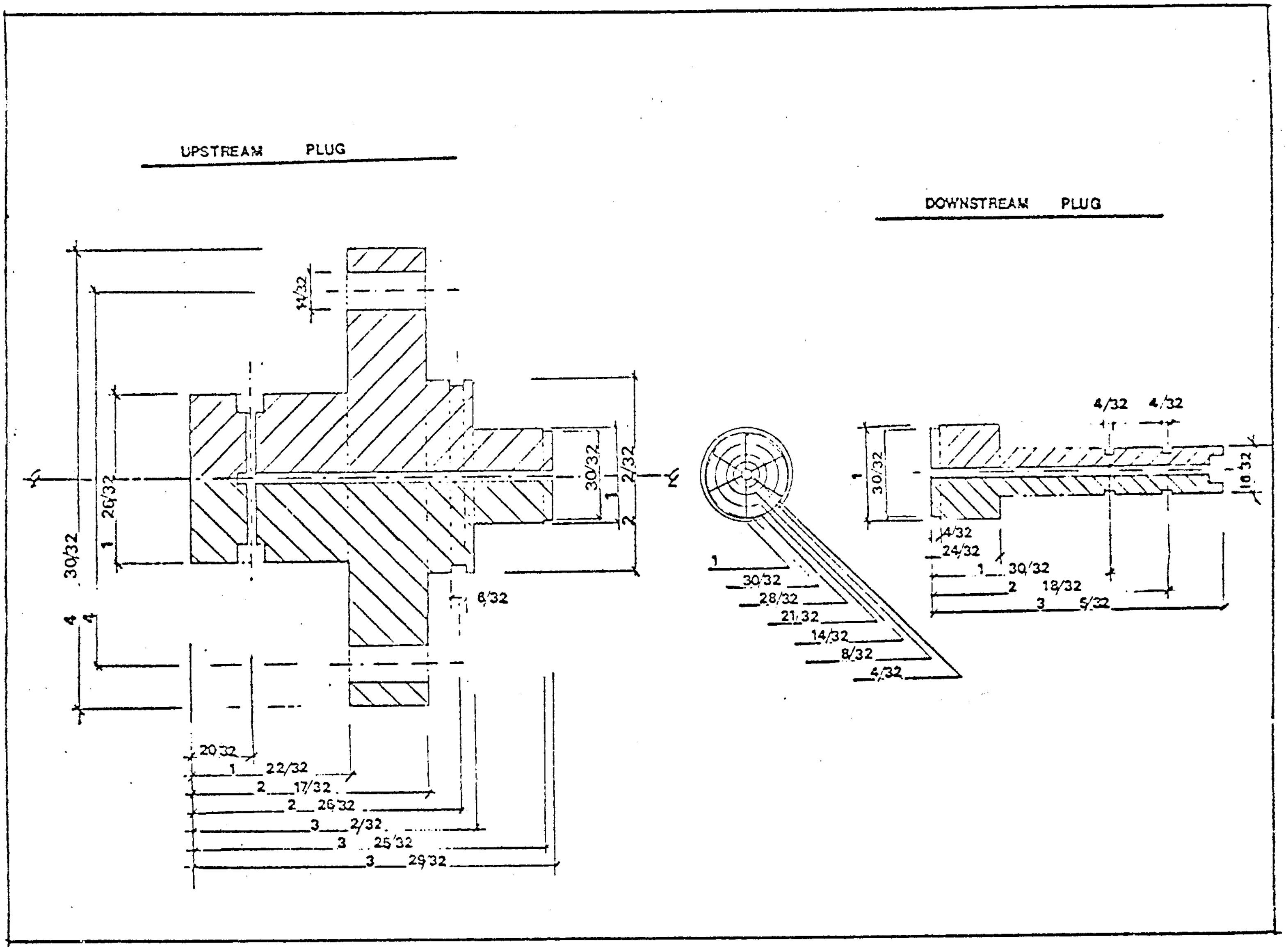


Figure 17 - UP STREAM AND DOWN STREAM CORE PLUGS BEFORE IMPROVEMENTS

4. Procedure

The main goal of this section is to advance an operating description so that the work can be reproduced. Furthermore, the mechanical behavior of the system is one of the sources for an evaluation of the system and what can be done with it in the future. Several problems and disagreements may orginate from a different and inconsistent procedure. Many schematics and diagrams in other sections will be referred to in the following section.

4.1 Sand Preparation

The Ottawa silica sand was carefully sieved. Two sands were used: mesh 120–150 (what is left on the 150 Mesh screen) and mesh 170–200 (what is left on the 200 mesh screen). An initial quantity of about 500 cc of sand is put on the top sieve. Then only the desired mesh is resieved four (4) more times. Sieving time is about 15–30 minutes for every cycle.

After a large enough quantity of the two grain sizes was on hand, washing commenced. The coarse portion (mesh 150–120) was washed under tap water through a mesh 270 screen three times, about 5 cc of sand at a time. Then all the sand was washed three times with distilled water. The finer sand (mesh 200–170) was washed three times with distilled water, not through a screen. The sands were dried in an oven at 60"-70°C .

In order to achieve a good sieving of the sand, the quantity on every sieve should be small. A thin layer of sand will expose a better fraction of the grains on a sieve to the holes. One cycle of sieving produced 10–30 cc of the single mesh sand.

4.2 Sand Packing

1. Wash the up stream core plug with water and acetone and dry. Protect

the "o" ring from the acetone.

2. Cut a 1 1/2" x 1 1/2" mesh 270 screen and place it on the core plug end. Put the screen ring on and tap down gently with a plastic hammer. Be sure that the screen is not dammaged. Cut the extra parts of the screen below the ring. Inspect carefully.
3. Repeat steps 1 and 2 for the down stream core plug.
4. Cut an 8" piece of viton tubing. Square one end and wash it with water. Wash the aluminum perforated sleeve and push the viton into the sleeve. Center the viton. Then dry the inside of the viton and, as much as possible, the aluminum sleeve.
5. Fit the squared viton end onto the up stream core plug so that two things happen: (1) the rubber sleeve goes as far on the end plug as possible and (2) the aluminum sleeve overlaps the core plug by the width of the screen ring, about 3/16". Clamp with a clamp that does not exceed the aluminum sleeve diameter. Put the clamp as close as possible to the aluminum sleeve. Make sure that the clamp does not cut the rubber. The core plug and sleeve are set vertically with the open end of the sleeve pointing upwards.
6. Take 100 cc of sand in a 100 cc beaker and weigh it.
7. Fill the sleeve with 30 cc of sand.
8. Use a stainless steel rod about 2 1/2" long and 3/8" in diameter with a rounded end. Let it drop on the sand from a height of about 2"-3". Pound the sand 50 times. (30 cc were used to protect the up stream screen) Then tap the aluminum sleeve with the handle

of a medium screwdriver, 50 times, at the sand face level, while turning the core 360° (on a circle).

9. Repeat steps 7 and 8 with a 20 cc increment until the level of the sand is 3/16" below the aluminum sleeve end.
10. Weigh the sand left in the beaker. (Figure 17)
11. Put up stream core plug in place. Tap it very gently. Make sure it is vertical. Clamp it as close as possible to the aluminum sleeve. Cut the viton at the upper level of the upstream core plug.

4.3 Geometry Measuring

For each run, the core dimensions were recorded on a data sheet like Figure 18. The upstream measurements are taken 90° apart. The down stream measurements are taken 120° apart.

4.4 Core Holder Packing

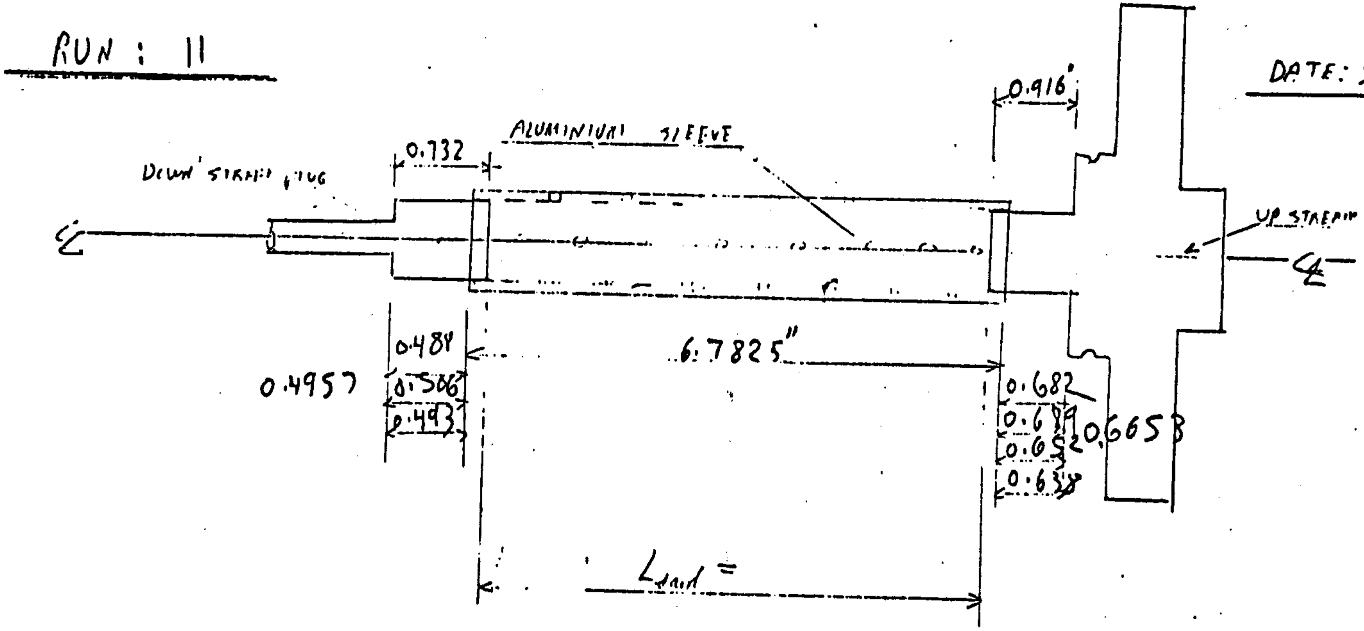
1. Set the core holder body in a vise with the flange pointing upwards.
2. Clean "o" rings' housing. Oil thinly.
3. Oil "o" rings thinly.
4. Clean flange surfaces.
5. Oil bolts.
6. Fit core into core holder body and tighten bolts in a 90° alternating manner. Use spring washers. Do not overtighten. Tighten to the same torque.

4.5 Confining System Preloading

Two things are done here: (1) Charge water in the high pressure vessel

RUN : 11

DATE: SEP 24 1986



$L_{sand} = 6.7825 + 0.4957 + 0.6653 - 0.732 - 0.916 = 6.2955'' = 15.99057$ cm

$D_{sand} = 1.022'' = 2.59588$ cm

$A_{sand} = \pi D_{sand}/4 = 5.29248$ cm^2

$V_{sand} = A_{sand} * L_{sand} = 84.62977$ cm^3

SAND

MESH - MIX : SINGLE 200 MESH

WEIGHT BEFORE PACKING = 304.70 g

WEIGHT AFTER PACKING = 170.15 g

NET SAND WEIGHT = W_{sand} = 134.55 g

PACKING SAND DENSITY : $\rho_s = \frac{W_{sand}}{V_{sand}} = \frac{134.55}{84.62977} = \underline{1.589866}\ \boxed{g/cc}$

Figure 18 - WORKING SHEET OF GEOMETRY MEASUREMENTS AND WEIGHTS

and (2) charge oil in the hand pump.

1. Close valve 34.
2. Open valve 32.
3. Open valve 33.
4. Connect a distilled water reservoir to port B.
5. Connect a vacuum trap to port A.
6. Pullalight vacuum until the water gets to the vacuum trap.
7. Close valve 33.
8. Disconnect vacuum system.
9. Fill oil (vacuum oil) in port C of the hand pump.

4.6 Pressure Transducer Calibration

Calibration is done with a mercury manometer for the 5 psi viscometer and a water manometer for the 1 psi plate. For the calibration, the transducers are disconeected from the main system and once the indicator and the recorder are calibrated, the transducers are put back in place.

4.7 Filter Inspection and Installation

The previously used up Stream filters and the down stream filter are disconnected and inspected. Usually, the filter elements have to be changed every other run. After putting in anew filter element (of the desired specifications), the filters are reinstalled.

4.8 Charging the Accumulator

Figure 3 .describes. this section.

1. Take accumulator off, including valve 27.
2. Wash liquid port.
3. Fill up liquid port with distilled water with the port facing upwards.

4. Apply pressure to the gas port until water flows through valve 27 (valve facing up).
5. As water is flowing through valve 27, close it.
6. Install the accumulator.
7. Charge the gas manifold with 300 psig.
8. Open valve 20.
9. Close valve 26.
10. Open valve 16 until pressure in the gas gauge is 195 psig.
11. Close valve 16.
12. The accumulator is ready for use at an average pore pressure of 200 psig.
13. Close the main gas valve on the bottle.
14. Open valve 19 to bleed off the gas manifold.
15. Close valve 19.

4.9 Washing the System (without the core)

1. Connect the by-pass instead of the core.
2. Install the by-pass for the down stream pressure tap.
3. Plug the upstream pressure tap; close valve 10.
4. Open valve 8.
5. Open valve 7.
6. Valve 5 points at valve 7.
7. Choose an upstream filter.

a. Open valve 31.

9. Open valve 28; make sure there is water.
10. Close valve 10.
11. Close valve 12.

12. open valves 11, 13, 14.
13. Set the pump at 500 and turn it on.
14. Wash with 250 to 500 cc.

4.10 Setting the Excess Loop Pressure

1. Take the hose off the pressure regulator (Figure 3).
2. Open the adjusting screws on the pressure regulator.
3. Close valve 7.
4. Look at the upstream gauge. It will oscillate ±10 psi around 150 psig.
5. Close the adjusting screws on the pressure regulator until the pressure on the upstream gauge oscillates around 250 psig.
6. Connect the excess flow hose.
7. Open valve 7 and bleed.
8. Stop the pump.

4.11 Vacuuming of the System (without the core)

1. Close valves 1, 7, 8, and 9.
2. Connect the vacuum pump trap. Start the pump.
3. Valves 23, 22 remain closed.
4. Open valve 21.
5. Open valve 15 to drain the transducer line.
6. Open valve 12.
7. Close valve 11; allow a few minutes to pass.
8. Close valve 12.
9. Open valve 11.
10. Close valve 15.
11. Open valve 10; allow a few minutes to pass.

12. Close valve 10.
13. Open valve 23.
14. Open valve 22; allow a few minutes to pass.
15. Close valve 22.
16. Close valve 23.
17. Connect the vacuum gauge to the valve 23 port.
18. Open valve 23 and vacuum to 2 torr or less.

4.12 Installing the Core Holder in the Air Bath

1. Close valve 21.
2. Open valve 15.
3. Stop the vacuum pump; allow a few minutes to pass.
4. Disconnect the by-passes in the bath (two of than).
5. Place the core holder in the mounting device.
6. Connect the confining port, down stream port, upstream port, upstream thermocouple, upstream pressure tap, and down stream pressure tap.
7. Tape the surface thermocouple to the core holder surface.

4.13 Charging Confining Water and Pressurizing

1. Remove the confining pressure plug, located at the top center of the coreholder.
2. Open valve 34.
3. Pump until water comes out of the port.
4. Stop the above port.
5. Pump confining pressure to 500 psig.
6. Bleed water from valve 33 until oil appears. .

7. Close valve 33.
8. Pressurize to 500 psig.

4.14 Vacuuming the system

1. Close valve 15.
2. Turn the vacuum pump on after emptying the trap.
3. Increase confining pressure by increments of 500 psi per 10 minutes.
4. Monitor vacuum quality.
5. For at least three to four hours, reduce the vacuum to 1 torr or less.
6. Check for confining pressure leaks and for movements of the down stream plug.
7. Be sure to protect the vacuum trap.

4.15 Flooding and Pressurizing the System

1. Close valve 23.
2. Disconnect the vacuum gauge.
3. Open valve 1.
4. Turn on the pump and set it at 150 cc/min.
5. Allow time to pass until water enters the trap.
6. Close valve 21.
7. Stop the vacuum pump and disconnect the trap.
8. Let pressure build up until the excess flow loop is flowing.
9. Open valve 27 to connect the accumulator.
10. Allow a few minutes for the pressure to stabilize.

4.16 Initiating Flow, Temperature Recording, Δp Recording, and Cooling System Flow

1. Switch on the indicators.
2. Turn on the cooling water at about 200–500 cc/min.
3. Turn on the temperature recorder.
4. Open valves 10 and 12.
5. Close valves 13 and 14.
6. Open needle valve 7 slightly while watching the 1 psi indicator. Stop when the indicator shows 0.5 psi.
7. Set the pump at 600 cc/min.
8. Allow 15 minutes to one hour to stabilize.
9. Be sure there is always a flow through the excess loop.

4.17 Measurements at Various Flowrates at a Constant Temperature (T, Δp, q)

To calibrate the recorder (Δp recorder) do the following:

For the viscometer:

1. Close valve 12.
2. Open valve 14.
3. Adjust the recorder needle to zero. Do not touch the indicator.
4. Close valve 14.
5. Open valve 12.

Operate the valves gently to prevent shocks.

For the core transducer:

6. Close valve 10.
7. Open valve 13.
8. Set the recorder needle to zero.
9. Close valve 13.
10. Open valve 10.

The Δp on the core, Δp_c, can be read on the corresponding pen on the recorder. Figure 19 shows an example of the Δp record,

Figure 20 shows an example of the temperature record, When the four bath thermocouple records agree, the temperature can be read on the scale. (The recorder was precalibrated).

Flow rate measurements are made with a burette. See Figure 10. The flow rate is changed by closing or opening valve 7. Always be sure that 100–200 cc/hour flows through the excess loop.

4.18 Heating the System

The bath was precalibrated. The target temperature was set and heating started; Figure 20 shows the heating profile for run #11. Heating of 50°F increments takes 2 to 2-1/2 hours. While heating, the confining liquid expands, and is bled by valve *33*. Valve **33** is a needle valve and the bleeding should be done gently to prevent surges. Surges can be seen in Figure 19. Usually, when the confining pressure reads 2050–2100 psig, it is bled to 2000 psig. Make sure that valve *34* (Figure *4)* is closed. The only time it is opened is when the hand pump is used.

4.19 Cooling the System

The bath has both an inlet and an outlet. Generally at temperatures exceeding 150°F, these vents are closed. To cool the system, open the vents and turn the temperature knob to the minimum setting. Watch the fluid temperature upstream from the core. When it gets to the desired temperature, set the knob to that temperature.

The cooling is at least as long a process as the heating. Cooling to room temperature may take six hours. During the cooling cycle,

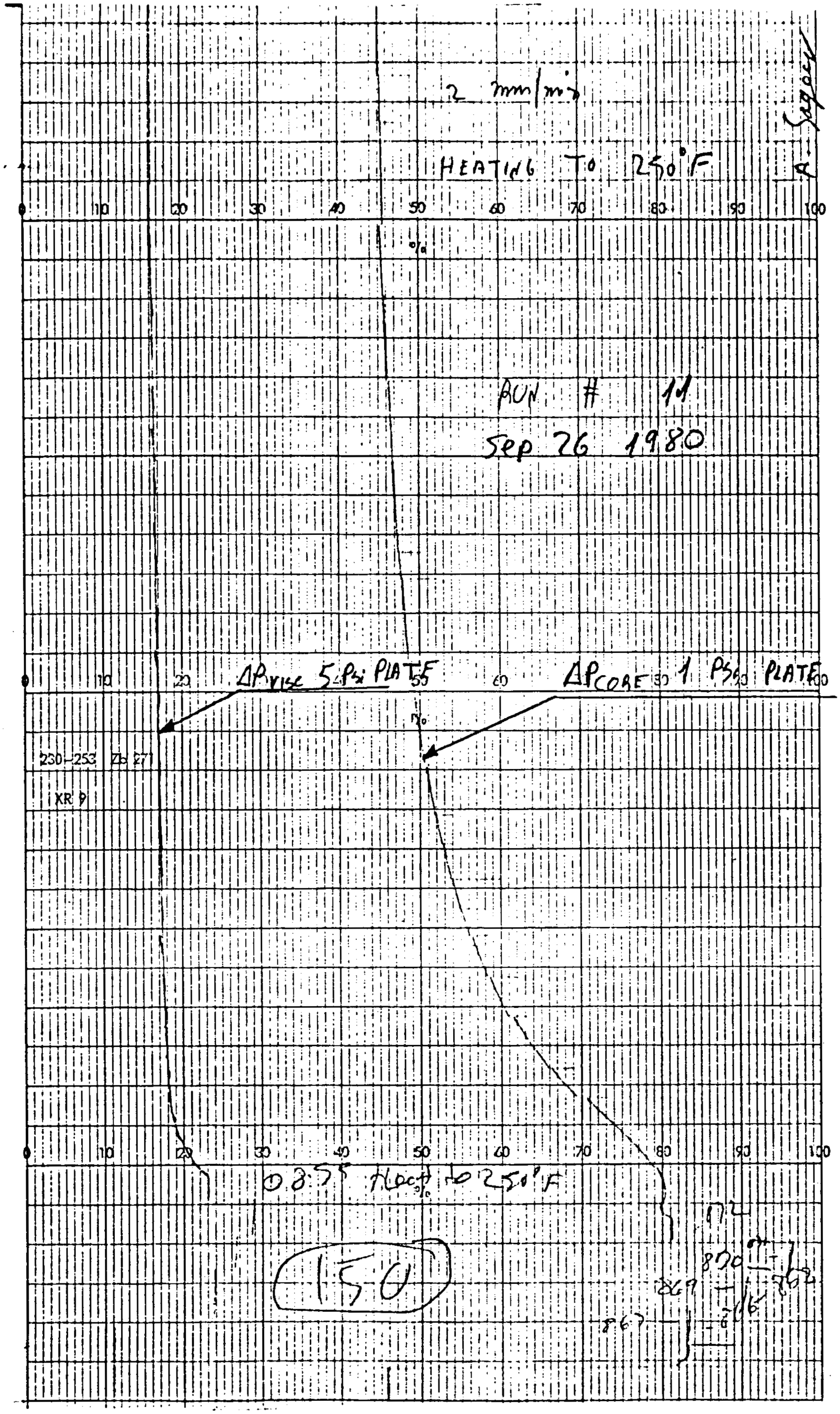
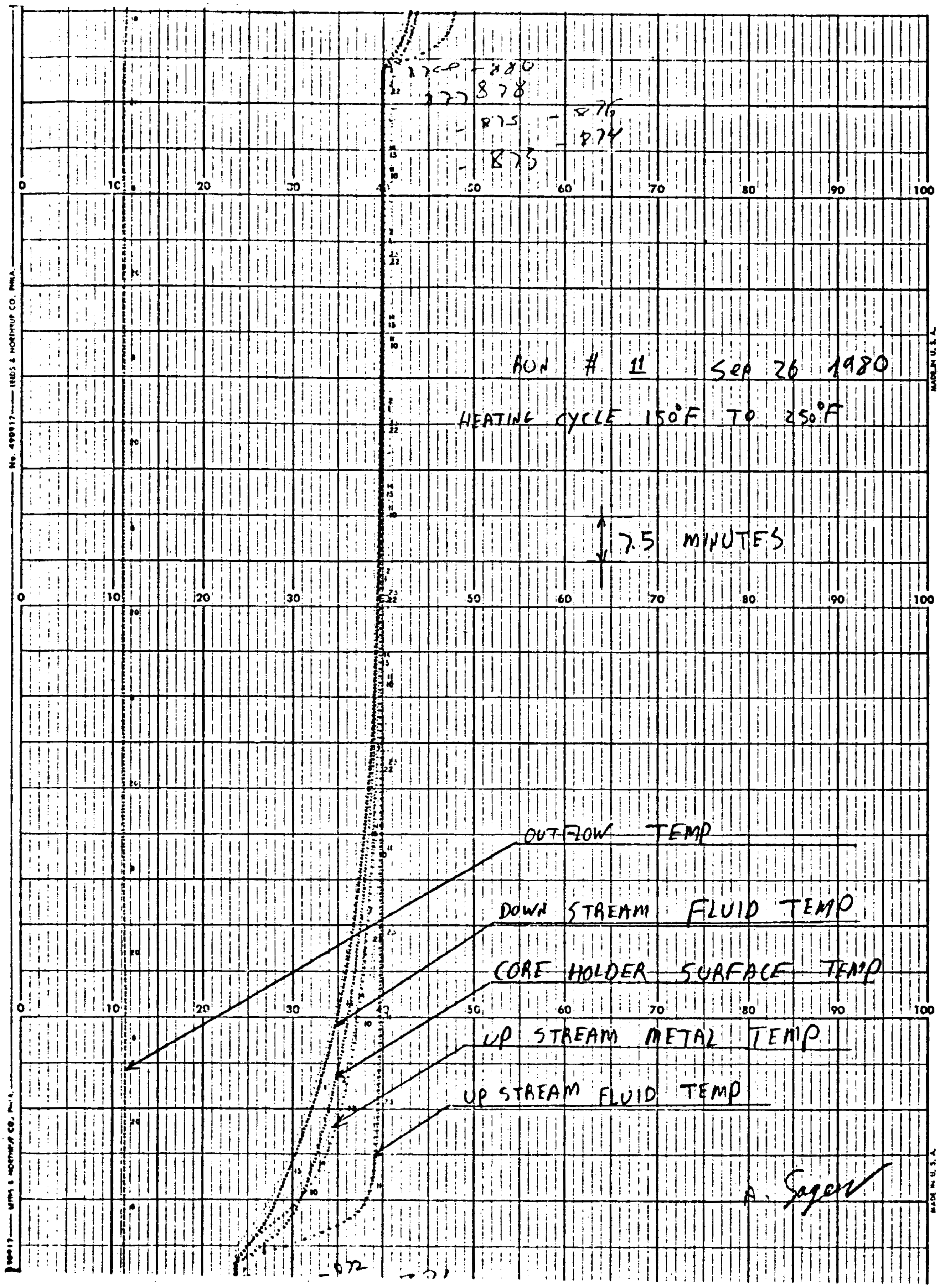


Figure 19 - PRESSURE DIFFERENTIAL RECORDING AT k MEASUREMENTS AND DURING HEATING



.**Figure** 20 – HEATING **CYCLE** PROFIEE: 150°F to 250°F, RUN #11 the confining pressure requires control. Open valve 34 and pump the pressure back to 2000 psig. Close valve 34. The gauge will read 2200 psig. Subtracting 200 psig for the average pore pressure will yield a confining pressure of 2000 psig.

4.20 Stopping the Flow

1. Close valve 7.
2. Close valve 1.
3. Close valve 27.
4. Stop the pump.
5. Close valve 29.
6. Open valve 7 and bleed the pressure to 0.
7. Shut down the recorders and the indicators.
8. Shut down the cooling water.

4.21 Confining Pressure Bleed Off

Open valve 33 and bleed the confining pressure slowly. Make sure the core pressure has dropped to zero before bleeding the confining pressure.

4.22 Removing the Core Holder

1. Disconnect the down stream pressure tap.
2. Remove the upstream pressure tap.
3. Disconnect the upstream metal and surface thermocouples.
4. Disconnect the upstream and down stream ports.
5. Close valve 33.
6. Disconnect the confining port.
7. Remove the core holder.

4.23 Taking the Core Holder Apart and Inspecting It

1. Put protectors on all six Swagelock fittings.
2. Set the core holder in vise, flanges up. Take the bolts apart.
3. Work the core plugs and core out with two screwdrivers.
4. Take the core plugs off.
5. Inspect: Sand Face
   Screens
   "0" rings
   Viton tubing

4.24 Problems

The main problems were filter and valve plugging.

4.24.1 Filter plugging

When the upstream filter plugs, switch to the other as follows:

Close valve 7

Switch valve 2 to the other filter

Open valve 7 (start the flow).

This procedure will not shock the system. Keep valves 3 and 4 always open.

When the downstream filter plugs, do the following:

Close valve 7

Close valve 31

Remove filter and change the element

Reinstall the filter

Open valve 31 until the flow is zero

Open valve 31 completely

Open valve 7 to start the flow.

4.24.2 Plugging of the down stream needle valve

This problem is common. Particles of 6µ and smaller will pass through the filters, but will not pass the valve. Tapping the valve casing will usually clean it. Sometimes it is necessary to open the valve completely. To do that, divert the flow to valve 6, then work valve 7 a few times, and direct the flow back to valve 7.

In most of the runs this problem disappeared after the first heating cycle.

5. Summary of Results

In this section, the calculation of permeability is shown and a sample calculation is presented. Finally, the results of the runs and a discussion are presented.

5.1 Permeability Calculations

The core used in this experiment has a cylindrical shape. The fluid flows in the axial direction through a circular cross section. The flow is considered linear and laminar. Laminar flow is guaranteed if the Reynolds number is less than unity:

$$R_e = \frac{\rho v d}{\mu} < 1.0 \tag{5-1}$$

where: ρ = density, g/cc
v = velocity, cm/sec
d = average grain diameter, cm
μ = viscosity of the flowing liquid, g/cm-sec

For the highest flow rate of about 1000 cc/hour at 300°F and with the unconsolidated sand used in this study:

ρ = 0.918 g/cc
v = 0.0525 cm/sec
$d = 160\,\mu = 0.016$ cm
μ = 0.1829 cp = 0.001829 g/cm-sec

And the corresponding Reynolds number is:

$$R_e = \frac{(0.918)\ (0.0525)\ (0.016)}{(0.001829)} = 0.42 < 1.0$$

For a linear laminar flow, Darcy's law applies:

$$q = k\,\frac{A\,\Delta p}{\mu L} \tag{5-2}$$

where: **q** = cc/sec at flow conditions
A = cm^2
Ap = at (1.0333 kg/cm^2)
L = cm
μ = cp
k = Darcies

Rearranging for **k:**

$$k = \frac{q \mu L}{A \Delta p} \qquad (5\text{-}3)$$

L and **A** are measured with a micrometer. q_{sc} is measured at room conditions and must be converted to q_{res}:

$$q_{res} = q_{sc}\left(\frac{\nu_T}{\nu_{sc}}\right) = \left(\frac{V_{sc}}{t}\right)\left(\frac{\nu_T}{\nu_{sc}}\right) \qquad (5\text{-}4)$$

where: ν = specific volume, cf/lb
V_{sc} = measured in the burette, usually 10 cc
t = time to flow V_{sc}, sec.

Ap is measured in psi, and is converted to atmospheres by:

14.696 Ap **,** .psi = **1** atm

This yields:

$$k = \frac{\left(\frac{V_{sc}}{t}\right)\left(\frac{\nu_T}{\nu_{sc}}\right)(\mu_T)(L)(14.696)}{(A)\ (\Delta p)} = \frac{(14.969)(V_{sc})(\nu_T)(\mu_T)(L)}{(A)\ (\Delta p)\ (t)\ (\nu_{sc})} \qquad (5\text{-}5)$$

Assuming that V_{sc} = 10 cc, and **A** = 5.292 cm^2, equation *(5-5)* becomes:

$$k,\ \text{Darcies} = 27.7677\ \frac{\left(\nu_T, \frac{ft^3}{lb}\right)\ (\mu_T,\ cp)\ (L,\ cm)}{(\Delta p,\ psi)\ (t,\ sec)\ \left(\nu_{sc}, \frac{ft^3}{lb}\right)} \qquad (5\text{-}6)$$

Any units may be used for the specific volume terms as long as both terms are consistent. The viscosity, μ **,** at run temperature is obtained from published data. Table **1** presents liquid water viscosity, and Figure 21

Table 1 - Water Viscosity

T, °F	Viscosity at Saturation Temp. *		Viscosity at 200 psi ***		$\frac{\mu_p}{\mu_{sat}}$	
	$10^3 \mu \frac{lb}{ft\ sec}$	μ, cp	$10^7 \mu \frac{lb\ sec}{ft^2}$	μ, cp		
32	1.20	1.786	366.0	1.752	0.9810	
40	1.04	1.548				
50	0.88	1.310	271.3	1.299	0.9916	
60	0.76	1.131		1.128	0.9927	**
70	0.658	0.9792		0.9732	0.9939	
80	0.578	0.8602		0.8561	0.9952	
90	0.514	0.7649		~~0.8561~~ 0.7621	0.9964	
100	0.458	0.6816	142.0	0.6799	0.9975	
150	0.292	0.4345	89.1	0.4266	0.9818	
200	0.205	0.3051	62.7	0.3002	0.9839	
250	0.158	0.2351	47.6	0.2279	0.9694	
300	0.126	0.1875	38.2	0.1829		
350	0.105	0.1563	31.8	0.1523		
400	0.091	0.1354				
450	0.080	0.1191				
500	0.071	0.1057				
550	0.064	0.0952				
600	0.058	0.0863				

* Principles of Heat Transfer, Kreith (1973).

**Completed Using Figure 23

***ASME Steam Tables, p. 280, table 10

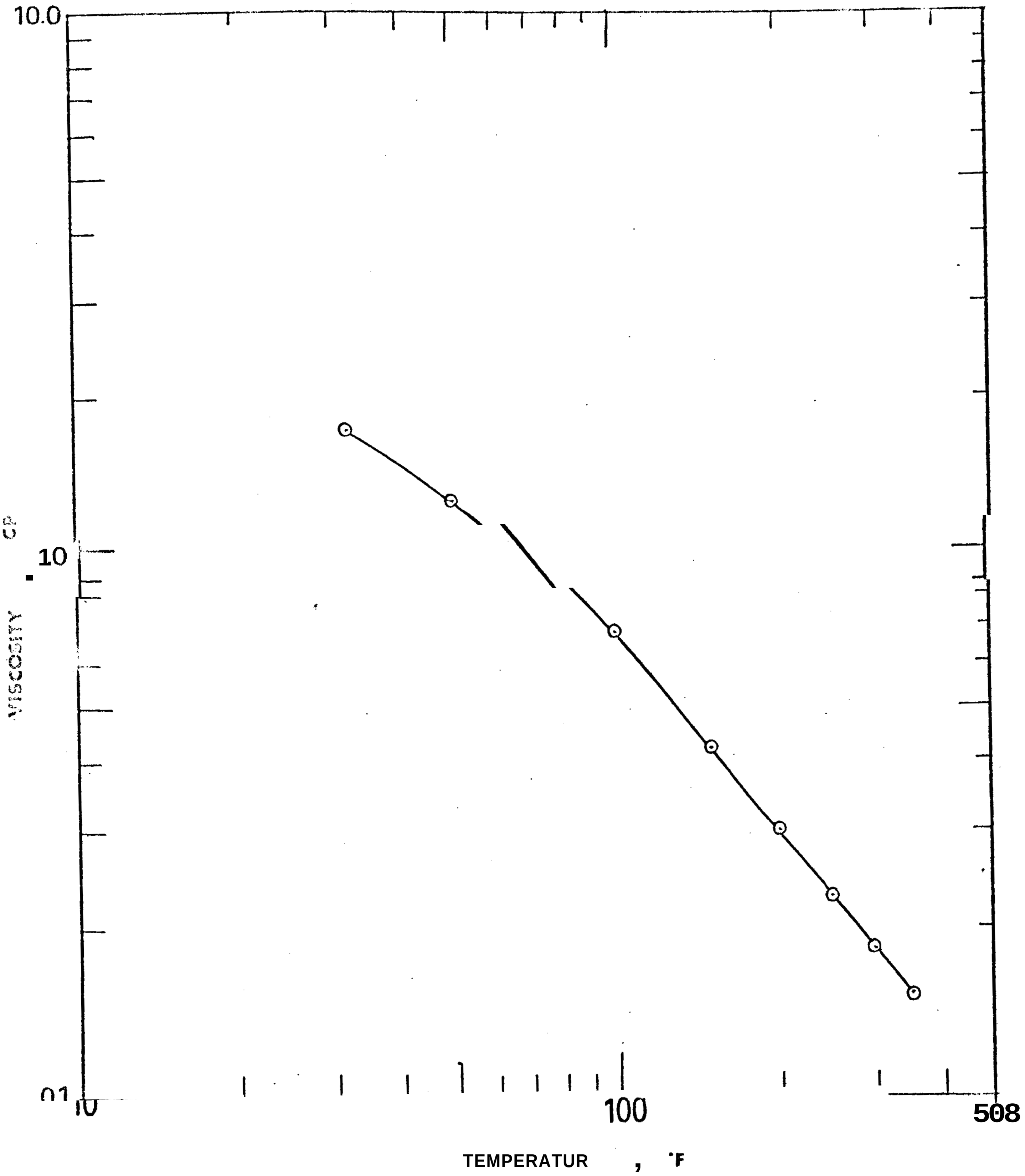


Figure 21 - VISCOSITY OF WATER vs TEMPERATURE AT 200 PSIA

is a graphical presentation. The effect of viscosity on permeability ,determination is given in the error analysis., section 5.2.

A sample calculation of the permeability at a given constant temperature follows. This example will establish the permeability for a case in run 11:

T = 250°F
Second cooling cycle
Record of measurements: 889–896

Measurement 889 will follow:

Date: September 26, 1980
$\Delta p_{core} = 0.664$ psi
$V = 10$ cc
$t = 60.75$ sec
$T_{sc} = 74$°F

From Table 4:

$\mu_{250} = 0.2279$ cp
$\nu_{250} = 0.016990$ ft^3/lb
$\nu_{74} = 0.016048$ ft^3/lb
$L = 15.9906$ cm
$A = 5.2924$ cm^2

Hence, equation (5–6) yields:

$$k_{250} = 27.7677 \frac{(0.016990)\ (0.2279)\ (15.9906)}{(0.664)\ (60.75)\ (0.016048)} = 2.656 \text{ Darcy}$$

This calculation was done for eight measurements at this temperature and the average of the eight is:

$$k_{250} = 2.673 \text{ Darcy}$$

The eight values of k_{250} are presented in Figure 28. The average value $\bar{k}_{250}$ is presented in Figure 29.

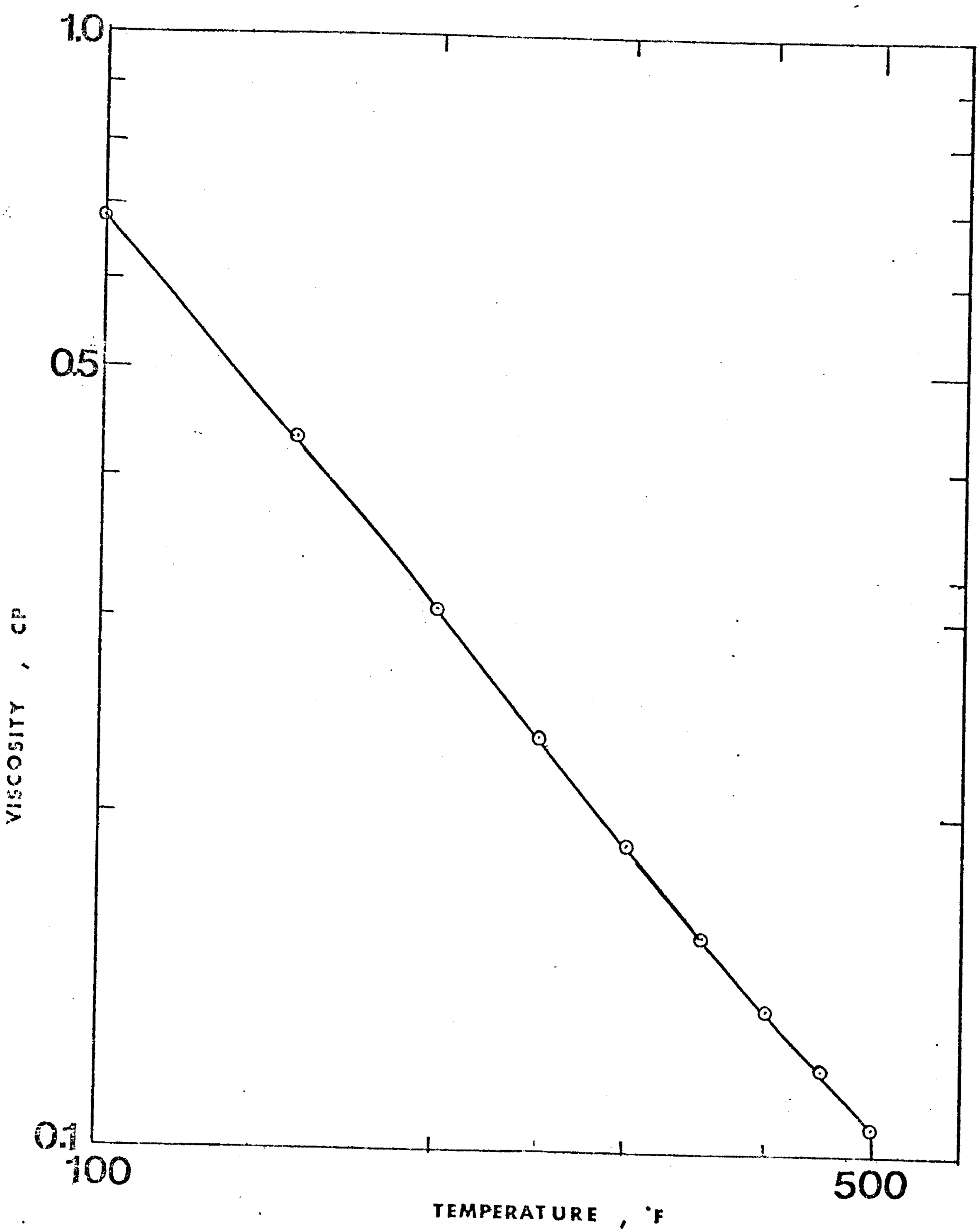


Figure 22 - VISCOSITY OF WATER vs TEMPERATURE AT SATURATION PRESSURE

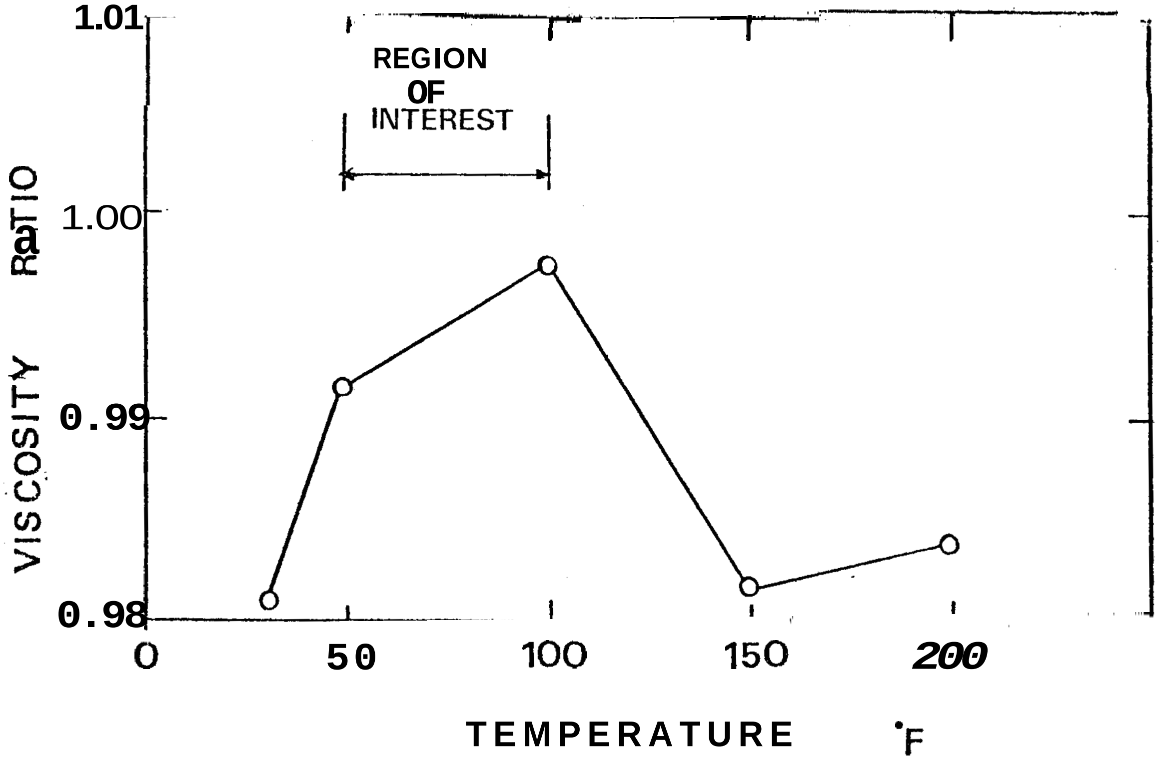


Figure 23 - μ_p/μ_{sat} vs TEMPERATURE

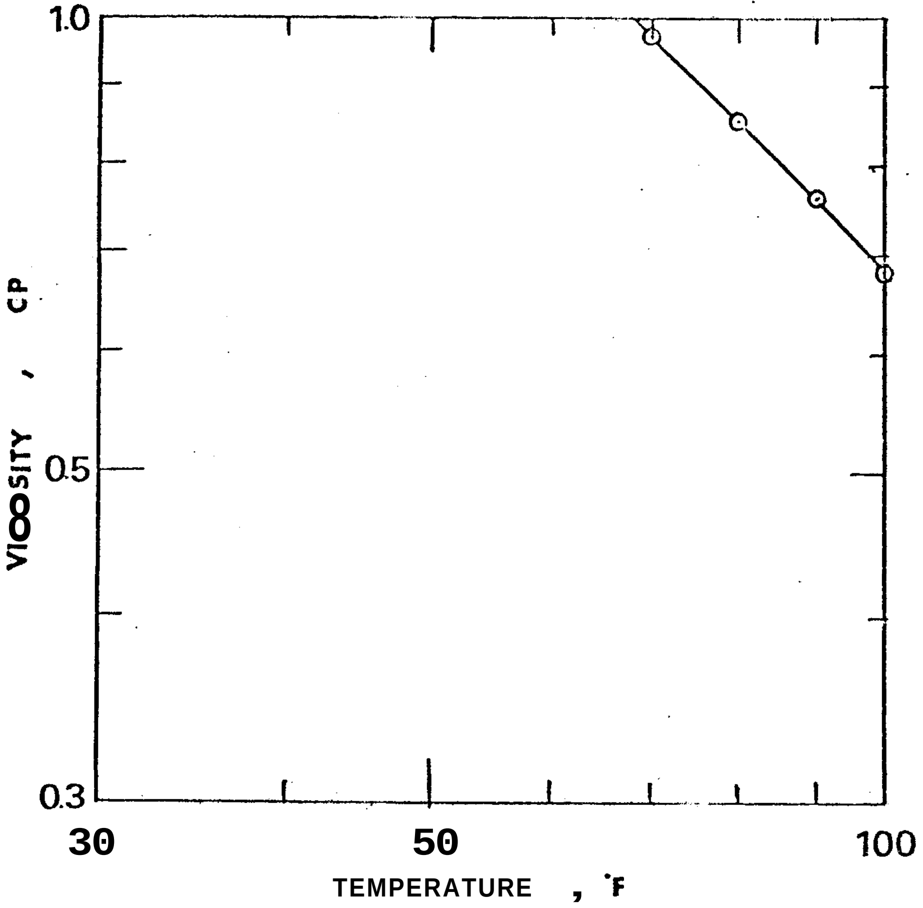


Figure 24 – VISCOSITY vs TEMPERATURE AT 200 PSIA
(Improved Range – 70°F to 100°F)

Temp Fahr t	Abs Press. Lb per Sq In. p	Specific Volume			Enthalpy			Entropy			Temp Fahr t
		Sat. Liquid v_f	Evap v_{fg}	Sat. Vapor v_g	Sat. Liquid h_f	Evap h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Evap s_{fg}	Sat. Vapor s_g	
110.1	75110	0.016510	50.21	5022	14800	990.2	1138.2	0.2631	1.5480	1.8111	180.0
111.1	7.850	0016522	48.172	18.189	150.01	989.0	1139.0	02662	1.5413	14075	182.0
184.0	8 203	0016534	46.232	46.249	152.01	987.8	1139.8	0.2694	1.5346	1.8040	184.0
186.0	a 568	0016517	44.383	44 400	154.02	986.5	1140.5	02725	15279	1.8004	186.0
188.0	8.947	0.016553	42.621	42.638	156 03	9u.3	11413	02756	1.5213	1.7969	188.0
190.0	9 340	0016572	40.941	40.957	158.04	984.1	1142.1	0.2787	15148	1.7934	190.0
192.0	9.747	0.016585	39.337	39.354	160.05	982.8	1142.9	0.2818	1.5082	1.7900	192.0
194.0	10.168	0016598	37.808	37.824	162 05	981.6	1143.7	0.2848	1.5017	1.7865	194.0
196.0	10.605	0016611	36.348	36.364	164 06	980.4	1144.4	0.2879	1.4952	1.7831	196.0
198.0	11.058	0.016624	34.954	34.970	166.08	979.1	11452	02910	1411118	1.7798	111.1
200.0	11.526	0 016637	33 622	33.639	16809	977.9	1146.0	0.2940	14024	1.7764	1d0.1
204J	12.512	0 016664	31.135	31.151	172.11	975 4	1147.5	0.3001	14697	1.7698	204.0
208.0	13.568	0 016691	28 862	28.878	176.14	972.8	1149.0	03061	1.4571	1.7632	208.0
212.0	14 696	0.016719	26.782	26.799	180.17	970.3	1150.5	03121	14447	1.7568	212.0
216.0	15.901	0 016747	24.878	24894	18420	967.8	1152.0	03181	1.4323	1.7505	216.0
220.0	17.186	0.016775	23.131	23.148	118.23	965.2	1153.4	03241	1 4201	1,7442	220.0
114J	18 556	0016805	21.529	21.545	19227	962.6	1154.9	03300	1.4081	1.7380	224.0
228.0	20.015	0 016834	20 056	20.073	196.31	960 0	1156.3	0.3359	1.3961	1.7320	*111.1*
232.0	21.567	0 016864	18.701	18.718	70035	957.4	1157.8	0.3417	13842	1.7260	232.0
236.0	23.216	0.016895	17.454	17.471	204.40	954.8	1159.2	03476	13725	1.7201	236.0
240.0	14.968	0.016926	16.304	16.321	208 45	952.1	1160.6	0.3533	1.3609	1.7142	240.0
244.0	26 826	0.016958	15.243	15.260	212.50	949.5	1162.0	03591	13494	1.7085	244J
248.0	28.796	0.016990	14.264	14.281	21636	946 8	1163.4	0.3649	13379	1,7028	141.1
252.0	30.883	0.017022	13.358	13.375	220.62	944.1	1164.7	03706	13266	1.6972	252.0
256.0	33.091	0017065	12.520	12.538	224.69	941.4	1166.1	03763	13154	1.6917	256.0
260.0	35.427	0.017089	11.745	11.762	228.76	938.6	1167.4	0.3819	1.3043	1.6862	260.0
264.0	37.894	0.017123	11.025	11.042	232.83	935.9	1168.7	0.3876	13933	1 6808	264.0
268.0	40.500	0.017157	10 358	10.375	236.91	933.1	1170.0	03932	1.2823	1.6755	268.0
272.0	43.249	0017193	9.738	9.755	240.99	930.3	1171.3	0.3987	12715	11.6702	171J
276.0	46.147	0.017228	9.162	9.180	245.08	927.5	11725	0 4043	12607	1.6650	276.0
280.0	49.200	0.017264	8.627	8 644	249.17	924.6	1173.8	04098	1.2501	1.6599	111.1
284.0	52.414	0.01730	*8.1180*	8 1453	253.3	921.7	1175.0	0.4154	12395	1.6548	284J
288.0	55.795	001734	7.6634	7.6807	257.4	918.8	1176.2	0 4208	1.2290	1.6498	288.0
111.1	59.350	0 01738	72301	72475	261.5	915.9	1177.4	0 4263	1.2186	1.6449	292.0
296.0	63.084	001711	6.8259	6 8433	265.6	913.0	1178 6	04317	12082	1 6400	296.0
300J	67.005	0 01145	6 4483	6 4658	269.7	910.0	1179.7	04372	1.1979	1.6351	300.0
304.0	71.119	0 01749	6 0955	6.1130	273.8	907.0	11809	0 4426	1.1877	1.6303	304.0
308.0	75.433	0 01753	5.7655	5.7830	278.0	9M.0	1182.0	04479	1.1776	1.6256	308.0
312.0	79.953	0.01757	54566	54742	282.1	901.0	1183.1	04533	1.1676	1.6209	312.0
316.0	84.688	0.01761	5.1673	5.1849	286.3	897.9	1184.1	04586	1.1576	1.6162	316.0
111.1	89.643	0.01766	4.8961	4.9138	290 4	894.8	1185.2	04640	1.1477	1.6116	320.0
324.0	94.826	0.01770	4 6418	4.6595	294.6	891.6	11862	0 4692	1.1378	16071	324.0
328.0	100.245	0 01774	4 4030	4.4208	298.7	888.5	11872	04745	1.1280	16025	111.1
332.0	105.907	0 01779	4.1788	4.1966	302.9	8853	1188.2	0.4798	1.1183	13981	332.0
336.0	111.820	0 01783	3.9681	3.9859	307.1	882.1	1189.1	04850	1.1086	15936	336.0
nu	117.992	001787	3.7699	3.7878	3113	878.8	1190.1	04902	1.0990	1.5892	340.0
344.0	124.430	001792	3.5834	3 6013	315.5	875.5	1191.0	0 4954	1.0894	13849	344.0
348.0	131.142	0.01797	3407a	3.4258	319.7	872.2	1191.1	0 5006	1.0799	1.5806	YIJ
352.0	138.138	0.01801	32423	3.2603	323 9	868 9	1192.7	0.5058	1.0705	15763	352.0
356.0	145.424	0.01806	3 0863	3.1044	328 1	865.5	1193.6	0.5110	1.0611	15721	356.0
360.0	153.010	0.01811	2.9392	2.9573	332.3	862.1	11944	03161	1.0517	15678	360.0
364.0	160 903	001816	2.8002	2.8184	336.5	858 6	11952	0.5212	1.0424	1.5637	364.0
368.0	169 113	001821	2 6691	2 6873	340 8	855.1	1195.9	*03163*	1.0332	15595	368.0
372.0	177.648	0 01826	2.5451	2.5633	345.0	851.6	11%.7	03314	1.0240	13554	372.0
376.0	186.517	0.01831	2.4279	2 4462	349.3	848.1	1197.4	05365	1.0148	15513	376.0
380.0	195.729	001836	2.3170	23353	353.6	844.5	1198.0	0.5416	1.0057	15473	380.0
384.0	205294	0.01842	2.2120	2.2304	357.9	840.8	1198.7	0 5466	0.9966	1.5432	384.0
388.0	215220	001847	2.1126	2.1311	3622	a372	1199.3	0.5516	0.9876	1.5392	388.0
392.0	225516	0.01853	2.0184	2 0369	366.5	a33 4	1199.9	0.5567	0.9786	1.5352	392.0
396.0	236193	0.01858	1.9291	1.9477	370.8	829.7	1200 4	0.5617	0 9696	1.5313	1161
400.0	247259	0.01864	1.8444	1 8630	375.1	825.9	1201.0	0.5667	0.9607	1.5274	40H
404J	258.725	0.01870	1.7640	1.7827	3794	822.0	1201.5	0.5717	0.9518	1.5234	4MJ
408.0	270.600	0.01875	1.6877	1.7064	383.8	818.2	12013	0 5766	0.9429	13195	408.0
412.0	282.894	0.01881	1.6152	1.6340	388.1	8142	1202.4	0.5816	0334l	15157	412.0
416.0	295.617	0.01887	1.5463	1.5651	3923	810.2	1202.8	0.5866	0.9253	15118	416.0
420.0	308.780	0.01894	1.4808	1.4997	396.9	806.2	1203.1	0.5915	0.9165	1.5080	420.0
414J	322391	0.01900	14184	1.4374	4013	8022	1203.5	a5964	0.9077	1.5042	424.0
428.0	336463	0.01906	1.3591	13782	405.7	7980	1203.7	0 6014	0.8990	1.5004	428.0
432.0	351.00	0.01913	1.30266	132179	410.1	793.9	1204.0	0.6063	0.8903	1.4966	432.0
UIJ	366.03	0.01919	124887	1.26806	414.6	789.7	1204.2	0.6112	0.8816	1.4928	436.0
440.0	381.54	0.01926	1.19761	121687	419.0	785.4	1204.4	0.6161	0.8729	14890	441J
U 4 J	397.56	0 01933	1.14874	1.16806	4235	781.1	1204.6	0.6210	08643	1.4853	444.0
448.0	414.09	0.01940	1.10212	1.12152	4280	776.7	1204.7	0.6259	04557	1.4815	448J
452.0	431.14	0.01947	1.05764	107711	4325	7723	1204.8	0.6308	0.8471	1.4778	4UJ
456.0	448.73	0.01954	ID1511	I.03472	437.0	767.8	1204.8	0.056	0.8385	1.4741	456.0

Table 2: SPECIFIC **VOLUME OF** WATER AT SATURATION

From: Steam Tables by C-E Power Systems

T, °F	V, $\frac{ft^3}{lb}$
400.	2.3598
390.	2.3203
380.	0.01836
370.	0.01823
360.	0.01811
350.	0.01798
340.	0.01787
330.	0.01775
320.	0.01765
310.	0.01754
300.	0.01744
29u.	0.01735
280.	0.01725
270.	0.01716
260.	0.01708
250.	0.01699
240.	0.01692
230.	0.01684
220.	0.01676
210.	0.01669
200.	0.01663
190.	0.01656
180.	0.01650
170.	0.01644
160.	0.01639
150.	0.01633
140.	0.01628
150.	0.01624
120.	0.01619
110.	0.01616
100.	0.01612
90.	0.01609
80.	0.01606
70.	0.01604
60.	0.01602
50.	0.01601
40.	0.01601
32.	0.01601

Table **3:** SPECIFIC VOLUME OF WATER AT 200 PSIA

From: ASME Steam Tables, **p.** 159, Table **3**

Table 4 - Water Viscosity and Specific Volumes at -200 psig (used in the calculations)

T (°F)	μ (cp)	V ft^3/lb
69	0.992	0.016038
70	0.9732	0.016040
70.5	0.970	0.016041
71	0.964	0.016042
71.5	0.960	0.016043
72	0.953	0.016044
72.5	0.945	0.016045
73	0.940	0.016046
74	0.925	0.016048
75	0.915	0.016050
76	0.903	0.016052
77	0.890	0.016054
78	0.880	0.016056
79	0.870	0.016058
80	0.8561	0.016060
82	0.837	0.016066
148	0.4316	0.016320
149	0.4291	0.016325
150	0.4266	0.016330
151	0.4241	0.016335
152	0.4216	0.016340
153	0.4191	0.016345
155	0.4141	0.016355
248	0.2303	0.016960
249	0.2291	0.016975
250	0.2279	0.016990
251	0.2267	0.017005
252	0.2255	0.017020
298	0.1853	0.017420
299	0.1841	0.017430
300	0.1829	0.017440
301	0.1817	0.017450

5.2 Error Analysis

The usual approximation for the error, ΔG, of a function $G(x)$ is:

$$\Delta G = \sum_{i=1}^{n} \left| \frac{\partial G}{\partial x_i} \right| \Delta x_i \tag{5-7}$$

The basic equation for permeability is:

$$k = \frac{\nu_T \mu_T L V_{sc}}{\Delta p_T \, t \, \nu_{sc} A} \tag{5-8}$$

Substituting $A = \pi D^2/4$ and Δp in psi, equation (5-8) yields:

$$k = 18.71277 \, \frac{\nu_T \mu_T L V_{sc}}{\Delta p_T \, t \, \nu_{sc} D^2} \tag{5-9}$$

The absolute error in the permeability, Δk_{abs}, can be estimated by equation (5-7), yielding:

$$\Delta k_{abs} = k \left[\frac{\Delta V}{V} + \frac{\Delta \nu_T}{\nu_T} + \frac{\Delta L}{L} + \frac{\Delta \mu_T}{\mu_T} + \frac{2\Delta D}{D} + \frac{\Delta(\Delta p)}{\Delta p} + \frac{\Delta t}{t} + \frac{\Delta \nu_{sc}}{\nu_{sc}} \right] \tag{5-10}$$

The relative error in the permeability, Δk_{rel}, refers only to the variables measured in each calculation. Hence $2\Delta D/D$ and $\Delta L/L$ cancel from equation (5-10) leaving:

$$\Delta k_{rel} = k \left[\frac{\Delta V}{V} + \frac{\Delta \nu_T}{\nu_T} + \frac{\Delta \mu_T}{\mu_T} + \frac{\Delta(\Delta p)}{\Delta p} + \frac{\Delta t}{t} + \frac{\Delta \nu_{sc}}{\nu_{sc}} \right] \tag{5-11}$$

The A values are:

ΔV = 0.025 cc
AL = 0.00254 cm
AD = 0.00254 cm
Δ(Δp) = 0.01 psi
At = 0.05 sec
AT = 1°F

v and 11 are functions of T(°F). Table 5 presents Δν and Δμ for various temperatures.

Table 5 - Δμ, Av For Various Temperatures

T (°F)	Room∿75°F	150"	250°	300°
Δμ (cp)	0.01	0.0025	0.0012	0.0012
Av $\left(\frac{ft^3}{1b}\right)$	0.000001	0.000003	0.000008	0.000010

A sample calculation for Ak_{abs} and Δk_{rel} follows:

Run 11
T = 250°F
Second Cooling Cycle
Numbers of measurements: 889-896

Measurement 889 follows:

k = 2.656 d
V = 10 cm^3
v_T = 0.016990 $ft^3/1b$
μ_T = 0.2279 (cp)
L = 15.9906 cm
Ap = 0.664 psi
ν_{sc} = 0.016048 $ft^3/1b$
t = 60.75 sec.
D = 2.59588 cm.

$\Delta V = 0.0025 \text{ cm}^3$
$AL = 0.00254 \text{ cm}$
$AD = 0.00254 \text{ cm}$
$\Delta(\Delta p) = 0.01 \text{ psi}$
$At = 0.05 \text{ sec}$
$\Delta \nu_T = 0.000008 \text{ ft}^3/\text{lb}$
$Av_{sc} = 0.000001 \text{ ft}^3/\text{lb}$
$\Delta \mu = 0.0012 \text{ cp}$

$$\Delta k_{abs} = 2.656 \left[\frac{0.025}{10} + \frac{0.000008}{0.016990} + \frac{0.00254}{15.9906} + \frac{0.0012}{0.2279} + \frac{2 \times 0.00254}{2.59588} + \frac{\cancel{0.01}}{0.665} + \frac{0.05}{0.665} + \frac{0.000001}{0.016048} \right] = 2.656 \left[0.037066 \right] = 0.098 \text{ darcy} = 98 \text{ md}$$

$\boxed{\Delta k_{abs} \text{ is about } 3.7\%}$

$$\Delta k_{rel} = 2.656 \left[\frac{0.025}{10} + \frac{0.000008}{0.016990} + \frac{0.0012}{0.2279} + \frac{0.01}{0.665} + \frac{0.05}{60.75} + \frac{0.000001}{0.016048} \right] =$$

$$2.656 \quad 0.02399 = 0.064 \text{ d} = 64 \text{ md}$$

$\boxed{\Delta k_{rel} \text{ is about } 2.4\%}$

For the above set of k, at 250° eight different Ak_{rel} for various flowrates were calculated. The average error was found, $\overline{\Delta k}_{rel}$. Δk_{rel} is indicated by vertical bars on Figure 29.

The objective **is** the relative change in the permeability as a function of the temperature and not the variation **in** the initial permeability of every core. A constant measuring procedure was used for all the reported runs. For a more detailed description, *see* Section *4.*

5.3 Results of Runs *8*, *9*, **10,** and **11**

Table *6* presents the $\overline{k}$ and $\overline{k}_{rel}$ for all the runs, Figures *25*, *26*, 27, **and** 28 present the calculated k for **all** runs.

The lines go through the $\bar{k}$ values. Table 6 summarizes all the runs and Figure 29 presents them in a graphical way. All data is tabulated in Tables 7 - 10.

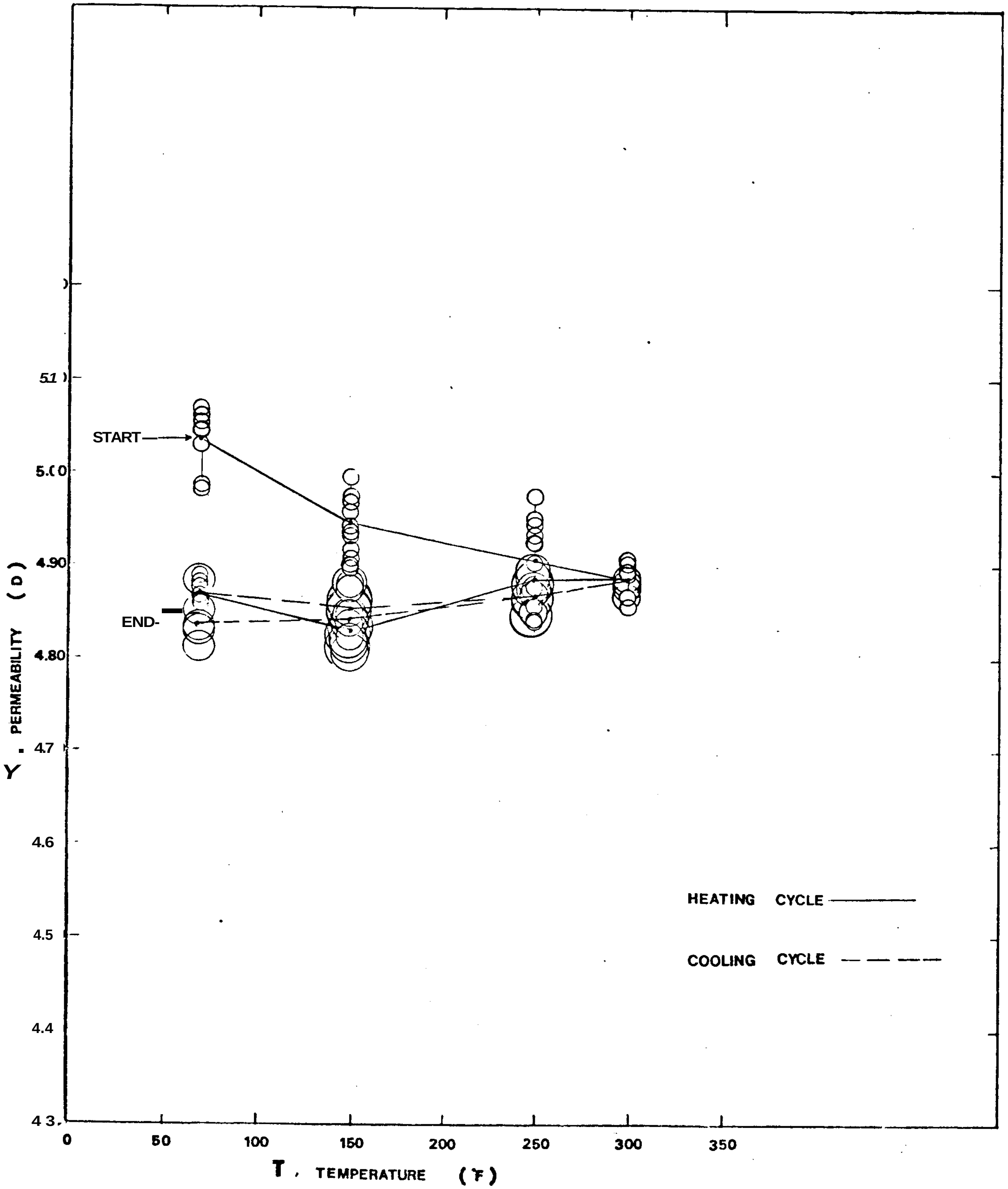


Figure 25: PERMEABILITY vs TEMPERATURE FOR 150 MESH SAND

RUN #8

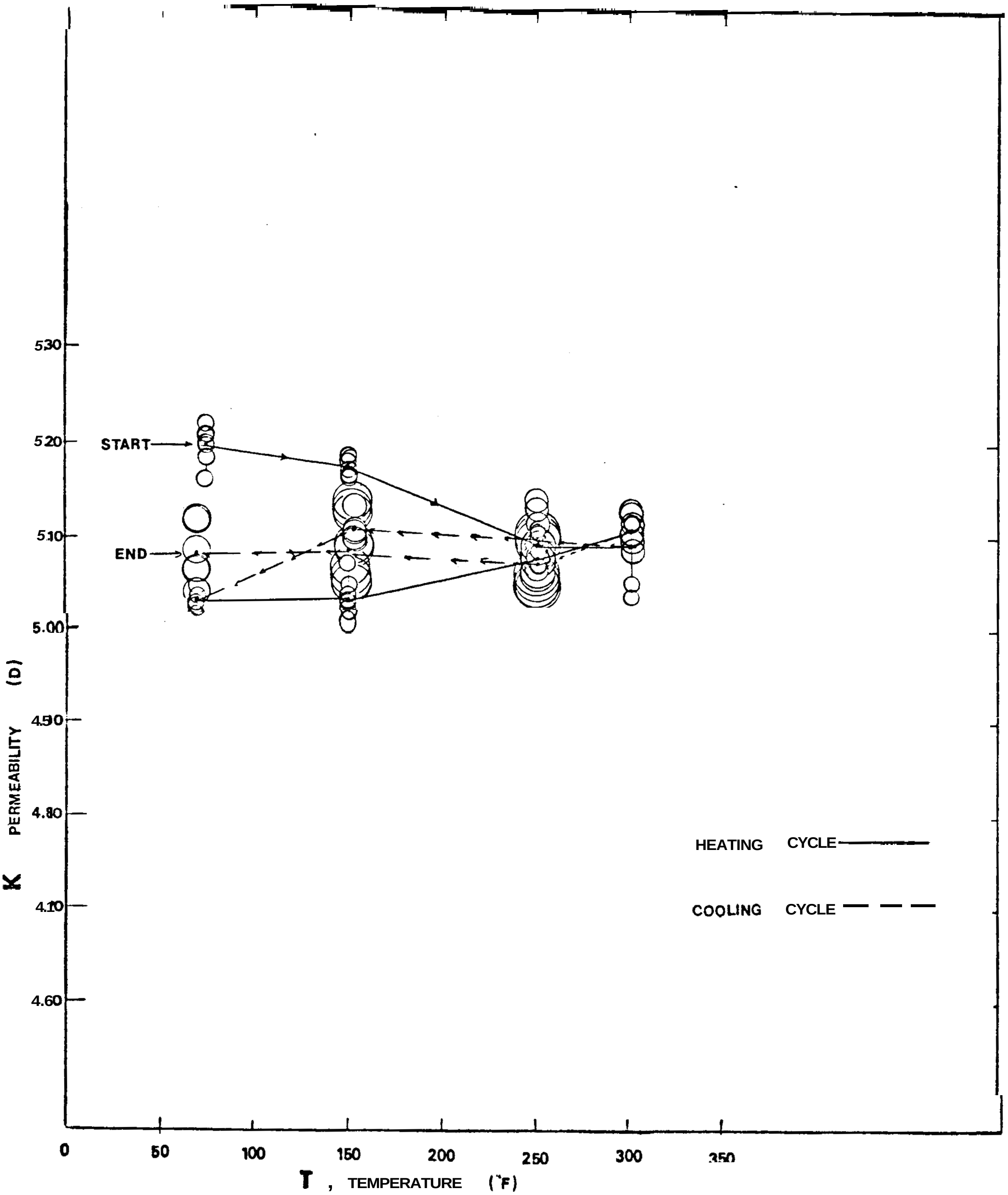


Figure 26: PERMEABILITY vs TEMPERATURE FOR 150 MESH **SAND**

. RUN #9

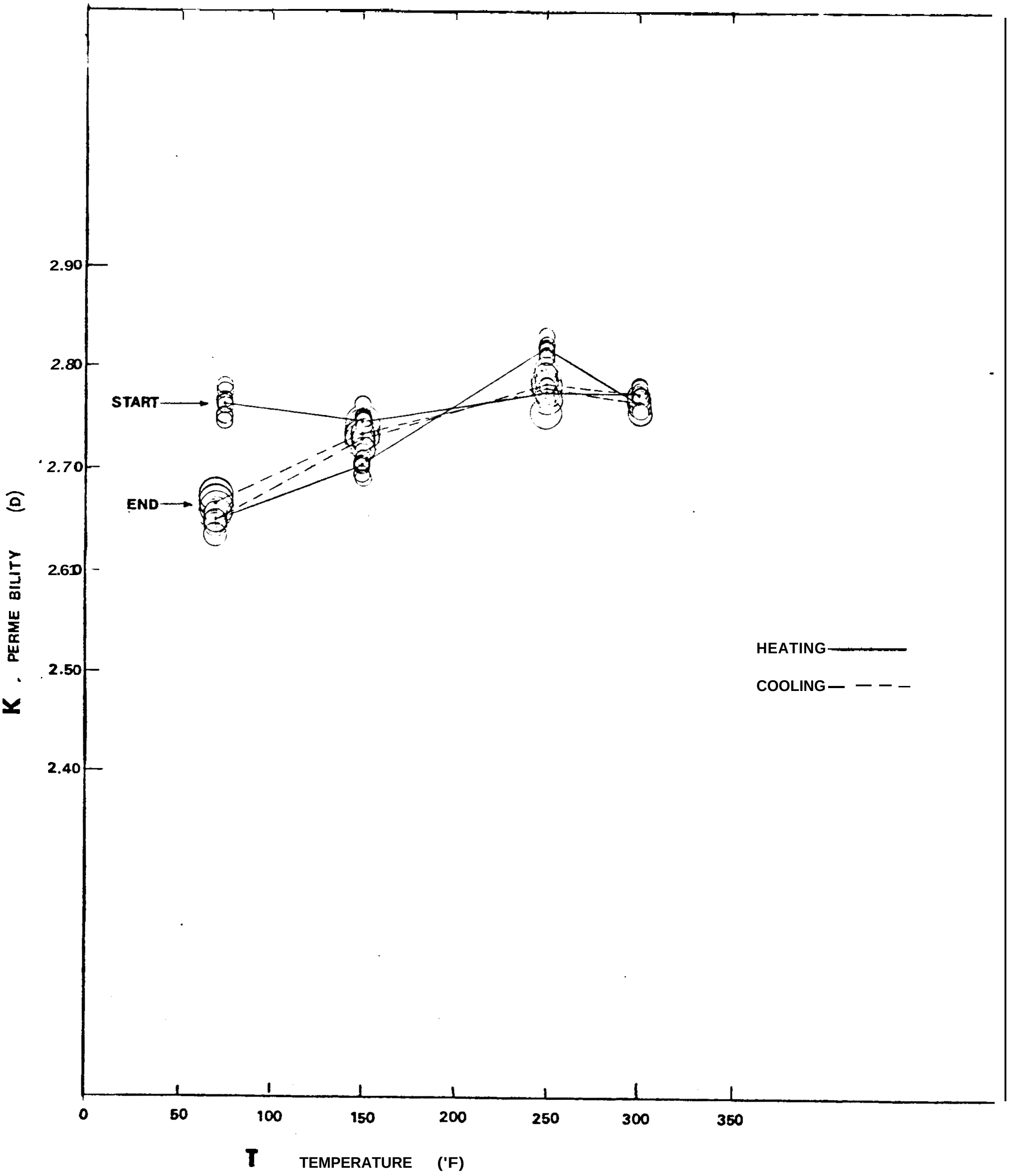


Figure 27: PERMEABILITY vs TEMPERATURE FOR 200 MESH SAND

RUN #10

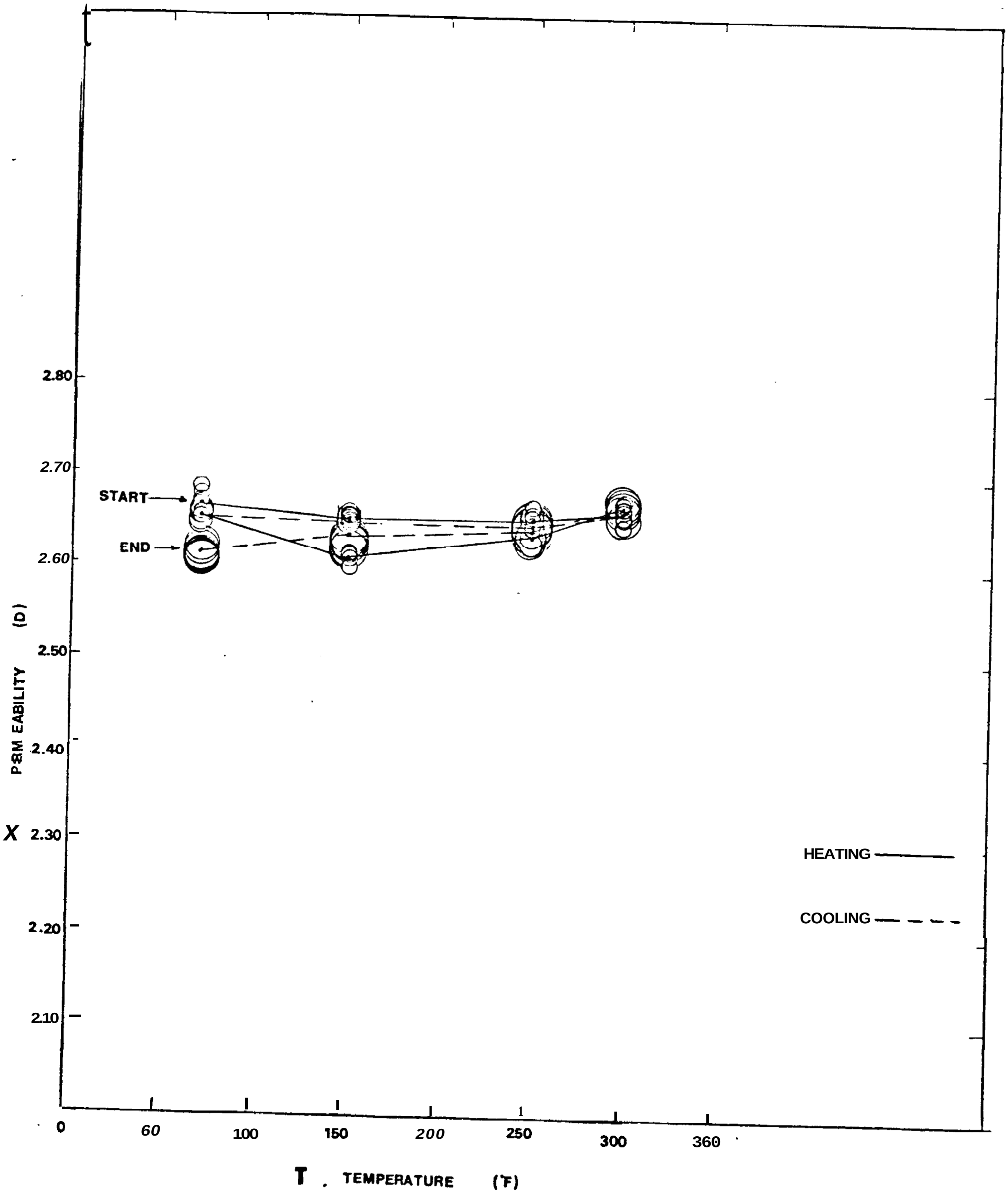


Figure 28: PERMEABILITY vs TEMPERATURE FOR 200 MESH SAND

RUN #11

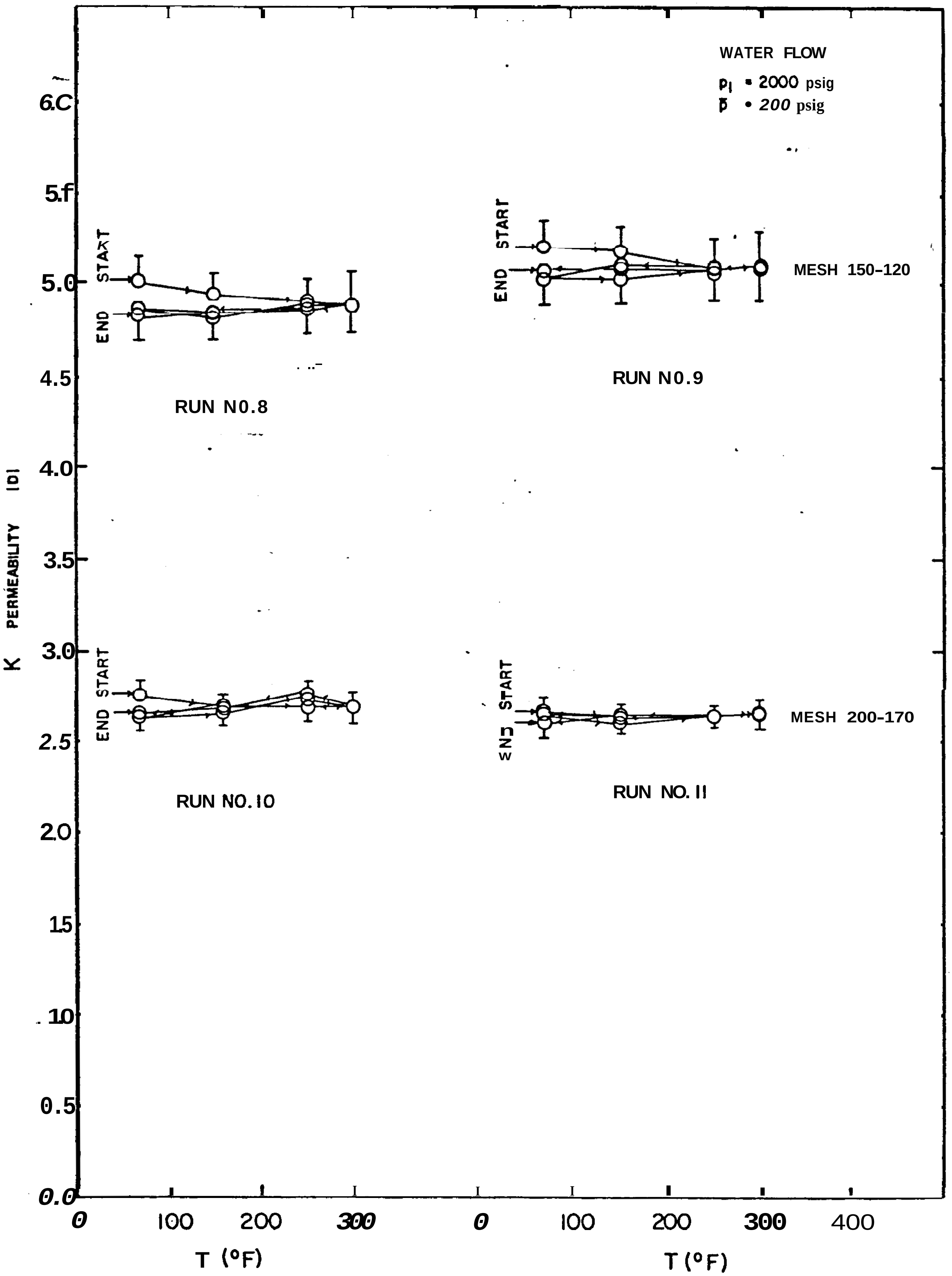


Figure 29 - PERMEABILITY VS TEMPERATURE FOR RUNS 8, 9, 10, and 11

6. Conclusions

The absolute permeability to distilled water of Ottawa silica sand was not dependent upon the temperature level from 70°F to 300°F. This result does not agree with much of the data in the literature. It is believed that some of the work done at Stanford University in recent years experienced mechanical problems that resulted in flow rate dependent permeability measurements which were interpreted as temperature dependent results. A sensitivity analysis of the apparatus helped in identifying sources of trouble. These problems were addressed and the performance of the apparatus improved.

In order to expand these conclusions it is recommended that future experiments be conducted, These experiments could study a range of consolidated sandstones, fluids, and confining and pore pressures. Then a study of the effect of temperature level on relative permeability should be resumed.

7. References

Amyx, J. W., Bass, D. M., Jr., and Whiting, R. L. Petroleum Reservoir Engineering, McGraw-Hill Book Company, Inc., New York, 1960.

Aruna, M. "The Effect of Temperature and Pressure on Absolute Permeability of Sandstones," Ph.D. Dissertation, Stanford University, 1976.

Cassé, F. J. "The Effect of Temperature and Confining Pressure on Fluid Flow Properties of Consolidated Rocks," Ph.D. Dissertation, Stanford University, 1974.

Danesh, A., Ehlig-Economides, C., and Ramey; H. J., Jr., "The Effect of Temperature Level on Absolute Permeability of Unconsolidated Silica and Stainless Steel," Transactions, Geothermal Resources Council, 2 (July, 1978), 137-139.

Gobran, B. D., Sufi, S. H., Sanyal, S. K., and Brigham, W. E. "Effects of Temperature on Permeability," Fossil Energy, 1980 Annual Heavy Oil/EOR Contractor Presentations-Proc., July 22-24, 1980.

Keenan, J. H., Keyes, G. F., Hill, G. P., and Moore, G. J. Steam Tables, English Units, Wiley and Sons, New York, 1969.

Kreith, F. Principles of Heat Transfer, Third Edition, Harper and Row Publishers, New York, 1973.

Muskat, M. Flow of Homogeneous Fluids Through Porous Media, McGraw-Hill Book Company, Inc., 1937.

Sanyal, S. K., Marsden, S. S., Jr., and Ramey, H. J., Jr. "Effect of Temperature on Petrophysical Properties of Reservoir Rocks," 49th Annual Fall Meeting, Houston, Texas, Society of Petroleum Engineers No. 4898, October 1974.

Sydansk, R. D. "Aqueous Permeability Variation with Temperature in Sandstone," Jour. Pet. Tech. August 1980, 1329-1330.

Thermodynamics and Transport Properties of Steam, American Society of Mechanical Engineers, New York, 1967.

Weinbrandt, R. M., Ramey, H. J., Jr., and Cassé, F. J. "Relative and Absolute Permeability of Sandstones," Society of Petroleum Engineering Journal, (October, 1975), 376-384.

8. Tables of Data

Table 6 - $\overline{k}_T$ and $\overline{\Delta k}_T$ for Runs 8, 9, 10, and 11. (Darcies)

Run \ T(°F)	Room 70°F-72°F	150	250	350
8	5.033/0.134	4.947/0.188	4.906/0.148	4.886/0.168
	4.869/0.133	4.851/0.119	4.868/0.151	
		4.828/0.115	4.883/0.152	4.889/0.175
	4.835/0.124	4.841/0.129	4.866/0.147	
9	5.201/0.144	5.180/0.133	5.094/0.160	5.094/0.199
	5.032/0.131	5.112/0.128	5.101/0.166	
		5.034/0.127	5.081/0.163	5.113/0.193
	5.086/0.145	5.089/0.136	5.058/0.163	
10	2.764/0.073	2.702/0.059	2.691/0.059	2.694/0.066
	2.642/0.066	2.695/0.063	2.699/0.059	
		2.658/0.059	2.739/0.060	2.700/0.074
	2.666/0.067	2.680/0.059	2.769/0.063	
11	2.671/0.067	2.652/0.055	2.652/0.060	2.663/0.068
	2.653/0.067	2.649/0.054	2.647/0.058	
		2.610/0.054	2.635/0.061	2.666/0.071
	2.612/0.067	2.634/0.054	2.646/0.062	

Table 7

Run no. 8: L = 16.350 cm; A = 5.293 cm^2; Mesh = 120-150; p_c = 2000 psig;

$\overline{p}$ = 200 psig

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
491	9/12/80	0.938	10	92.10	71	71	5067
492	"	0.938	"	92.80	"	"	5029
493	"	0.938	"	92.50	"	"	5045
494	"	0.739	"	117.05	"	"	5060
495	"	0.739	"	117.80	"	"	5028
500	"	0.553	"	156.65	"	"	5053
501	"	0.553	"	157.10	"	"	5038
504	"	0.724	"	116.90	73	73	5043
506	"	0.881	"	100.70	70	69	4981
507	"	0.882	"	100.50	"	"	4985
508	9/14/80	0.9115	"	43.35	152	68	4936
509	"	0.9115	"	43.40	"	"	4931
510	"	0.9115	"	43.30	"	"	4942
511	"	0.714	"	54.90	"	"	4976
512	"	0.714	"	54.70	"	"	4994
513	"	0.4675	"	83.65	"	"	4988
514	"	0.4675	"	83.50	"	"	4997
515	"	0.7275	"	54.10	"	"	4956
516	"	0.7275	"	53.90	"	"	4974
517	"	0.928	"	42.90	"	"	4900
518	"	0.928	"	42.75	"	"	4917
519	"	0.928	"	42.85	"	"	4905
520	"	0.461	"	46.42	"	"	4896
521	"	0.431	"	51.85	250	73	4903
522	"	0.416	"	54.40	"	"	4872
523	"	0.552	"	40.30	"	"	4925
524	"	0.552	"	40.15	"	"	4944
525	"	0.550	"	40.40	"	"	4931
526	"	0.323	"	69.85	"	"	4856
527	"	0.600	"	36.70	"	"	4976
528	"	0.581	"	38.10	"	"	4950
529	"	0.517	"	43.80	"	"	4839
530	"	0.544	"	40.90	"	"	4925
531	"	0.4155	"	54.10	"	"	4874
532	"	0.493	"	37.70	300	75	4855
533	"	0.487	"	37.85	"	"	4896
534	"	0.349	"	52.70	"	"	4906
535	"	0.378	"	49.05	"	"	4867
536	"	0.432	"	42.60	"	"	4903
537	"	0.435	"	42.40	"	"	4893
538	"	0.394	"	57.05	250	73	4849

Table 7

Run no. 8: L = 16.350 cm; A = 5.293 cm^2; Mesh = 120-150, p_c = 2000 psig;

$\bar{p}$ = 200 psig

Number of Measurements	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
539	9/14/80	0.394	10	56.80	250	73	4870
540	"	0.538	"	41.75	"	"	4852
541	"	0.538	"	42.15	"	"	4809
542	"	0.538	"	41.75	"	"	4852
543	"	0.582	"	38.45	"	"	4870
544	"	0.582	"	38.75	"	"	4833
545	"	0.370	"	60.95	"	"	4833
546	"	0.370	"	61.15	"	"	4817
547	9/15/80	0.941	"	41.80	155	72	4873
548	"	0.942	"	42.20	"	"	4822
549	"	0.770	"	51.45	"	"	4838
550	"	0.770	"	51.35	"	"	4848
551	"	0.484	"	81.70	"	"	4847
552	"	0.783	"	81.30	"	"	4880
553	"	0.778	"	115.40	71	69	4877
554	"	0.777	"	115.45	"	"	4881
555	"	0.918	"	98.00	"	"	4867
556	"	0.917	"	98.45	"	"	4850
557	"	0.462	"	193.80	"	"	4890
558	"	0.466	"	193.60	"	"	4853
559	9/16/80	0.923	"	97.40	"	67	4870
560	"	0.923	"	97.55	"	"	4863
561	"	0.902	"	45.00	152	70	4804
562	"	0.902	"	44.90	"	"	4815
563	"	0.770	"	52.45	"	"	4829
564	"	0.791	"	50.85	"	"	4848
566	"	0.590	"	68.30	"	"	4839
567	"	0.589	"	68.40	"	"	4840
568	"	0.603	"	67.00	"	"	4827
569	"	0.378	"	59.20	250	76	4894
570	"	0.378	"	59.70	"	"	4853
571	"	0.485		46.20	"	"	4888
572	"	0.485	"	46.10	"	"	4899
573	"	0 ,547	"	41.10	"	"	4872
574	"	0.547	"	40.90	"	"	4896
575	"	0.400	"	46.15	300	77	4887
576	"	0.399	"	46.20	"	"	4894
577	"	0.528	"	35.10	"	"	4868
578	"	0.522	"	35.40	"	"	4882
579	"	0.307	"	60.10	"	"	4890
580	"	0.306	"	60.00	"	"	4914

Table 7

Run no. 8: L = 16.350; A = 5.293 cm^2 ; **Mesh** = 120-150; p_c = 2000 psig;

$\bar{p}$ = 200 psig

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
581	9/16/80	0.482	10	38.25	300	77	4893
582	"	0.444	"	51.05	250	76	4865
583	"	0.444	"	50.90	"	"	4879
584	"	0.523	"	42.90	"	"	4882
585	"	0.524	"	42.95	"	"	4867
586	"	0.575	"	39.10	"	"	4872
587	"	0.575	"	39.30	"	"	4847
588	"	0.350	"	64.60	"	"	4844
589	"	0.352	"	63.85	"	"	4873
590	"	0.624	"	64.65	152	73	4832
591	"	0.623	"	64.35	"	"	4863
592	"	0.889	"	45.20	"	"	4880
593	"	0.889	"	45.10	"	"	4862
594	"	0.762	"	52.90	"	"	4836
595	"	0.762	"	52.70	"	"	4854
596	"	0.356	"	113.85	"	"	4809
597	"	0.355	"	113.85	"	"	4823
600	9/17/80	0.983	"	91.45	72	74	4812
601	"	0.983	"	91.45	"	"	4812
602	"	0.841	"	105.30	"	"	4885
603	"	0.842	"	106.30	"	"	4833
604	"	0.628	"	142.60	"	"	4831

Table 8

Run no. 9: L = 16.118 cm; A = 5.293 cm^2; Mesh = 120-150; p_c = 2000 psig

$\bar{p}$ = 200 psig

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
605	9/17/80	0.966	10	80.25	76	75.5	5223
606	"	0.965	"	80.30	"	"	5216
607	"	0.816	"	95.90	"	"	5165
608	"	0.815	"	96.50	"	"	5203
609	"	0.614	"	126.85	"	"	5189
610	"	0.614	"	126.40	"	"	5208
611	"	0.523	"	147.85	"	"	5227
612	"	0.958	"	81.30	"	"	5189
613	9/18/80	0.459	"	80.60	152	75	5193
614	"	0.459	"	80.70	"	"	5186
615	"	0.740	"	50.00	"	"	5192
616	"	0.740	"	50.15	"	"	5177
617	"	0.964	"	38.55	"	"	5170
618	"	0.963	"	38.60	"	"	5168
619	"	0.530	"	70.15	"	"	5167
620	"	0.535	"	69.20	"	"	5189
621	"	0.429	"	49.30	250	74	5106
622	"	0.429	"	49.25	"	"	5111
623	"	0.550	"	38.40	"	"	5113
624	"	0.549	"	38.55	"	"	5103
625	"	0.5115	"	41.50	"	"	5087
626	"	0.518	"	41.00	"	"	5085
627	"	0.371	"	57.40	"	"	5071
628	"	0.369	"	57.70	"	"	5072
629	"	0.420	"	41.80	301	74	5037
630	"	0.433	"	39.90	"	"	5119
631	"	0.355	"	49.30	"	"	5053
632	"	0.348	"	49.65	"	"	5118
633	"	0.277	"	62.35	"	"	5120
634	"	0.278	"	62.15	"	"	5118
635	"	0.392	"	44.40	"	"	5081
636	"	0.394	"	43.95	"	"	5107
637	"	0.357	"	58.80	250	76	5143
638	"	0.357	"	58.90	"	"	5133
639	"	0.460	"	45.85	"	"	5118
640	"	0.460	"	46.05	"	"	5096
641	"	0.546	"	38.90	"	"	5083
642	"	0.546	"	38.80	"	"	5096
643	"	0.403	"	52.75	"	"	5078
644	"	0.402	"	53.00	"	"	5067

Table 8

Run no 9: L = 16.118 cm; A = 5.293 cm^2 ; Mesh = 120-150; p_c = 2000 psig;

$\overline{p}$ = 200 psig

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
647	9/18/80	0.401	10	81.20	153	76	5103
648	"	0.614	"	60.90	"	"	5108
649	"	0.614	"	60.55	"	"	5137
650	"	0.888	"	42.10	"	"	5109
651	"	0.889	"	42.10	"	"	5101
652	9/19/80	0.795	"	106.50	72	72	5038
653	"	0.813	"	103.90	"	"	5050
654	"	0.902	"	94.05	"	"	5028
655	"	0.617	"	126.75	"	"	5015
656	"	0.860	"	98.60	"	"	5030
657	"	0.606	"	63.75	151	70	5004
658	"	0.605	"	63.50	"	"	5032
659	"	0.6045	"	63.65	"	"	5025
660	"	0.787	"	48.40	"	"	5075
661	"	0.787	"	48.80	"	"	5033
662	"	0.910	"	42.15	"	"	5040
663	"	0.905	"	42.30	"	"	5050
664	"	0.3605	"	106.90	"	"	5016
665	"	0.370	"	57.40	250	75	5084
666	"	0.370	"	57.60	"	"	5066
667	"	0.463	"	45.90	"	80	5078
668	"	0.465	"	45.55	"	"	5095
669	"	0.558	"	37.95	"	"	5096
670	"	0.559	"	37.95	"	"	5087
671	"	0.370	"	57.60	"	"	5064
672	"	0.4155	"	41.85	300	86	5108
673	"	0.424	"	40.80	"	"	5134
674	"	0.513	"	33.90	"	"	5107
675	"	0.369	"	47.30	"	"	5089
676	"	0.369	"	47.20	"	"	5099
677	"	0.298	"	58.10	"	90	5130
678	"	0.297	"	58.40	"	"	5121
679	"	0.4215	"	50.00	251	81	5099
680	"	0.405	"	51.95	"	78	5108
681	"	0.533	"	39.85	250	76	5060
682	"	0.533	"	39.50	"	"	5104
683	"	0.533	"	39.80	"	"	5066
684	"	0.449	"	47.65	"	"	5024
685	"	0.449	"	47.35	"	"	5056
686	"	0.298	"	71.05	"	"	5077

Table 8

Run no. 9: L = 16.118 cm; A = 5.293 cm^2; Mesh = 120-150; p_c = 2000 psig

$\bar{p}$ = 200 psig.

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
		0.4035	10	92.20	153	76	5134
		0.4045	"	91.80	"	"	5144
		0.571	"	65.20	"	"	5131
690		0.572	"	65.55	"	"	5094
691	"	0.920	"	41.10	"	74	5053
692	"	0.920	"	41.20	"	"	5040
693	"	0.820	"	46.20	152	"	5072
694	"	0.821	"	46.20	"	"	5066
695	"	0.493	"	77.00	"	"	5061
696	"	0.493	"	76.55	"	"	5091
697	9/20/81	0.850	"	100.40	71	69	5089
698	"	0.850	"	100.75	"	"	5071
699	"	0.6815	"	124.35	"	"	5124
700	"	0.680	"	124.65	"	"	5123
701	"	0.535	"	160.75	"	"	5068
702	"	0.532	"	111.90	"	"	5042

Table 9

Run no. 10: $L = 16.303$; $A = 5.293\ cm^2$; Mesh = 170-200; $p_c = 2000$ psig; $\bar{p} = 200$ psig.

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
704	9/21/80	0.867	5	85.25	76	78	2765
705	"	0.884	"	84.05	"	"	2750
706	"	0.790	"	93.40	"	"	2770
707	"	0.8025	"	92.50	"	"	2785
708	"	0.686	"	106.95	"	"	2763
709	"	0.702	"	105.35	"	"	2745
710	"	0.702	"	106.05	"	"	2752
711	"	0.964	"	76.30	"	"	2778
714	"	0.689	10	104.50	152	75	2699
715	"	0.677	"	106.10	"	"	2705
716	"	0.802	"	89.65	"	"	2703
717	"	0.784	"	91.75	"	"	2701
718	"	0.951	"	75.50	"	"	2706
719	"	0.712	"	101.25	"	"	2707
720	"	0.907	"	79.15	"	"	2703
721	"	0.907	"	79.25	"	"	2696
723	9/22/80	0.972	"	41.80	250	72	2689
724	"	0.955	"	42.40	"	"	2698
725	"	0.948	"	43.00	"	"	2680
726	"	0.812	"	49.90	"	"	2697
727	"	0.752	"	54.20	"	"	2681
728	"	0.579	"	70.25	"	"	2686
729	"	0.761	"	53.30	"	"	2694
730	"	0.783	"	51.70	"	"	2699
731	"	0.962	"	34.55	301	75	2691
732	"	0.811	"	40.95	"	"	2693
733	"	0.820	"	40.75	"	"	2676
734	"	0.707	"	46.95	"	"	2694
735	"	0.703	"	47.20	"	"	2695
736	"	0.593	"	55.80	"	"	2703
737	"	0.595	"	55.75	"	"	2696
738	"	0.847	"	39.05	"	"	2704
739	"	0.729	"	55.40	250	75	2704
740	"	0.729	"	55.50	"	"	2699
741	"	0.830	"	49.05	"	"	2682
742	"	0.831	"	48.05	"	"	2709
743	"	0.920	"	43.95	"	"	2701
744	"	0.921	"	44.10	"	"	2689
745	"	0.793	"	50.70	"	"	2716
746	"	0.717	"	56.65	"	"	2689

Table '9

Run no. 10: L = 16.303 cm; A = 5.293 cm^2; Mesh = 170-200; p_c = psig;

$\overline{p}$ = 200 psig.

Number of Measurements	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
747	9/22/80	0.570	10	125.90	152.5	78	2699
748	"	0.571	"	125.55	"	"	2702
749	"	0.753	"	95.50	"	76	2693
750	"	0.7705	"	93.10	"	"	2700
751	"	0.919	"	78.35	"	"	2690
752	"	0.952	"	75.40	"	"	2699
753	"	0.743	"	97.25	"	"	2681
754	"	0.7445	"	96.60	"	"	2694
755	9/23/80	0.838	5	97.40	71.5	70	2663
756	"	0.837	5	98.55	"	"	2635
757	"	0.959	5.05	86.70	"	"	2641
758	"	0.959	5	85.90	"	"	2638
759	"	0.725	"	113.30	"	"	2646
760	"	0.726	"	114.10	"	"	2624
761	"	0.895	"	91.65	"	"	2650
762	"	0.893	"	92.15	"	"	2641
763	"	0.6535	10	113.40	151	74	2637
764	"	0.6565	"	112.15	"	"	2655
765	"	0.971	"	75.30	"	"	2673
766	"	0.9745	"	75.40	"	"	2660
767	"	0.814	"	70.05	151.5	73	2659
768	"	0.8155	"	89.80	"	"	2661
769	"	0.715	"	102.35	"	"	2663
770	"	0.7155	"	102.70	"	"	2652
771	"	0.758	"	52.80	249	78	2740
772	"	0.759	"	52.90	"	"	2731
773	"	0.783	"	50.85	"	"	2754
774	"	0.784	"	51.05	"	"	2740
775	"	0.8845	"	45.40	"	"	2731
776	"	0.8875	"	45.20	"	"	2734
777	"	0.740	"	54.10	"	"	2739
778	"	0.740	"	54.00	"	"	2744
780	"	0.703	"	46.30	300	82	2705
781	"	0.602	"	55.20	"	"	2703
782	"	0.604	"	55.05	"	80	2704
783	"	0.510	"	65.00	"	78	2698
784	"	0.509	"	65.50	"	"	2700
785	"	0.691	"	48.20	"	"	2702
786	"	0.687	"	48.45	"	"	2686
787	"	0.568	"	58.95	"	"	2698

Table 9

Run no. 10: L = 16.303 cm; A = 5.293 cm^2; Mesh = 170–200; p_c = 2000 psig

$\bar{p}$ = 200 psig

Number of measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
789	9/23/80	0.623	10	65.70	250	76	2668
790	"	0.625	"	65.10	"	"	2684
791	"	0.7345	"	55.05	"	"	2701
792	"	0.758	"	53.40	"	"	2698
793	"	0.835	"	48.40	"	"	2702
794	"	0.8365	"	48.45	"	"	2695
795	"	0.665	"	61.03	"	"	2691
796	"	0.665	"	60.75	"	"	2700
797	"	0.956	"	76.70	150	78	2679
798	"	0.952	"	76.20	"	"	2694
799	"	0.871	"	84.40	"	"	2673
800	"	0.8735	"	83.50	"	"	2692
801	"	0.722	"	101.75	"	"	2674
802	"	0.727	"	100.90	"	"	2678
805	"	0.570	"	129.00	"	"	2672
806	9/24/80	0.755	10	213.25	72.5	72	2658
807	"	0.749	5	108.05	"	"	2746
808	"	0.932	10	172.35	"	"	2664
809	"	0.934	5	86.80	72	"	2639
810	"	0.866	10.3	192.70	"	"	2641
811	"	0.873	10	185.12	"	"	2648

Table 10

Run no. **11:** L = 15.991 cm; A = 5.293 cm^2; Mesh = 170–200; p_c = 2000 psig

$\overline{p}$ = 200 psig

Number of measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
811a	9/24/80	0.856	10	175.70	76.5	77	2651
812	"	0.853	"	175.70	76	"	2675
813	"	0.955	"	157.60	"	"	2664
814	"	0.953	"	157.75	"	"	2667
815	"	0.768	"	196.40	"	"	2658
818	9/25/80	0.935	"	163.40	74	74	2689
819	"	0.933	"	164.05	"	"	2684
820	"	0.934	"	164.10	"	73	2680
821	"	0.961	"	76.25	148	72	2666
822	"	0.960	"	76.60	"	"	2651
823	"	0.900	"	81.55	"	"	2656
824	"	0.900	"	81.85	"	"	2646
825	"	0.817	"	90.10	"	"	2648
826	"	0.816	"	89.95	"	"	2656
827	"	0.756	"	97.20	"	"	2653
828	"	0.960	"	76.70	"	"	2648
829	"	0.8315	"	48.50	250	74	2656
830	"	0.8265	"	48.75	"	"	2659
831	"	0.755	"	53.60	"	"	2648
832	"	0.7485	"	53.70	"	"	2666
833	"	0.655	"	61.60	"	"	2656
834	"	0.658	"	61.60	"	"	2643
835	"	0.7825	"	51.80	"	73	2643
836	"	0.7275	"	45.50	300	76	2666
837	"	0.734	"	46.25	"	"	2664
838	"	0.669	"	49.70	"	"	2654
839	"	0.670	"	49.30	"	"	2671
840	"	0.615	"	53.65	"	"	2674
841	"	0.619	10.15	54.65	"	"	2648
842	"	0.740	10	44.70	"	"	2668
843	"	0.648	"	51.25	"	"	2657
844	"	0.763	"	52.55	252	74	2649
845	"	0.764	"	52.25	"	"	2660
846	"	0.823	10.15	49.90	"	"	2626
847	"	0.823	10	48.65	"	"	2652
848	"	0.717	"	56.40	"	"	2645
849	"	0.7145	"	56.00	"	"	2564
850	"	0.884	"	45.30	"	"	2651
851	"	0.883	"	45.60	"	"	2638
852	"	0.9615	"	74.70	152	"	2654

Table 10

Run no. 11: L = 15.991 cm; A = 5.293 cm^2; Mesh = 170-200; p_c = 2000 psig

$\bar{p}$ = 200 psig

Number of measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
853	9/25/80	0.966	10	74.55	152	74	2647
854	"	0.902	"	79.60	"	"	2655
855	"	0.9065	"	79.50	"	"	2645
856	"	0.8195	"	87.80	"	"	2649
857	"	0.824	"	87.55	"	"	2642
858	"	0.967	"	74.30	"	"	2653
859	"	0.856	10.01	84.70	"	"	2647
860	9/26/80	0.846	10	185.80	73	73	2655
861	"	0.849	"	185.10	"	"	2656
962	"	0.932	"	169.05	"	"	2649
863	"	0.938	"	167.40	"	"	2658
864	"	0.800	"	196.30	"	"	2658
865	"	0.802	"	196.90	"	"	2643
866	"	0.832	"	88.65	150	74	2614
867	"	0.833	"	89.05	"	"	2599
868	"	0.902	"	81.75	"	"	2614
869	"	0.905	"	81.50	"	"	2613
870	"	0.954	"	76.95	"	"	2612
871	"	0.962	"	76.85	"	"	2607
872	"	0.812	"	90.85	"	73	2613
873	"	0.689	"	59.70	248	72	2638
874	"	0.689	"	59.60	"	"	2633
875	"	0.735	"	55.80	"	"	2636
876	"	0.735	"	55.80	"	"	2636
877	"	0.797	"	51.50	"	"	2635
878	"	0.799	"	51.25	"	"	2637
879	"	0.681	"	60.20	"	"	2636
880	"	0.682	"	60.20	"	"	2634
881	"	0.600	"	55.70	298	76	2671
882	"	0.600	"	55.90	"	"	2662
883	"	0.640	"	52.30	"	"	2667
884	"	0.641	"	52.10	"	"	2675
885	"	0.694	"	48.20	"	75	2670
886	"	0.695	"	48.15	"	"	2669
887	"	0.568	"	59.25	"	"	2653
888	"	0.569	"	58.95	"	"	2663
889	"	0.665	"	60.75	250	74	2652
890	"	0.666	"	60.70	"	"	2650
891	"	0.743	"	54.50	"	"	2647
892	"	0.7455	"	54.50	"	"	2638

Table 10

Run no. 11: L = 15.991 cm ; A = 5.293 cm^2; Mesh = 170-200; p_c = 2000 psig; $\bar{p}$ = 200 psig.

Number of Measurement	Date	Δp_{core} (psi)	V (cc)	t (sec)	Run Temp. (°F)	Effluent Temp. (°F)	k (md)
893	9/26/80	0.796	10	50.80	250	74	2640
894	"	0.798	"	50.75	"	"	2645
895	"	0.679	"	59.80	"	"	2634
896	"	0.680	"	59.55	"	"	2645
897	"	0.979	"	74.35	151	74	2633
898	"	0.983	"	73.80	"	"	2642
899	"	0.8755	"	83.15	"	"	2634
900	"	0.880	"	82.50	150.5	"	2640
901	"	0.824	"	88.40	"	"	2632
902	"	0.828	"	87.75	"	"	2638
903	"	0.868	10.05	84.45	"	"	2627
904	"	0.873	10	83.80	"	"	2620
905	9/27/80	0.917	10	176.85	72	72	2609
906	"	0.917	10.05	177.65	"	"	2611
907	"	0.964	10	168.35	"	"	2608
908	"	0.9645	10	168.80	71.5	71.5	2618
909	"	0.855	10.15	194.15	"	"	2606
910	"	0.856	10	189.85	"	"	2623