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EFFECTS OF TEMPERATURE ON THE ABSOLUTE PERMEABILITY OF CONSOLIDATED SANDSTONE

SUPRI TR-41

BY

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ABSTRACT

The effect of temperature on absolute permeability has been a point of disagreement in the petroleum literature for many years. Recent work at Stanford University has shown no dependence on temperature of the absolute permeability to water of unconsolidated sand cores. The objective of this report is to extend the investigation to consolidated sandstone by following similar experimental procedures and observing whether any temperature effects exist.

Fontainebleau sandstone was chosen as the core sample because of its low porosity and relatively clay-free composition. These characteristics allow the nature of consolidated sandstone permeability to be studied, while minimizing the effects of extraneous factors. Such factors, often present in Berea and Boise sandstones, include interstitial clay swelling in the presence of distilled water.

Properties of sandstone differ from those of unconsolidated sand. Consequently, the effects of throughput water volume and flow rate, in addition to temperature, are studied. Mechanical difficulties with parts of the experimental apparatus have prevented the development of a satisfactory conclusion based on results obtained thus far. Recommendations are provided for necessary modifications before further experiments are performed. When these changes are implemented, a final run can be made to complete the analysis.

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1. INTRODUCTION

The behavior of fluid flow through porous media is a subject of primary importance in petroleum engineering. An understanding of the movement of fluids in rock is essential to the proper description and development of hydrocarbon reservoirs. The factors that determine the nature of flow have been quantified and expressed in a relation known as Darcy's law. Darcy's law defines a property known as permeability, which is the ability of a porous medium to transmit fluids.

One method of determining reservoir parameters is core analysis, in which the permeability of a small sample of the reservoir rock is measured. In order for the core sample to provide a reliable estimate of formation permeability, relevant reservoir conditions are reproduced in the laboratory. Traditionally permeability measurements have been made at room temperature based on the assumption that permeability is independent of temperature. This assumption has been a topic of debate in the literature for many years. Although a consensus has yet to be reached, temperature effects on permeability would make revisions in analytical practices necessary in order to more closely represent reservoir conditions. Not only will core analysis be affected, but with the increasing implementation of thermal recovery techniques, possible permeability variations need to be investigated.

2. LITERATURE SURVEY

Permeability is a property used to describe the ability of a porous medium to transmit fluids. The absolute permeability is measured with the porous medium 100% saturated with a single fluid. It was originally assumed that the permeability was a fixed constant for a given porous medium and was not affected by the choice of fluid or temperature at which the measurement was made. Muskat (1937) stated that the absolute permeability is "...a constant determined only by the structure of the medium in question and is entirely independent of the nature of the fluid."

Observed alterations in the flow behavior of fluids with changing temperature led to attempts to define more clearly the factors governing flow. The familiar relation used to describe linear flow in porous media is Darcy's Law:

$$q = \frac{-kA}{\mu} \frac{dp}{dx}$$

which expresses flow rate q in terms of the cross-sectional area of flow A, the viscosity of the flowing fluid μ, the pressure gradient $\frac{dp}{dx}$, and the absolute permeability k.

In early experiments, variations in pressure gradients at constant flow rates observed with changing temperature did not reveal the nature of variations in the other terms. It is generally accepted that the viscosity of a liquid decreases with increasing temperature. Grunberg and Nissan (1943) found that although the temperature effect on fluid viscosity could account for some of the observed variations, this was not the only property affecting flow as temperature fluctuated. They studied the flow of aqueous solutions through Jena glass filters over a range of temperatures, and derived a direct relation between permeability and temperature. The correlation described a linear decrease in absolute permeability with increasing temperature. This effect was attributed to different effective cross-sections under viscous flow for different liquids and temperatures caused by differences in the thickness of adsorbed layers. Since permeability did appear to vary with temperature, the work of Grunberg and Nissan generated doubt as to whether it could be assumed constant.

Greenberg et al. (1968) studied the variation of absolute permeability with temperature. Nine different artificially consolidated cores were used to simulate the properties of reservoir rocks. The absolute permeability to water was measured over a range of 80°F to 140°F with no confining pressure applied. The results were that an approximate 20% reduction in permeability was found in five of the cores, no change in two, and a slight increase in the two others.

It should be noted that the two investigations mentioned thus far were performed with porous media unlike reservoir rock and under conditions that failed to represent those in any oil reservoir. However, the important point is that the conflicting results obtained stimulated further research on possible temperature effects on permeability.

A parameter affecting the flow of reservoir fluids that gained considerable attention is overburden pressure. Much research has been directed toward explaining the effect of overburden pressure on permeability. Using confining pressure to apply uniform loading on a core, the effect of the overburden can be reproduced. One of the first studies in this area was performed by Fatt and Davis (1952). The absolute permeability to gas of sandstone cores was found to decrease up to 41% when subjected to a confining pressure of 3,000 psi. Wilhelmi and Somerton (1967) extended the results of Fatt and Davis by finding a 25% to 60% reduction in permeability at a confining pressure of 15,000 psi.

In order to more closely simulate reservoir properties, Afinogenov (1969) considered the combined effects on permeability of temperature and pressure. Using oil as the flowing fluid, absolute permeability reductions of up to 95% were found when temperature increased from room temperature to 200°F.

Weinbrandt (1972) measured absolute permeability to establish the rock properties of cores later used in relative permeability experiments. The absolute permeability to water was measured with the cores subjected to a radial confining pressure of 2,000 psi and a temperature range of 70°F to 175°F. The results were in general agreement with those of Afinogenov. For five Boise sandstone cores, Weinbrandt noted an average decrease from 2,050 md at room temperature to 884 md at 175°F, or a 57% reduction.

Casse (1974) continued the work Weinbrandt had started on absolute permeability. A confining pressure of 2,000 psi was again used while measuring absolute permeabilities to water, oil, and gas. A temperature effect was detected only with water as the flowing fluid. Casse obtained results that agreed closely with Weinbrandt's for Boise sandstone when water was the flowing fluid. Two Berea sandstone cores were also used with a resulting permeability reduction from 106 md at room temperature to 61 md at 300°F, or a reduction of 42%.

The results of Weinbrandt and Casse were combined and published, Weinbrandt _et al._ (1975). The conclusions discarded the previous postulate of Poston _et al_. (1970) that temperature effects were a result of wettability changes. The observed effect was considered too great to be explained solely by variations in wettability. Instead, Weinbrandt _et al_. attributed the temperature effect to thermally-induced mechanical stresses which caused constrictions of pore openings. Since tight openings would likely be closed by such thermal expansion of the rock grains, permeability would be reduced. An interesting aspect of their conclusions is the important dependence of observed temperature effects on confining pressure. Casse and Ramey (1979) used a "minimum level of stress" to define a combination of mechanical and thermal stresses above which a temperature dependence of permeability occurs. At levels of stress below this minimum, thermal expansion alone will not affect pore configuration significantly since the low confining pressure does not prevent free expansion of the rock matrix. However, as confining pressure increases, pore opening constriction due to thermal expansion will be accentuated by large external forces.

This explanation can be applied to the somewhat inconclusive results of Greenberg _et al_. (1968) mentioned previously, as well as to the work of Arihara (1974). Arihara found no temperature effects on absolute permeability over a temperature range of 76°F to 340°F using a relatively low confining pressure of 400 psi.

Another study of the temperature effects on permeability was done by Atkan and Farouq Ali (1975). Without applying confining pressure, they measured absolute permeabilities to brine and air of Berea and Boise sandstone between 80°F and 500°F. The results indicated a slight but progressive increase in permeability with increasing temperature. They cited the formation of microfractures induced by temperature as an explanation.

Aruna (1976) used virtually clay-free sandstone cores to study temperature effects. He observed a 50% to 60% decrease in absolute permeability to water between 70°F and 300°F over the entire range of confining pressures. Due to the absence of expandable clay, Aruna rejected the clay-swelling hypothesis of permeability reduction. Instead, he referred to a change in the chemical interaction between water and silica as temperature varied, which caused a reduction in effective cross-section. This reasoning is essentially the same as that of Grunberg and Nissan (1943).

Sageev (1980) designed an apparatus for absolute permeability measurement that specifically addressed inadequacies of previously used systems. He measured absolute permeabilities to water between 70°F and 300°F of unconsolidated sand cores and observed no temperature effects. One of the improvements was a redesigned core holder end plug that distributes the flow more evenly over the entire cross section of the sandface. Earlier experiments had used single input and output channels that resulted in additional pressure drops due to end effects. These effects were found to depend significantly on flow rate resulting in a rate dependence of measured permeability. After improving this and other aspects of the experimental procedure, Sageev was able to measure permeabilities with greater precision and consistency.

Gobran et al. (1981) investigated the effects of several parameters on absolute permeability. No temperature effect on absolute permeability to water was found for unconsolidated sand at temperatures between 100°F and 300°F and confining pressures between 2,000 and 8,000 psi. Explaining the contradiction of the results with previous work that had shown permeability reductions under similar conditions, he suggested improper experimental procedures. These included measuring pressure under non-isothermal conditions, not allowing permeability to stabilize at ambient conditions, and using transducers that were not sensivitive enough to accurately read the pressure drops. Gobran also tested two consolidated Berea sandstone cores; however, the results were not internally consistent with the conclusion that was reached for unconsolidated sands.

A recent study by Contreras et al. (1982) measured horizontal and vertical permeabilities of Cerro Prieto sandstone core samples. The absolute permeability to distilled water, brine, and KCl solution were found generally found to decrease between 70°F and 500°F. An empirical expression was presented that related permeability inversely to temperature with corrections for fluid composition and confining pressure. The observed permeability reductions were attributed to changes in effective cross section due to thermal expansion of rock matrix under mechanical stress. Considering that the range of measured permeabilities was on the order of 0.01 to 10 millidarcies, the grain expansion explanation is a reasonable one. The clay content of the sandstone under investigation was not mentioned; consequently, the influence of clay swelling and migration on the results is not clear.

To summarize, many different factors have been studied to determine the effects of temperature on permeability. Early work concentrated on fluid properites such as viscosity and chemical interaction with the solid matrix. When explanations of observed phenomena based on these factors proved inadequate, pressure was considered as a possible influence. It has been well established that increases in overburden pressure cause reductions in permeability. The combined effect of temperature and pressure has been the topic of the latest research in the area of absolute permeability.

3. PROBLEM STATEMENT

A majority of the works in the literature state that there is a reduction of absolute permeability with increasing temperature. The results indicating such a temperature dependence have most often been explained in terms of changes in rock matrix and rock-fluid interaction. The most recent work done at Stanford (Sageev, 1980, and Gobran *et al.*, 1981) has shown no temperature effect. These experiments appear to have refined permeability measurements to a point where they are reliable. Although the results are conclusive for unconsolidated sand, a more complete study is necessary before the theory can be extended to consolidated sandstone. Consequently, the objective of this investigation is to measure the absolute permeability to water of consolidated sandstone at elevated temperatures and observe whether any temperature effects occur.

4. EXPERIMENTAL APPARATUS

The experimental apparatus used to measure absolute permeability at various temperatures is described in this section. In order to simplify the explanation, the equipment is divided into three sections. The first illustrates the path of the fluid through the system. The second section considers the pressure measurement loop. The last section describes the confining pressure system.

4.1 FLUID FLOW SYSTEM

Distilled water is used as the flowing fluid. It is introduced into the system by a Ruska constant rate pump, equipped with two 500cc cylinders that can alternately discharge and fill. In this mode, the pump is designed to deliver an indefinite constant rate of flow. Figure 1 is a schematic representation of the flow system. When the Ruska pump was operated during construction of the apparatus, the cylinders were found to be considerably corroded and in need of repair. Although both cylinders were repeatedly flushed until the effluent was clean and rust-free, the intake valve mechanism in the right side cylinder is not operational. As a result, it is impossible to fill this cylinder to more than 10% its capacity under normal pump operation. In order to avoid complete loss of pore pressure and risk steam formation in the core, only the left side cylinder is discharged at constant rate and recharged manually.

Before flow is initiated, the system is evacuated to remove any air

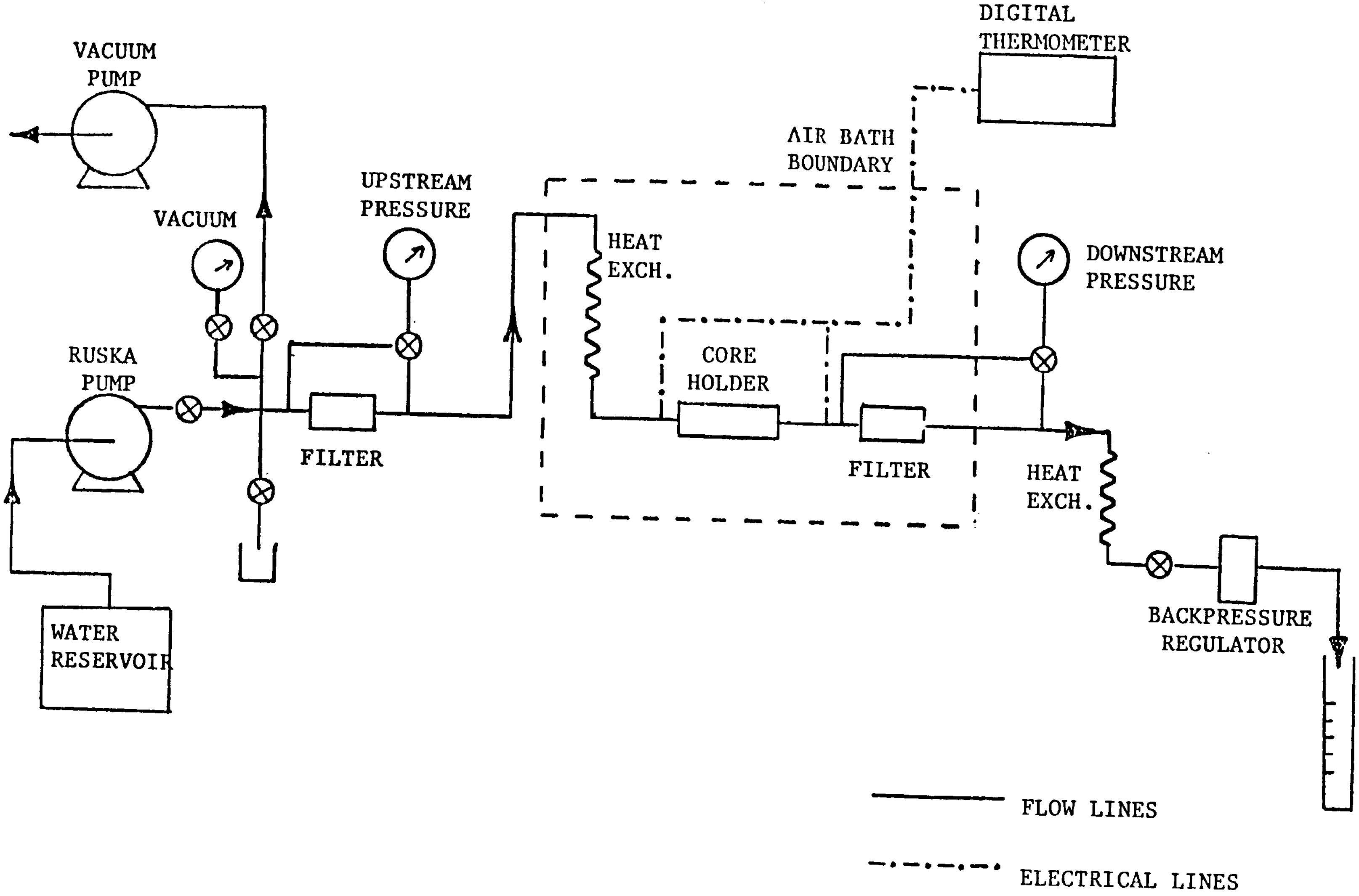


Fig. 1. Schematic Diagram of Fluid Flow System

present in the flow lines and core. A pressure relief valve set at 2,000 psi is included to minimize the possibility of inadvertently over pressuring the system. The pump is designed to operate against a maximum backpressure of 4,000 psi. Since the pore pressure is maintained at pressures much lower than 2,000 psi during experimental runs, and the lowest pressure-rating of any valve in the system is 2,500 psi, the relief setting will provide an acceptable margin of safety.

The water then flows through a 7 micron filter, which traps fine particles from the pump cylinders before they can enter the core. Pressure drop across the filter is measured to indicate plugging, at which time the filter is replaced. A second 7 micron filter is located immediately downstream of the core to prevent particulates out of the core from entering the backpressure regulator and hampering its operation.

Upon entering the air bath, a heat exchanger elevates the temperature of the water to that of the air bath. The temperature inside the air bath is measured by a thermocouple hanging above the core holder. The water temperature is measured by thermocouples in the flow line at the inlet and outlet of the core holder. All three "J" type thermocouples are connected to a multichannel digital temperature readout. The permeability is not calculated until the three temperatures are within 1°F of each other. In some past experiments the water temperature was measured at the core inlet only. Significant error is introduced by assuming an equilibrium temperature for the permeability calculation based on one flow line temperature. The sensitivity of fluid viscosity to temperature is the reason for the error. When the air bath temperature is increasing during a heating cycle, the inlet and outlet core temperatures take quite some time to stabilize. The outlet temperature is lower until the temperature of the core itself equalizes with that of the air bath. The viscosity of water at the upstream temperature is lower than the viscosity of the water in the core which is not as hot. Assuming the lower viscosity will yield too low a calculated permeability at an assumed equilibrium temperature. If the experiment is not designed to achieve and verify thermal equilibrium throughout the core, the results might be mistakenly interpreted as a temperature effect on permeability.

A second heat exchanger is located downstream of the air bath. Tap water flows around the coils of hot water to cool it to room temperature. A dome-loaded nitrogen backpressure regulator is used to maintain the pressure in the system at a value higher than the vapor pressure of water. Over the range of temperatures used in this study a constant pore pressure of 220 psi is sufficient to insure single phase flow in the core, (ASME Steam Tables, 1979). Finally, the water empties into a graduated cylinder in which the throughput volume and flowrate can be monitored.

4.2 PRESSURE MEASUREMENT

Figure 2 shows the experimental apparatus in simplified form with two additional features, one of which is the pressure measurement loop. The pressure gradient across the core, used in the calculation of absolute permeability, is measured by pressure taps in the flow line at the inlet and outlet of the core holder. The pressure taps lead to a manifold of differential pressure transducers, each consisting of a

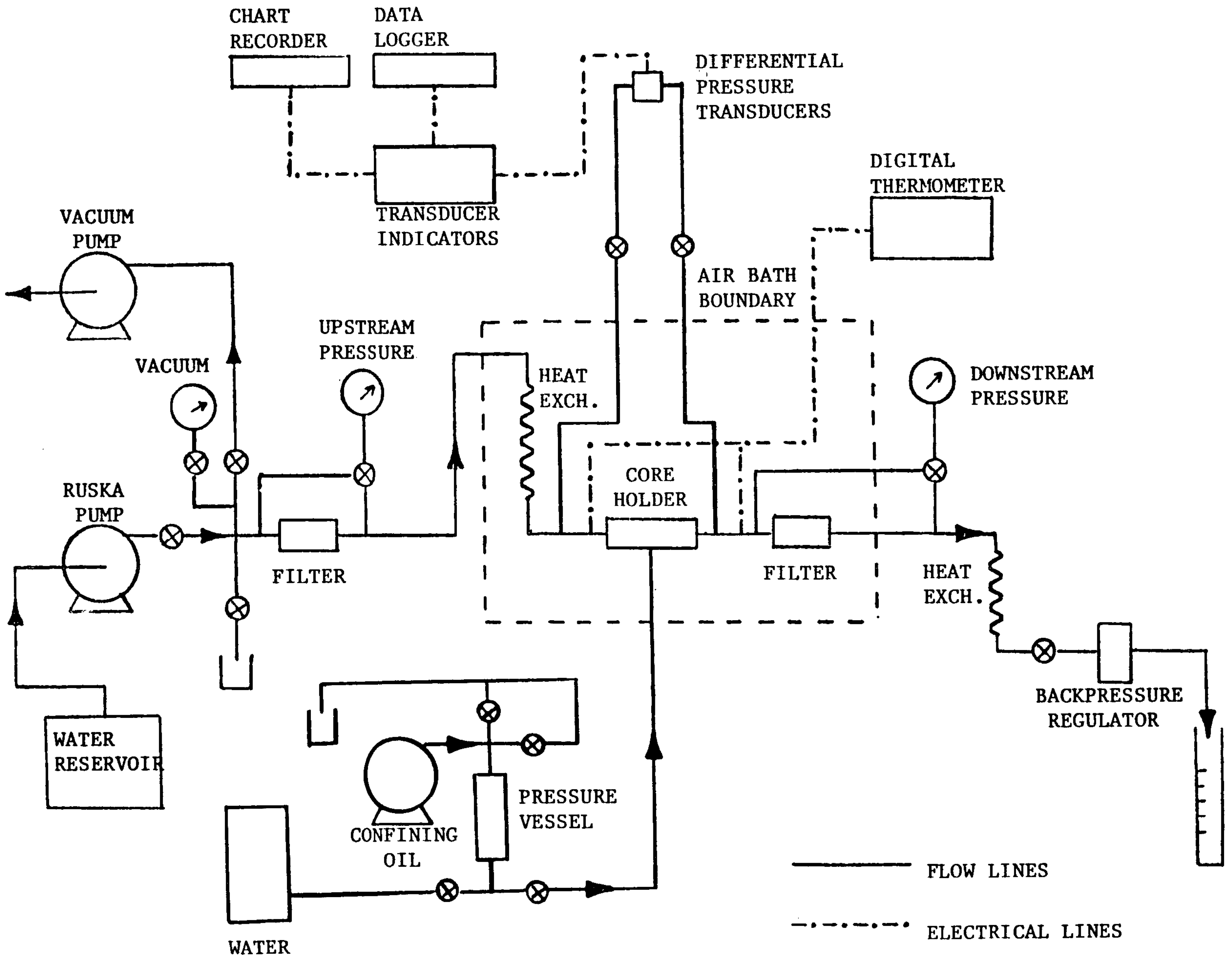


Fig. 2. Schematic Diagram of Entire System

diaphragm which detects the difference between inlet and outlet pressure. Since the pressure gradients vary widely over the ranges of flowrates and temperatures used, three transducers are provided. Connected in parallel, the transducers have ranges of 0 to 5, 0 to 25, and 0 to 100 psi respectively; therefore, a high degree of accuracy in measurement is possible. A three-way valve allows either full scale pressure drop or zero differential pressure to be applied selectively to each of the transducers. Each transducer is connected to an indicator which sends a signal between 0 and 10V to a digital multimeter and a three channel chart recorder which keeps a continuous account of differential pressure. A voltage regulator is used to prevent fluctuation in the power supply to the measuring and recording devices.

4.3 CONFINING PRESSURE SYSTEM

The confining pressure system is also indicated in Figure 2. Distilled water is the fluid used to apply confining pressure to the core. The consolidated core is surrounded by a sleeve of heat-shrinkable FEP teflon, which isolates the core from the confining fluid while allowing pressure to be applied. Water was selected as the confining fluid for several reasons. First of all, due to the relatively small compressibility of water, leaks anywhere in the confining pressure line can be immediately detected by a decrease in the pressure reading. Secondly, if the teflon sleeve should happen to leak, using the same fluid for confining and flowing eliminates the need to clean the core before continuing the run. Finally, a safety consideration mentioned by Sageev (1980, p.8) was that a spill of oil in the air bath at 300°F represents a potential hazard.

Pressure is applied to the system by using a hand pump to force oil into the pressure vessel which acts as an accumulator. The accumulator is initially filled with water from below. When the oil is pumped in from the top, pressure is built up around the core. A constant confining pressure of 2,000 psi was selected to simulate the effect of the overburden. The core temperature is controlled by the flow in the air bath. When the temperature increases, the confining pressure is maintained by a spring-loaded pressure relief valve set to regulate between 2,000 and 2,050 psi. During cooling cycles, pressure is applied manually with the hand pump to maintain confining pressure. These measures are necessary to compensate for expansion and contraction of the confining fluid with changing temperature.

5. EXPERIMENTAL PROCEDURE

The experimental procedure is designed to isolate the effect of temperature on the absolute permeability of the sandstone core. As previously mentioned, many factors contribute to the behavior of fluid flowing in porous media. In order to study a single factor, other relevant parameters must be known with reasonable certainty. Using a core of known dimensions and flowing distilled water of known viscosity at a constant rate, all the terms in Darcy's law are defined except Δp. Therefore, permeability can be calculated if Δp is known. See Appendix A for sample calculation.

Preparation begins with the cutting of a Fontainebleau sandstone core, which was chosen for its relatively clay-free composition. The core sample used in the first experiment was 0.971 inches in diameter and 6.275 inches in length. The core was then dried at 500°F for six hours at which time it was weighed. After saturation for twelve hours with distilled water in an evacuated chamber, the core was again weighed. The dry and saturated weights were used to calculate pore volume and porosity, which are 8.80 cm^3 and 11.6% respectively. The core was again dried to facilitate evacuation of the system. Next, the core was mounted between the endplugs and the teflon sleeve allowed to shrink for four hours at 300°F. Hose clamps around the endplugs provide the necessary seal between the teflon and the stainless steel. After assembly of the entire core holder, pressure and flow lines were connected and the system was evacuated overnight. A liquid nitrogen cold trap prevents any liquid from entering the vacuum pump oil. This precaution allows a much better vacuum to be achieved. The pressure transducers were then calibrated, and the vacuum resumed for two more hours. Finally, water was allowed into the system and the experimental runs began.

In previous work, Gobran et al. (1981), dependence of permeability on cumulative throughput volume and flow rate was considered. The former effect is especially important when using consolidated cores as it can indicate the degree to which certain phenomena within the core, such as clay swelling or fines migration, are affecting permeability. In order to identify the existence of any volumetric throughput or flow rate dependence, the first step was to measure permeability at a fixed temperature over a wide range of flow rates for a large number of pore volumes injected.

The next step is to investigate the character of absolute permeability at different temperatures. Temperature in the core was raised in 50°F increments, and permeability measurements were made only when the air bath, inlet, and outlet temperatures were within 1°F of each other. At each temperature, permeability was measured at four different flow rates. The three highest flow rates were each maintained for thirty pore volumes, and the permeability was measured at ten, twenty, and thirty pore volumes injected. An average of the three values is given for the flow rate. The lowest rate was continued for only ten pore volumes. Each time a differential pressure reading was taken for the calculation of permeability, the three-way valve on the transducer loop in use was switched so that the zero reading could be recorded to indicate, and correct for, instrumentation error.

6. RESULTS

The first run of the experiment with the Fontainebleau core was performed at constant temperature of 100°F and a flow rate of 414 cc/hr. Five hundred pore volumes of distilled water were pumped through the core, and periodic permeability measurements were made to indicate any throughput dependence. Figure 3 exhibits a slight trend of reducing permeability from 343 millidarcies to 303 millidarcies with increased cumulative water injected. The bars on the graph, representing experimental error, indicate that observed changes are greater than expected from random or systematic errors in measurement devices.

The calculation of experimental error is described in Appendix B and is primarily influenced by the error in differential pressure measurement. The highest degree of error, indicated by the largest bars, is introduced when a transducer is used to measure a Δp that is significantly less than the full scale rating of the transducer plate.

The trend of decreasing permeability with increasing throughput volume, also noticeable at other flow rates as shown in Figure 4, suggests the possible migration of fines and/or the presence of swelling clays. This suspicion was later verified by scanning electron microscope photographs of the Fontainebleau sandstone matrix (Sageev, 1981). Figure 5 is a reproduction of some of the photographs. Fine clay particles are evident in Figures 5.1 and 5.3 as small white specks among the larger sand grains. Two of these particles are further magnified in Figures 5.2, and 5.4. Although the clay platelets are sparsely distributed compared to those in Berea sandstone, the low porosity and tight pore constrictions of the Fontainebleau will result

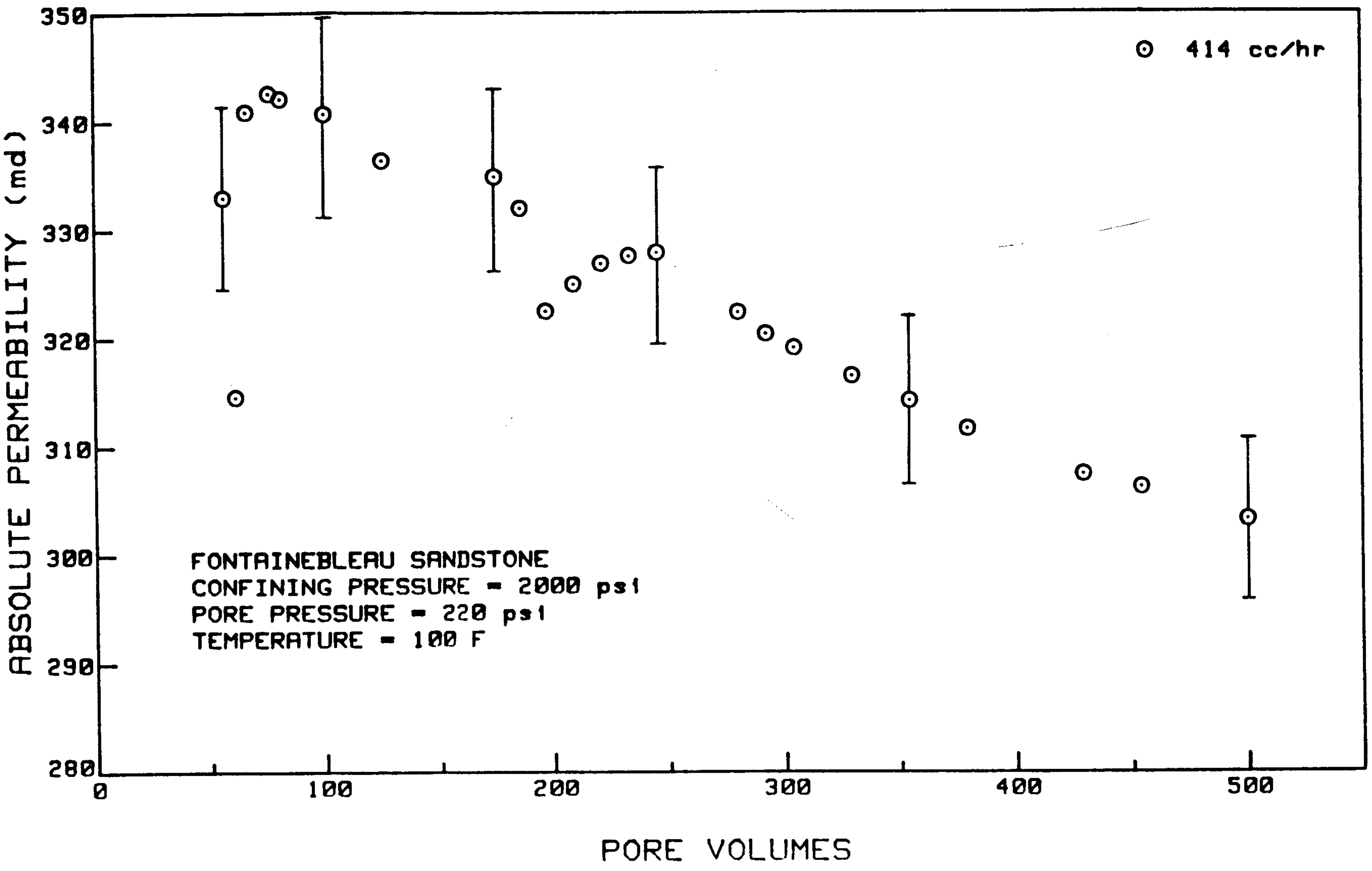


Fig. 3. Permeability vs. Throughput

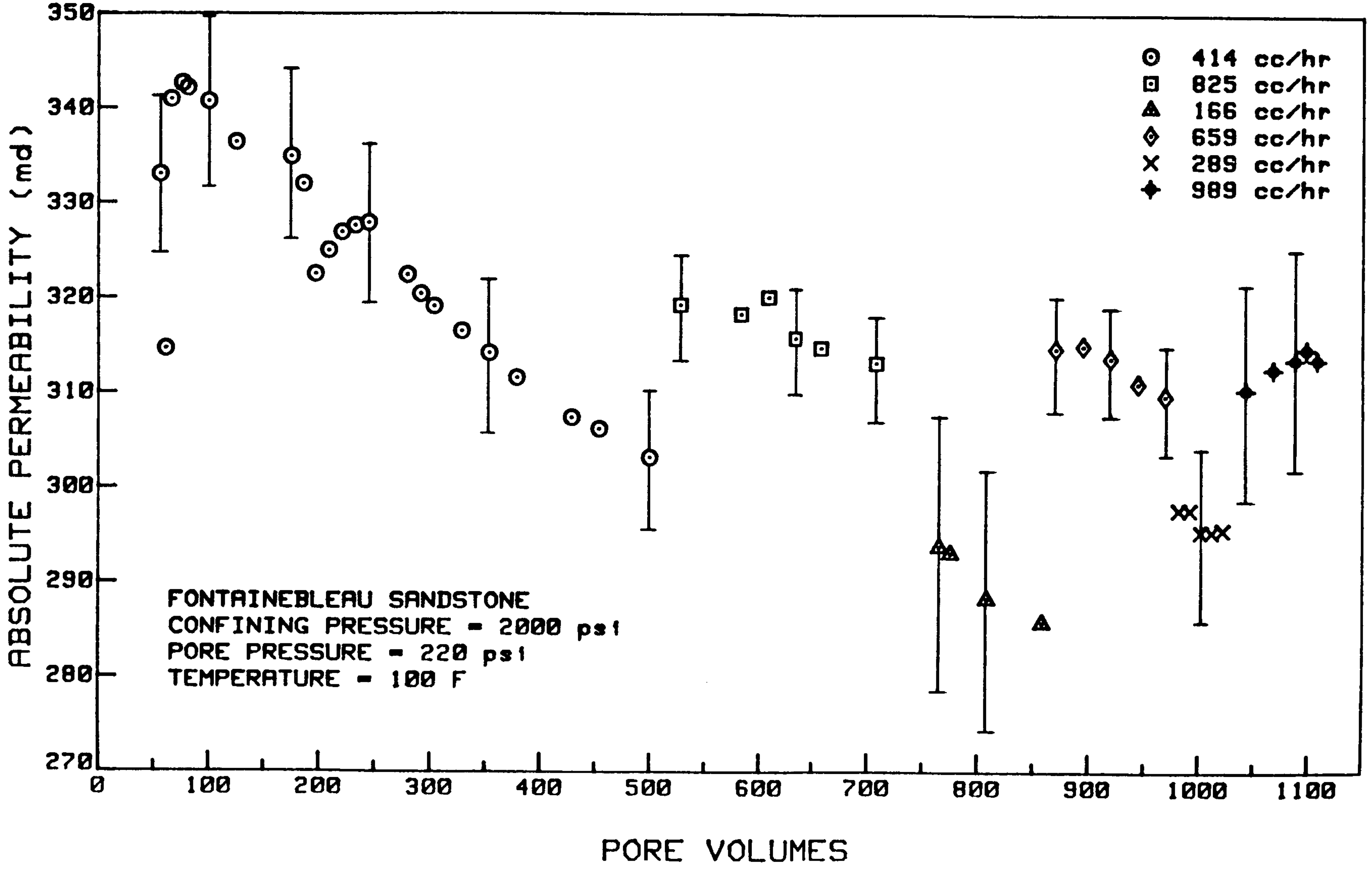
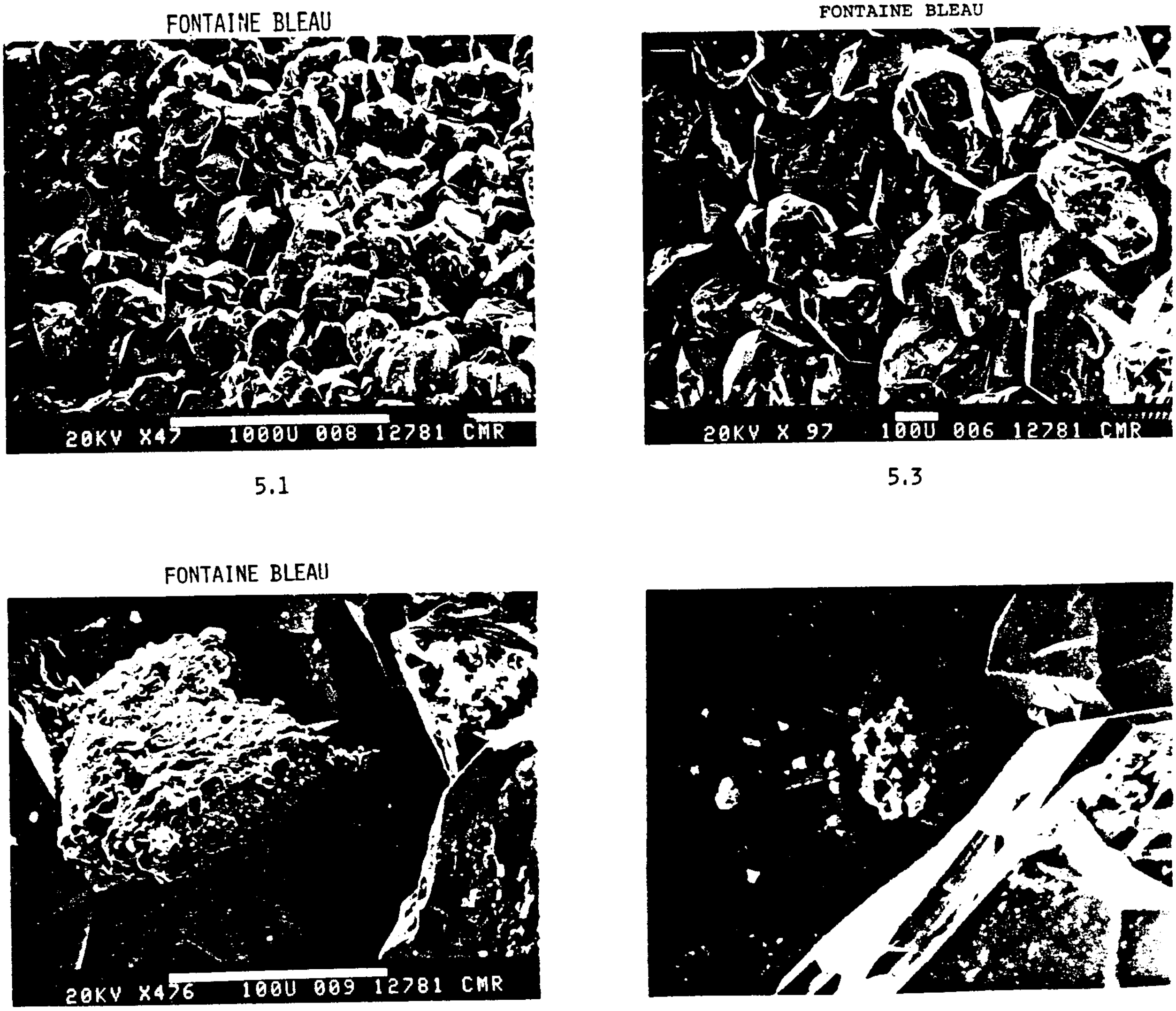


Fig. 4. Permeability vs. Throughput

Each photograph is coded with information regarding magnification, scale, and date.

e.g. 20KV = microscope setting, 20,000 volts
X476 = magnification power, 476 times
100U = length of bar scale, 100 microns
12781 = date, July 12, 1981
CMR, Center for Materials Research

Note: These photographs were reduced to 64% of original size for inclusion in this report.



5.1

5.3

5.2

5.4

Fig. 5. SEM Photographs of Fontainebleau Sandstone

in permeability reductions with even small amounts of clay expansion.

The dependence of permeability on flow rate was investigated next by varying the rate of the Ruska pump between 166 and 989 cc/hr. At each pump setting, the flow rate into a graduated cylinder was measured with a stopwatch three times. The averages indicate that over the range of flow rates measured, the values supplied by the manufacturer understate the actual rate by 3.16%. Figure 4 shows that in general, high permeabilities were measured at high flow rates.

The effect of temperature on the permeability of the sandstone is illustrated in two ways. Figure 6 shows absolute permeability as a function of temperature at a constant confining pressure of 2,000 psi and pore pressure of 220 psi. The results are also plotted on Figure 7, which expresses the ratio of permeability at the run temperature to that at a datum temperature of 100°F. The datum was chosen since 100°F is the lowest controllable temperature setting on the air bath. Temperature effects can be detected on Figure 7 as deviations from the $k/k_{100}=1$ line.

A peculiar phenomenon was observed during the experiment that is worth noting. At two different times while water was flowing at constant rate, back pressure, and temperature, the differential pressure reading on the chart recorder abruptly increased by approximately 100%. Figure 8 is a reproduction of the chart reading during one of the differential pressure anomalies. The most notable feature is the sudden jump from 5.05 psi to 11.7 psi (conversion to psi based on a full scale of 25 psi). These large fluctuations in pressure drop across the core were not found to result from sudden variations in any of the controlled parameters. The possibility of a foreign particle plugging the inlet

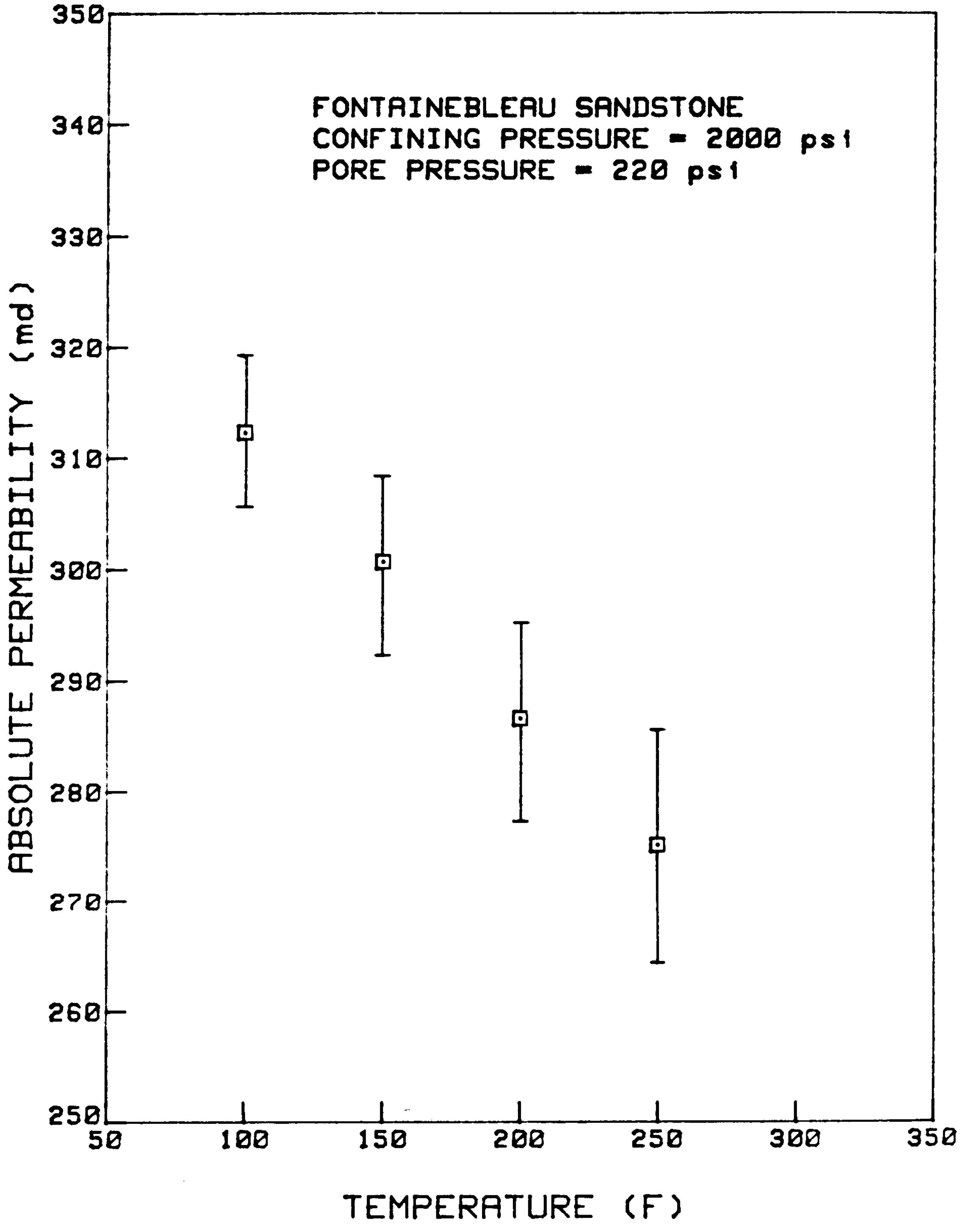


Fig. 6. Permeability vs. Temperature

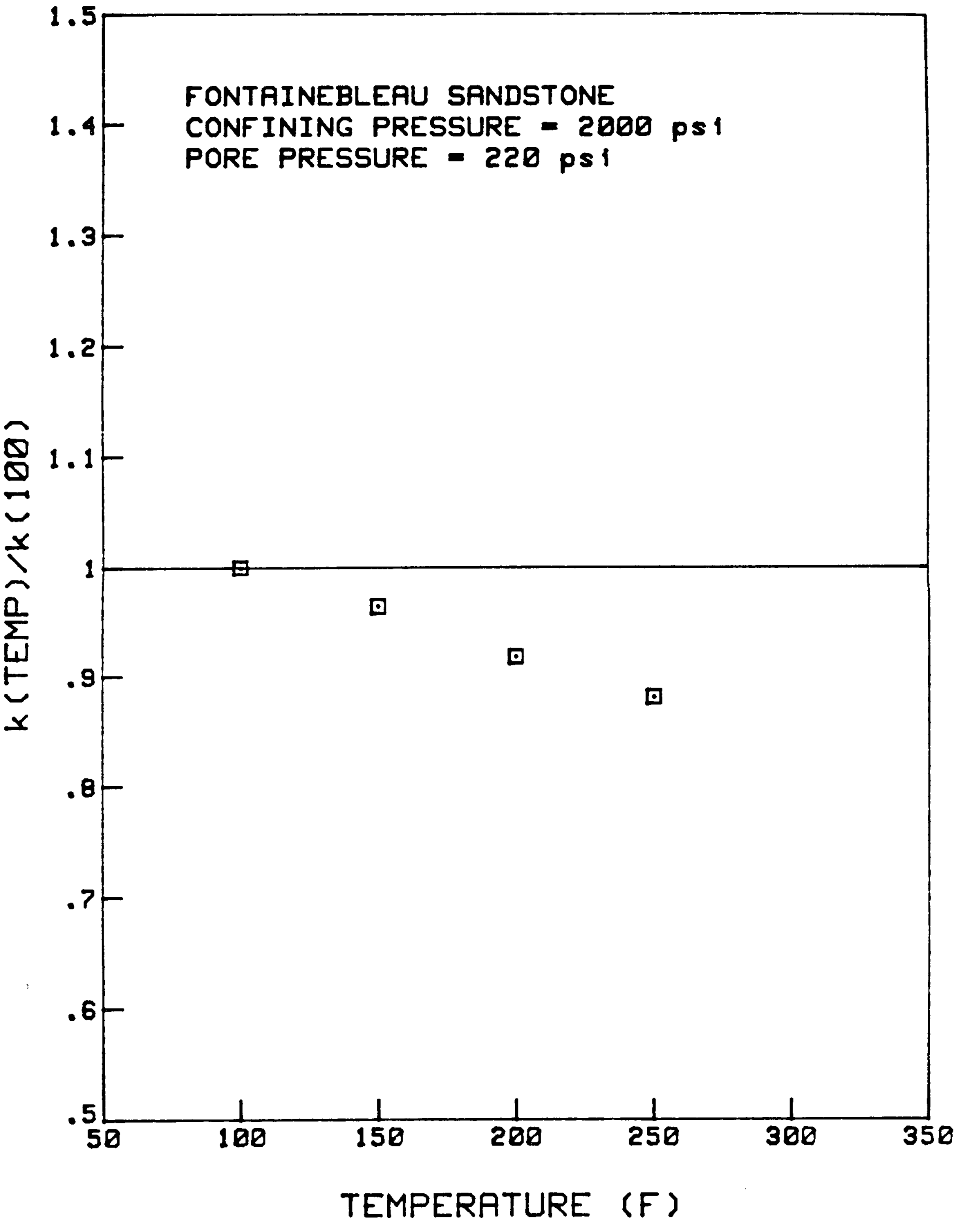


Fig. 7. Permeability Ratio vs. Temperature

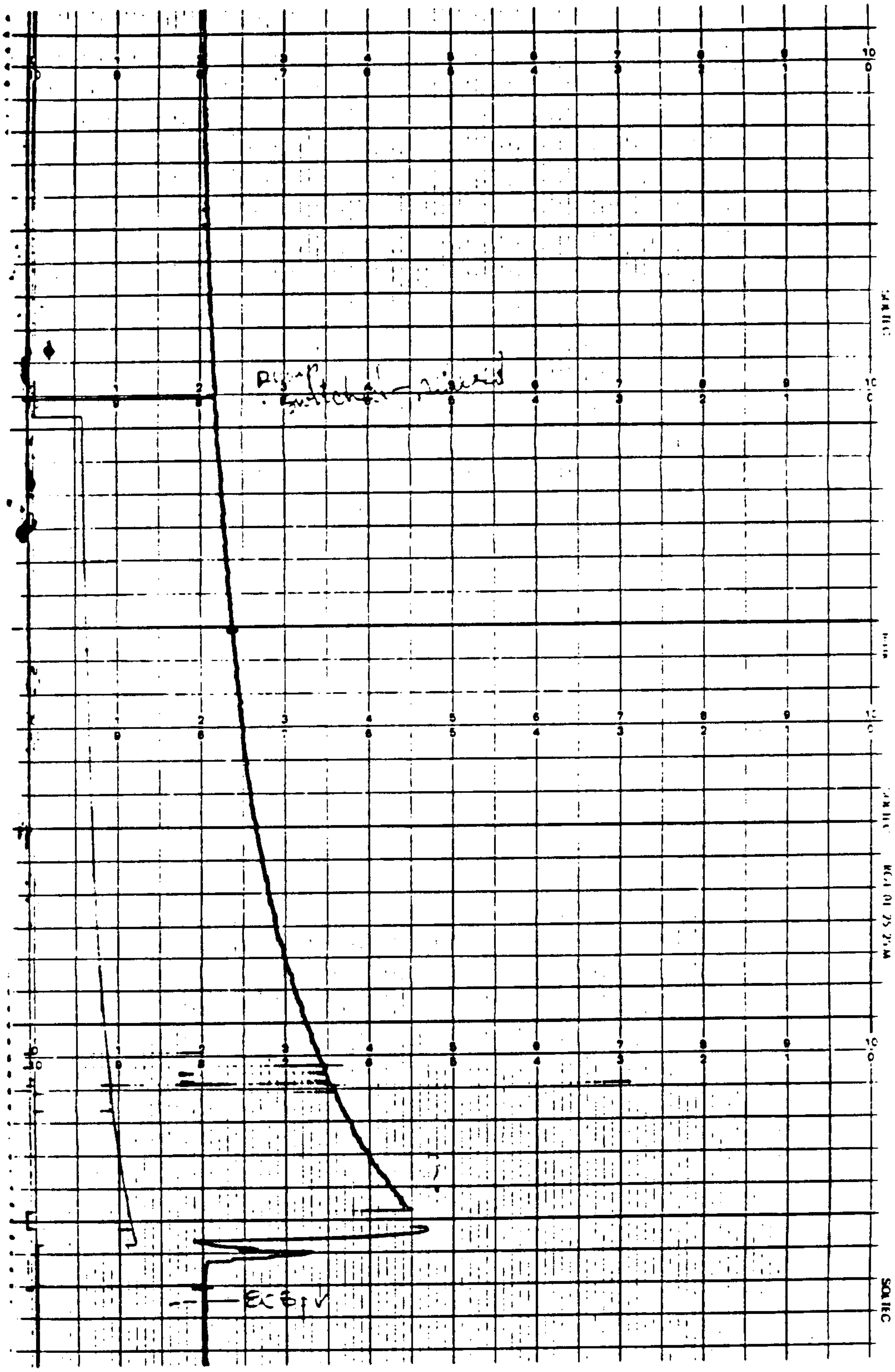


Fig. 8. Differential Pressure Anomaly

sandface was discarded since the Δp reading was observed to gradually decline back to its previously stable value. This decrease after the jump resembled an exponential decline and restabilized after approximately twenty pore volumes. A solid particle could not be expected to pass through the porous medium with such ease. No explanation has yet been found for this strange behavior.

The first run investigating temperature effects on permeability was continued only up to 250°F. During the heating cycle from 250°F to 300°F, the teflon sleeve developed a leak, making it impossible to maintain confining pressure. The core holder was disassembled, and the teflon sleeve was replaced. In the next run, the permeability was to be measured between 70°F and 200°F. By decreasing the temperature during the cooling cycle, repeatability of measurement could be investigated. Since the teflon failed at 275°F in the first run, 200°F was considered a safe maximum temperature. After the cooling cycle, the temperature could then be raised gradually above 200°F to observe high temperature behavior. However, the sleeve developed a leak at 150°F in the first heating cycle and the second run was discontinued.

7. DISCUSSION

The results of the volumetric throughput dependence run exhibit some interesting trends. The consistent decrease in permeability with pore volumes injected suggests a plugging of pore openings by fines migration and/or clay expansion. The migration hypothesis is further supported by abrupt changes in permeability when flow is stopped and restarted. Such a discontinuity in flow disrupts the accumulation of fines in pore constrictions in some manner. This occurred at 190 pore volumes on Figure 3, and between each flow rate setting on Figure 4. Although measured permeabilities are higher at greater rates, the throughput effect seems to prevail throughout the run. The occurrence of higher permeability measurements at the high flow rates in Figure 4 suggests a rate sensitivity of permeability. Large variation in pore pressure with rate was considered as a possible explanation. However, the average pore pressure varied less than 10% over the entire range of flow rates investigated.

The conclusion drawn from the first two phases of the experiment is that permeability is reduced with increasing throughput water volume due to a plugging action in the core. This accumulation in the pore constrictions increases with cumulative water volume through the core and is found to reverse somewhat when the rate of flow is disrupted. Permeability exhibits some variation with flow rate, but this effect has not been isolated from volumetric throughput phenomena by this experimental procedure. Consequently, it is considered beyond the scope of this study to define the flow rate effect on consolidated sandstone permeability.

The results of the first elevated temperature run, which are plotted in Figures 6 and 7, are basically inconclusive due to the lack of data for decreasing temperature. A permeability reduction of 11.8% is observed between 100°F and 250°F. It is not clear whether this change can be attributed to a temperature effect or a continuation of the previously observed volumetric throughput dependence of permeability. A means of determining the cause of the reduction would be to continue the run back down to lower temperatures and compare measured permeability for the heating and cooling cycles. A close repeatability of measurements would suggest the existence of temperature effects. Consistently lower values on the cooling cycle could substantiate the dependence of the sandstone permeability on throughput volume.

The reliability of heat shrinking teflon as a Hassler sleeve material for high temperature experiments is questionable based on the two unsuccessful trials. The Fontainebleau core that was cut for these runs had a small chip at one end. This slight indentation, adjacent to the downstream end plug, represents a point at which confining stresses are concentrated, and where the leaks developed at high pressure and temperature. In order to eliminate such weak points in the sleeve, care must be taken to cut the core sample with a smooth and uniform diameter. Another safeguard against leaks that has been considered is the use of teflon around the core surrounded by an outer sleeve of viton tubing. The additional strength of the viton will prevent stress concentration at the sandface -- end plug interface, while still allowing the application of confining pressure.

8. RECOMMENDATIONS FOR FURTHER WORK

The first experimental run suggests a phenomenon occurring in the porous medium that results in reduced permeability with increasing throughput water volume. In order to further identify the nature of this effect, an experiment should be performed to measure the permeability of the sandstone over a number of heating and cooling cycles. Necessary revisions of the experimental procedure include the use of a new core sample of uniform diameter and a modified confining sleeve capable of withstanding high pressure and temperature.

9. ADDITIONAL WORK

The difficulties with the teflon sleeve encountered in the first two runs of the experiment prevented a complete analysis of the relationship between temperature and absolute permeability. However, after several changes had been made in the experimental apparatus and procedure, a more useful set of data was obtained. The results of the third experimental run helped answer some of the questions regarding the effects of temperature and throughput volume on permeability.

The first alteration addressed the problem of a reliable sleeve material to isolate the flowing fluid from the fluid used to apply confining pressure. The combination of teflon and viton tubing was found to be adequate under the conditions of pressure and temperature used in this study. After a new core was cut and mounted between the endplugs, the teflon was heated for five hours at 300°F in order to obtain a close fit around the core sample. In the two previous attempts, the core and endplugs were mounted horizontally in a large C-clamp and placed in the air bath. This arrangement was found to result in uneven shrinkage and gaps at the sandface -- endplug interface. Consequently, by mounting the core between the endplugs vertically with the teflon around them, a tighter, more even fit was achieved. Once the core was allowed to cool, a sleeve of one-inch viton tubing was placed around the core sample over the teflon sleeve. Hose clamps around the viton were used to secure the two sleeves to the endplugs. During the subsequent experimental run, the sleeve successfully maintained the confining pressure at 2000 psi at temperatures as high as 300°F.

In response to the importance for a core sample with a uniform diameter, a new Fontainebleau core was cut to 0.973 inches in diameter and 6.330 inches in length. Using the same evacuation and saturation procedure as before, the pore volume was calculated as 8.70 cm^3, and the porosity, 11.3%.

The objective of the third experimental run was to more clearly define the behavior of the absolute permeability of the Fontainebleau sandstone at varying temperatures and cumulative throughput volume. As mentioned before, the degree of repeatability of permeabililty measurements over several heating and cooling cycles could indicate whether temperature or throughput effects are the dominant cause of observed permeability variations. To accomplish this, the experiment was designed to vary temperature from the outset rather than beginning with extended flow at constant temperature to investigate throughput and flowrate effects.

The experimental procedure began by evacuating the system overnight using the liquid nitrogen cold trap in conjunction with the vacuum pump. Again, the differential pressure transducers were calibrated, and the evacuation was continued for two more hours before the run commenced. In the first run, discontinuities were observed in the otherwise smooth decline of permeability vs. throughput volume when the flow was stopped. Therefore, the flow was planned to be maintained throughout the run with only brief interruptions during the refilling of the pump cylinder.

The results are first considered in terms of the cumulative volumetric throughput to verify that the new core exhibited similar behavior to the first one used. Figure 9 shows a general decrease in absolute permeability with increasing cumulative water through the core. Each point represents an average of the three highest flow rates at each temperature. It is important to note that the jumps in the curve result from temperature variations; however, these do not alter the general trend. Additionally, the relative significance of these temperature-related permeability variations diminishes with higher throughput volume. This is also noticeable on the permeability vs. temperature plot.

In order to analyze the relative importance of temperature and throughput effects, permeability is plotted as a function of temperature in Figure 10. The arrows on the lines between points indicate the sequence in which the temperature was varied during the experiment. The most obvious feature is the sharp decline in permeability over the first two heating cycles during which the temperature was raised to 300°F. It is important to note, however, that the permeability continued to decline slightly in the following cooling cycle from 300°F down to room temperature. Finally, the permeability was found to change relatively little with temperature variations as the curve flattened on the last heating cycle.

At the end of the run, the core holder was disassembled and the inlet sandface inspected visually for residue. No evidence of plugging at the inlet face appeared; consequently, any plugging must have been a result of particles originating within the porous medium.

The conclusion drawn from these results is that volumetric throughput effects, caused by plugging of pore constrictions by migrating fine particles, are the main cause of the observed permeability decline. Since the decrease in permeability is found to stabilize at higher cumulative throughput volumes when the plugging phenomenon has reached a maximum, the absolute permeability of this sandstone can be considered independent of temperature.

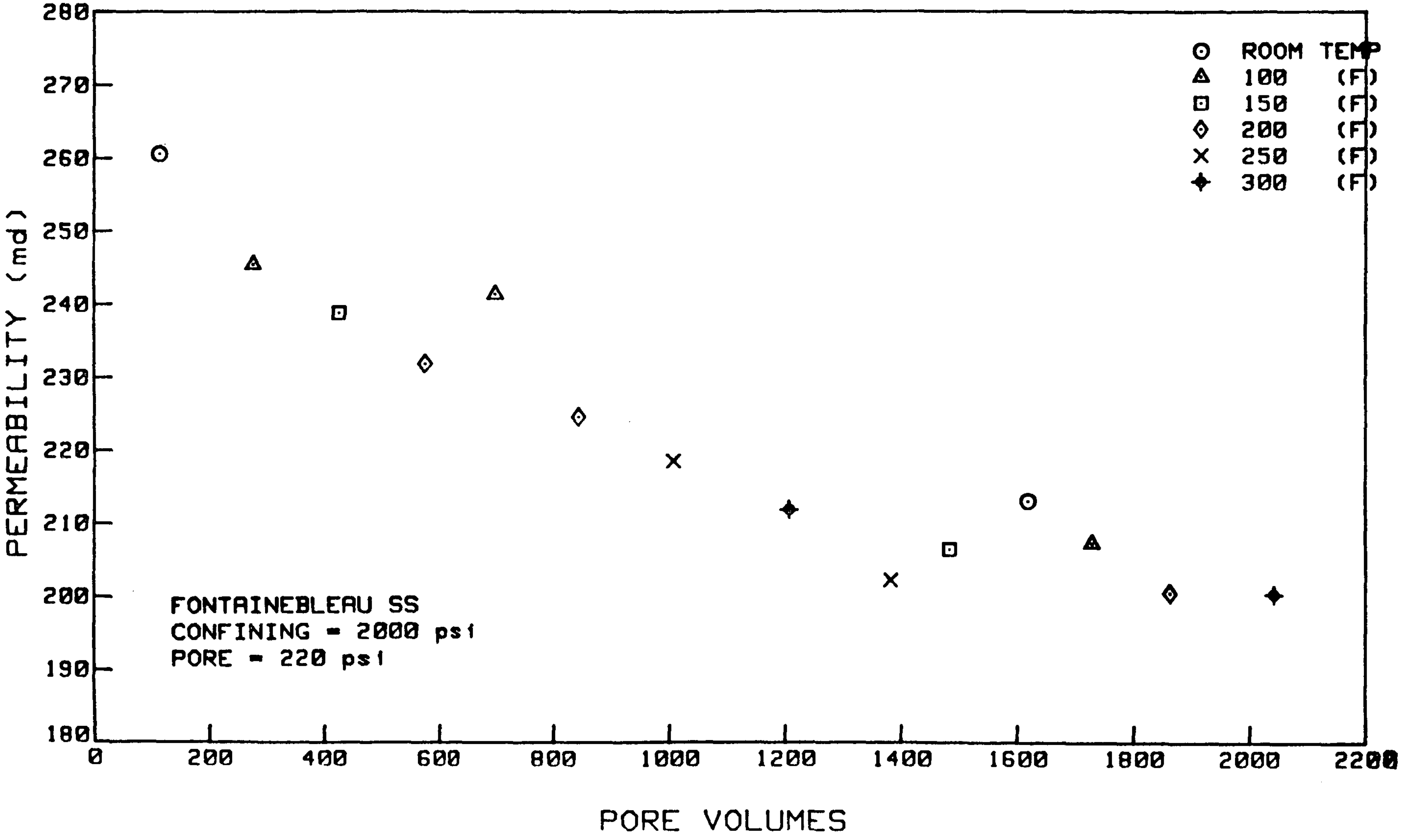


Fig. 9. Permeability vs. Throughput

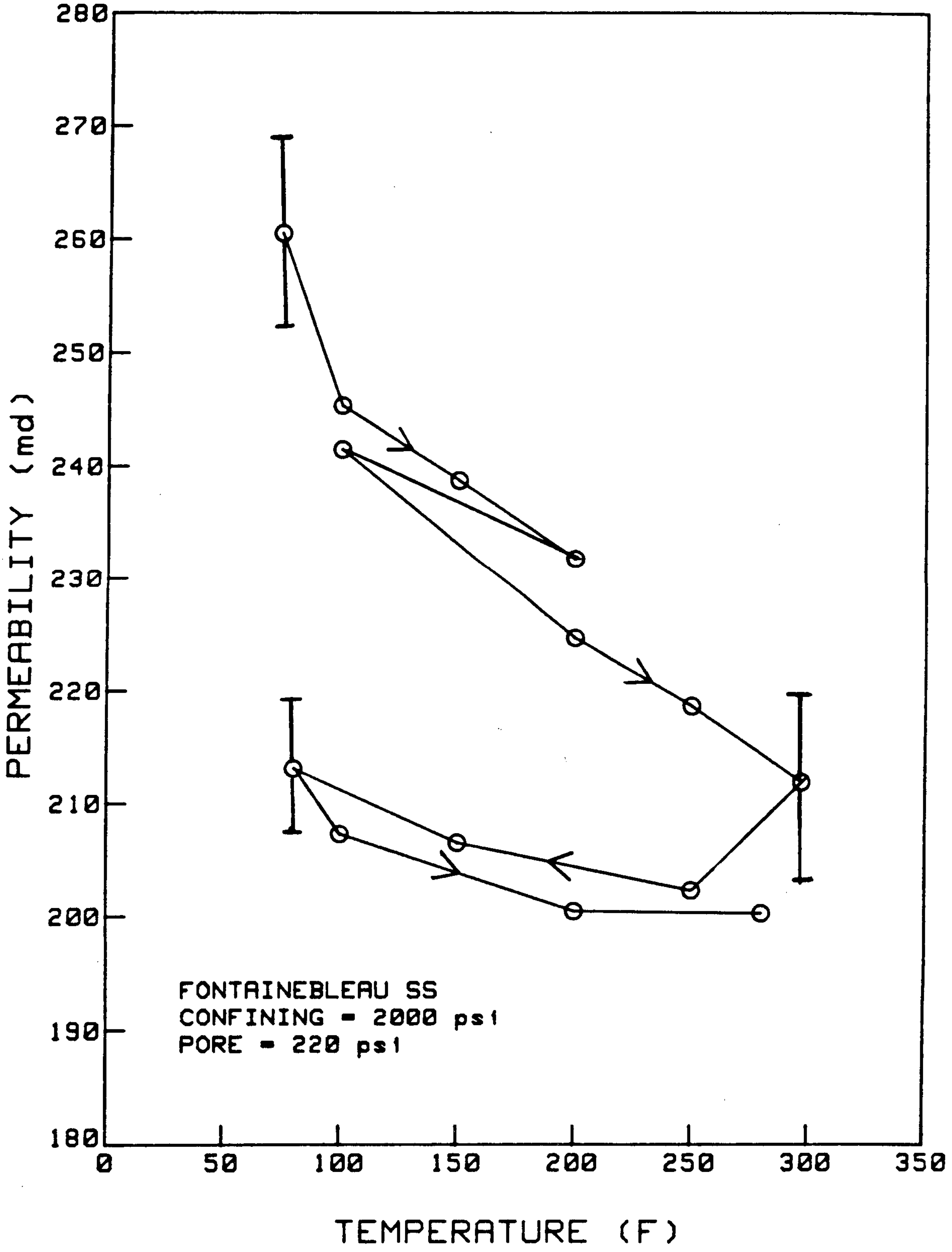


Fig. 10. Permeability vs. Temperature

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APPENDIX A

CALCULATION OF PERMEABILITY

Permeability can be defined in terms of Darcy's law as follows:

$$k = -\frac{q\mu L}{A\Delta p} \qquad \text{(A-1)}$$

Where, q = volumetric flow rate in cc/hr.

μ = viscosity of flowing fluid in cp.

L = length of core sample in cm.

A = cross-sectional area of core in cm^2.

Δp = pressure differential across core in atm.

k = absolute permeability to flowing fluid in darcies.

Since the volumetric flow rate is measured at room conditions of pressure and temperature (14.70 psia and 70°F), q must be corrected to conditions in the core. This correction can be accomplished by expressing a mass flow rate which is constant in steady state flow according to the continuity equation:

$$q\rho = q_{sc}\rho_{sc} \qquad \text{(A-2)}$$

Where, $q\rho$ = mass flow rate at core conditions.

$q_{sc}\rho_{sc}$ = mass flow rate at standard (room) conditions, 70°F and 14.70 psia.

ρ_{sc} = 62.3053 lbm/ft^3

ρ = density in lbm/ft^3 from Table 1.

Fluid viscosity must also be corrected to flowing conditions in the core. Viscosity values at 220 psi for the appropriate temperatures are found in Table 1. The values of A and L are determined by the dimensions of the core sample used:

$$A = 4.776 \text{ cm}^2$$

$$L = 15.94 \text{ cm}$$

Darcy's law can now be expressed:

$$k = -\frac{q_{sc}\rho_{sc}\mu L}{\rho\ A\ \Delta p} \qquad \text{(A-3)}$$

TABLE A-1

DENSITY AND VISCOSITY OF WATER AT 220 PSI

Temperature (°F)	Density(lbm/ft^3)	Viscosity(cp)
100	62.0347	0.6813
150	61.2370	0.4304
200	60.1685	0.3036
250	58.8582	0.2298
300	57.3394	0.1834

APPENDIX B

ERROR ANALYSIS

In order to determine the error in permeability measurements, equation A-3 can be differentiated as follows to express a change in permeability as a function of the other parameters in Darcy's law.

$$dk = -\frac{\rho_{sc} L}{A} \left\{ dq_{sc}\left(\frac{\mu}{\rho \Delta p}\right) + d\mu\left(\frac{q_{sc}}{\rho \Delta p}\right) - d\rho\left(\frac{q_{sc}\mu}{\rho^2 \Delta p}\right) - d(\Delta p)\left(\frac{q_{sc}\mu}{\rho \Delta p^2}\right) \right\} \quad \text{(B-1)}$$

where ρ_{sc}, L, and A, are constant. In other words, any error in the measurement of these quantities will tend to contribute equally in magnitude and direction to all permeability calculations.

The flow rate can be expressed as follows.

$$q_{sc} = \frac{v_{sc}}{t} \quad \text{(B-2)}$$

where v_{sc} is the volume of water at standard conditions. Consequently, when flow rate is measured error can be introduced in both volume and time.

$$dq_{sc} = dv_{sc}\left(\frac{1}{t}\right) - dt\left(\frac{v_{sc}}{t^2}\right) \quad \text{(B-3)}$$

where dt = ±0.05 seconds and is therefore considered negligible.

It is assumed that if temperature and back pressure on the system are maintained at constant values for an experimental run, errors in μ and ρ are negligible (i.e. $d\mu$ and $d\rho$ are approximately zero).

$$dk = -\frac{\rho_{sc}L}{A}\left\{ dq_{sc}\left(\frac{\mu}{\rho\Delta p}\right) - d(\Delta p)\left(\frac{q_{sc}\mu}{\rho\Delta p^2}\right) \right\} \qquad \text{(B-4)}$$

Substituting equations B-2 and B-3 into B-4,

$$dk = -\frac{\rho_{sc}L}{A}\left\{ \frac{dv_{sc}}{t}\left(\frac{\mu}{\rho\Delta p}\right) - d(\Delta p)\left(\frac{v_{sc}\mu}{t\rho\Delta p^2}\right) \right\} \qquad \text{(B-5)}$$

The percent error in permeability is found by dividing the term representing an infinitesimal change by the actual value.

$$\frac{dk}{k} = \frac{dv_{sc}}{v_{sc}} - \frac{d(\Delta p)}{\Delta p} \qquad \text{(B-6)}$$

or,

$$dk = k\left\{ \frac{dv_{sc}}{v_{sc}} - \frac{d(\Delta p)}{\Delta p} \right\} \qquad \text{(B-7)}$$

Since the dv_{sc} and $d(\Delta p)$ terms express only the magnitude of error in the corresponding terms, the measurement can deviate from the true value in either a positive or negative direction. Therefore, the actual error in permeability is obtained by addition of the squares of the error terms.

$$dk = k\sqrt{\left(\frac{dv_{sc}}{v_{sc}}\right)^2 + \left(\frac{d(\Delta p)}{\Delta p}\right)^2} \qquad \text{(B-8)}$$

The method employed for volumetric flow rate measurement consisted of monitoring the time required to fill a 100 ml cylinder. Due to the size of the graduations on the vessel and the nature of the reading technique,

±1 ml is used as an estimate for dv_{sc}. At each flow rate setting, the measurements were made three times and an average calculated; consequently, the flow rate error is somewhat less than 1%. However, a simplification has been made by assuming that $\frac{dv_{sc}}{v_{sc}} = \pm 0.01$.

The amount of error introduced by the differential pressure measurement depends on the relative sizes of the full scale rating of the transducer and the actual Δp . As a result, the pressure drop error term in equation B-8 can be expressed as follows, based on transducer diaphragm and indicator errors of 1% each.

$$\frac{d(\Delta p)}{\Delta p} = \frac{0.01 \sqrt{\Delta p_{max}^2 + \Delta p^2}}{\Delta p} \qquad (B-9)$$

Where, Δp_{max} = the absolute value of the range of the transducer diaphragm in use.

Δp = the measured pressure differential across core.

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