A STUDY OF CYCLIC CAPILLARY PRESSURE EFFECTS

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CHAPTER I

INTRODUCTION

In recent years the petroleum and natural gas industry has focused an increasing amount of attention upon flow mechanisms involved in the injection and withdrawal of fluids from porous formations in the same well. Principal among these processes are the storage of natural gas in aquifers and a method of thermal oil recovery known as the steam soak. The basic theories discussed in this study apply to both of these fluid systems, that is water-gas and water-oil systems; however, this investigation deals with a water-gas system exclusively.

At this point it is advantageous to define some terms which are used extensively in this treatise. The term "drainage" is used to indicate saturation changes in the direction of decreasing wetting phase saturation. "Imbibition" refers to increasing wetting phase saturation. A "cycle" denotes a drainage process followed by an imbibition process.

In this study, cyclic capillary pressure versus water saturation relationships are obtained experimentally for two complete cycles. This is done for two different core samples with results in both cases which are quite contrary to all original expectations. The capillary pressure data is then used in an attempt to determine first cycle relative permeability curves for the samples which would compare favorably with those obtained by a direct experimental method. This conversion is based on mathematical models previously derived by others. A comparison of relative permeabilities obtained by varying one constant in the expressions relating capillary pressure to relative permeabilities is illustrated.

CHAPTER II

PREVIOUS INVESTIGATIONS

The work with regard to capillary pressure which has been done prior to this study has been divided into three categories for discussion purposes. In order of presentation they are:

A. Definition and Characteristics of Capillary Pressure

B. Experimental Methods for Determining Capillary Pressure

C. Techniques for Relating Capillary Pressure Data to Relative Permeability.

Definition and Characteristics of Capillary Pressure

The most descriptive definition of capillary pressure is that presented by Hassler, Brunner, and Deahl (9) in which they described capillary pressure in a manner that took into account the effects of hysteresis. Capillary pressure in a porous medium was defined accordingly by these authors as

> the pressure difference that occurs between the mobile interconnected masses of the two fluids in question, and it will be associated with the saturation at which it occurs, even though the relation is not altogether permanent.

They pointed out that capillary pressure is not only a function of the saturation but also depends upon the saturation history of the system. In addition, they noted that hysteresis arises from the complex geometry of the porous medium that allows the fluids to be in equilibrium with different distributions and different capillary pressures.

Experimental Methods for Determining Capillary Pressure

There are five principal methods in common use for measuring capillary pressure. These are capillary diaphragm, gravity drainage, centrifugal, mercury injection, and the dynamic method.

The capillary diaphragm, better known as the "restored state technique," as discussed by Bruce and Welge (3) is the most practical procedure for measuring cyclic capillary pressures. This method consists of placing a core sample, saturated with a wetting fluid, in capillary contact with a porous diaphragm permeable only to the wetting phase. By application of a known pressure to the non-wetting phase which is confined above the diaphragm, a portion of the wetting phase is expelled from the core sample. As higher pressures are applied, a relationship between capillary pressure and fluid saturation may be obtained for the drainage part of the curve. Upon reversing the process and decreasing the pressure in finite increments, the fluid will imbibe back into the core sample and thus the imbibition portion of the curve can be obtained. This is the technique used to obtain the experimental data given in this study.

Hassler and Brunner (8) summarized the gravity drainage method which consists of allowing a column of sand saturated with liquid to reach equilibrium by gravity drainage and subsequently determining the saturation at various points in the column by cutting it into sections and separately measuring the saturation in each section. This method is rather impractical for laboratory use because very long columns would be required for low saturations to be obtained in consolidated sands. This severely limits its use on samples from actual reservoirs. In addition, it is impossible to conduct cyclic tests using this method.

The length of time and the large sample size required by the gravity drainage method are due to the low value of gravitational acceleration at the earth's surface. These problems can be partially overcome through use of a centrifuge (8). By using specially adapted centrifuge tubes as core holders, a capillary drainage curve may be obtained. There is, however, no apparent way to obtain an imbibition relationship with this device.

The technique of mercury injection as developed by Purcell (11) has very great possibilities where a reasonably accurate drainage curve is desired in a minimum time. This method has the distinct advantage that irregular samples may be tested with results as valid as may be obtained for regular shapes. The procedure consists of injecting a non-wetting fluid (mercury) into the sample and measuring the mercury saturation at each pressure. The data thus obtained can be converted to water-gas data by employing a ratio of the products of surface tension and cosine of the contact angle. It should be emphasized that this procedure will only produce drainage information.

Dynamic capillary pressure may be determined by a modification of the technique developed by Hassler (7). In this method as discussed by Brown (2), both phases are permitted to flow through the core sample, with control being maintained over the pressure difference existing between them. At equilibrium, the two phases continue to flow but their respective saturations do not change. This technique, as was pointed out by Mattax (10), appears to have the greatest possibility for continued study under simulated reservoir conditions.

Techniques for Relating Capillary Pressure Data to Relative Permeability

The original work in this area was done by Purcell (12). By equating Darcy's Law for flow through a porous medium to Poiseuelle's Equation for flow through a bundle of capillary tubes of non-uniform radii, he developed an expression for the permeability of a system of parallel cylindrical capillaries of equal lengths and various radii. This expression then relates permeability to capillary pressure, porosity, and volumes of the component parts in an ideal system. A so-called lithology factor was introduced to account for difference between flow in the capillary model and a natural rock.

An extension of the above work was reported by Fatt and Dykstra (5). They derived an expression giving the relative water permeability as a function of water saturation by assuming that the core sample could be represented by a bundle of capillary tubes in which the fluid path length was not the same as the bulk length and in which the fluid path length varied with saturation. The resulting expression for relative water permeability is:

$$Krw = \frac{\int_{0}^{Sw} \frac{dSw}{Pc^{2(1+b)}}}{\int_{0}^{100} \frac{dSw}{Pc^{2(1+b)}}} \qquad (1)$$

The authors indicated that the value of the constant b may vary with the type of sand, but in general, they recommended a value of ½.

Arman (1) reported reasonably good agreement with experimental relative permeability by using a value of $b=\frac{1}{2}$ for an unconsolidated glass bead pack with water and oil as the flowing fluids. He also concluded that the method due to Fatt and Dykstra (5) was valid for an imbibition capillary pressure curve obtained from the glass bead packs.

Considerable agreement with experimentally determined relative permeability for both the wetting and non-wetting phases on the drainage part of a cycle was reported by Stahl (13, 14). The technique that he enlarged upon contains a term called the "effective tortuosity" which was originally proposed by Burdine (4). The Burdine method assumed that the tortuosity ratio of the wetting phase varied linearly with saturation from a value of zero at the minimum or irreducible water saturation to a value of one at a water saturation of 100 percent. The tortuosity ratio of the non-wetting phase was also assumed to vary linearly from a value of zero at Sw=1-Snr (Snr=Minimum non-wetting phase saturation) to one at the irreducible water saturation. This method is employed in this study and details of its use are given in Chapter IV.

An interesting amount of substantiation was added to the theory of Burdine by Wyllie and Gardner (16, 17). They visualized a porous medium which consisted of a bundle of capillary tubes of various radii cut into thin slices and these slices arranged randomly. By applying statistical probability, they arrived at expressions relating capillary pressure to wetting and non-wetting phase relative permeability. The point of interest here is that the resulting expressions were the same as developed by Burdine if the minimum gas saturation is assumed to be zero. Basically this model is the same integral form as that proposed by Fatt and Dykstra (5) with the exception that the value of b is taken as zero.

CHAPTER III

STATEMENT OF THE PROBLEM

In recent years, the storage of natural gas in aquifers has become an accepted practice among companies engaged in the production, transportation, and distribution of the gas. The demand for this product fluctuates enormously with the season of the year, thus causing the gas to be injected and stored during the warmer months and withdrawn and used during the colder part of the year. Also, a method of thermal oil recovery has been developed in which steam is injected into a producing well for a period of time. The injection of steam is then stopped, and the condensed steam is produced from the formation along with the oil. This process, known as the steam soak or "huff and puff" (12), may be repeated a number of times. It is this cyclic injection and withdrawal of fluids which brings out some of the problems investigated in this study.

The purpose of this investigation was twofold. First, it was desired to investigate the relationship between capillary pressure and water saturation in a gas-water system for more than one cycle of injection and withdrawal in an effort to see if this relationship remained constant for each cycle, if each cycle had its own characteristics, or if any definite trends could be established. Second, an attempt was made to verify existing correlations of capillary pressure with relative permeability and to extend this concept to the imbibition part of a cycle. As originally derived, the correlations applied only to the drainage portion of a cycle. The criteria for this verification was to be a series of relative permeability tests which had been conducted previously by a modified Penn. State technique on the samples studied in this work.

CHAPTER IV

THEORETICAL DEVELOPMENT

A considerable amount of attention has been devoted by various investigators to the problem of relating capillary pressure data to relative permeability data. Notable among these attempts are those of Purcell (11) and Fatt and Dykstra (5). The basic assumption underlying their work is that the core sample can be represented by a bundle of capillary tubes.

Darcy's Law for linear flow of an incompressible fluid in a porous medium is:

$$Q = \frac{KA\,\Delta P}{\mu L} \tag{2}$$

where Q is the flow rate, K is the permeability, A is the cross sectional area to flow, L is the length, μ is the viscosity, and ΔP is the pressure drop.

Poiseuille's Law for flow through a capillary tube can be expressed as:

$$Q = \frac{\Pi r^4 \Delta P}{8 \mu L} \tag{3}$$

where r is the radius of the tube and the other symbols have the same meaning as before.

By equating these two laws, Fatt and Dykstra arrived at the following expression for wetting phase relative permeability:

$$Krw = \frac{\int_{0}^{Sw} \frac{dSw}{Pc^{2(1+b)}}}{\int_{0}^{100} \frac{dSw}{Pc^{2(1+b)}}} \qquad (1)$$

where Krw is the wetting phase relative permeability, and Pc is the capillary pressure corresponding to the wetting phase saturation Sw.

In order to provide a better agreement between calculated and experimentally determined relative permeabilities, the concept of tortuosity as discussed by Stahl (13, 14) was introduced. This was done to account for the difference in the bulk length of the sample and the actual flow path length. Including the concept of tortuosity, the above equation for Krw becomes:

$$Krw = T \frac{\int_{0}^{Sw} \frac{dSw}{Pc^{2(1+b)}}}{\int_{0}^{100} \frac{dSw}{Pc^{2(1+b)}}} \qquad (4)$$

where T is the tortuosity factor.

The evaluation of tortuosity by Burdine (4) was reported by Stahl (13) to give considerable agreement with experimentally determined relative permeability values. Burdine assumed that the tortuosity for the wetting phase varied linearly with saturation from a value of zero at the minimum wetting phase saturation to a value of one at the maximum wetting phase saturation. He further assumed that the tortuosity of the non-wetting phase varied linearly from a value of zero at Sw=1-Snr (Snr is the minimum non-wetting phase saturation) to one at the minimum wetting phase saturation. The resulting Burdine expressions for wetting and non-wetting relative permeability were then:

$$Krw = \left[\frac{Sw-Swr}{1-Swr}\right]^2 \frac{\int_0^{Sw} \frac{dSw}{Pc^{2(1+b)}}}{\int_0^{100} \frac{dSw}{Pc^{2(1+b)}}} \qquad (5)$$

and

$$Krnw = \left[1-\frac{Sw-Swr}{1-Snr-Swr}\right]^2 \frac{\int_{Sw}^{1} \frac{dSw}{Pc^{2(1+b)}}}{\int_0^{100} \frac{dSw}{Pc^{2(1+b)}}} \qquad (6)$$

where Swr is the minimum wetting phase saturation.

The normal method of solving these equations consists of plotting, as a function of water saturation, the reciprocal of capillary pressure raised to the power determined by the value of b. The area under this curve corresponding to the limits on the integrals can be determined by planimitering or by numerical techniques on a digital computer. A program to carry out this numerical integration and to solve for Krw and Krnw at one percent saturation intervals was written in Fortran for the IBM 1620 by the author. A program listing along with its table of symbols is given in the Appendix.

CHAPTER V

EXPERIMENTAL APPARATUS AND TECHNIQUES

The procedure used for determining the experimental capillary pressure curves was similar to the restored-state technique as described by Bruce and Welge (3). A description of this procedure can best be handled by discussing first the apparatus used and then the techniques employed in its use.

Apparatus

A schematic drawing of the capillary pressure test equipment appears in Figure 1. The heart of this apparatus was a pyrex Buchner funnel fitted with an ultra fine fritted glass disc. The pore size distribution and wettability characteristics of this disc were such that the nitrogen which was used as the non-wetting phase in the tests would not pass through the disc when it was wet with water. This was verified by a number of preliminary pressure tests up to the manufacturer's suggested maximum pressure differential of 15 psi. A picture of the funnel in its mounting bracket appears in Figure 2.

Gas pressure was supplied to the funnel from a nitrogen bottle equipped with a Hoke 901B14 two-stage regulator. The gas was passed through a water-filled gas bubbler in an attempt

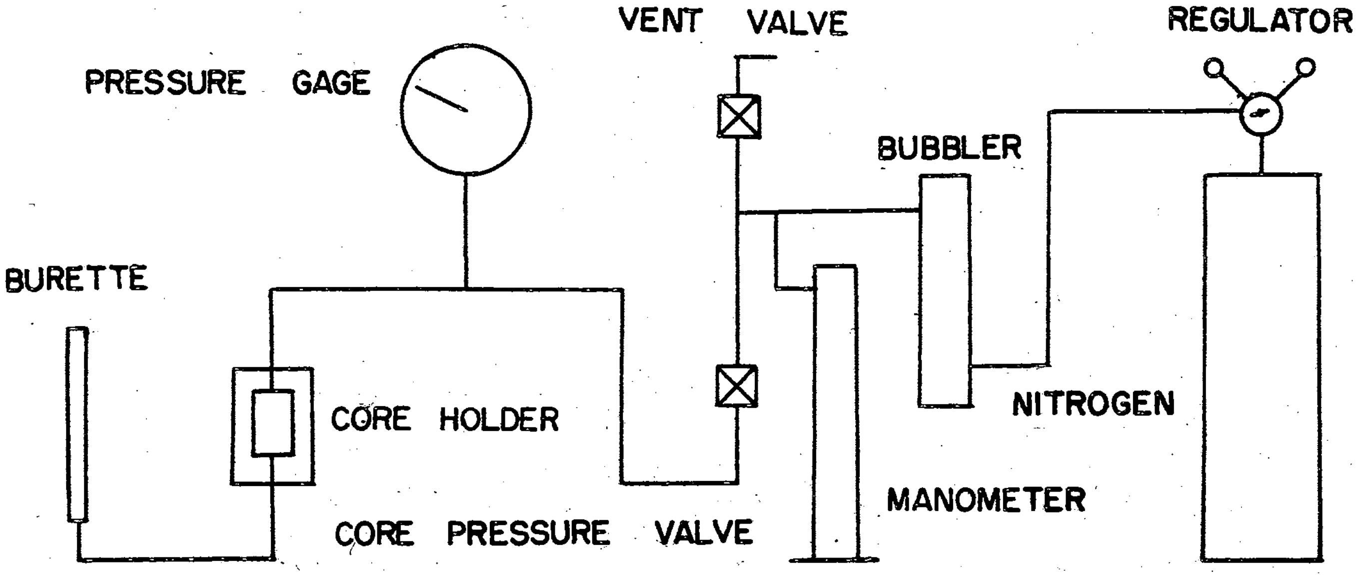

Figure 1. Schematic of Capillary Pressure Apparatus

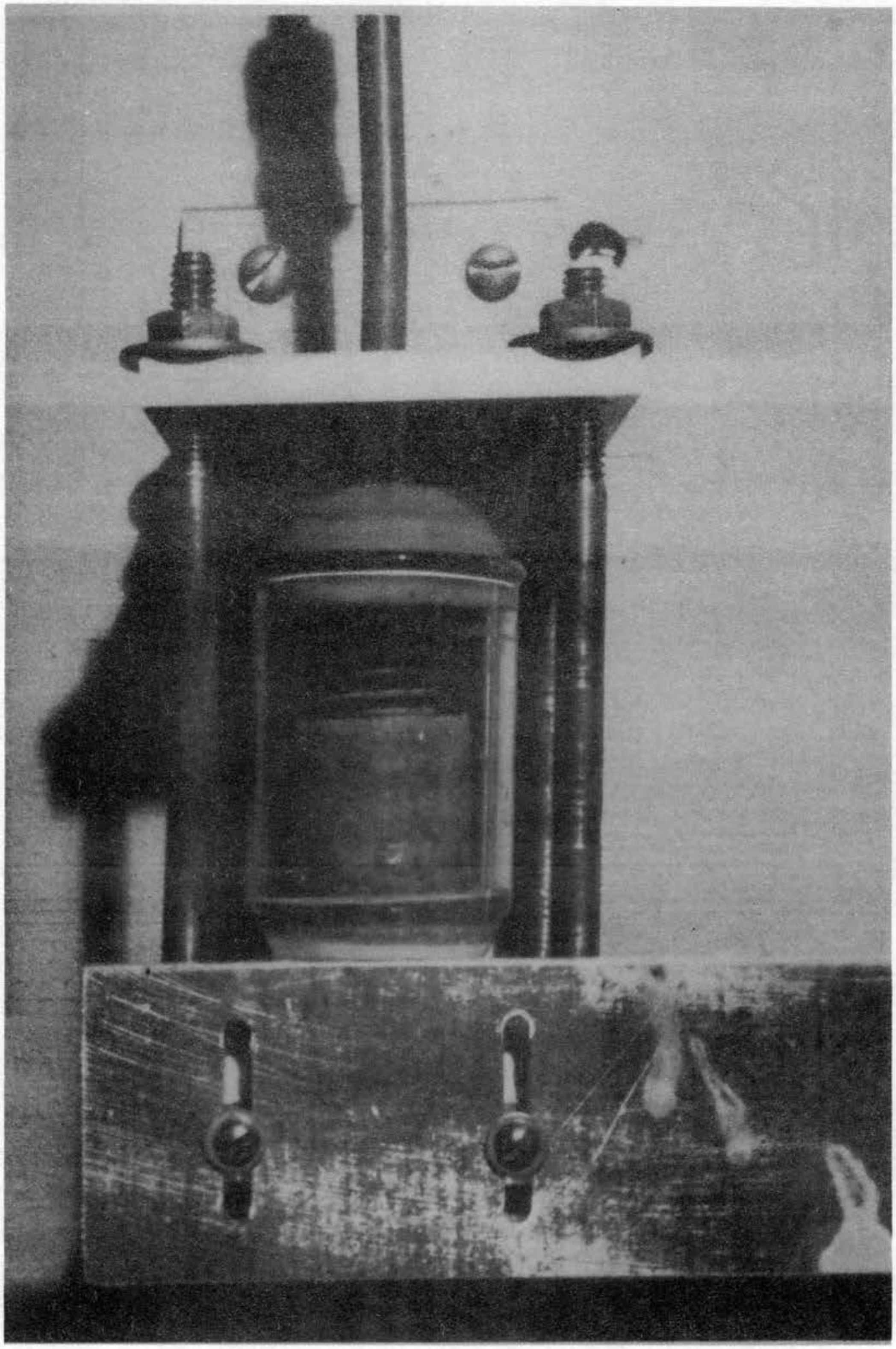

Figure 2. Buchner Funnel in Mounting Bracket

to eliminate evaporation losses from the core sample. An upstream manometer was incorporated in the system as a means of setting the desired pressure before applying it to the sample and as a means of checking the gage pressure readings. These pressure readings were made on a Wallace and Tiernan gage which was calibrated to 0.01 psi. Net changes in water volume within the core were measured by using a burette calibrated to read in 0.01 c.c. divisions.

The funnel, pressure gage, burette, and a thermometer were mounted on a plywood panel along with the control valves. This entire assembly, including the upstream mercury manometer and gas bubbler, was placed in a Tenney environment chamber for the duration of the complete test run. The temperature during a test was maintained at 25°C. (±1°) due to the calibration of the pressure gage having been done at that temperature. The complete assembly installed in the environment chamber is shown in Figure 3.

Techniques

The core samples tested in this study had previously been subjected to relative permeability tests as reported by Foster (6). The modified Penn. State technique for determining relative permeability as discussed by Woods (15) required that platinum band electrodes be attached to the samples and that the cores be encased (except for the ends) in plastic. These features can be observed in Figure 4 which shows a cross section of one of the core samples.

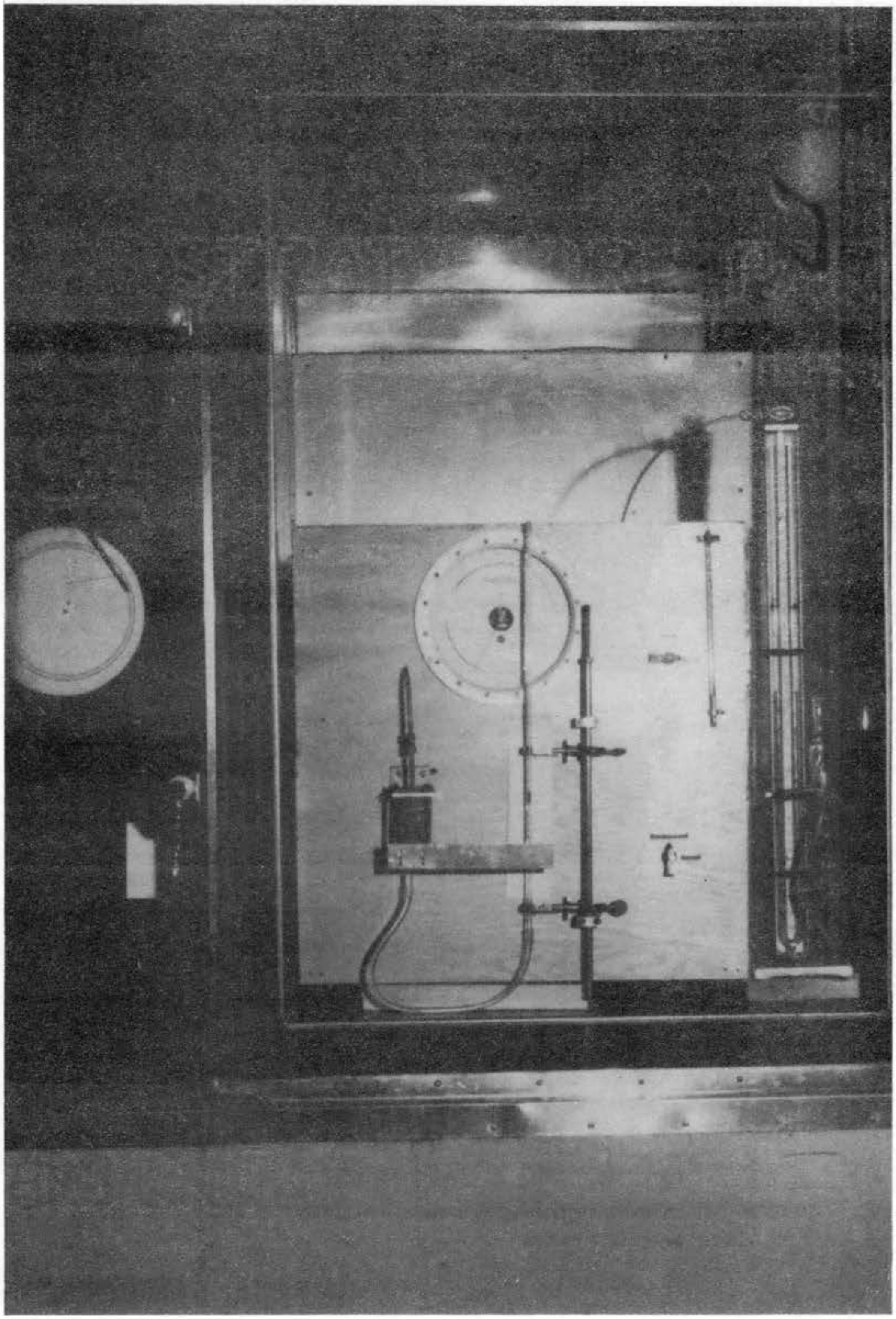

Figure 3. Pc Apparatus in Environment Chamber

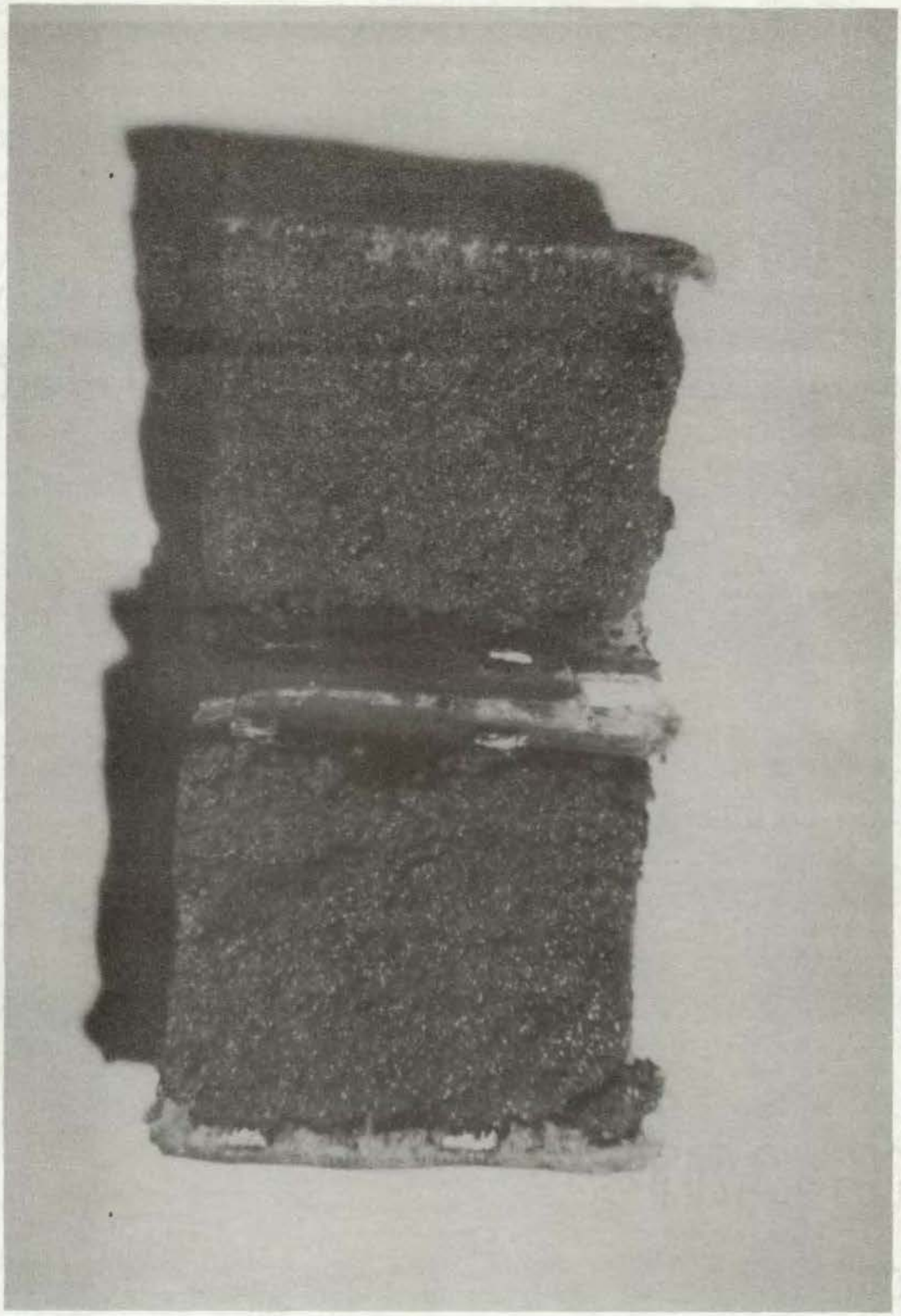

Figure 4. Cross Section of a Core Sample

Prior to mounting each core sample in the test apparatus a number of preparatory steps were taken. First, it was cut to a length of approximately 1.1 inches in order to make it fit in the Buchner funnel. Next, a number of very small holes were drilled through the plastic coating in an attempt to speed up steady state fluid distribution at any given pressure. Third, it was baked in an oven for eight to ten hours and a subsequent dry weight was obtained. Finally, it was saturated completely with distilled water using a vacuum saturation process and a saturated weight was obtained. At the conclusion of the above steps, the core was placed in capillary contact with the fritted disc by means of four to eight circular pieces of Kleenex installed between the sample and the disc. A coil spring was placed on top of the core, the neoprene stopper put in place, and the funnel clamped to the test panel. The water-filled tygon tubing connecting the outlet side of the funnel to the burette was attached and the test was ready to begin.

Once the core was installed and the test under way, the procedure for obtaining data was as follows. The core chamber was isolated from the gas supply by closing the "core pressure" valve. The desired pressure to be applied to the sample was set on the manometer by using the pressure regulator and "vent" valve. This procedure was applied to both drainage and imbibition tests. After approximately eight hours had elapsed and essentially steady state conditions had been reached, the gage pressure, manometer reading, burette reading, temperature of the chamber, and barometric pressure were recorded. This procedure was continued until two complete cycles had been run. The total time involved was approximately one month for each sample tested. It can be noted at this point that if many samples were to be tested, some type of manifold system should be used in order to test more than one sample at a time.

The calculation of capillary pressure-saturation data from the raw data obtained by this procedure is quite simple but very repetitious. For this reason a "capillary pressure" program was written in Fortran for the IBM 1620 by the author. The program computed the volume of water in the core sample when fully saturated and compared this with the volume changes measured with the burette to obtain the water saturation at any pressure. In addition, the gage pressures recorded as part of the raw data were adjusted by the program to a common barometric pressure base. A listing of this program appears in the Appendix along with its symbol list.

CHAPTER VI

RESULTS

Two different samples were tested during this study. The first, designated as Core S1-F2 was a naturally occurring fine-grained sandstone while the second, designated as Core Art 7AH was an artificial core. Basic properties of these two samples are given in Table I.

TABLE I

CORE SAMPLE SPECIFICATIONS

Sample No.	S1-F2	Art 7AH
Formation	Lower Franconia	Artificial
Depth, Feet	1897	
Lithology	Sandstone, fine grain	70% by weight 50-70 mesh sand
Weight % cement		30
Orientation	Horizontal	Horizontal
Porosity	23.7%	38.7%
Permeability, md		
Klinkenberg	154.0	155.4
Water, Maximum	137.4	152.9
Water, Minimum	124.7	143.4
Water, Average	131.0	148.1

The capillary pressure data obtained for Core S1-F2 is shown numerically in Table II and graphically in Figure 5. Similar data for Core Art 7AH is shown in Table III and Figure 6.

An examination of the data presented for Core S1-F2 will indicate that a portion of the first drainage was run twice. This initial segment of the drainage curve was repeated the second time in an effort to get a better description of the curve at the high water saturations and as a check on the reproducibility of the data. Some discrepancy was obtained at the beginning of the curve, but in general the results were reproducible.

The most striking feature of the capillary pressure data for both cores is the apparent change in "irreducible" water saturation from one cycle to the next. It can be seen from the curves that in both cases the minimum water saturation for the second cycle was somewhat higher than for the first cycle while the trapped gas saturation remained essentially constant. Since it had been assumed that the second cycle would follow much the same curve as the first, this was contrary to all expectations. A few rough points were run on a third cycle for Core Art 7AH and it appeared that this shift would continue to occur. All attempts to discount this phenomenon on the basis of experimental error have failed, so it must be concluded that this saturation shift actually occurred.

Input data for the conversion of capillary pressure to relative permeability data was provided by reading a value of

TABLE II

CYCLIC CAPILLARY PRESSURE DATA, CORE S1-F2

```
     INPUT DATA

CORE S1-F2  CAPILLARY PRESSURE  AUGUST 1964

WETWT      DRYWT      DENS      BSEVL        A          B        PBASE
 GM.        GM.      GM./CC                                    IN. HG.

 35.519    31.005     1.0        4.16      -.019      1.006      29.04

PGAGE      HG         VOL        TEMP      PBAR
PSI        IN.        CC        DEG. C      IN.

 0.020     0.00      4.160      24.5      29.04
 0.620     1.250     3.350      24.5      29.10
 1.290     2.550     2.90       24.5      29.025
 1.730     3.550     1.590      24.5      29.06
 2.30      4.70      0.890      25.0      28.97
 2.76      5.55      0.710      25.0      29.07
 3.64      7.40      0.570      25.0      28.985
 3.93      7.95      0.55       25.0      29.10
 4.80      9.70      0.50       25.0      29.01
 5.420     11.00     0.480      25.0      29.065
 6.17      12.54     0.470      25.0      29.040
 7.12      14.40     0.460      25.0      29.035
 7.670     15.65     0.450      25.0      28.975
 8.820     18.00     0.440      25.0      29.025
 9.880     20.20     0.440      25.0      28.980
 12.080    24.60     0.435      25.0      29.035
 13.820    28.10     0.435      25.0      28.970
 11.350    23.10     0.440      25.0      28.955
 9.960     18.35     0.445      25.5      28.910
 8.290     17.00     0.450      24.0      29.120
 7.330     14.90     0.460      25.0      29.060
 6.030     12.20     0.490      25.0      29.040
 5.070     10.20     0.520      25.0      29.065
 4.20      8.50      0.550      25.0      28.940
 3.750     7.50      0.590      25.0      28.760
 3.560     7.150     0.620      25.0      29.020
 3.020     6.20      0.670      24.0      29.190
 2.660     5.450     0.720      23.5      29.080
 2.20      4.550     0.770      24.0      28.960
 1.90      3.90      0.870      24.0      28.925
 1.650     3.350     1.020      23.5      29.055
 1.230     2.550     1.240      24.0      29.165
 0.750     1.450     1.920      24.5      29.025
 0.470     1.000     2.360      24.5      29.080
 0.360     0.850     2.490      24.0      29.040
 0.030     0.0       2.830      24.0      29.010
 0.70      1.450     2.740      25.0      29.0
 1.25      2.55      2.08       25.0      28.710
 1.78      3.70      1.45       25.0      28.710
 2.46      4.95      1.17       25.0      28.805
 3.46      7.00      0.97       25.0      28.870
 4.41      8.95      0.90       25.0      29.02
 5.88      11.90     0.84       25.0      29.015
 7.510     15.35     0.81       25.0      29.125
 10.04     20.50     0.77       25.0      29.075
 13.59     27.70     0.73       25.0      29.120
 9.63      19.65     0.73       25.0      29.050
 6.72      13.65     0.74       24.0      29.105
 5.18      10.50     0.75       25.0      28.975
 4.12      8.40      0.78       25.0      28.950
 3.22      6.55      0.83       25.0      28.930
 2.24      4.65      0.89       24.0      28.91
 1.66      3.40      1.04       25.0      28.84
 0.84      1.75      1.98       24.0      28.755
 0.08      0.0       2.78       25.0      28.685
```

TABLE II (Continued)

```
     OUTPUT DATA

CORE S1-F2  CAPILLARY PRESSURE  AUGUST 1964
     WATER SAT.   PC(GAGE)     PC(HG)    TEMP.
     PER CENT       PSI.        PSI.   DEG.C
        100.000       .001       .000     24.500
         82.055       .634       .613     24.500
         72.086      1.271      1.252     24.500
         43.066      1.731      1.743     24.500
         27.558      2.260      2.307     25.000
         23.571      2.772      2.725     25.000
         20.469      3.615      3.633     25.000
         20.026      3.964      3.903     25.000
         18.918      4.794      4.762     25.000
         18.475      5.445      5.401     25.000
         18.254      6.188      6.157     25.000
         18.032      7.141      7.070     25.000
         17.811      7.664      7.684     25.000
         17.589      8.846      8.838     25.000
         17.589      9.890      9.918     25.000
         17.478     12.131     12.078     25.000
         17.478     13.849     13.797     25.000
         17.589     11.357     11.342     25.000
         17.700      9.936      9.009     25.500
         17.811      8.360      8.347     24.000
         18.032      7.364      7.315     25.000
         18.697      6.047      5.990     25.000
         19.361      5.093      5.008     25.000
         20.026      4.156      4.173     25.000
         20.912      3.615      3.682     25.000
         21.577      3.552      3.510     25.000
         22.684      3.093      3.044     24.000
         23.792      2.676      2.675     23.500
         24.900      2.154      2.234     24.000
         27.115      1.835      1.914     24.000
         30.438      1.648      1.644     23.500
         35.312      1.280      1.252     24.000
         50.376       .728       .711     24.500
         60.124       .473       .491     24.500
         63.003       .343       .417     24.000
         70.536      -.003       .000     24.000
         68.542       .665       .711     25.000
         53.921      1.075      1.252     25.000
         39.964      1.608      1.816     25.000
         33.761      2.339      2.430     25.000
         29.330      3.377      3.437     25.000
         27.780      4.407      4.394     25.000
         26.451      5.883      5.842     25.000
         25.786      7.578      7.536     25.000
         24.900     10.098     10.065     25.000
         24.014     13.692     13.600     25.000
         24.014      9.673      9.648     25.000
         24.235      6.773      6.702     24.000
         24.457      5.159      5.155     25.000
         25.121      4.081      4.124     25.000
         26.229      3.165      3.216     25.000
         27.558      2.170      2.283     24.000
         30.881      1.552      1.669     25.000
         51.705       .685       .859     24.000
         69.428      -.113       .000     25.000
```

TABLE II (Continued)

```
      INPUT DATA

S1-F2  PARTIAL 1ST DRAIN (RERUN)

WETWT       DRYWT       DENS        BSEVL         A           B          PBASE
 GM.         GM.        GM./CC                                          IN. HG.

34.692      31.195      1.00         4.360      -.019       1.006        29.110

PGAGE       HG          VOL          TEMP       PBAR
PSI         IN.         CC          DEG. C       IN.

 0.02       0.0         4.41         24.5       29.225
 0.01       0.0         4.36         24.0       29.110
 0.28       0.55        4.15         24.0       29.06
 0.44       0.89        4.12         24.0       29.07
 0.62       1.25        4.09         24.5       29.13
 0.84       1.70        4.07         24.0       29.11
 1.00       2.10        4.07         24.0       29.22
 1.26       2.55        3.97         24.5       29.10
 1.70       3.50        2.99         24.50      29.08
 2.15       4.40        1.99         24.5       29.05
 2.72       5.50        1.65         24.5       28.97
 5.60       11.40       1.58         24.5       28.97
```

```
      OUTPUT DATA

S1-F2  PARTIAL 1ST DRAIN (RERUN)
      WATER SAT.    PC(GAGE)       PC(HG)     TEMP.
      PER CENT        PSI.          PSI.     DEG.C
         100.000       -.008         .000      24.000
          93.994        .237         .270      24.000
          93.136        .403         .436      24.000
          92.279        .614         .613      24.500
          91.707        .826         .834      24.000
          91.707       1.041        1.031      24.000
          88.847       1.243        1.252      24.500
          60.823       1.676        1.718      24.500
          32.227       2.114        2.160      24.500
          22.505       2.648        2.700      24.500
          20.503       5.545        5.597      24.500
```

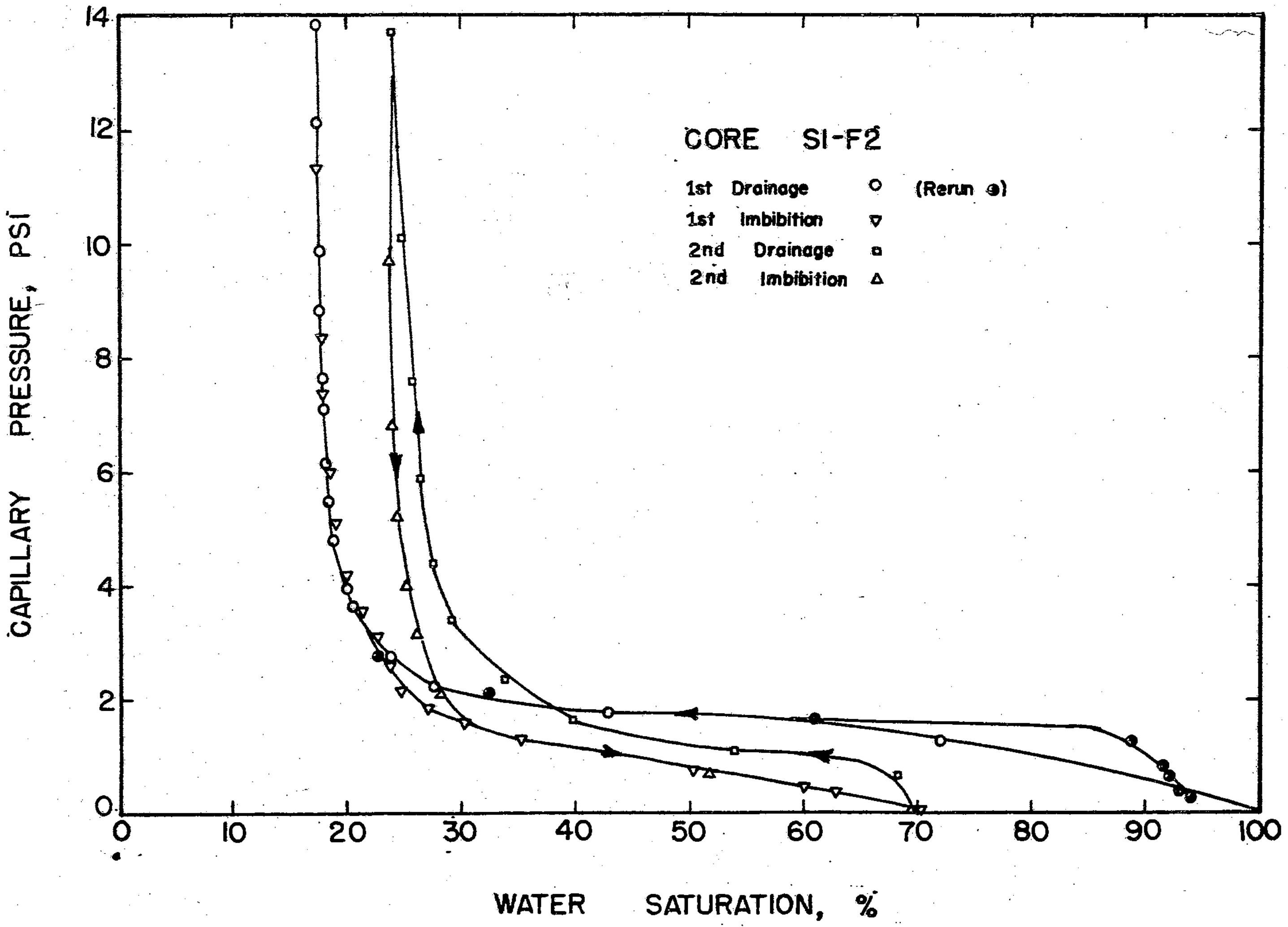

Figure 5. Cyclic Capillary Pressure, Core S1-F2

TABLE III

CYCLIC CAPILLARY PRESSURE DATA, CORE ART 7AH

INPUT DATA

CORE 7AH CAPILLARY PRESSURE SEPT 1964

WETWT GM.	DRYWT GM.	DENS GM./CC	BSEVL	A	B	PBASE IN. HG.
27.951	22.448	1.0	4.85	-.019	1.006	28.93

PGAGE PSI	HG IN.	VOL CC	TEMP DEG. C	PBAR IN.
.020	0.0	4.85	24.0	28.93
.26	.55	4.36	24.0	29.02
.46	.95	4.19	24.0	29.02
.83	1.80	4.03	24.0	29.11
1.43	3.05	2.85	24.0	29.06
2.18	4.50	2.19	24.0	29.06
3.09	6.30	1.73	24.0	29.08
3.82	7.70	1.55	25.0	28.98
5.18	10.50	1.34	25.0	29.045
5.98	12.20	1.25	24.0	29.16
7.12	14.50	1.17	24.0	29.15
8.27	16.90	1.11	24.5	29.25
9.88	20.25	1.07	24.5	29.19
11.43	23.30	1.04	24.5	29.125
14.14	28.65	1.02	24.0	29.020
11.75	23.90	1.03	24.0	28.915
8.95	17.3	1.07	24.0	29.040
7.18	14.65	1.12	24.0	29.275
5.42	11.05	1.19	24.0	29.285
4.10	8.35	1.32	24.0	29.15
2.97	6.10	1.46	25.0	29.04
2.34	4.75	1.67	24.5	29.03
1.64	3.35	2.03	24.0	29.08
.89	1.75	2.65	25.0	29.03
.40	.85	3.56	24.5	29.10
.44	.85	3.82	24.0	29.14
.28	.55	4.05	24.0	29.07
.02	0.0	4.44	24.0	29.07
.03	0.0	4.56	24.0	29.03
.20	.45	4.20	24.5	28.89
.32	.65	4.12	24.0	29.12
.74	1.50	3.84	25.0	29.13
1.41	2.95	2.93	24.0	29.12
1.94	4.00	2.49	24.0	29.075
2.70	5.50	2.13	25.0	28.99
3.53	7.15	1.94	25.0	29.30
4.70	9.55	1.77	24.0	29.36
5.95	12.15	1.66	24.0	29.48
7.52	15.35	1.60	25.0	29.41
8.80	18.05	1.55	24.0	29.38
9.97	20.45	1.52	25.0	29.075
11.62	23.70	1.51	24.5	29.26
14.03	28.50	1.49	24.5	29.15
12.14	24.70	1.50	24.5	29.00
10.04	20.55	1.52	24.5	28.98
8.62	17.65	1.54	24.0	29.19
7.12	14.55	1.58	25.0	29.20
5.81	11.75	1.66	25.0	29.285
4.43	9.05	1.72	24.0	29.275
3.37	6.80	1.82	25.0	29.20
2.62	5.40	1.94	24.0	29.10
1.75	3.60	2.14	24.0	29.11
1.16	2.37	2.67	24.0	29.125
.59	1.230	3.30	24.0	29.15
0.40	0.75	4.02	24.0	29.205
0.08	0.18	4.59	24.0	29.16
0.02	0.0	4.60	24.0	29.185

TABLE III (Continued)

```
OUTPUT DATA

CORE 7AH  CAPILLARY PRESSURE  SEPT 1964
   WATER SAT.     PC(GAGE)       PC(HG)     TEMP.
   PER CENT         PSI.          PSI.     DEG.C
      100.000        .001          .000     24.000
       91.095        .287          .270     24.000
       88.006        .488          .466     24.000
       85.099        .904          .883     24.000
       63.656       1.483         1.497     24.000
       51.662       2.238         2.209     24.000
       43.303       3.163         3.093     24.000
       40.032       3.848         3.780     25.000
       36.216       5.248         5.155     25.000
       34.581       6.110         5.990     24.000
       33.127       7.252         7.119     24.000
       32.037       8.458         8.297     24.500
       31.310      10.048         9.942     24.500
       30.765      11.575        11.440     24.500
       30.401      14.250        14.067     24.000
       30.583      11.794        11.734     24.000
       31.310       9.039         8.494     24.000
       32.218       7.374         7.193     24.000
       33.490       5.608         5.425     24.000
       35.853       4.214         4.099     24.000
       38.397       3.023         2.995     25.000
       42.213       2.384         2.332     24.500
       48.755       1.704         1.644     24.000
       60.021        .925          .859     25.000
       76.558        .467          .417     24.500
       81.282        .527          .417     24.000
       85.462        .331          .270     24.000
       92.549        .070          .000     24.000
       94.730        .060          .000     24.000
       88.188        .162          .220     24.500
       86.734        .396          .319     24.000
       81.646        .824          .736     25.000
       65.109       1.493         1.448     24.000
       57.114       2.004         1.964     24.000
       50.572       2.726         2.700     25.000
       47.119       3.714         3.510     25.000
       44.030       4.921         4.689     24.000
       42.031       6.238         5.965     24.000
       40.941       7.783         7.536     25.000
       40.032       9.056         8.862     24.000
       39.487      10.082        10.040     25.000
       39.305      11.833        11.636     24.500
       38.942      14.203        13.993     24.500
       39.124      12.228        12.127     24.500
       39.487      10.105        10.090     24.500
       39.851       8.781         8.666     24.000
       40.577       7.277         7.144     25.000
       42.031       6.001         5.769     25.000
       43.121       4.607         4.443     24.000
       44.939       3.504         3.338     25.000
       47.119       2.700         2.651     24.000
       50.754       1.830         1.767     24.000
       60.385       1.244         1.163     24.000
       71.833        .683          .603     24.000
       84.917        .519          .368     24.000
       95.275        .175          .088     24.000
       95.457        .127          .000     24.000
```

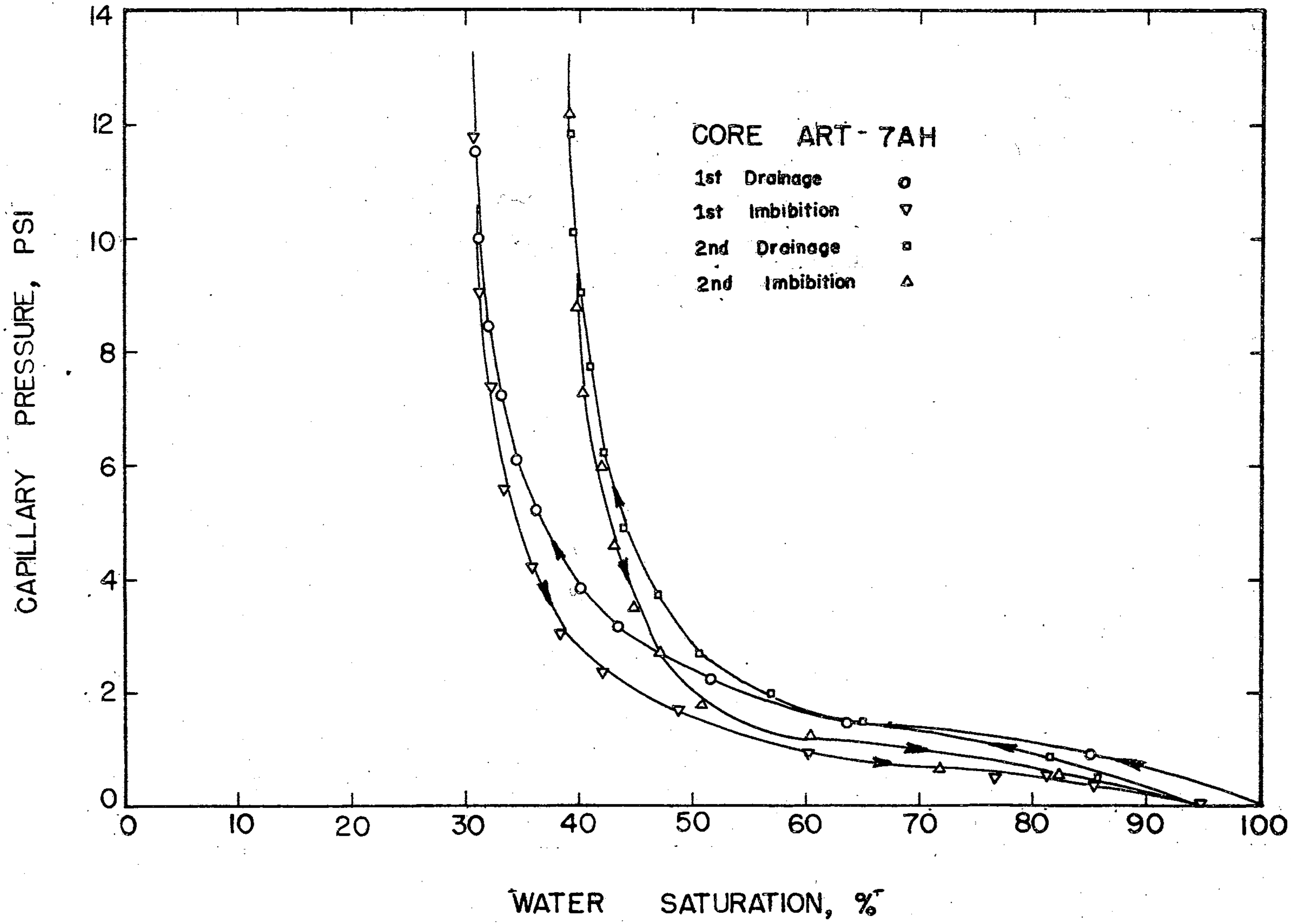

Figure 6. Cyclic Capillary Pressure, Core Art 7AH

capillary pressure from the experimental curves at each one percent of water saturation. A corresponding value of relative wetting and non-wetting phase permeability was then calculated for each percent of saturation. However, it was deemed unnecessary to plot each point separately so only a representative cross section of the data is presented here.

The first drainage and first imbibition curves for Core S1-F2 were converted to relative permeability data using values of the exponent on the terms inside the integral in the equations for relative permeability of 1, 2, and 3. In other words, the constant b was allowed to take on the values of -0.5, 0.0, and 0.5. The selected data that resulted from these trials appears numerically as Tables IV, V, and VI. The graphical representation of this same data appears as Figures 7, 8, and 9. Relative permeability curves obtained by the modified Penn. State method are also shown in the figures for comparison purposes. It can be seen from these figures that a value of the exponent of 1.0 (b=-0.5) gave the best overall agreement with the experimental curves. In general, the wetting phase relative permeabilities were in much better agreement than the non-wetting permeabilities which were consistently high at all saturations.

A procedure similar to the above was followed in the case of Core Art 7AH. For this core a value of the exponent of 3.0 (b=0.5) gave the best agreement with experimental results which contrasted with the exponent of 1.0 obtained for Core S1-F2. Only the selected data for the curve with the closest

TABLE IV

RELATIVE PERMEABILITY DATA, CORE S1-F2, EXPONENT OF 1.0

```
     INPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST DRAINAGE)

  B        ISWR MAXSW AREA     SWR       SNR

 -0.5        17    93  1.0     17.0       5.0          A=1.0

  SW       PC

 25.0     2.55
 30.0     2.10
 35.0     1.90
 40.0     1.78
 45.0     1.74
 50.0     1.70
 55.0     1.67
 60.0     1.62
 65.0     1.59
 70.0     1.58
 75.0     1.55
 80.0     1.50
 85.0     1.48
 90.0     1.10
 93.0     0.48


     OUTPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST DRAINAGE)  EXP(A)=1.0
       MAXIMUM (BASE) AREA=     45.105

           SW        KRW        KRNW       1/PC**EXP

           28.0      .001       .682       .44444444
           32.0      .003       .575       .50000000
           35.0      .007       .502       .52631578
           40.0      .016       .391       .56179775
           45.0      .031       .297       .57471264
           50.0      .053       .219       .58823529
           55.0      .084       .156       .59880239
           60.0      .126       .106       .61728395
           65.0      .181       .067       .62893081
           70.0      .249       .039       .63291139
           75.0      .333       .020       .64516129
           80.0      .434       .009       .66666666
           85.0      .556       .002       .67567567
           90.0      .705       .000       .90909090
           93.0      .838       .000      2.08333330
```

TABLE IV (Continued)

```
     INPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST IMBIBITION)

 B         ISWR MAXSW AREA      SWR        SNR

-0.5         17   59 45.105     17.0       18.6            A=1.0

 SW         PC

25.0       2.20
30.0       1.60
35.0       1.29
40.0       1.15
45.0       0.95
50.0       0.78
55.0       0.60
59.0       0.49




     OUTPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST IMBIBITION)       EXP(A)=1.0
          MAXIMUM (BASE) AREA=     37.588


               SW          KRW          KRNW        1/PC**EXP

               25.0         .000         .725         .45454545
               27.0         .001         .655         .54054054
               30.0         .003         .555         .62500000
               35.0         .010         .404         .77519379
               40.0         .025         .276         .86956521
               45.0         .052         .173        1.05263160
               50.0         .097         .091        1.28205130
               55.0         .169         .032        1.66666670
               59.0         .256         .000        2.04081630
```

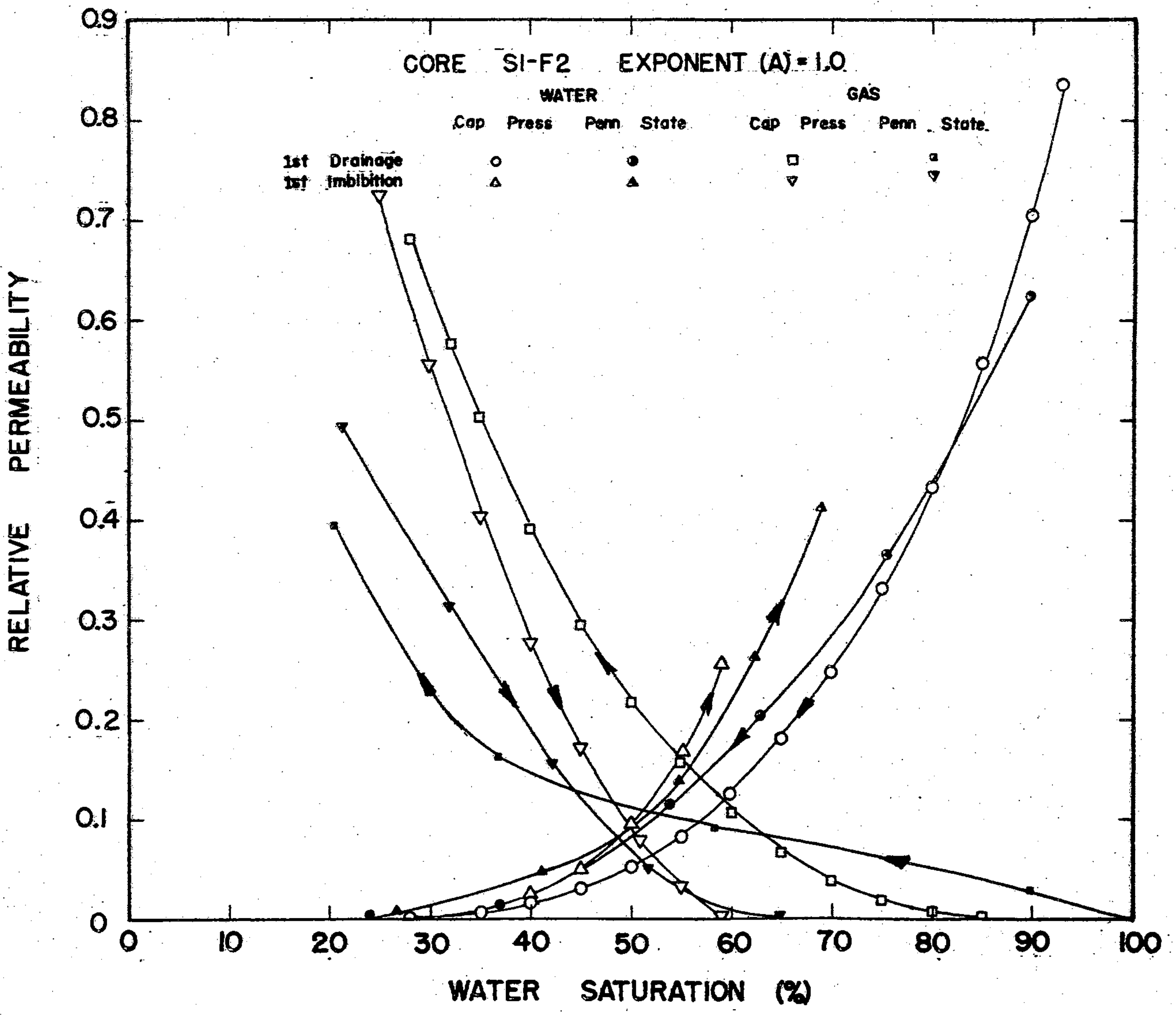

Figure 7. Relative Permeability, Core S1-F2, Exponent of 1.0

TABLE V

RELATIVE PERMEABILITY DATA, CORE S1-F2, EXPONENT OF 2.0

```
     INPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST DRAINAGE)

 B         ISWR MAXSW AREA      SWR        SNR

 0.0         17   93  1.0      17.0        5.0             A=2.0

 SW         PC

 25.0       2.55
 30.0       2.10
 35.0       1.90
 40.0       1.78
 45.0       1.74
 50.0       1.70
 55.0       1.67
 60.0       1.62
 65.0       1.59
 70.0       1.58
 75.0       1.55
 80.0       1.50
 85.0       1.48
 90.0       1.10
 93.0       0.48


     OUTPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST DRAINAGE)        EXP(A)=2.0
         MAXIMUM (BASE) AREA=    30.154

           SW         KRW         KRNW       1/PC**EXP

           25.0        .000        .788        .15378700
           30.0        .001        .657        .22675739
           35.0        .004        .535        .27700833
           40.0        .011        .424        .31561672
           45.0        .022        .329        .33029463
           50.0        .040        .247        .34602076
           55.0        .065        .180        .35856433
           60.0        .100        .125        .38103949
           65.0        .146        .082        .39555397
           70.0        .205        .050        .40057683
           75.0        .279        .028        .41623309
           80.0        .370        .013        .44444444
           85.0        .482        .004        .45653761
           90.0        .627        .000        .82644628
           93.0        .838        .000       4.34027770
```

TABLE V (Continued)

```
     INPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST IMBIBITION)

 B         ISWR MAXSW AREA      SWR        SNR

 0.0         17    59 30.154    17.0       18.6           A=2.0

 SW         PC

 25.0      2.20
 30.0      1.60
 35.0      1.29
 40.0      1.15
 45.0      0.95
 50.0      0.78
 55.0      0.60
 59.0      0.49
```

```
     OUTPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST IMBIBITION)       EXP(A)=2.0
          MAXIMUM (BASE) AREA=    43.330

               SW          KRW          KRNW        1/PC**EXP

               25.0          .000          .756        .20661157
               30.0          .001          .605        .39062500
               35.0          .005          .463        .60092542
               40.0          .014          .337        .75614366
               45.0          .033          .226       1.10803320
               50.0          .071          .130       1.64365550
               55.0          .145          .051       2.77777760
               59.0          .256          .000       4.16493110
```

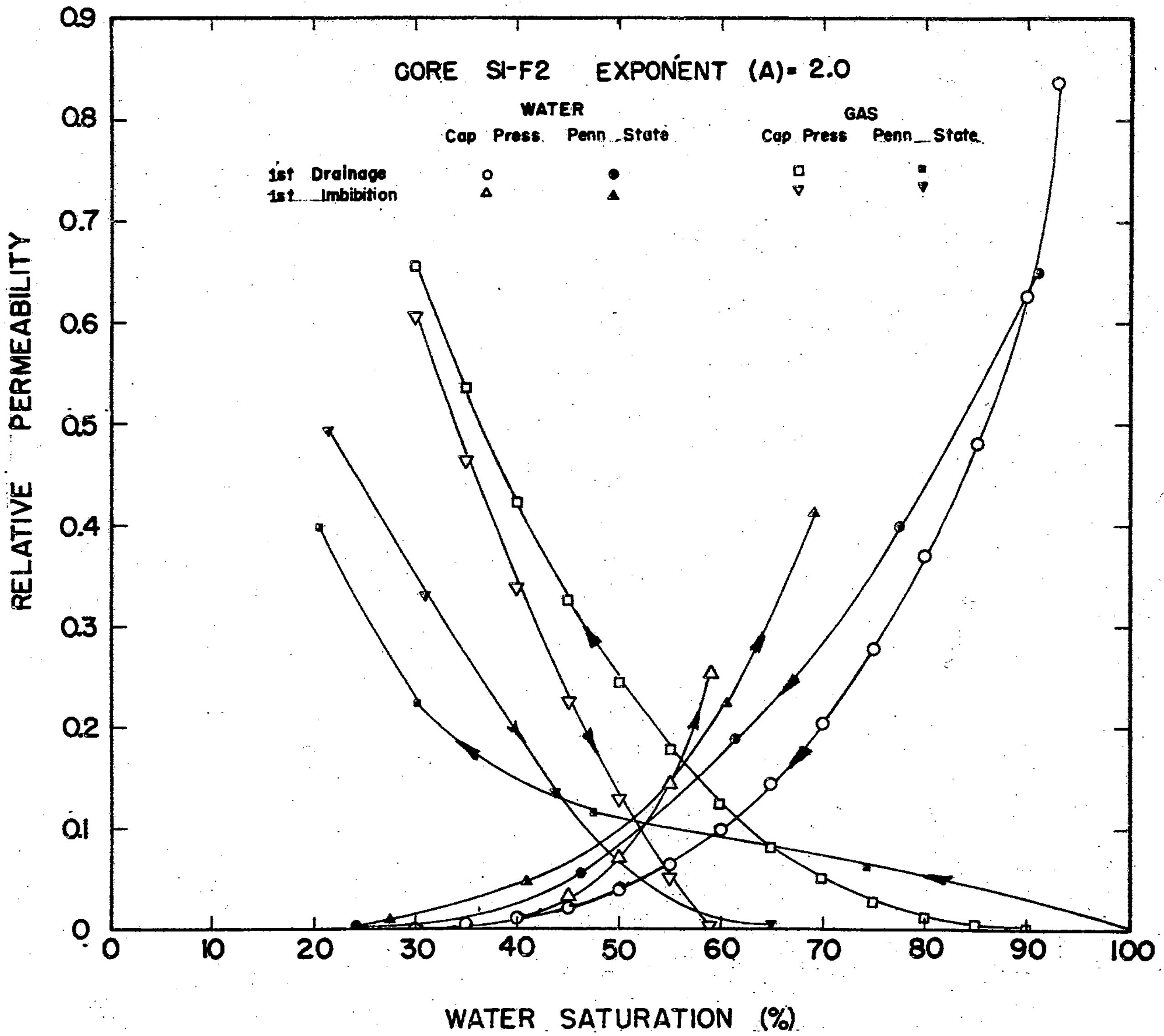

Figure 8. Relative Permeability, Core S1-F2, Exponent of 2.0

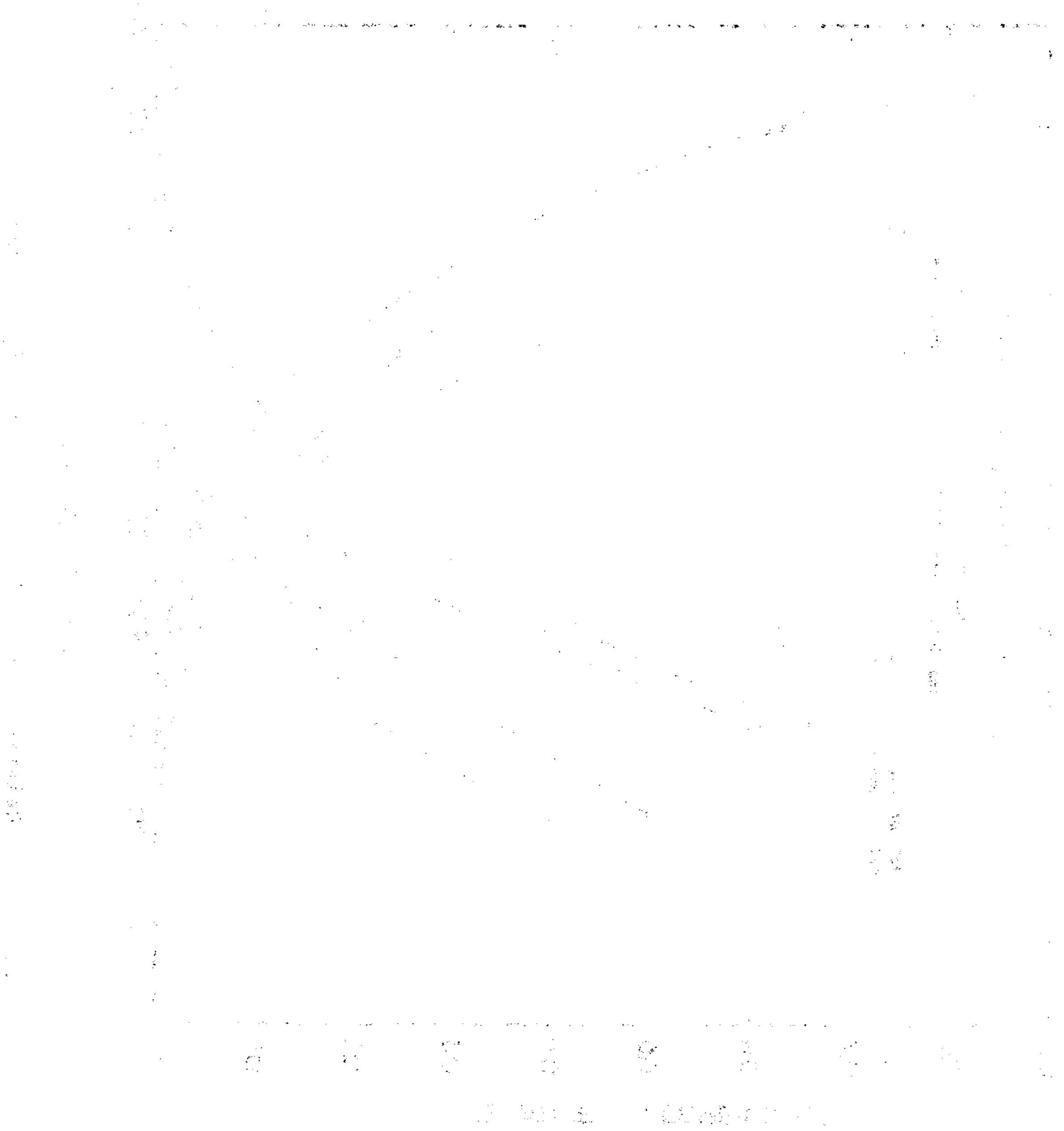

TABLE VI

RELATIVE PERMEABILITY DATA, CORE S1-F2, EXPONENT OF 3.0

```
     INPUT DATA

 CORE S1-F2 PC TO KR CONVERSION  (1ST DRAINAGE)

  B         ISWR MAXSW AREA      SWR        SNR

  0.5         17    93  1.0       17.0       5.0          A=3.0

  SW        PC

  25.0      2.55
  30.0      2.10
  35.0      1.90
  40.0      1.78
  45.0      1.74
  50.0      1.70
  55.0      1.67
  60.0      1.62
  65.0      1.59
  70.0      1.58
  75.0      1.55
  80.0      1.50
  85.0      1.48
  90.0      1.10
  93.0      0.48


      OUTPUT DATA

 CORE S1-F2 PC TO KR CONVERSION  (1ST DRAINAGE)       EXP(A)=3.0
        MAXIMUM (BASE) AREA=    23.836


          SW         KRW         KRNW        1/PC**EXP

          25.0        .000        .798        .06030862
          30.0        .000        .675        .10797970
          32.0        .001        .628        .12500000
          35.0        .002        .560        .14579385
          40.0        .006        .453        .17731277
          45.0        .014        .358        .18982450
          50.0        .026        .276        .20354163
          55.0        .044        .207        .21470918
          60.0        .069        .149        .23520956
          65.0        .103        .102        .24877609
          70.0        .147        .065        .25352965
          75.0        .203        .038        .26853749
          80.0        .274        .019        .29629630
          85.0        .361        .007        .30847138
          90.0        .486        .001        .75131480
          93.0        .838        .000       9.04224530
```

TABLE VI (Continued)

```
     INPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST IMBIBITION)

  B        ISWR MAXSW AREA      SWR        SNR

 0.5         17    59 23.836     17.0       18.6           A=3.0

  SW         PC

 25.0       2.20
 30.0       1.60
 35.0       1.29
 40.0       1.15
 45.0       0.95
 50.0       0.78
 55.0       0.60
 59.0       0.49
```

```
     OUTPUT DATA

CORE S1-F2 PC TO KR CONVERSION  (1ST IMBIBITION)     EXP(A)=3.0
        MAXIMUM (BASE) AREA=     57.966

             SW          KRW          KRNW        1/PC**EXP

             25.0         .000         .764        .09391435
             30.0         .000         .625        .24414064
             33.0         .001         .545        .37235365
             35.0         .002         .493        .46583366
             40.0         .007         .373        .65751623
             45.0         .019         .263       1.16635080
             50.0         .049         .162       2.10725060
             55.0         .121         .070       4.62962940
             59.0         .256         .000       8.49985970
```

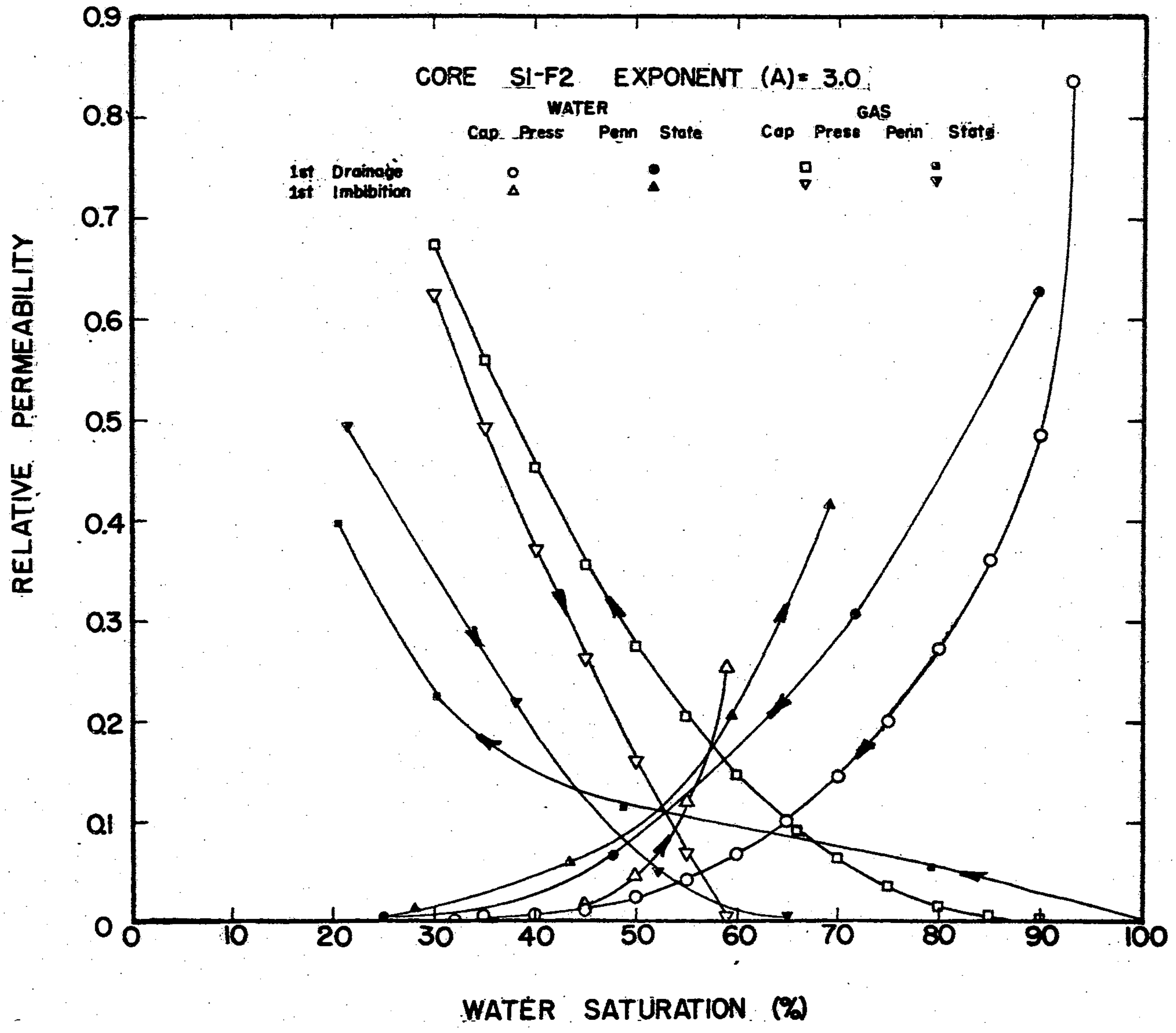

Figure 9. Relative Permeability, Core S1-F2, Exponent of 3.0

agreement is presented here for Core Art 7AH. It appears numerically in Table VII and graphically in Figure 10. From Figure 10 it can be observed that a reasonable agreement for both the wetting and non-wetting phases was obtained on the first drainage curves. However, the first imbibition data produced results for the wetting phase relative permeabilities which were too high and for the non-wetting phase relative permeabilities which were too low to agree with the experimental values.

TABLE VII

RELATIVE PERMEABILITY DATA, CORE ART 7AH

```
      INPUT DATA

 CORE 7AH PC TO KR CONVERSION  (1ST DRAINAGE)  EXP(A)=3.0

   B        ISWR MAXSW AREA      SWR        SNR

  0.5         30    92  1.0      30.0       5.0

   SW         PC

  40.0       3.90
  45.0       2.97
  50.0       2.40
  55.0       1.96
  60.0       1.64
  65.0       1.50
  70.0       1.39
  75.0       1.29
  80.0       1.11
  83.0       1.00
  85.0       0.90
  88.0       0.78
  90.0       0.67
```

```
      OUTPUT DATA

 CORE 7AH PC TO KR CONVERSION  (1ST DRAINAGE)  EXP(A)=3.0
            MAXIMUM (BASE) AREA=     34.679

            SW          KRW          KRNW        1/PC**EXP

           40.0         .000         .714         .01685800
           45.0         .000         .588         .03817075
           50.0         .001         .472         .07233797
           55.0         .003         .368         .13281031
           60.0         .009         .274         .22670884
           65.0         .023         .193         .29629630
           70.0         .046         .126         .37235365
           75.0         .082         .075         .46583366
           80.0         .144         .038         .73119138
           83.0         .204         .021        1.00000000
           85.0         .262         .013        1.37174200
           88.0         .393         .004        2.10725060
           90.0         .537         .001        3.32487670
```

TABLE VII (Continued)

```
     INPUT DATA

CORE 7AH PC TO KR CONVERSION (1ST IMB.)    EXP(A)=3.0

  B        ISWR MAXSW AREA      SWR        SNR

 0.5         30    80 34.679    30.        5.0

  SW        PC

 40.0      2.75
 45.0      2.10
 48.0      1.80
 50.0      1.60
 55.0      1.21
 60.0      0.96
 65.0      0.90
 70.0      0.85
 73.0      0.79
 75.0      0.75
 78.0      0.67
 80.0      0.60
```

```
     OUTPUT DATA

CORE 7AH PC TO KR CONVERSION (1ST IMB.)    EXP(A)=3.0
          MAXIMUM (BASE) AREA=     47.828

          SW          KRW          KRNW        1/PC**EXP

          40.0        .000         .713         .04808414
          45.0        .000         .585         .10797970
          48.0        .001         .512         .17146778
          50.0        .002         .465         .24414064
          55.0        .008         .353         .56447393
          60.0        .028         .245        1.13028070
          65.0        .073         .150        1.37174200
          70.0        .146         .081        1.62833290
          73.0        .212         .049        2.02823710
          75.0        .270         .032        2.37037030
          78.0        .393         .011        3.32487670
          80.0        .510         .000        4.62962940
```

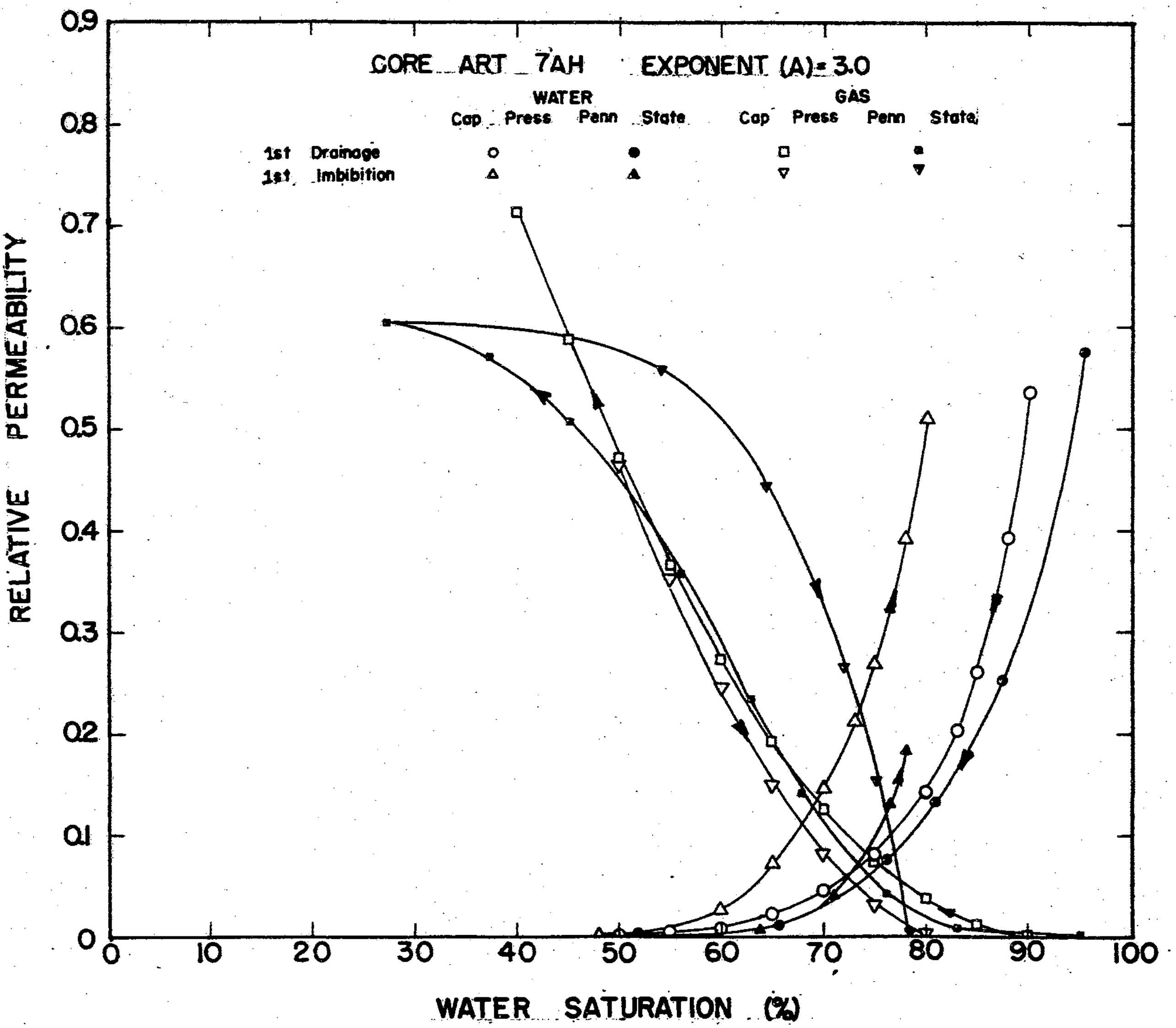

Figure 10. Relative Permeability, Core Art 7AH

CHAPTER VII

CONCLUSIONS

The study of cyclic capillary pressure effects is complicated by a number of factors which are extremely difficult to measure quantitatively as they occur in a porous medium. Such considerations as actual flow path length and wetting characteristics at the fluid-solid interfaces are extremely complex to evaluate. For this reason, many of the problems of flow through porous media defy exact numerical solutions. In spite of the difficulties mentioned, several conclusions can be drawn from this study.

It has been noted in Chapter VI that the second cycle of capillary pressure versus water saturation produces a higher minimum water saturation than the first. At the same time, the trapped gas saturation remains constant for both complete cycles. This leads to the conclusion that the so-called "irreducible" water saturation for a given rock is a function of its saturation history in much the same way that relative permeability is known to be a function of the saturation history. A plausible explanation for this shift in minimum saturations might be that the gas which is trapped in the pore spaces after the first imbibition cycle tends to reduce the permeability of the core to water at low water saturations, thus causing the minimum saturation to increase. However, experimental relative permeability data on the samples tested does not give any clear evidence of this effect. Actually, in the low saturation range there is little difference in the experimental water relative permeability from one cycle to the next.

The technique proposed by Burdine (4) for converting capillary pressure data to relative permeability data produces only approximate agreement with experimentally determined data. It should be noted that the agreement is significantly better for the wetting phase than for the non-wetting phase in most cases.

Finally, the Burdine conversion method seems to be equally as valid for the imbibition portion of a cycle as for the drainage part for which it was derived. As a part of this study, the denominator of the term

$$\frac{\int_{0}^{Sw} \frac{dSw}{Pc^{2(1+b)}}}{\int_{0}^{100} \frac{dSw}{Pc^{2(1+b)}}} \qquad (1)$$

was evaluated using capillary pressure data from the first drainage curve and also from the first imbibition with the numerator being consistently evaluated using first imbibition data in both cases. The results of these investigations indicate that the imbibition relative permeabilities are more accurately obtained by using imbibition capillary pressure data in both the numerator and denominator of the above expression.

CHAPTER VIII

RECOMMENDATIONS FOR FUTURE STUDY

In the course of this study, a number of questions developed which can only be answered by more thorough and extensive work in the area of capillary pressure hysteresis. The unsolved problems can be classified as those relating to the capillary pressure-saturation relationships and those pertaining to the relation between capillary pressure and relative permeability.

Capillary Pressure-Saturation Relationships

The two-cycle tests conducted in the course of this work produced one result,, which more than any other, needs to be substantiated or refuted by additional experimental work. This of course was the shift in minimum wetting phase saturation obtained on the second cycle. If further work continues to validate the results obtained here, then three, four, or more cycles need to be run and an effort made to determine more precisely the displacement mechanism involved. This would be of significant value in many of the cyclic operations now under way.

Observations made during the course of the capillary pressure tests indicate that essentially steady state conditions at each pressure may be reached in as little as thirty minutes with a water-gas system as used here. This contrasts with the normal six to twenty four hours which is usually allowed. If this observation proves to be correct, a tremendous saving in time would result.

Capillary Pressure-Relative Permeability Relationships

The relationships which have been derived to relate capillary pressure to relative permeability have, of necessity, been based on mathematical models of a porous media. These models have produced theoretical relationships which must be modified if they are to accurately describe real physical phenomena. For example, the equations discussed in Chapter IV need to be investigated in the following ways.

First, there is obviously a lower limit of capillary pressure beyond which the conversion equations are not valid. In other words, the value of $\frac{dSw}{Pc^{2(1+b)}}$ becomes extremely large as Pc approaches zero. After many trials on the computer, this author decided upon a minimum value of $Pc=0.5$ psi. as the lower limit.

Next, the value of the exponent A (derived as $2(1+b)$ in the above integral) appears to defy being assigned a constant value. As can be observed from the data presented in Chapter VI, Core S1-F2 produced better results with this exponent equal to one while Core Art 7AH produced better results with the exponent equal to three. Some means of determining in advance what the exponent should be for a given sample needs to be developed. This might be done by evaluating pore size distribution data which can be obtained by a method analogous to capillary pressure determination.

Finally, the assumption that the modifying tortuosity term can be expressed as a linear relationship is open to some question. This is especially true for the non-wetting phase where attempts to back-calculate the exponent C in the term $\left[1-\frac{Sw-Swr}{1-Snr-Swr}\right]^{C}$ from experimental data were met with widely varying values of C.

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APPENDIX

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C     CAPILLARY PRESSURE PROGRAM  KEN W. BOLT  JUNE 1964
C  WETWT= WET WEIGHT OF CORE (GM.)
C  DRYWT= DRY WEIGHT OF CORE (GM.)
C  DENS= DENSITY OF SATURATING FLUID (GM./CC.)
C  BSEVL= INITIAL READING OF BURRETTE
C  A= INTERCEPT OF TRUE PRESS. VS. GAGE PRESS. CURVE
C  B= SLOPE OF ABOVE CURVE
C  PBASE= BAROMETRIC PRESS. AT BSEVL (IN. OF HG.)
      READ 106
      READ 101,WETWT,DRYWT,DENS,BSEVL,A,B,PBASE
      WTH2O=WETWT-DRYWT
      VLH2O=WTH2O/DENS
      IF (SENSE SWITCH 1)5,10
 5    TYPE 106
      TYPE 103
      TYPE 104
      GO TO 15
 10   PUNCH 106
      PUNCH 103
      PUNCH 104
 15   READ 102,PGAGE,HG,VOL,TEMP,PBAR
      SW=100.-((BSEVL-VOL)*100.)/VLH2O
      PCHG=HG*0.491
      IF (SENSE SWITCH 2)65,60
 65   DELP=(PBAR-PBASE)*0.491
      IF (DELP)55,60,55
 55   PGAGE=PGAGE+DELP
 60   PCGA=A+(B*PGAGE)
      IF (SENSE SWITCH 1)20,25
 20   TYPE 105,SW,PCGA,PCHG,TEMP
      GO TO 15
 25   PUNCH 105,SW,PCGA,PCHG,TEMP
      GO TO 15
101   FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
102   FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0)
103   FORMAT(6X,10HWATER SAT.,3X,8HPC(GAGE),5X,6HPC(HG),4X,5HTEMP.)
104   FORMAT(6X,8HPER CENT,7X,4HPSI.,8X,4HPSI.,4X,5HDEG.C)
105   FORMAT(6X,F10.3,3X,F8.3,3X,F8.3,3X,F8.3)
106   FORMAT(49H CORE IDENTIFICATION                             )
      END
```

CAPILLARY PRESSURE PROGRAM SYMBOL LIST

A	Intercept of true pressure versus gage pressure curve
B	Slope of the above curve
BSEVL	Burette reading at start of test
DELP	Difference between barometric pressure at a test point and at beginning of test
DENS	Density of saturating fluid, grams/c.c.
DRYWT	Dry weight of core, grams
HG	Manometer reading at a data point
PBAR	Barometric pressure at a data point
PBASE	Barometric pressure at start of test
PCGA	Corrected gage pressure
PCHG	Manometer reading converted to psi
PGAGE	Pressure gage reading
SW	Water saturation in the core
TEMP	Temperature
VLH2O	Volume of water in the core, c.c.
VOL	Burette reading, c.c.
WETWT	Wet weight of core, grams
WTH2O	Weight of water in core, grams

```
C     RELATIVE PERMEABILITY FROM CAPILLARY PRESSURE DATA
              (BURDINES METHOD - MODIFIED)
C     SW1 ON FOR TYPED OUTPUT,OFF FOR PUNCHED OUTPUT
C     SW 2 ON TO CALCULATE AREA UNDER 1/PC**EXP CURVE
C     SW 2 OFF TO READ AREA
C     ISWR=IRREDUCIBLE WATER SATURATION (FIXED POINT FORM)
C     MAXSW=MAX.SW ATTAINED ON THE CURVE BEING STUDIED (FIXED POINT)
C     NOTE-THIS VALUE OF MAXSW MUST CORRESPOND TO A MINIMUM PRESSURE OF
C          NOT LESS THAN 0.5 PSI
C     B=CONSTANT WHICH DETERMINES THE VALUE OF THE EXPONENT A
C     BSEAR=AREA UNDER 1/PC**ACURVE OF THE FIRST DRAINAGE CYCLE
C     NOTE-BSEAR CAN BE COMPUTED ON 1ST DRAINAGE AND ENTERED ON A CARD
C          FOR SUBSEQUENT CYCLES
C     SWR=PERCENT IRREDUCIBLE WATER SATURATION
C     SNR=PERCENT IRREDUCIBLE GAS SATURATION
C     SW(I)=PERCENT WATER SATURATION
C     PC(I)=CAPILLARY PRESSURE CORRESPONDING TO SW(I)
      DIMENSION PC(100),SW(100),RPCEX(100)
      READ 108
      IF (SENSE SWITCH 1)50,51
 50   TYPE 108
      GO TO 52
 51   PUNCH 108
 52   READ 101,B,ISWR,MAXSW,BSEAR,SWR,SNR
      A=2.*(1.+B)
      DSW=0.5
      I=ISWR
      RPCEX(I)=0.0
      J=I+1
      N=MAXSW
      AREA=BSEAR
      DO 7 I=J,N
      READ 102,SW(I),PC(I)
 7    CONTINUE
      I=ISWR
      J=I+1
      N=MAXSW
      IF (SENSE SWITCH 2)5,41
 5    AREA=0.0
      DO 10 I=J,N
      RPCEX(I)=1./(PC(I)**A)
      L=I-1
 10   AREA=AREA+((RPCEX(I)+RPCEX(L))*DSW)
 41   TYPE 106,AREA
      IF (SENSE SWITCH 1)2,4
 2    TYPE 103
      GO TO 20
 4    PUNCH 106,AREA
      PUNCH 103
 20   I=ISWR
      J=I+1
      N=MAXSW
      RPCEX(I)=0.0
      RPERW=0.0
      RPERN=1.0
      IF (SENSE SWITCH 1)16,17
 16   TYPE 107,ISWR,RPERW,RPERN,RPCEX(I)
      GO TO 201
 17   PUNCH 107,ISWR,RPERW,RPERN,RPCEX(I)
 201  SUM=0.0
      DO 15 I=J,N
      RPCEX(I)=1./(PC(I)**A)
      L=I-1
      SUM=SUM+((RPCEX(I)+RPCEX(L))*DSW)
      RPERW=(SUM/AREA)*(((SW(I)-SWR)/(100.-SWR))**2)
      RPERN=((AREA-SUM)/AREA)*((1.-((SW(I)-SWR)/(100.-(SWR+SNR))))**2)
      IF (SENSE SWITCH 1)11,12
 11   TYPE 105,SW(I),RPERW,RPERN,RPCEX(I)
      GO TO 15
 12   PUNCH 105,SW(I),RPERW,RPERN,RPCEX(I)
 15   CONTINUE
 101  FORMAT(F10.0,I5,I5,F10.0,F10.0,F10.0)
 102  FORMAT(F10.0,F10.0)
 103  FORMAT(12X,2HSW,9X,3HKRW,9X,4HKRNW,7X,9H1/PC**EXP/)
 105  FORMAT(10X,F6.1,5X,F7.3,5X,F7.3,4X,F12.8)
 106  FORMAT(10X,20HMAXIMUM (BASE) AREA=,F10.3//)
 107  FORMAT(10X,I4,7X,F6.3,7X,F6.3,4X,F12.8)
 108  FORMAT(49H IDENTIFICATION                                  )
      END
```

CAPILLARY PRESSURE TO RELATIVE PERMEABILITY CONVERSION PROGRAM SYMBOL LIST

A	Exponent defined in text as 2(1+b)
AREA	Area under reciprocal capillary pressure curve
B	Constant which determines the value of the exponent A
BSEAR	Constant which allows the "area" to be read instead of calculated
DSW	Saturation increment used in numerical integration
I	A computer indexing number
ISWR	Minimum water saturation (fixed point form)
J	A computer indexing number
L	A computer indexing number
MAXSW	Maximum water saturation (fixed point form)
N	A computer indexing number
PC	Value of Capillary Pressure
RPCEX	Reciprocal capillary pressure to some exponential power
RPERN	Non wetting phase relative permeability
RPERW	Wetting phase relative permeability
SW	Value of water saturation
SNR	Minimum non-wetting phase saturation
SWR	Minimum water saturation (floating point form)

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