THE DEVELOPMENT OF A MODEL FOR STUDYING AQUIFER PERFORMANCE

By

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CHAPTER I

INTRODUCTION

In the past, natural gas companies have depended on depleted gas and oil reservoirs for the storage of natural gas. Due to the expansion of old industrial centers, to the appearance of new industrial centers, and to the increase in population in these areas, there is a large fluctuation in the demand of natural gas from season to season. Since some of these industrial centers are removed a great distance from their gas supply, new methods of storage of natural gas have become necessary. Considerable investigation has been done on the feasibility of using water-bearing sands, commonly called aquifers, for the storage of natural gas underground.

It has been found that the cyclic effect of two-phase flow in water-bearing sands, or aquifers, is quite complex. Associated with two-phase flow is the phenomena of relative permeability hysteresis or "trap hysteresis". Due to the inherent difference in flow characteristics of various aquifers, there is a wide range of fifteen to fifty per cent trapped gas that is lost upon initial injection. Therefore, it is quite necessary, from an economic point of view, to determine the feasibility of a proposed aquifer.

Once a suitable structure has been located, it is necessary to develop properly the aquifer for storage of natural gas. The correct development requires that injection and withdrawal wells be located appropriately to obtain the maximum storage capacity of the aquifer. Also, a calculated injection and withdrawal program is necessary for the economic maintenance of the aquifer.

Mathematical models and computer programs have been derived for predicting the performance of aquifers with cyclic two-phase flow. The subject of this research investigation was the development of a fluid model having natural rock characteristics, and yet susceptible to the necessary instrumentation, for the verification of currently used mathematical models and computer programs in predicting aquifer performance.

A single layer model was developed that simulates natural rock characteristics and which is suitable for instrumentation for the study of aquifer performance.

CHAPTER II

PREVIOUS INVESTIGATION

Theoretical and experimental investigations have been done since the late nineteenth century on the assemblies of spheres of equal size. Since this time, numerous investigators have published papers on homogeneously distributed particles, the physics of porous media, and techniques for attempting to simulate natural rock (2, 3, 6, 7, 9). Considerable advances have been made in this area of engineering technology in the last few years.

The development of homogeneously packed particles has progressed since Currie and Gregory (3) applied for a patent in 1957. Their work consisted of an invention of a "particle distributor" used in the production of unconsolidated homogeneous packs.

Also, of interest, is the work done by Naar and Wygal (6) on the structure and properties of unconsolidated aggregates. Of particular importance in their paper was the discussion on the determination of porosity, permeability, and the capillary pressure curve of a random mixture of spherical grains having any size distribution if given the same properties for uniform-size aggregates and for binary mixtures at maximum density. However, their work is for unconsolidated aggregates and not for consolidated aggregates as in many aquifers.

For simulation of natural rock characteristics, consolidated or poorly consolidated aggregates are required. In a recent publication, Wygal (9) has presented a technique for the construction of models that simulate oil reservoirs. A method is presented by which homogeneous, isotropic, and reproducible aggregates of various particles such as glass beads, ground glass, sand, et cetera, may be produced. Wygal explains some factors which limit the usefulness of unconsolidated packs for simulating reservoir rock which may be overcome through artificial cementation of the aggregates.

Also Boyd (1) has presented a paper on the construction of an artificial sandstone for use in model studies. His work explains the necessity of taking into consideration the theory of solid-solid blending for the proper mixing of Portland cement and silica sand (4). After proper mixing of sand and cement, the theory of liquid-solid blending is used for the addition of water to assure the coating of the sand grains with cement (5).

Boyd (1) and Wygal (9) discuss the proper procedure for pouring the mixture to obtain a homogeneously consolidated pack. Both authors have expressed the necessity of utilizing a "particle distributor" to obtain the desired kinetic energy for a pack to have stable mechanical properties.

All of these works that have been reviewed have made important contributions in the preparation of homogeneously consolidated and unconsolidated porous media. But, to date, no one has published results of the use of artificial porous media in models with suitable instrumentation for the prediction of aquifer or secondary recovery performance. It is in the area of natural gas storage facilities that this thesis seeks to make a contribution.

CHAPTER III

STATEMENT OF PROBLEM

Literature is available pertaining to model studies on reservoirs of simple or complex geometry (2, 7). Some of these model studies have been made using a natural rock such as the Boise sandstone quarried in Boise, Idaho. There have been no limitations as to having simple geometries, but considerable limitations are imposed on using desired instrumentation, such as, insertion of thermocouples for temperature measurement. Also, the use of unconsolidated or consolidated glass beads with diminutive instrumentation has greatly simplified the construction of fluid models.

Substantial investigation has been done on consolidating glass beads with epoxy resin. This porous media has relative permeability characteristics similar to consolidated sandstone except the imbibition-trapped non-wetting phase saturation is quite lower than that occurring in natural rock. Therefore, natural rock characteristics are not obtained.

Some investigation has been done on the preparation of artificial porous media (9). To this author's knowledge, no one has reported on the use of this porous media in fluid model studies. Thus, the problem was to develop a model employing an artificial porous media that has natural rock characteristics and that was susceptible to various types of instrumentation. One use of such a model would be in the engineering development of underground gas storage facilities.

CHAPTER IV

CONSTRUCTION OF ARTIFICIAL POROUS MEDIA

If a model is to be used as a valuable tool in study, one of the most important factors to be considered in its construction is the porous media used to simulate the reservoir rock. The media selected must represent as nearly as possible the actual reservoir rock under study. Numerous investigations of different types of artificial media such as sand packs, glass beads consolidated by tamping, glass beads consolidated with epoxy resin, and sand consolidated with epoxy resin have been tested. These tests have shown that the properties of these different packs do not exhibit similar properties observed in actual reservoir rocks.

In this investigation a porous media whose properties did closely resemble actual reservoir rocks was constructed from a mixture of water, silica sand, and Portland cement. The two phases of study in developing this media of sand, cement, and water were:

1. The theory of solid-solid blending, liquid-solid blending, and the packing of this blend into the model.
2. Laboratory procedure in constructing this media.

Development

The mixing of solids is an age-old process. However, even a simple blend presents the difficult problem of the attainment of a uniform blend which has stable mechanical and electrical properties.

In the blending of solids, random motion is the main force which causes a blend to occur. With this random motion as a premise, a theory on solid-solid blending can be stated: If solid particles of one size are placed in the presence of particles of a different size, and random motion is imparted to these particles, a uniform distribution of the particles can occur. This theory holds true only in idealized cases. In actuality, when two solids are blended, various physical phenomena occur which make a uniform distribution of particles impossible. These phenomena can cause segregation of particles, agglomeration or particle breakdown, and coating of one size particle with particles of a smaller size.

In the random motion mixing of cement and sand, the sand grains tend to gain momentum by rolling over each other, while the cement particles gain momentum through a sort of aerated suspension. The difference in the methods by which the sand and cement particles gain their motion tends to cause the segregation of the sand and cement particles. This segregation can be overcome by reducing the rate of mixing which decreases the amount of cement dusting that occurs in the blending process.

The coating of the sand grains by the cement particles also makes a uniform blend impossible. However, this coating effect is beneficial in producing an artificial media which is similar to a reservoir rock. To produce a satisfactory coating of cement on sand grains, the sand grains must be of uniform size. If the sand grains are not uniform in size, the cement particles will tend to coat only the larger grains, thus causing unsatisfactory pack properties.

An additional factor to be reckoned with in the blending of cement and sand is that of the electrostatic charges caused by the mixing process. These surface charges can be a dominant factor in the "unblending" of a mixture. The random motion of the mixing process tends to cause these electrostatic charges. As the motion of the particles occurs, surface electron states are unbalanced by the friction initiated when the particles of cement and sand are rubbed together. Even though these charges may be small, they can become a major blending problem when they are imposed upon the dynamic forces caused by random motion. The easiest way to prevent particle segregation caused by electrostatic charges is to stop the blending when a satisfactory blend is achieved.

After achieving a good blend of sand and cement through random motion mixing, the addition of water creates additional problems. When adding water to a blend of sand and cement, certain techniques of liquid-solid blending must be used. As stated above, to achieve a good blend of cement and sand, the mixing should be stopped when a satisfactory blend is achieved. However, this blend must have random motion while the water is added. This extra motion, after a good blend has already been achieved, would seem to cause segregation of the cement and sand; however, this is not the case. The addition of water inhibits the motion of the cement and sand particles by partially eliminating the aerated suspension of the cement particles. When this suspension is eliminated, the cement and sand particles no longer have a tendency to become segregated.

The agglomerates formed by the addition of water to the blend of cement and sand cause undesirable properties to the blend. These agglomerates are caused by the tendency of the cement to absorb the water droplets. By absorbing the water added, the cement particles become lumpy and make a uniform blend impossible.

Another problem in liquid-solid blending is the type of random motion that must be maintained. Unwetted areas of the mix must constantly be exposed to the water. If one part of the mix is in a "dead area", an area where the water cannot reach, the blend will not be uniform.

The manner in which the water is added presents two problems:

1. The minute size of water particles necessary for a uniform blend.
2. The tendency of the water added to coat the sides of the mixing vessel.

The size of the water droplets should be as small as possible. A fog of micron-sized droplets is desirable. If larger water droplets are used, the blend will become lumpy, with one part of the blend having too much water and another part being deficient in water content. This fog of water has an affinity for the sides of the mixing vessel which must be overcome so that all the water added will go into the blend. In an ideal arrangement, the particles of the fog should only be able to "see" the solid particles of the blend.

To achieve a good blend of sand, cement, and water, proper proportions of each material must be present in the blend. If there are not enough cement and sand particles to absorb all the liquid added, a lumpy blend will occur. On the other hand, if not enough water is added, a uniform blend will be impossible.

Thus, to obtain a satisfactory blend of water, cement, and sand:

1. Achieve a random motion that is not too fast.
2. Use sand grains of uniform size.
3. Use the proper proportion of each constituent.
4. Add the water in the form of a fog which coats only the cement and sand and not the sides of the mixing vessel.
5. Eliminate all dead areas in the mix.

For an artificial porous media to exhibit the characteristics of actual reservoir rocks, it must be packed into the model correctly. Wygal (9) has suggested the use of a particle distributor to pack the model. This device is based on the use of a stream of falling particles which pass through several layers of meshed wire. These particles strike the wire matrix which gives them the right amount of kinetic energy and dispersion necessary to achieve stable positions in the model. Studies made on the packing of models by pouring the particles into the model, have shown that the packs achieved are unconsolidated and have a high porosity. The unconsolidation and high porosity of this type of pack seem to prove that the particles do not assume a stable position in the model. Thus, the acquisition of stable particle dispersion with a particle distributor enables the pack to be consolidated and have natural rock characteristics.

Laboratory Procedure

The laboratory procedure used in making an artificial media of cement, sand, and water can be broken down into three phases: 1) The blending of the water, cement, and sand, 2) the packing of the model, and 3) the curing of the model.

To get excellent blending results of the water, cement, and sand, a blender such as a twin-shell blender may be used. However, it was found that with a small, portable cement mixer, satisfactory results could be achieved if a cover was made to place over the mouth of the mixer. The purpose of this cover was to reduce the loss of cement due to dusting during the blending operation. By spraying the water on a small plate 6 inches from the base of the mixer, it was possible to minimize the effect of the liquid droplets "seeing" the sides of the mixer. This piece of plate also enabled the liquid fog to be dispersed in such a manner as not to form lumps in the mixture.

After the cover was made, a 15 weight per cent mixture of cement and 30 - 50 mesh sand was blended in the mixer until a satisfactory blend was obtained. The water was added with an ordinary paint spray gun which had an adjustable valve on the handle which afforded a means of controlling the size of water particles added. Approximately 5 weight per cent water was added. This amount of water was enough to settle the cement that was in suspension in the blend. When a thorough blend of sand, cement, and water was obtained, the mixing was stopped. As stated before, prolonged rotation of the blend would have tended to cause particle segregation.

The next stage was the packing of the media into the model. For the proposed model, a particle distributor was made of two pieces of 1/8 inch mesh screen spaced one inch apart. The particle distributor is shown in Figure 1. This screen spacing was obtained by trial and error with different packs. The mesh of the screen should be of a size to allow the particles to pass through without bridging. The height of fall from the distributor to the model was also obtained by trial and error. A height of 20 inches was found to be satisfactory. In Figure 2 is shown the model and distributor prior to pouring. To prevent discontinuities in the model, the pouring rate was held constant until the model was filled.

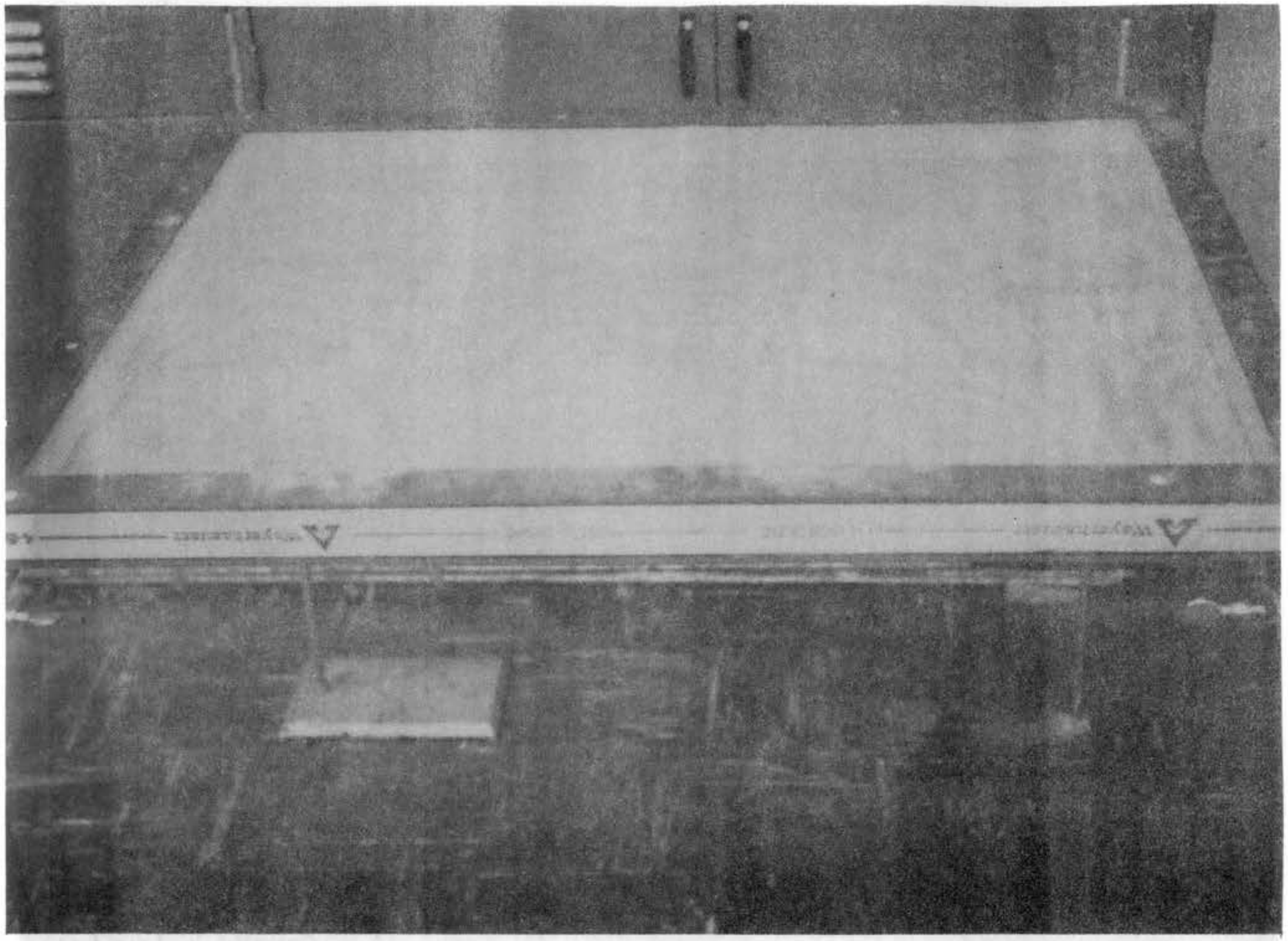

Figure 1. Particle Distributor

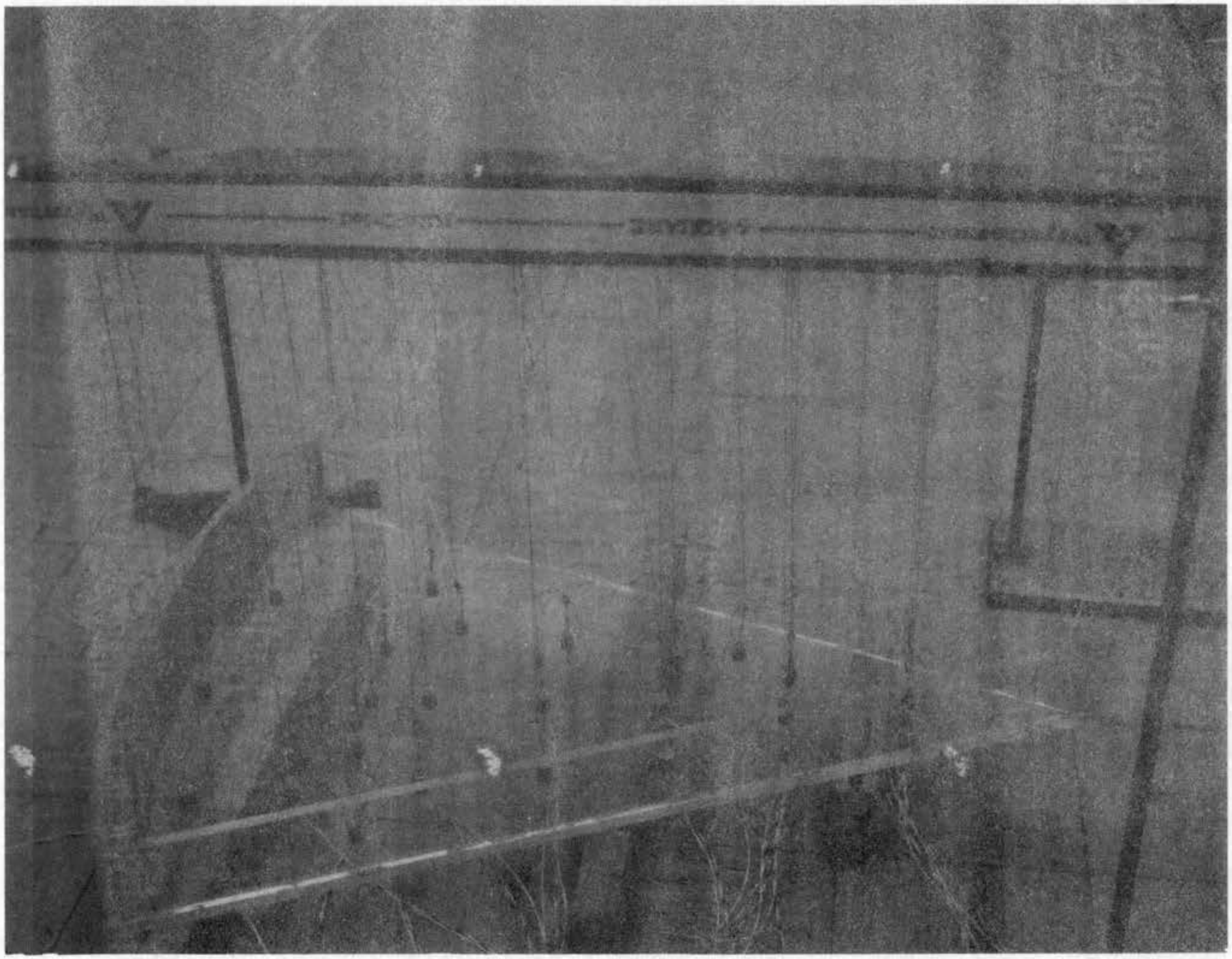

Figure 2. Model and Distributor Prior to Pouring

The model was packed further by tapping the sides of the model as the mix was poured.

After the model was filled, steps were taken to further consolidate the blend. These steps transformed the mixture of cement, sand, and water into an artificial sandstone. Immediately after packing, the model was flooded with water at imbibition rates. This imbibition rate has to be high enough to trap a certain amount of air in the rock--approximately 20 per cent of the pore volume. This trapped air is a must for the formation of natural rock characteristics. A water flow rate of 1000 cc/hr was found to be adequate to trap this amount of air. The model was then covered and allowed to hydrate for five days. After the hydration period was complete, the model was flooded with a 6 weight per cent soda ash solution. About 10 pore volumes of this solution were enough to prevent the leaching of the pack by water and brine. This leaching effect is prevented by the conversion of the free calcium hydroxide in the pack to relatively insoluble calcium carbonate. After the soda ash flood was completed, the pack was again flooded with water. After flushing was completed, the model was placed in an oven and baked at 100°F for 48 hours.

The experimental results which have been obtained from a pack made of cement, sand, and water show that this type of artificial media has characteristics similar to those of an actual reservoir rock. These results are found in Chapter VII.

CHAPTER V

DEVELOPMENT OF ELECTRODES

Once a porous media was developed that was susceptible to instrumentation, model studies could be made on several aspects of underground storage. It was the intention of this investigation to develop a model that could later be used to study the flow characteristics and saturation distributions in aquifers. Several authors, including this one, have developed a method for correlating changes in saturation with changes in electrical resistance. Therefore, it was necessary to develop electrodes which could: 1) be placed throughout the model, 2) cause a minimum amount of distortion to the flow pattern, and 3) measure the changes in electrical resistance corresponding to the changes in saturation.

The electrode that was used in the model is shown in Figure 3. The electrode consists of two 20 gauge solid hook-up wires with 118 caliber BB's soldered on the ends. A ceramic insulator was used to achieve the proper spacing. The wires were run through a 1/4 inch tubing x 1/8 inch pipe union that was screwed in the model.

After a suitable electrode was developed, it was hoped that a D. C. power supply could be used that would permit the

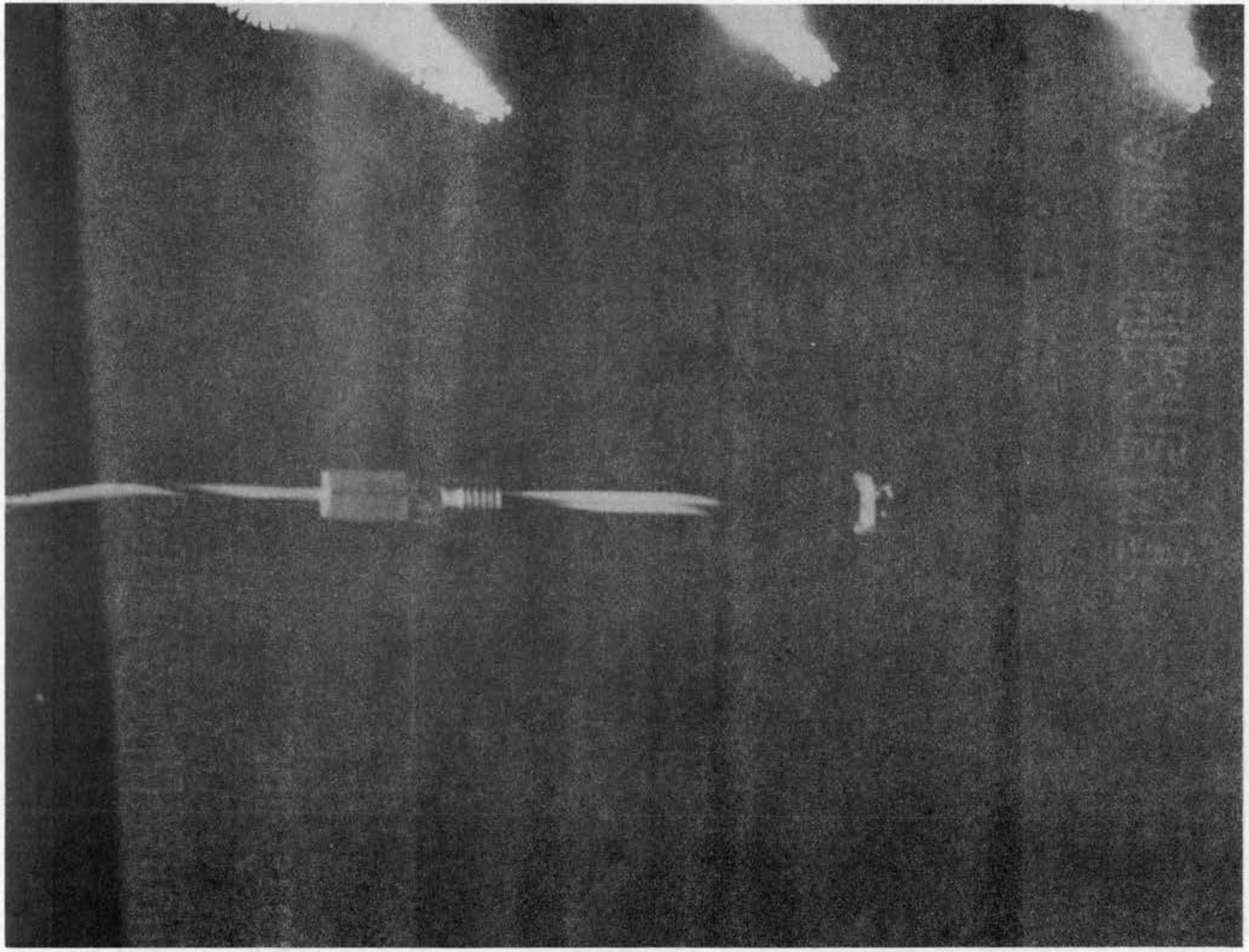

Figure 3. Typical Electrode

use of a 24 point recorder for the simultaneous recording of resistances, and therefore, the determination of saturations. A simple electrical circuit was investigated which consisted of the model, a resistor of known value, a constant D. C. output supply, and a voltmeter (to be replaced by a 24 point recorder). By measuring the voltage drop across the known resistor, it was possible to calculate the current in the circuit. By knowing the current, the voltage drop across the known resistor, and the output of the D. C. power supply, it was possible to calculate the resistance across the model. However, it was discovered through experimentation that electrolysis was occurring in the model with voltages as low as 0.5 volts. Therefore, reliable results could not be obtained.

Since D. C. power could not be used it was necessary to use A. C. voltages. An A. C. conductivity bridge (Industrial Instruments Model Number RC16B2) was used to measure electrical resistance. This proved to give reliable results, but simultaneous recording of resistances was impossible since there was a time lapse involved when measuring the resistances of the 29 electrodes with a single conductivity bridge.

CHAPTER VI

MODEL CONSTRUCTION

The model that was developed in this study consists of several pieces of 1/2 inch G grade plexiglass which were machined in the machine shop and then assembled with dichloro-ethane and plexiglass cement. It was decided to use plexiglass for visual observation of the flood front and to see if channeling did occur. Since channeling did occur upon initial injection of test fluids, it was necessary to drill small holes in the model and flow plexiglass cement between the plexiglass and the artificial porous media. After allowing the plexiglass cement to dry, the problem of channeling was overcome. The completed model and its related instrumentation is shown in Figure 4.

The model was made "pie-shaped" to see by visual observation if radial flow did exist in the reservoir. However, the addition of the cement to stop channeling prevented any visual observations from being made. During the construction of the model, it was realized that visual observations might be impossible so four electrodes were placed around wellbores W2 and W3 each as shown in Figure 6. These electrodes were arranged so that it would be possible to determine if radial flow was occurring in the model.

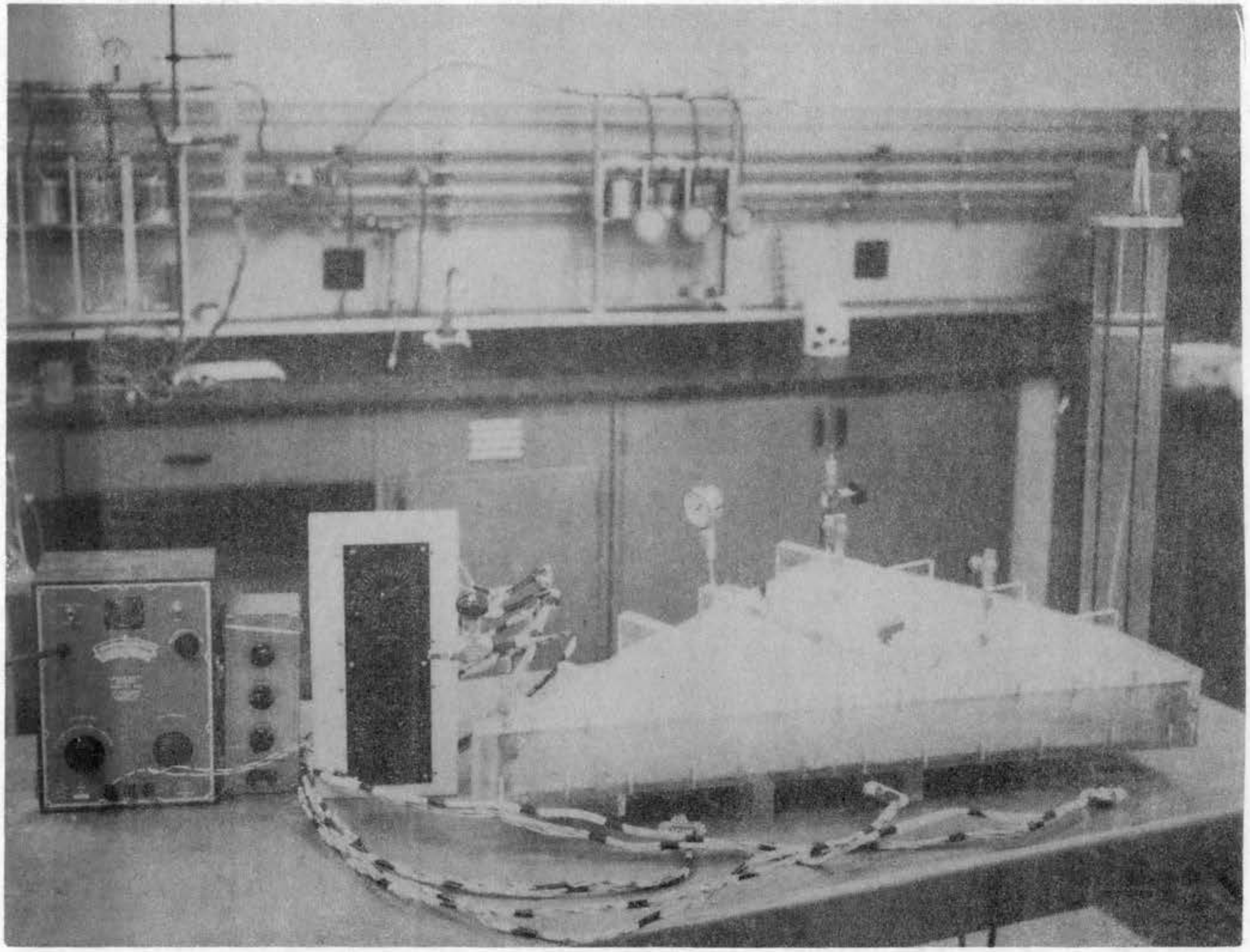

Figure 4. Finished Model and Accessory Equipment

Electrode number 20 was placed in its location for a specific purpose. If wellbores W2 and W3 were used for injecting gas, electrode number 20 could be used to ascertain if a zone or bank of water was trapped due to pressure forces arising from wellbores W2 and W3. If this were the case, considerable storage capacity would be lost due to an improper injection program.

When two fluids flow concurrently, saturation distributions are a function of time. Therefore, it is desirable to obtain resistance readings of all electrodes simultaneously. Since D. C. power could not be used, this was impossible. However, a switching network was made, see Figure 4, which allowed the recording of all resistances in a matter of a few minutes.

As shown in Figure 5, a wire screen was assembled at the effluent end of the model. The purpose of the wire screen was to prevent flow disturbances as water was displaced from the model. This would be the same as having a reservoir of infinite radius. The screen was held in place by roughening the ends of 1 inch plexiglass spacers. The roughened ends were cemented to the aluminum screen by using dichloro-ethane and plexiglass cement. The other end of the spacer was cemented to the end piece of the model with dichloro-ethane and plexiglass cement.

Since the model was to be maintained under pressure, it was necessary to devise a method for inserting the electrodes and wellbores so the model could be used under pressure. As

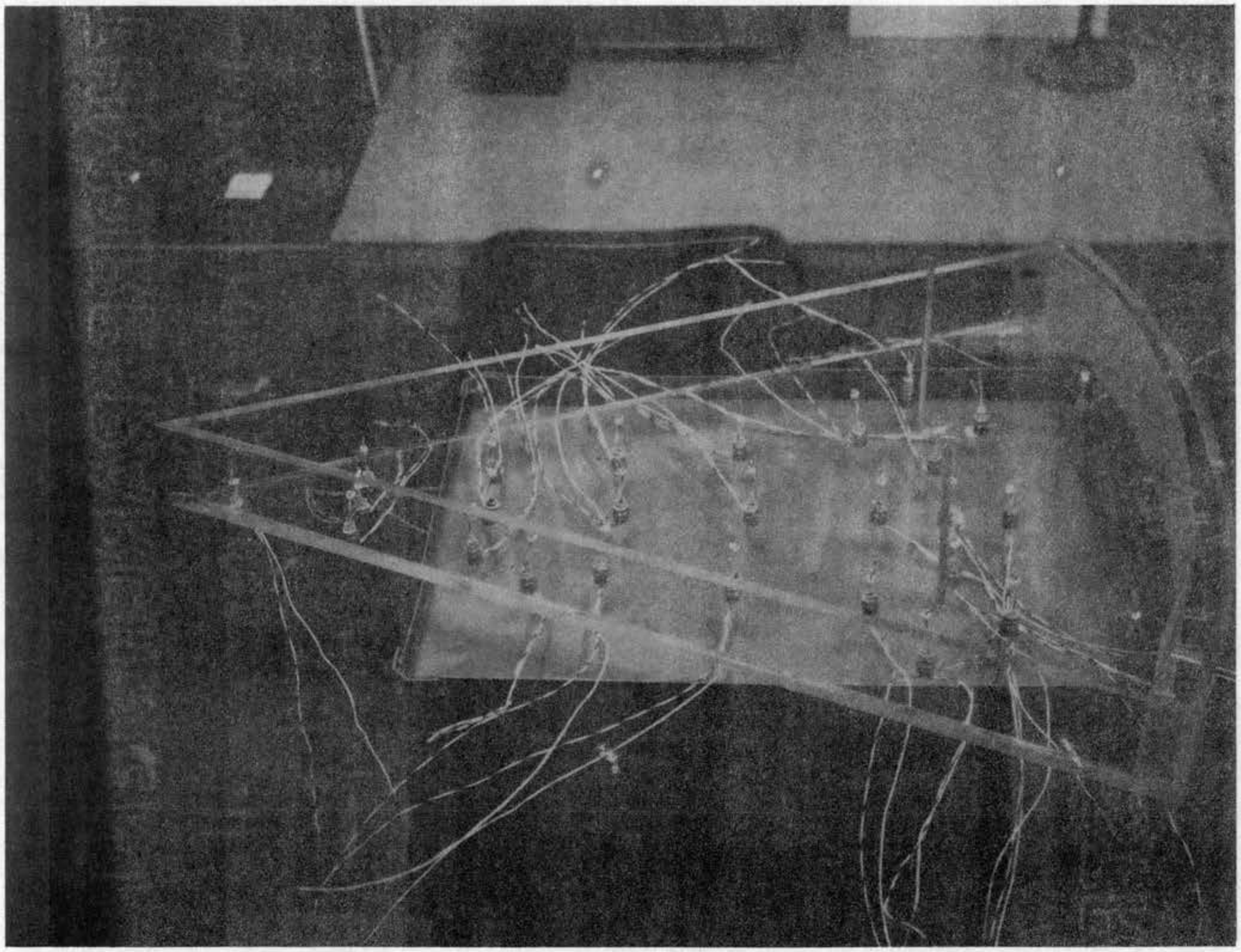

Figure 5. Model Prior to Pouring

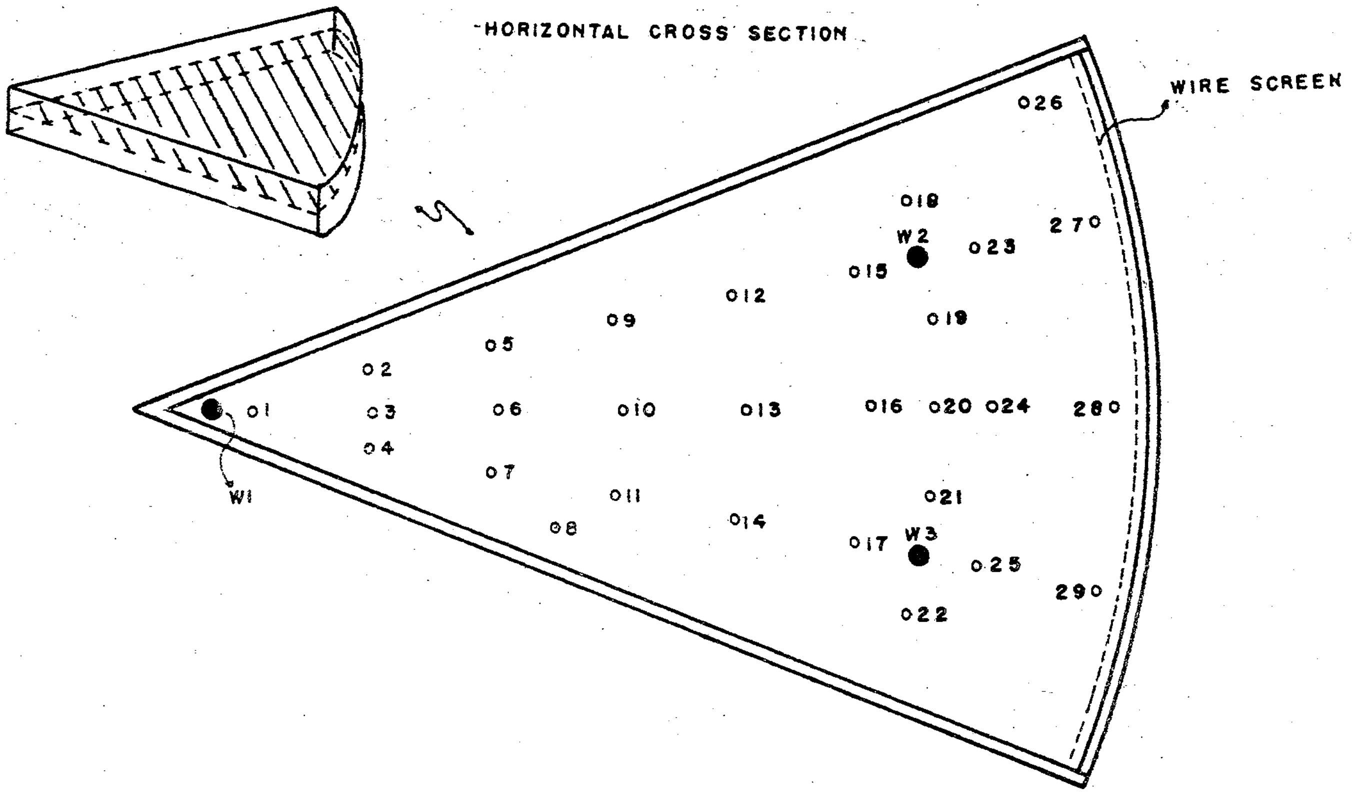

Figure 6. Model Cross Section Showing Electrode and Wellbore Locations.

mentioned previously, the wires of the electrodes were run through a 1/8 inch x 1/4 inch tubing union. The 1/8 inch pipe thread was screwed into the model and a chase washer and nut with a teflon insert was used on the other end. When the nut was tightened, the teflon extruded out the hole in the chase washer sealing the electrode to 300 psi satisfactorily. The same size fitting was used to seal the wellbores. A ferrule was placed around the 1/4 inch aluminum tubing wellbores to insure proper sealing. This was also tested to 300 psi.

It was hoped that fluid could be displaced under conditions other than atmospheric, therefore, maintaining the reservoir pressure. This was solved with the aid of the cylinder shown at the effluent end of the model in Figure 4.

The cylinder was fitted with a piston made of 1 inch thick plexiglass. The piston was fitted with an o-ring so fluid, with a minimum amount of leakage, could be displaced on one side of the cylinder and the piston held in position with air pressure on the other side. Therefore, the cylinder was calibrated so, by knowing the volume of water displaced, an average saturation behind the flood front could be calculated.

The orientation of the electrodes was basically on three radial lines as shown in Figure 6. It was felt that this arrangement would give the resistance readings required to study saturation distributions.

CHAPTER VII

EXPERIMENTAL RESULTS

The experimental results presented here represent a resistance-saturation correlation, single-phase permeability tests, and a cyclic relative permeability test for one of several synthetic porous medias produced during this study. Also, results of single-phase permeability tests and a cyclic relative permeability test of a natural sandstone is presented for comparison. Core specifications are given in Table I. In general, the results on the artificial core were as expected and are presented later in this chapter.

The artificial porous media, core Art 7AH, consisted of 70% by weight 50-70 mesh silica sand and 30% by weight Portland cement. In Figure 7 is shown this porous media magnified 100 times. It can be seen that a frosty coating of the sand grains with cement was achieved by the artificial cementation procedure explained in Chapter IV.

The experimental results were obtained by using a relative permeability experimental apparatus which is described by Woods (8). The liquid test fluid was distilled water containing 1250 ppm sodium chloride and 10 ppm mercuric chloride. The mercuric chloride was used to prevent bacterial growth. The gas test fluid was dry nitrogen. All data

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
Dry Weight, Grams (with electrodes and plastic covering)	50.904	38.954
Length, Inches	1.849	1.898
Diameter, Inches	0.933	0.953
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
Electrode Spacing, Inches	0.50	0.50
Pressure Pickup Spacing, Inches	1.04	1.04

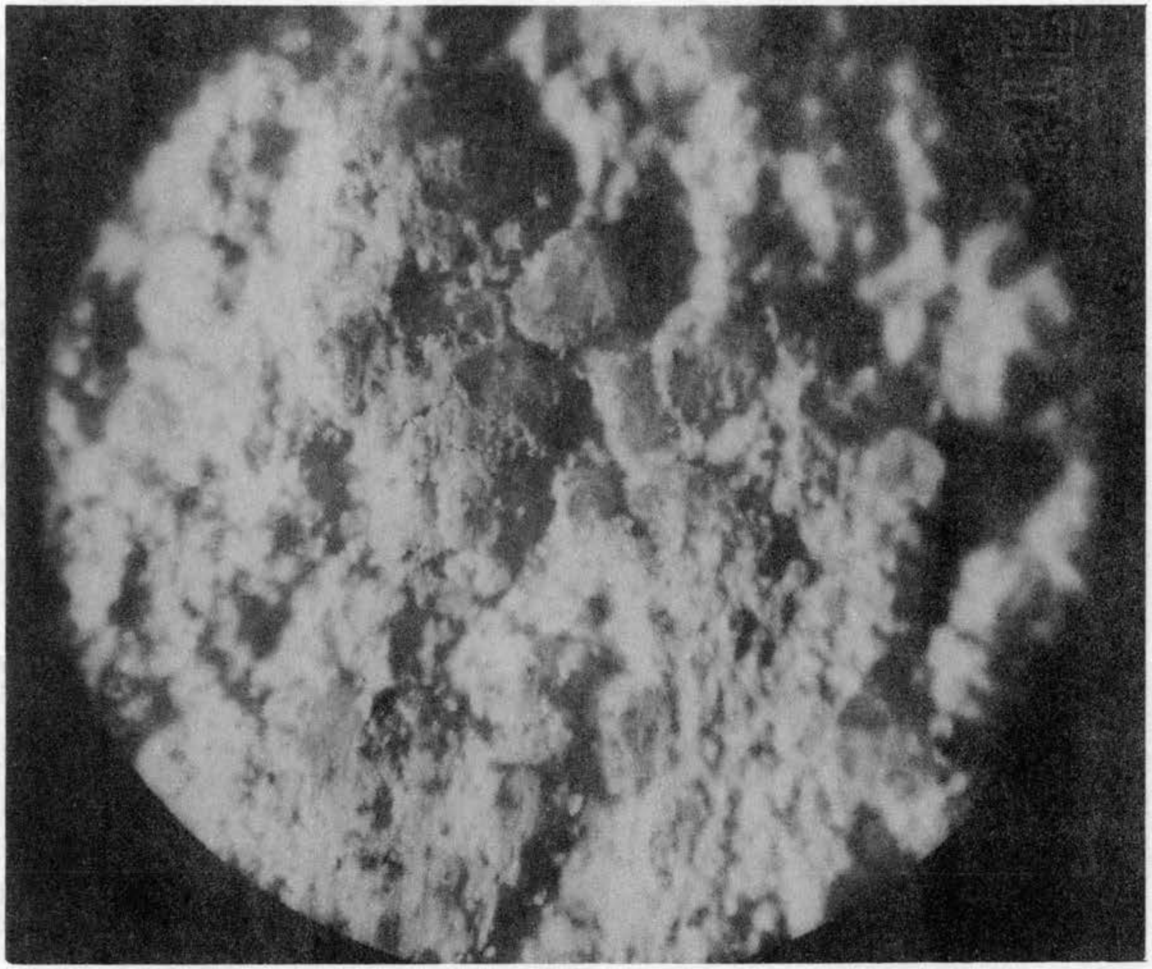

Figure 7. Core Art 7AH Magnified 100 Times

reduction was accomplished with the aid of an IBM 1620 digital computer.

Resistance-Saturation Measurement

During a relative permeability experimental run or when determining saturation distributions in the model, it is necessary to determine saturation under flowing conditions. This saturation was determined by utilizing a previously resolved resistance-saturation correlation.

To develop this relationship, the core was saturated to 100% water saturation before the gaseous phase was introduced into the test core. Starting with 100% water saturation, a portion of the water was displaced at which time the flow of nitrogen was interrupted. As soon as steady-state conditions for resistance was reached, the sample was removed from the core holder and weighed. The preceding two steps were continued until all displaceable water was removed. By using a computer, these experimental points were converted to an equivalent resistance at 68° F and then curve-fitted into a straight line plot on log-log paper of resistance-ratio versus water saturation. The resistance-saturation correlation for core Art 7AH is shown in Figure 8 and Table II.

Single-Phase Permeability

The single-phase permeability of the test core to test liquid and to nitrogen was measured. The gas permeability was calculated by using the Klinkenberg method. For core Art 7AH,

TABLE II

RESISTANCE-SATURATION INPUT AND OUTPUT DATA, CORE ART 7AH

```
INPUT DATA
CORE ART 7AH  RESISTANCE-SATURATION 8/9/64


 BR        TBR      N
OHM       DEG. F

71.00     68.0      13

IDENT    R       T        WT        DWT
        OHM   DEG. F     GM.        GM.

  1     71.0   68.0    47.551     38.954
  2    152.0   68.5    45.781     38.954
  3    152.0   68.5    45.781     38.954
  4    179.0   69.3    45.428     38.954
  5    180.0   69.3    45.428     38.954
  6    298.0   70.0    44.419     38.954
  7    298.0   70.0    44.419     38.954
  8    380.0   70.7    43.814     38.954
  9    379.0   70.7    43.814     38.954
 10    441.0   70.7    43.430     38.954
 11    439.0   70.7    43.430     38.954
 12    1338.   78.3    41.779     38.954
 13    1338.   78.3    41.779     38.954



OUTPUT DATA

CORE ART 7AH  RESISTANCE-SATURATION 8/9/64
      A                B           MAX WTR WT    BASE RES     RR (20)
                                     GRAMS       KILOHMS
  .2458E 05     -.264164E 01        9.1476        71.00       70.214
 IDENT          WTR SAT          RES RATIO
    1             93.9              1.00
    2             74.6              2.15
    3             74.6              2.15
    4             70.7              2.56
    5             70.7              2.57
    6             59.7              4.30
    7             59.7              4.30
    8             53.1              5.53
    9             53.1              5.51
   10             48.9              6.41
   11             48.9              6.38
   12             30.8             21.24
   13             30.8             21.24
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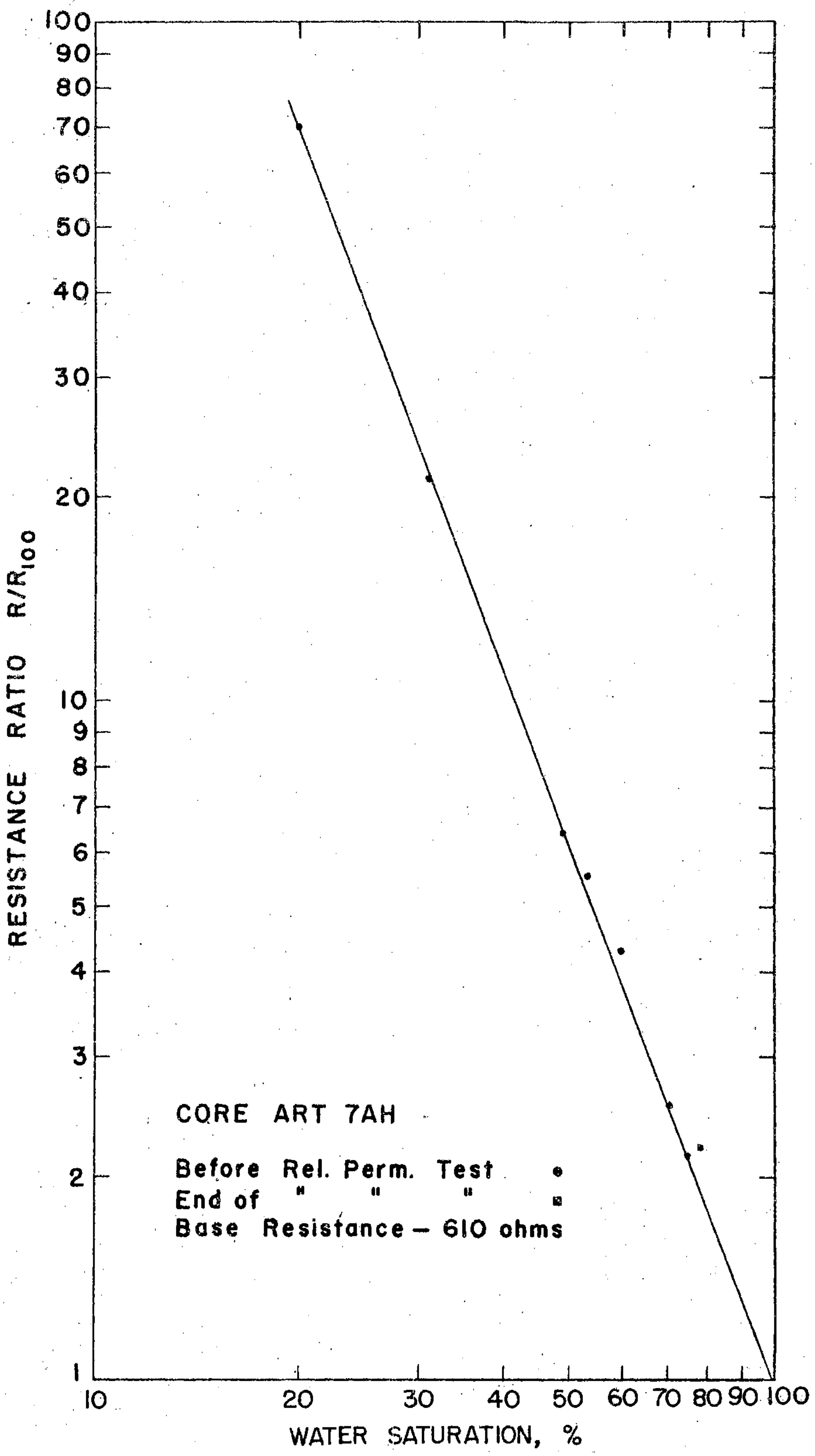

Figure 8. Resistance-Saturation, Core Art 7AH

the Klinkenberg permeability was 155.4 md. For the same test section, the water permeability tended to lie in the range from 143.3 - 152.9 md. These results are typical of a natural sandstone since water permeability is usually lower than the gas permeability because water is normally a reactant fluid. The difference in permeability is attributed to a reaction occurring in the core with water which will not occur with gas since it is a non-reactant fluid. The results of single-phase permeability testing on core Art 7AH are shown in Figure 9 and in Tables III and IV.

A natural sandstone currently being used for underground storage was also tested. The Klinkenberg permeability of the Lower Franconia Formation, denoted as core S1-F2, was 154 md. as compared to 155.4 md. for the artificial core. The water permeability of core S1-F2 tended to lie in the range from 124.7 - 137.4 md. as compared to 143.4 - 152.9 md. for the artificial porous media. The greater difference between gas and liquid permeability in the natural sandstone can be attributed to the presence of more reactant materials in the natural sandstone, such as, clays and drilling mud. The results of testing the natural sandstone are shown in Figure 10 and Table V.

Relative Permeability

Gas-water relative permeability curves have been determined experimentally for core Art 7AH, artificial porous media, and for a core from the Lower Franconia

TABLE III

KLINKENBERG PERMEABILITY INPUT AND OUTPUT DATA, CORE ART 7 AH

```
INPUT DATA
 CORE ART 7AH KLINKENBERG PERMEABILITY 8/12/64

    D           X          PB        N
   CM          CM        MM HG

 2.4206     2.6416      741.3      14

N        QG          TIME     DELTA P    P2          TC       DMV       GMV        K
                     SEC.      DIV.     DIV.      DEG. F     MV        MV

1       0.100       30.90      235.0    174.0       73.3      1.00      5.00       1
2       0.100       31.00      235.0    174.0       74.3      1.00      5.00       1
3       0.100       30.90      207.0    222.0       75.4      1.00      5.00       1
4       0.100       30.90      206.0    222.0       75.5      1.00      5.00       1
5       0.100       30.90      183.0    110.0       76.2      1.00      12.5       1
6       0.100       30.90      185.0    110.0       76.2      1.00      12.5       1
7       0.100       30.80      167.0    130.0       76.2      1.00      12.5       1
8       0.100       30.80      165.0    130.0       76.3      1.00      12.5       1
9       0.100       30.90      150.0    150.0       76.6      1.00      12.5       1
10      0.100       30.90      152.0    150.0       76.6      1.00      12.5       1
11      0.100       30.90      138.0    168.0       76.2      1.00      12.5       1
12      0.100       30.90      138.0    168.0       76.6      1.00      12.5       1
13      0.100       30.90      169.0    128.0       76.3      1.00      12.5       1
14      0.100       30.90      165.0    128.0       76.3      1.00      12.5       1


OUTPUT DATA

 CORE ART 7AH KLINKENBERG PERMEABILITY 8/12/64
      IDENT.          FLOW RATE          1/MEAN PRESS.          PERM.
        NO.           C.C./SEC.            1/(ATM.)          MILLIDARCYS
         1             91.640                .250               167.24
         2             91.345                .250               166.93
         3             91.640                .219               166.91
         4             91.640                .219               167.85
         5             91.640                .192               165.71
         6             91.640                .191               163.74
         7             91.938                .171               162.67
         8             91.938                .171               164.83
         9             91.640                .154               163.24
        10             91.640                .154               160.95
        11             91.640                .142               162.99
        12             91.640                .142               163.08
        13             91.640                .173               161.95
        14             91.640                .173               166.21
KLINKENBERG PERM 155.4MD.    SLOPE 49.277MD./ATM.
```

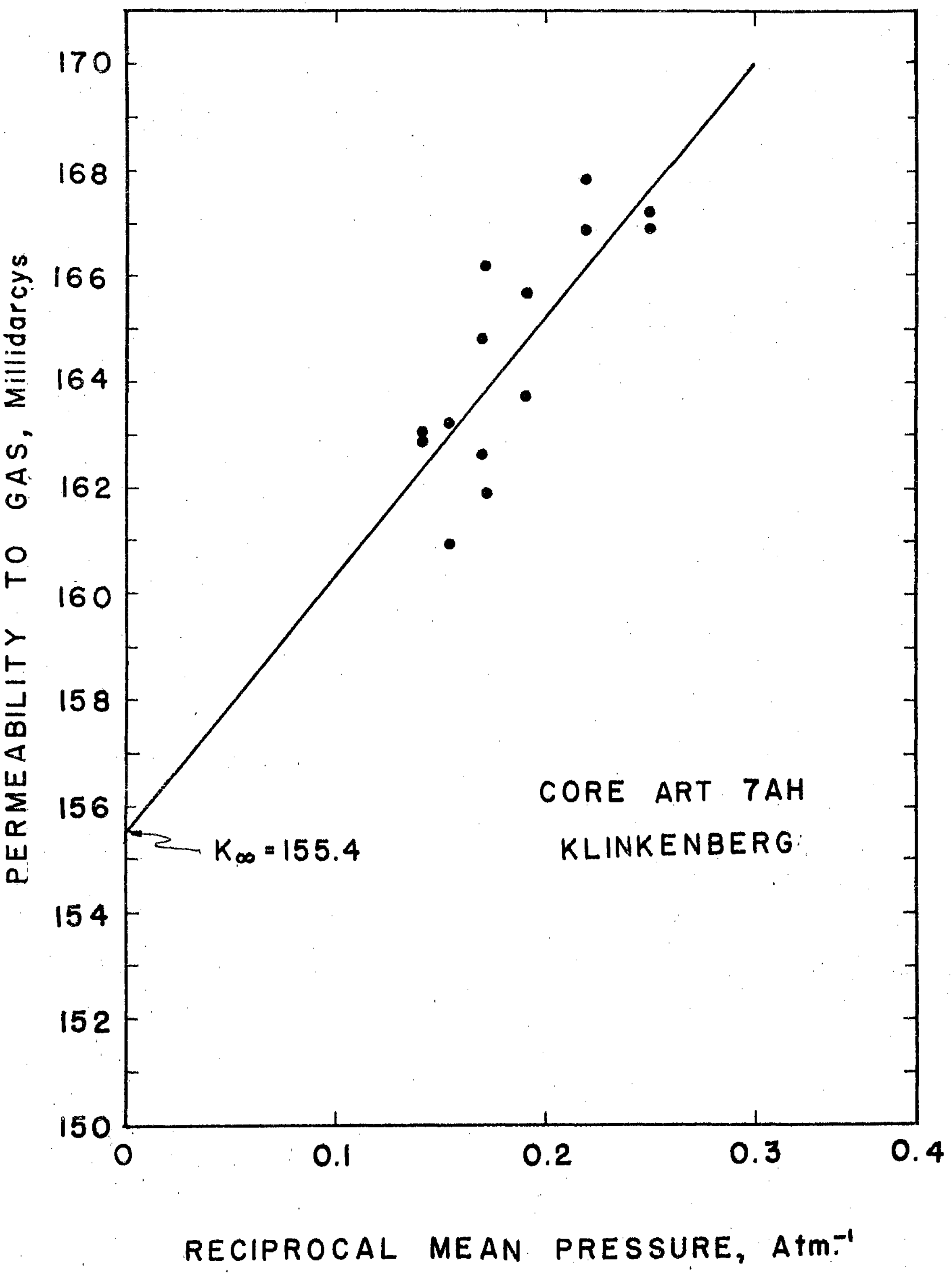

Figure 9. Klinkenberg Permeability, Core Art 7AH

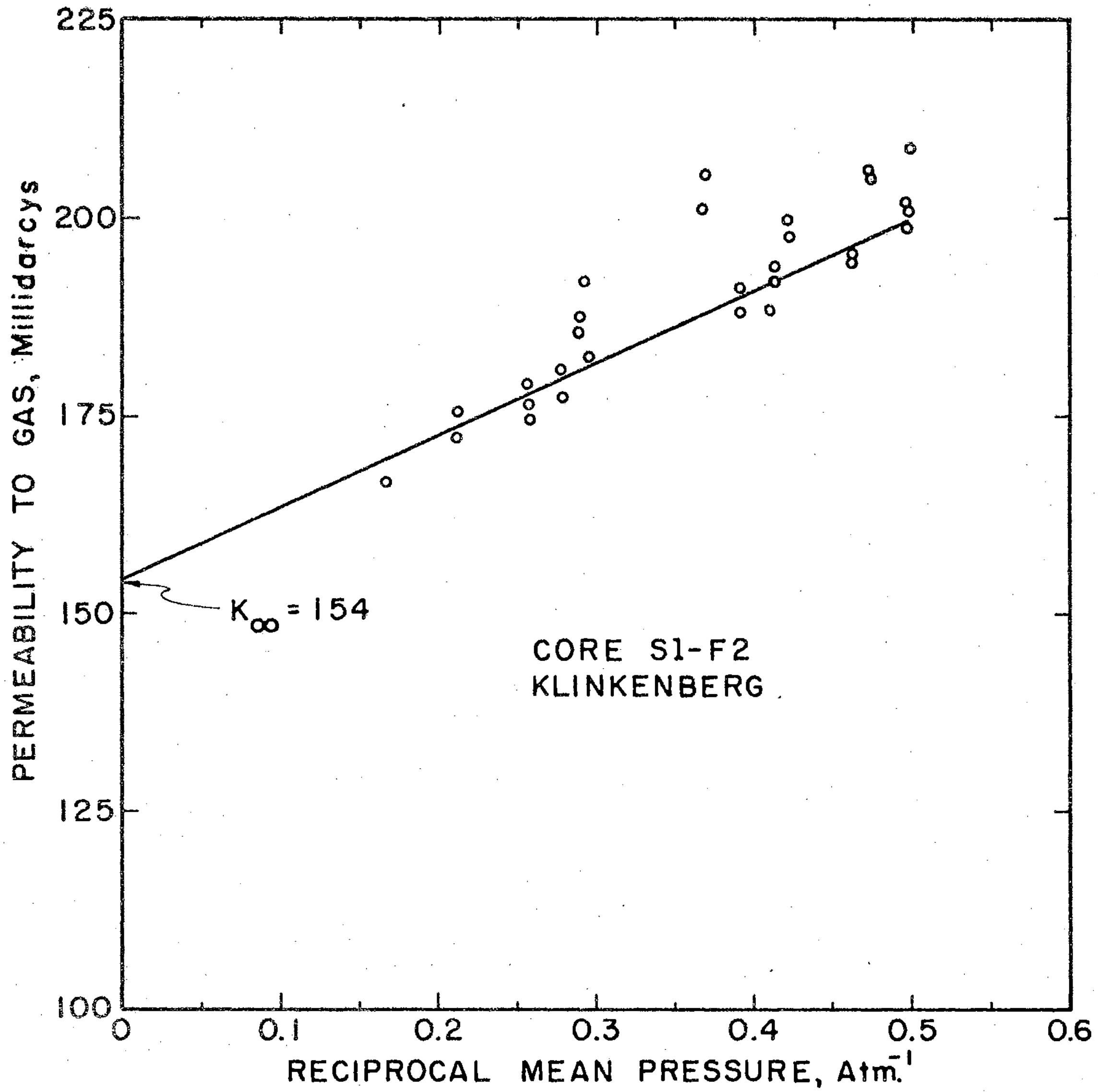

Figure 10. Klinkenberg Permeability, Core S1-F2

TABLE IV

WATER PERMEABILITY INPUT AND OUTPUT DATA, CORE ART 7AH

```
INPUT DATA
 CORE ART 7AH  WATER PERMS  8 - 10 - 64

      D        X       PB    PS       BR      TBR      BK          B      RT
     CM       CM     MM HG  PSI      OHMS    DEG. F    MD               DEG. F

  2.4206  2.6416  731.9  0.00     275.0    68.00   1.000  -2.64164  80.5

 N      QW        QG        TIME  DELTA P   P2      R        TC     DMV      GMV     K
      CC/HR                 SEC.    DIV    DIV    OHMS    DEG. F   MV       MV

7     1025.3    0.000    1.000   160.0   235.0   346.0    79.0    1.00     2.50    1
8     1025.3    0.000    1.000   160.0   235.0   346.0    79.0    1.00     2.50    1
9     1025.3    0.000    1.000   164.0   142.0   348.0    79.3    1.00     5.00    1
10    1025.3    0.000    1.000   164.0   142.0   348.0    79.3    1.00     5.00    1
11    1025.3    0.000    1.000   166.0   170.0   378.0    79.3    1.00     5.00    1
12    1025.3    0.000    1.000   166.0   170.0   378.0    79.3    1.00     5.00    1
13    1025.3    0.000    1.000   167.0   213.0   370.0    78.7    1.00     5.00    1
14    1025.3    0.000    1.000   167.0   213.0   370.0    78.7    1.00     5.00    1
15    1025.3    0.000    1.000   165.0   109.0   375.0    78.7    1.00     12.5    1
16    1025.3    0.000    1.000   165.0   109.0   375.0    78.7    1.00     12.5    1
17    1025.3    0.000    1.000   162.0   128.0   380.0    79.0    1.00     12.5    1
18    1025.3     .000    1.000   162.0   128.0   380.0    79.0    1.00     12.5    1
19    1025.3    0.000    1.000   161.0   150.0   380.0    79.0    1.00     12.5    1
20    1025.3    0.000    1.000   161.0   150.0   380.0    79.0    1.00     12.5    1
21    1025.3    0.000    1.000   161.0   128.0   388.0    79.1    1.00     12.5    1
22    1025.3    0.000    1.000   161.0   128.0   388.0    79.1    1.00     12.5    1
23    1025.3    0.000    1.000   161.0   108.0   394.0    79.1    1.00     12.5    1
24    1025.3    0.000    1.000   161.0   108.0   394.0    79.1    1.00     12.5    1
25    1025.3    0.000    1.000   164.0   212.0   411.0    78.9    1.00     5.00    1
26    1025.3    0.000    1.000   164.0   212.0   411.0    78.9    1.00     5.00    1
27    1025.3    0.000    1.000   167.5   159.0   426.0    78.9    1.00     5.00    1
28    1025.3    0.000    1.000   167.5   159.0   426.0    78.9    1.00     5.00    1
29    1025.3    0.000    1.000   169.0   234.0   429.0    78.8    1.00     2.50    1
30    1025.3    0.000    1.000   169.0   234.0   429.0    78.8    1.00     2.50    1
31    1025.3    0.000    1.000   170.0   123.0   445.0    78.8    1.00     2.50    1
32    1025.3    0.000    1.000   170.0   123.0   445.0    78.8    1.00     2.50    1
33    1025.3    0.000    1.000   171.5   219.0   452.0    78.6    1.00     1.00    1
34    1025.3    0.000    1.000   171.5   219.0   452.0    78.6    1.00     1.00    1
```

```
OUTPUT DATA

 CORE ART 7AH  WATER PERMS  8 - 10 - 64
IDENT    WATER SAT   REL.        REL.      MEAN PRES       FG
          PERCENT  GAS PERM WATER PERM      ATM                      FD
    7      87.35     .0000 152.9039        3.008        .0000       .0000
    8      87.35     .0000 152.9039        3.008        .0000       .0000
    9      87.05     .0000 148.6181        3.349        .0000       .0000
   10      87.05     .0000 148.6181        3.349        .0000       .0000
   11      84.37     .0000 146.8275        3.731        .0000       .0000
   12      84.37     .0000 146.8275        3.731        .0000       .0000
   13      85.26     .0000 147.0445        4.313        .0000       .0000
   14      85.26     .0000 147.0445        4.313        .0000       .0000
   15      84.83     .0000 148.8269        5.108        .0000       .0000
   16      84.83     .0000 148.8269        5.108        .0000       .0000
   17      84.30     .0000 151.0162        5.738        .0000       .0000
   18      84.30     .0000 151.0162        5.738        .0000       .0000
   19      84.30     .0000 151.9542        6.475        .0000       .0000
   20      84.30     .0000 151.9542        6.475        .0000       .0000
   21      83.61     .0000 151.7649        5.735        .0000       .0000
   22      83.61     .0000 151.7649        5.735        .0000       .0000
   23      83.12     .0000 151.7649        5.062        .0000       .0000
   24      83.12     .0000 151.7649        5.062        .0000       .0000
   25      81.87     .0000 149.3608        4.291        .0000       .0000
   26      81.87     .0000 149.3608        4.291        .0000       .0000
   27      80.77     .0000 146.2398        3.588        .0000       .0000
   28      80.77     .0000 146.2398        3.588        .0000       .0000
   29      80.59     .0000 145.1229        3.027        .0000       .0000
   30      80.59     .0000 145.1229        3.027        .0000       .0000
   31      79.48     .0000 144.2693        2.283        .0000       .0000
   32      79.48     .0000 144.2693        2.283        .0000       .0000
   33      79.07     .0000 143.3654        2.049        .0000       .0000
```

TABLE V

WATER PERMEABILITY INPUT AND OUTPUT DATA, CORE S1-F2

```
INPUT DATA
CORE S1 F2  WATER PERM                      4/28/64

     D         X        PB    PS       BR       TBR      BK              B        RT
    CM        CM     MM HG   PSI      OHMS    DEG. F    MD                    DEG. F

   2.522   2.6416   734.2       0.0    1315.     71.0    1.00     -1.25350   79.0

 N      QW        QG       TIME  DELTA P   P2        R        TC     DMV      GMV    K
      CC/HR                SEC.    DIV    DIV      OHMS    DEG. F   MV       MV

1    1025.3    0.000    0.000   165.0   107.0   1445.    79.0    1.00    1.00    1
2    1025.3    0.000    0.000   164.0   107.0   1440.    79.0    1.00    1.00    1
3    1025.3    0.000    0.000   164.0   160.0   1440.    81.4    1.00    2.50    1
4    1025.3    0.000    0.000   165.0   160.0   1440.    81.4    1.00    2.50    1
5    1025.3    0.000    0.000   170.0   130.0   1420.    81.4    1.00    5.00    1
6    1025.3    0.000    0.000   170.0   131.0   1430.    81.4    1.00    5.00    1
7    1025.3    0.000    0.000   170.0   246.0   1420.    84.0    1.00    5.00    1
8    1025.3    0.000    0.000   170.0   244.0   1423.    84.0    1.00    5.00    1
9    1025.3    0.000    0.000   170.0   114.0   1400.    83.0    1.00    12.5    1
10   1025.3    0.000    0.000   170.0   114.0   1420.    83.0    1.00    12.5    1
11   1025.3    0.000    0.000   170.0   145.0   1420.    83.0    1.00    12.5    1
12   1025.3    0.000    0.000   170.0   145.0   1420.    83.0    1.00    12.5    1
13   1025.3    0.000    0.000   172.0   160.0   1419.    83.0    1.00    12.5    1
14   1025.3    0.000    0.000   171.0   160.0   1419.    83.0    1.00    12.5    1
15   1025.3    0.000    0.000   171.0   180.0   1420.    82.7    1.00    12.5    1
16   1025.3    0.000    0.000   172.0   180.0   1420.    82.7    1.00    12.5    1
17   1025.3    0.000    0.000   172.0   177.0   1420.    82.7    1.00    5.00    1
18   1025.3    0.000    0.000   172.0   177.0   1420.    82.7    1.00    5.00    1
19   1025.3    0.000    0.000   171.0   177.0   1130.    82.7    1.00    5.00    1


OUTPUT DATA

CORE S1 F2  WATER PERM                      4/28/64
IDENT   WATER SAT    REL.       REL.      MEAN PRES        FG
         PERCENT   GAS PERM WATER PERM      ATM                          FD
    1     86.25     .0000  136.5874       1.732         .0000          .0000
    2     86.49     .0000  137.4202       1.729         .0000          .0000
    3     84.73     .0000  133.4046       2.518         .0000          .0000
    4     84.73     .0000  132.5961       2.521         .0000          .0000
    5     85.68     .0000  128.6962       3.208         .0000          .0000
    6     85.20     .0000  128.6962       3.221         .0000          .0000
    7     83.84     .0000  124.7027       4.769         .0000          .0000
    8     83.70     .0000  124.7027       4.742         .0000          .0000
    9     85.50     .0000  126.2145       5.293         .0000          .0000
   10     84.53     .0000  126.2145       5.293         .0000          .0000
   11     84.53     .0000  126.2145       6.336         .0000          .0000
   12     84.53     .0000  126.2145       6.336         .0000          .0000
   13     84.58     .0000  124.7469       6.847         .0000          .0000
   14     84.58     .0000  125.4764       6.844         .0000          .0000
   15     84.75     .0000  125.9331       7.516         .0000          .0000
   16     84.75     .0000  125.2009       7.519         .0000          .0000
   17     84.75     .0000  125.2009       3.846         .0000          .0000
   18     84.75     .0000  125.2009       3.846         .0000          .0000
   19    101.69     .0000  125.9331       3.843         .0000          .0000
```

Formation, core S1-F2. The equipment used was the previously mentioned modified Penn State experimental apparatus. Because steady-state conditions were reached rapidly at intermediate points, it was possible to carry the tests through three complete drainage-imbibition cycles for S1-F2 and two complete cycles for Art 7AH.

The relative permeability characteristics of core Art 7AH were determined and it was found that the imbibition-trapped non-wetting phase saturation, or imbibition hysteresis phenomenon, was exhibited which is characteristic of a natural sandstone, such as the Lower Franconia Formation, being subjected to two-phase flow. The aforesaid characteristic of imbibition hysteresis phenomenon is not exhibited with glass beads. The results of relative permeability testing are shown in Figure 11 and Table VI for core Art 7AH and in Figure 12 and Table VII for core S1-F2.

The imbibition-trapped gas saturation for core S1-F2 was 34% (66% water saturation) as compared to 22% (78% water saturation) for core Art 7AH. The first drainage cycle for S1-F2 continued until a water saturation of 20% was reached. A water saturation of 27% was reached on the first drainage cycle of Art 7AH. As can be seen from the figures, both cores exhibit relative permeability characteristics of a poorly consolidated natural sandstone.

Due to difficulties with experimental apparatus, relative permeability curves were not determined for all the artificial cores produced. However, comparing the results of testing on

TABLE VI

RELATIVE PERMEABILITY INPUT AND OUTPUT DATA, CORE ART 7AH

```
INPUT DATA
 CORE 7AH 1ST DRAINAGE 8/10/64

     D        X       PB    PS       BR      TBR      BK           B      RT
    CM       CM     MM HG   PSI      OHMS    DEG. F   MD                  DEG. F

  2.4206   2.6416   729.8   0.00     610.0   68.00    155.4  -2.64164   80.0

N     QW        QG       TIME DELTA P  P2      R       TC     DMV     GMV    K
     CC/HR               SEC.   DIV    DIV    OHMS   DEG. F   MV      MV

1    1025.3    0.000    1.000  192.0  83.00  502.0    78.5   1.00    1.00   1
4    1025.3    10.00    34.90  109.0  163.0  600.0    80.0   2.50    1.00   0
5    816.52    50.00    21.60  190.0  205.0  770.0    79.3   2.50    1.00   0
7    753.70    100.0    22.30  247.0  247.0  850.0    79.3   2.50    1.00   0
9    607.64    250.0    56.80  142.0  120.0  945.0    79.1   5.00    2.50   0
11   607.64    250.0    23.40  177.0  155.0  1015.    79.1   5.00    2.50   0
13   436.74    250.0    23.30  160.0  132.0  1060.    78.8   5.00    2.50   0
15   436.74    0.020    33.60  181.0  167.0  1110.    78.0   5.00    2.50   1
17   274.23    0.020    33.60  151.0  138.0  1180.    78.0   5.00    2.50   1
19   274.23    0.020    21.00  176.0  180.0  1240.    77.5   5.00    2.50   1
21   148.17    0.050    49.80  130.0  148.0  1330.    76.0   5.00    2.50   1
23   148.17    0.100    38.90  193.0  134.0  1470.    74.8   5.00    5.00   1
25   93.034    0.100    24.50  217.0  170.0  1750.    72.8   5.00    5.00   1
27   53.909    0.200    42.80  208.0  174.0  1950.    72.4   5.00    5.00   1
29   20.257    0.200    38.50  190.0  170.0  2300.    71.8   5.00    5.00   1
31   14.744    0.200    49.70  156.0  130.0  2450.    70.8   5.00    5.00   1
36   5.8705    0.300    71.80  139.0  129.0  2740.    70.0   5.00    5.00   1
39   3.4788    0.300    71.60  133.0  123.0  3090.    70.0   5.00    5.00   1
41   0.0000    0.100    24.00  115.0  97.00  8200.    70.0   5.00    5.00   1
44   0.0000    0.200    47.60  113.0  90.00 18200.    70.0   5.00    5.00   1
```

```
OUTPUT DATA

 CORE 7AH 1ST DRAINAGE 8/10/64
IDENT   WATER SAT    REL.       REL.     MEAN PRES        FG
         PERCENT  GAS PERM WATER PERM      ATM                        FD
    1    102.79     .0000     .8250       1.740         .0000        .0000
    4     95.49     .0000     .5705       2.189         .0026        .0026
    5     87.13     .0167     .2629       2.902         .7547        .7547
    7     83.93     .0223     .1867       3.428         .8525        .8525
   11     78.54     .0294     .1076       4.514         .9297        .9297
   15     76.28     .0443     .0767       4.651         .9659        .9659
   17     74.53     .0615     .0577       4.031         .9812        .9812
   19     73.30     .0729     .0498       4.668         .9863        .9863
   21     71.83     .1273     .0371       3.800         .9942        .9942
   23     69.52     .1514     .0254       5.501         .9967        .9967
   25     65.65     .1850     .0145       6.326         .9985        .9985
   27     63.12     .2233     .0088       6.252         .9992        .9992
   29     59.46     .2861     .0036       5.943         .9997        .9997
   31     58.32     .3240     .0032       4.922         .9998        .9998
   36     56.10     .3971     .0014       4.668         .9999        .9999
   39     53.60     .4315     .0009       4.502         .9999        .9999
   41     37.05     .5731     .0000       3.897        1.0000       1.0000
   44     27.39     .6072     .0000       3.775        1.0000       1.0000
```

TABLE VI (Continued)

```
INPUT DATA
 CORE 7AH 1ST IMBIBITION 8/10/64

     D         X        PB     PS       BR       TBR       BK          B        RT
    CM        CM      MM HG   PSI      OHMS     DEG. F    MD                  DEG. F

  2.4206   2.6416   730.6   3.00     610.0    68.00     155.4   -2.64164   79.0

 N       QW         QG        TIME  DELTA P   P2       R        TC      DMV       GMV    K
        CC/HR                 SEC.    DIV     DIV     OHMS    DEG. F    MV        MV

44    0.0000     0.200      47.60   113.0   90.00   18200.    70.0     5.00      5.00   1
46    3.4788     0.200      56.00   111.0   149.0    2990.    70.0     5.00      2.50   1
50    7.3722     0.100      36.30   100.0   152.0    2400.    71.2     5.00      2.50   1
52    14.744     0.100      41.80   188.0   138.0    2100.    71.3     2.50      2.50   1
56    53.909     0.050      44.00   149.0   231.0    1590.    72.9     2.50      1.00   1
60    148.17     0.050      73.60   140.0   206.0    1270.    74.3     2.50      1.00   1
62    274.23     100.0      34.50   97.00   130.0    1080.    76.8     2.50      1.00   0
67    436.74     25.00      60.40   154.0   165.0    1080.    75.0     2.50      1.00   0
68    436.74     0.000      1.000   149.0   164.0    1060.    75.0     2.50      1.00   0


OUTPUT DATA

 CORE 7AH 1ST IMBIBITION 8/10/64
IDENT   WATER SAT    REL.        REL.      MEAN PRES       FG
         PERCENT   GAS PERM  WATER PERM       ATM                         FD
   44     27.39      .6071      .0000        3.774        1.0000        1.0000
   46     54.28      .5604      .0011        3.537         .9999         .9999
   50     58.67      .5011      .0025        3.402         .9999         .9999
   52     61.68      .4737      .0053        3.254         .9997         .9997
   56     68.04      .3483      .0240        2.664         .9986         .9986
   60     73.63      .2339      .0690        2.532         .9943         .9943
   62     77.46      .0628      .1785        2.015         .9462         .9462
   67     78.06      .0032      .1832        2.523         .4765         .4765
   68     78.61      .0000      .1893        2.484         .0000         .0000
```

TABLE VI (Continued)

```
INPUT DATA
CORE 7AH 2ND DRAINAGE 8/11/64

     D         X        PB     PS       BR        TBR       BK             B       RT
    CM        CM      MM HG   PSI      OHMS     DEG. F     MD                    DEG. F

  2.4206   2.6416   731.5   0.00      610.0     68.00     155.4   -2.64164   79.0

 N      QW         QG         TIME  DELTA P   P2        R         TC      DMV       GMV     K
       CC/HR                  SEC.    DIV     DIV     OHMS     DEG. F    MV        MV

71    436.74     5.000      38.10   159.0   167.0   1085.      76.6     2.50      1.00    0
75    274.23     25.00      44.60   125.0   120.0   1062.      78.3     2.50      1.00    0
80    148.17     250.0      32.80   148.0   160.0   1380.      77.3     2.50      1.00    0
82    93.034     250.0      25.10   130.0   155.0   1500.      77.0     2.50      1.00    0
86    53.909     0.020      29.00   154.5   202.0   1770.      75.7     2.50      1.00    1
90    20.257     0.020      16.40   168.5   99.00   2280.      74.0     2.50      2.50    1
93    14.744     0.100      46.40   221.0   149.0   2580.      72.7     2.50      2.50    1
100   7.3722     0.200      53.70   133.0   208.0   3210.      71.5     5.00      2.50    1
104   3.4788     0.300      71.30   136.0   216.0   3820.      71.3     5.00      2.50    1
106   0.0000     0.300      67.50   125.0   185.0  10000.      71.3     5.00      2.50    1
108   0.0000     0.300      67.00   124.0   180.0  15300.      71.0     5.00      2.50    1
110   0.0000     0.300      66.80   122.0   181.0  21100.      71.0     5.00      2.50    1


OUTPUT DATA

CORE 7AH 2ND DRAINAGE 8/11/64
IDENT   WATER SAT   REL.       REL.      MEAN PRES       FG
         PERCENT  GAS PERM WATER PERM      ATM                         FD
   71     77.39     .0001     .1738       2.565         .0280         .0280
   75     77.47     .0077     .1359       2.191         .7360         .7360
   80     70.45     .0905     .0628       2.466         .9862         .9862
   82     68.34     .1433     .0450       2.322         .9937         .9937
   86     64.55     .2087     .0223       2.626         .9978         .9978
   90     59.08     .3102     .0078       2.850         .9995         .9995
   93     56.70     .3327     .0044       3.567         .9997         .9997
  100     52.48     .4112     .0019       4.254         .9999         .9999
  104     49.18     .4430     .0008       4.350         .9999         .9999
  106     34.16     .5556     .0000       3.986        1.0000        1.0000
  108     29.12     .5705     .0000       3.938        1.0000        1.0000
  110     25.78     .5848     .0000       3.916        1.0000        1.0000
```

TABLE VI (Continued)

```
INPUT DATA
 CORE 7AH 2ND IMBIBITION 8/11/64

     D        X       PB    PS       BR      TBR      BK           B     RT
    CM       CM    MM HG   PSI     OHMS   DEG. F    MD                DEG. F

  2.4206   2.6416   736.5   3.00     610.0    68.00    155.4  -2.64164  80.0

 N      QW        QG        TIME  DELTA P   P2        R       TC      DMV      GMV    K
       CC/HR                SEC.    DIV     DIV     OHMS    DEG. F   MV       MV

110  0.0000    0.300     66.80   122.0   181.0  21100.    71.0    5.00     2.50    1
111  3.4788    0.200     53.00   122.0   160.0   3410.    70.7    5.00     2.50    1
114  5.8705    0.100     29.90   115.0   162.0   2995.    71.2    5.00     2.50    1
118  14.744    0.100     43.90   198.0   126.0   2270.    71.8    2.50     2.50    1
121  53.909    0.050     33.40   184.0   110.0   1800.    73.2    2.50     2.50    1
126  93.034    0.020     24.00   151.0   202.0   1500.    74.3    2.50     1.00    1
128  148.17    0.020     42.10   136.0   162.0   1340.    75.8    2.50     1.00    1
130  274.23    100.0     22.30   107.0   120.0   1115.    77.0    2.50     1.00    0
133  436.74    5.000     36.90   143.0   162.0   1135.    78.0    2.50     1.00    0


OUTPUT DATA

 CORE 7AH 2ND IMBIBITION 8/11/64
IDENT   WATER SAT   REL.      REL.     MEAN PRES        FG
         PERCENT  GAS PERM WATER PERM     ATM                           FD
  110     25.78     .5848     .0000      3.916        1.0000        1.0000
  111     51.48     .5092     .0009      3.775         .9999         .9999
  114     53.95     .4919     .0017      3.690         .9999         .9999
  118     59.76     .4330     .0050      3.255         .9997         .9997
  121     64.84     .3286     .0193      3.046         .9988         .9988
  126     69.14     .2608     .0401      2.610         .9970         .9970
  128     71.69     .1805     .0696      2.393         .9924         .9924
  130     76.47     .0875     .1614      2.070         .9643         .9643
  133     75.64     .0001     .1899      2.444         .0436         .0436
```

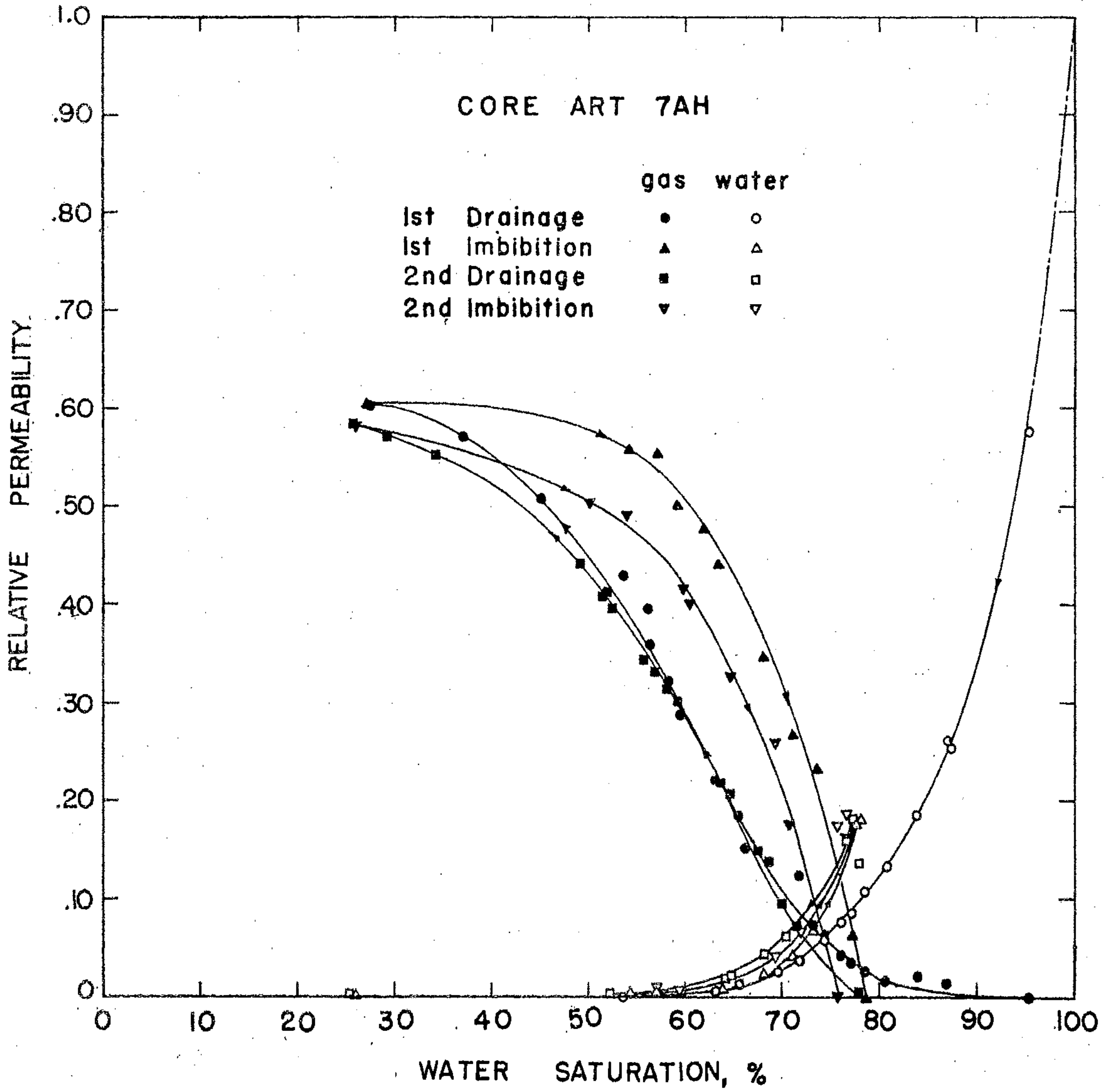

Figure 11. Relative Permeability, Core Art 7AH

TABLE VII

RELATIVE PERMEABILITY INPUT AND OUTPUT DATA, CORE S1-F2

```
INPUT DATA
CORE S1 F2  FIRST DRAINAGE                4/28/64

     D         X       PB    PS      BR       TBR      BK              B       RT
    CM        CM     MM HG  PSI     OHMS    DEG. F    MD                     DEG. F

   2.522   2.6416    734.0       0.0    1315.     71.0    154.0   -1.25350   80.0

  N      QW        QG        TIME  DELTA P   P2        R        TC      DMV      GMV    K
        CC/HR                SEC.    DIV     DIV     OHMS    DEG. F    MV       MV

 19    1025.3    0.000    0.000   171.0   177.0   1130.     82.7    1.00     5.00   1
 22    1025.3    50.00    24.10   220.0   185.0   1382.     78.5    1.00     2.50   0
 28    753.71    0.020    38.40   175.0   165.0   1980.     78.3    2.50     5.00   1
 33    607.64    0.040    47.20   216.0   180.0   2360.     78.3    2.50     5.00   1
 35    446.64    0.040    32.80   123.0   188.0   2700.     78.3    5.00     5.00   1
 37    347.78    0.040    30.10   123.0   186.0   2920.     78.3    5.00     5.00   1
 45    180.04    0.060    41.80   192.0   127.0   3450.     78.3    2.50     12.5   1
  49   137.12    0.060    41.40   178.0   124.0   3550.     78.3    2.50     12.5   1
  54   103.05    0.060    29.60   201.0   131.0   4210.     78.3    2.50     12.5   1
  60   81.255    0.100    31.70   124.0   142.0   5000.     75.2    5.00     12.5   1
  63   53.909    0.100    27.20   126.0   144.0   5690.     74.1    5.00     12.5   1
  69   14.744    0.300    61.00   132.0   147.0   7210.     73.4    5.00     12.5   1
  70   14.744    0.300    61.00   130.0   145.0   7190.     73.4    5.00     12.5   1
  76   3.4788    0.300    61.00   105.0   133.0   9500.     73.4     5.0     12.5   1


OUTPUT DATA

CORE S1 F2  FIRST DRAINAGE              4/28/64
IDENT   WATER SAT  REL.       REL.      MEAN PRES        FG
         PERCENT  GAS PERM WATER PERM     ATM                          FD
   19    101.69    .0000     .8177       3.843          .0000        .0000
   22     89.76    .0291     .6693       2.848          .6798        .6798
   28     67.49    .0760     .2480       4.455          .9375        .9375
   33     58.67    .0908     .1620       4.954          .9648        .9648
   35     52.70    .1114     .1069       5.239          .9807        .9807
   37     49.51    .1221     .0832       5.212          .9862        .9862
   45     43.34    .1299     .0540       6.630          .9915        .9915
   49     42.36    .1460     .0443       6.427          .9938        .9938
   54     36.97    .1705     .0295       6.830          .9964        .9964
   60     33.13    .1985     .0200       7.500          .9980        .9980
   63     30.19    .2240     .0132       7.596          .9988        .9988
   69     25.15    .2787     .0035       7.782          .9997        .9997
   70     25.21    .2865     .0035       7.686          .9997        .9997
   76     20.18    .3935     .0010       6.928          .9999        .9999
```

TABLE VII (Continued)

```
INPUT DATA
CORE S1 F2   FIRST IMBIBITION             4/28/64

     D          X        PB    PS        BR        TBR       BK            B         RT
    CM         CM      MM HG   PSI      OHMS     DEG. F     MD                     DEG. F

  2.522     2.6416     731.6      32.0      1315.       71.0      154.0    -1.25350   79.0

 N      QW        QG        TIME  DELTA P   P2        R         TC      DMV       GMV    K
       CC/HR                SEC.    DIV     DIV      OHMS     DEG. F    MV        MV

 82   3.4788     0.300     65.20   174.0   115.0   8950.      74.0     2.50      12.5    1
 88   5.8705     0.300     74.10   164.0   116.0   8050.      74.0     2.50      12.5    1
 91   14.744     0.200     67.40   148.0   110.0   6650.      72.3     2.50      12.5    1
 94   26.015     0.200     81.50   142.0   108.0   5970.      72.1     2.50      12.5    1
 98   53.909     0.100     65.50   124.0   102.0   4700.      72.3     2.50      12.5    1
101   81.255     0.040     64.10   222.0   97.00   3650.      75.8     1.00      12.5    1
104   103.05     250.0     38.60   175.0   219.0   3130.      75.8     1.00      5.00    0
107   137.12     250.0     50.20   95.00   231.0   2795.      76.5     2.50      5.00    0
110   180.04     50.00     35.20   70.00   192.0   2590.      76.3     2.50      5.00    0
113   241.93     10.00     40.70   120.0   163.0   2450.      76.3      1.0      5.00    0
116   347.88     0.000     0.000   125.0   157.0   2100.      76.3     1.00      5.00    1


OUTPUT DATA

CORE S1  F2   FIRST  IMBIBITION            4/28/64
IDENT   WATER SAT   REL.        REL.      MEAN PRES          FG
          PERCENT  GAS PERM WATER PERM       ATM                             FD
    82      21.05     .4940      .0012       6.092           .9999           .9999
    88      22.91     .4641      .0021       6.053           .9999           .9999
    91      27.10     .3955      .0061       5.736           .9997           .9997
    94      29.60     .3473      .0114       5.625           .9993           .9993
    98      35.75     .2629      .0270       5.292           .9980           .9980
   101      42.36     .1644      .0543       4.869           .9935           .9935
   104      47.89     .0834      .0875       4.416           .9797           .9797
   107      52.09     .0434      .0850       4.759           .9624           .9624
   110      55.45     .0186      .1519       4.054           .8607           .8607
   113      57.96     .0043      .2977       3.503           .4220           .4220
   116      65.55     .0000      .4109       3.437           .0000           .0000
```

TABLE VII (Continued)

INPUT DATA
CORE S1 F2 SECOND DRAINAGE

D CM	X CM	PB MM HG	PS PSI	BR OHMS	TBR DEG. F	BK MD	B	RT DEG. F
2.522	2.6416	731.4	0.0	1315.	71.0	154.0	-1.25350	77.0

N	QW CC/HR	QG	TIME SEC.	DELTA P DIV	P2 DIV	R OHMS	TC DEG. F	DMV MV	GMV MV	K
118	347.88	0.000	0.000	130.0	160.0	2080.	76.5	1.00	5.00	1
119	241.93	0.050	62.40	191.0	227.0	3150.	76.7	2.50	5.00	1
122	180.04	0.050	63.90	181.0	220.0	3400.	76.7	2.50	5.00	1
126	137.12	0.050	48.30	204.0	101.0	3760.	76.3	2.50	12.5	1
130	103.05	0.100	78.30	210.0	105.0	4220.	76.3	2.50	12.5	1
134	53.909	0.200	86.50	194.0	119.0	5450.	75.1	2.50	12.5	1
137	26.015	0.200	72.30	186.0	119.0	6450.	74.7	2.50	12.5	1
143	14.744	0.200	75.40	160.0	110.0	7050.	74.7	2.50	12.5	1
144	5.8705	0.200	70.80	145.0	106.0	8250.	74.4	2.50	12.5	1
148	3.4788	0.200	64.60	144.0	105.0	9150.	74.0	2.50	12.5	1
150	0.0000	0.200	43.20	188.0	99.00	13700.	72.8	2.50	12.5	1
154	0.0000	0.300	63.30	177.0	178.0	22000.	71.9	2.50	5.00	1

OUTPUT DATA

CORE S1 F2 SECOND DRAINAGE

IDENT	WATER SAT PERCENT	REL. GAS PERM	REL. WATER PERM	MEAN PRES ATM	FG	FD
118	65.93	.0000	.3941	3.492	.0000	.0000
119	47.26	.0892	.0744	5.401	.9835	.9835
122	44.47	.0949	.0584	5.235	.9878	.9878
126	41.18	.0998	.0397	5.839	.9921	.9921
130	37.56	.1161	.0289	6.017	.9950	.9950
134	30.96	.2143	.0166	6.372	.9984	.9984
137	27.16	.2696	.0084	6.314	.9993	.9993
143	25.30	.3259	.0055	5.822	.9996	.9996
144	22.38	.3992	.0024	5.579	.9998	.9998
148	20.68	.4432	.0014	5.538	.9999	.9999
150	15.15	.4953	.0000	5.655	1.0000	1.0000
154	10.47	.6540	.0000	4.641	1.0000	1.0000

TABLE VII (Continued)

```
INPUT DATA
CORE S1 F2   SECOND IMBIBITION            4/28/64

       D          X        PB    PS        BR        TBR       BK                B        RT
      CM         CM     MM HG   PSI       OHMS     DEG. F     MD                      DEG. F

   2.522   2.6416     728.7      20.0    1315.      71.0     154.0   -1.25350   76.0

  N      QW         QG         TIME  DELTA P   P2          R        TC       DMV       GMV     K
        CC/HR                  SEC.    DIV     DIV       OHMS     DEG. F    MV        MV

158   3.7488     0.200      54.30   156.0   188.0  12900.     70.8     2.50      5.00    1
162   5.8705     0.200      60.30   157.0   191.0   8100.     69.8     2.50      5.00    1
164   14.744     0.100      46.40   136.0   176.0   6350.     70.8     2.50      5.00    1
167   53.909     0.100      66.20   124.0   171.0   5400.     71.1     2.50      5.00    1
171   81.255     0.050      56.30   111.0   164.0   4360.     72.4     2.50      5.00    1
174   103.05     250.0      14.70   186.0   161.0   3700.     73.0     1.00      5.00    0
177   180.04     50.00      32.70   124.0   160.0   2500.     74.5     1.00      5.00    0
183   241.93     3.000      12.50   133.0   93.00   2190.     74.7     1.00      5.00    0
186   347.78     0.000      0.000   127.0   105.0   2030.     74.5     1.00      5.00    0


OUTPUT DATA

CORE S1 F2   SECOND IMBIBITION            4/28/64
IDENT    WATER SAT      REL.        REL.      MEAN PRES           FG
          PERCENT   GAS PERM  WATER PERM      ATM                                 FD
   158      16.20      .5761      .0015       4.619            .9999            .9999
   162      23.71      .5085      .0024       4.667            .9999            .9999
   164      28.52      .4140      .0068       4.313            .9996            .9996
   167      32.37      .3301      .0274       4.158            .9984            .9984
   171      37.92      .2278      .0454       3.970            .9962            .9962
   174      42.99      .2489      .0853       3.664            .9935            .9935
   177      57.97      .0329      .2194       3.471            .8857            .8857
   183      64.31      .0050      .2741       2.591            .4849            .4849
   186      68.45      .0000      .4138       2.735            .0000            .0000
```

TABLE VII (Continued)

```
INPUT DATA
CORE S1 F2   THIRD DRAINAGE              4/28/64

     D          X        PB    PS       BR        TBR       BK              B        RT
    CM         CM     MM HG   PSI      OHMS     DEG. F     MD                     DEG. F

   2.522   2.6416    725.5      0.0     1315.      71.0     154.0   -1.25350   77.0

  N      QW        QG         TIME  DELTA P   P2        R        TC      DMV       GMV    K
       CC/HR                  SEC.    DIV     DIV      OHMS    DEG. F    MV        MV

187   347.78    0.000      0.000   123.0    105.0   2030.     74.5     1.00      5.00   0
188   241.93    50.00      47.70   108.0    146.0   2210.     75.5     1.00      5.00   0
192   180.04    50.00      47.90   85.00    142.0   2300.     75.5     1.00      5.00   0
195   137.12    100.0      21.20   140.0    155.0   2800.     76.3     1.00      5.00   0
199   103.05    250.0      14.60   103.0    182.0   3720.     76.3     2.50      5.00   0
202   81.255    0.020      26.50   126.0    196.0   4230.     76.3     2.50      5.00   1
204   53.909    0.100      80.50   168.0    214.0   5100.     75.4     2.50      5.00   1
208   26.015    0.100      63.10   185.0    95.00   6250.     74.5     2.50      12.5   1
214   5.8705    0.100      47.70   190.0    91.00   8850.     73.7     2.50      12.5   1
218   3.4788    0.100      42.80   193.0    93.00   9800.     73.7     2.50      12.5   1
221   0.0000    0.100      37.70   195.0    137.0  18400.     72.7     2.50      5.00   1


OUTPUT DATA

CORE S1 F2   THIRD DRAINAGE                 4/28/64
IDENT    WATER SAT    REL.       REL.     MEAN PRES         FG
          PERCENT   GAS PERM WATER PERM     ATM                           FD
  187      68.45      .0000     .4272       2.724         .0000          .0000
  188      63.39      .0282     .3341       3.232         .8112          .8112
  192      61.40      .0377     .3160       3.111         .8587          .8587
  195      52.10      .0976     .1446       3.446         .9714          .9714
  199      41.54      .1610     .0590       4.150         .9927          .9927
  202      37.49      .1509     .0380       4.505         .9950          .9950
  204      32.56      .1660     .0191       5.052         .9977          .9977
  208      27.91      .1765     .0085       5.491         .9990          .9990
  214      21.30      .2310     .0018       5.393         .9998          .9998
  218      19.63      .2494     .0011       5.482         .9999          .9999
  221      11.99      .3633     .0000       4.212        1.0000         1.0000
```

TABLE VII (Continued)

```
INPUT DATA
CORE S1 F2   THIRD IMBIBITION             4/28/64

    D          X        PB    PS         BR        TBR       BK               B        RT
   CM         CM     MM HG   PSI       OHMS     DEG. F     MD                       DEG. F

  2.522  2.6416    724.7     20.0    1315.      71.0    154.0  -1.25350   77.0

 N      QW        QG         TIME  DELTA P   P2       R       T C     DMV     GMV    K
       CC/HR                 SEC.    DIV    DIV     OHMS   DEG. F    MV      MV

223   3.4788    0.100     37.40   146.0   159.0   9500.    71.8    2.50    5.00   1
231   14.744    0.100     48.40   134.0   160.0   7380.    71.8    2.50    5.00   1
234   26.015    0.100     65.60   119.0   152.0   6280.    72.3    2.50    5.00   1
237   53.909    0.100     96.10   110.0   144.0   4700.    73.0    2.50    5.00   1
241   81.255    0.050     64.90   114.0   143.0   3920.    73.3    2.50    5.00   1
244   103.05    0.050     82.10   125.0   148.0   3500.    73.7    2.50    5.00   1
246   137.12    0.030     62.20   111.0   155.0   3180.    74.0    2.50    5.00   1
249   180.04    0.020     64.20   110.0   155.0   2900.    74.0    2.50    5.00   1
254   241.93    100.0     74.70   100.0   141.0   2610.    74.7    2.50    5.00   0
256   241.93    10.00     34.00   148.0   151.0   2450.    74.2    1.00    2.50   0
261   241.93    0.000     0.000   142.0   144.0   2350.    74.2    1.00    2.50   0


OUTPUT DATA

CORE S1  F2  THIRD  IMBIBITION              4/28/64
IDENT    WATER SAT    REL.       REL.      MEAN PRES          FG
          PERCENT   GAS PERM  WATER PERM     ATM                             FD
  223      20.49      .4951      .0014       4.151          .9999            .9999
  231      25.06      .4243      .0068       4.078          .9996            .9996
  234      28.37      .3727      .0135       3.861          .9993            .9993
  237      35.52      .2885      .0302       3.688          .9980            .9980
  241      40.94      .2056      .0437       3.704          .9959            .9959
  244      44.65      .1426      .0503       3.851          .9932            .9932
  246      48.07      .1274      .0751       3.844          .9887            .9887
  249      51.73      .0828      .0995       3.836          .9774            .9774
  254      55.91      .0139      .1458       3.575          .8314            .8314
  256      59.07      .0063      .2479       2.398          .5716            .5716
  261      61.07      .0000      .2584       2.334          .0000            .0000
```

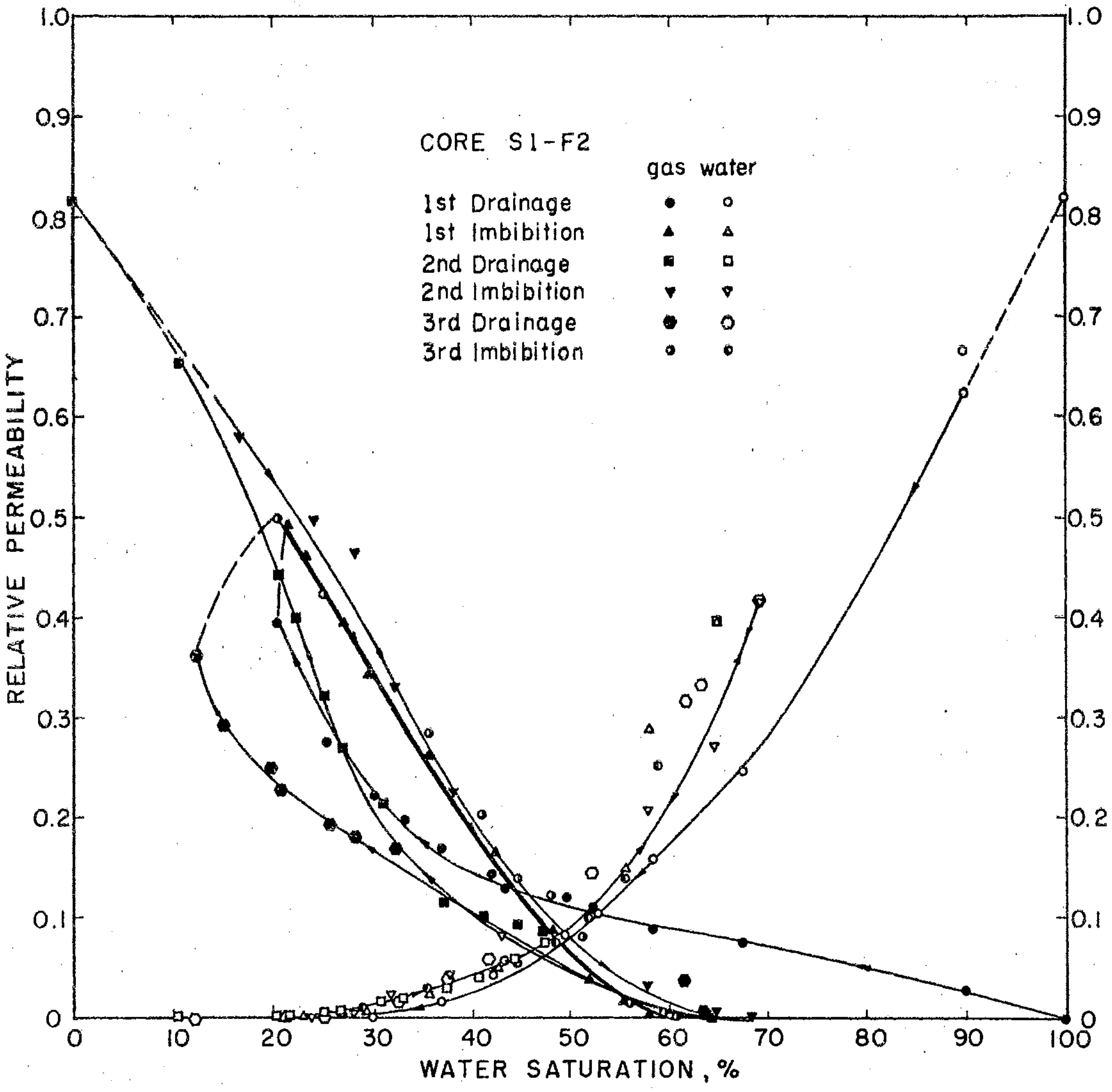

Figure 12. Relative Permeability, Core S1-F2

core Art 7AH and core S1-F2, it is observed that a natural sandstone can be simulated by artificial cementation of sand with Portland cement.

CHAPTER VIII

CONCLUSIONS

The utilization of virgin aquifers for natural gas storage is increasing steadily with a justifiable degree of success. A majority of these ventures have been undertaken without adequate prior knowledge of the aquifer's susceptibility for storing or expelling natural gas. Also, many additional problems have arisen in underground storage because of the complexity of two-phase flow mechanics augmented by improper injection-withdrawal programs. If a study of the two-phase flow characteristics of the formation and a thorough model study were made prior to initial injection of gas in the aquifer, many problems could be eliminated. Thus, the aquifer's storage and withdrawal capabilities could reach its maximum potential. This would bestow the natural gas company with an economical storage facility.

The material derived from this investigation presented information in which several conclusions may be drawn. The model developed in this investigation simulated a water-bearing sandstone, or aquifer, in which cyclic flow of gas and water would occur.

The research investigation by this author led to the following conclusions for models simulating aquifers:

1. A synthesized rock constructed during this investigation, Art 7AH, did have characteristics similar to the Lower Franconia Formation which is currently being used as an underground storage facility. The similarity can be seen by comparing Figure 9 with Figure 10 and Figure 11 with Figure 12.

2. A porous media was made which was susceptible to complex instrumentation, even more than was necessary during this investigation.

3. An electrode was developed which was suitable for measuring the changes in electrical resistances as saturation changes and yet causing a minimum amount of disturbances in the flow pattern.

4. A D. C. power source cannot be used in the determination of electrical resistances across an electrode in a model because of electrolysis.

5. A model was developed which had natural rock characteristics, yet susceptible to instrumentation, for the study of saturation distributions in an aquifer.

6. Models constructed by the method presented herein would give reliable results on aquifer or secondary recovery performance.

CHAPTER IX

RECOMMENDATIONS FOR FUTURE STUDY

Many avenues are available for future study in the area of model studies simulating aquifers or oil reservoirs. These avenues would not be limited only to the construction of fluid models since many theoretical aspects could be made toward the perfection of producing artificial porous media. This author feels that with considerable experimental investigation, it would be possible to predict porosity and permeability of any mixture if given sand grain size and weight per cent of sand and cement. It is known at this time that permeability decreases as weight per cent cement increases. Porosity is dependent on sand grain sizes, rate of pouring, and height of fall from the "particle distributor" to the model. With a thorough investigation of all these parameters, one should be able to predict the properties of artificially prepared porous media.

One of the most undesirable occurrences during the construction period was the "shrinking" of the sandstone during the consolidation period. This "shrinking" caused a gap to occur between the plexiglass and the sandstone, resulting in a sufficient amount of channeling to give unreliable results. This problem was solved by the injection of the plexiglass cement as reported earlier. The injection of the cement made visual observation impossible which is undesirable for demonstration purposes. A possible solution to this problem would be to coat the sides of the container with a clear cement prior to pouring.

The model constructed in this investigation was equipped with electrodes for the study of saturation distributions. However, the procedure for producing this artificial porous media and pouring it does not limit the use of only electrodes as instrumentation. It would be very possible to construct a model that included electrodes, thermocouples, and pressure pick-ups for the complete development of underground storage facilities or secondary recovery predictions.

The ultimate objective in model studies would be the adequate description of all phases of underground storage facilities under any given conditions. The accomplishment of this objective would permit economical storage facilities with a minimum amount of expenditure.

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