A STUDY OF RESERVOIR CORE SAMPLE SATURATION DETERMINATION

By

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CHAPTER I

INTRODUCTION

Accurate predictions of behavior of flowing fluids in underground porous media are difficult. However, when considering the importance of reservoir production characteristics, all possible efforts should be made to obtain an accurate description of two phase fluid behavior within the rocks. One method of obtaining the required information necessary in foretelling the fluid's behavior in reservoirs is by testing reservoir samples. Many of these fundamental properties have as a common parameter, fluid saturation. To establish a valid relationship between the discussed variable and fluid saturation, it is necessary that both of the functions be accurately defined; otherwise, any predictions made using these characteristic values will be in error. Therefore, the methods of determining fluid saturation must be improved in order to obtain an accurate relationship between the reservoir behavior variable and fluid saturation.

Under this research, it is proposed to review the literature for saturation determination, and to propose and experimentally verify any new techniques for saturation determination. After surveying the literature, it was concluded that the capacitance method shows the most potential for being developed into a reliable means of determining saturation.

An improved capacitance method of determining saturation was developed using theoretical assertions. Experimental results substantiated the theoretical developments and the improved capacitance method.

CHAPTER II

LITERATURE SURVEY

A thorough study of the published literature indicated that there were two broad classifications of techniques, direct and indirect, currently being utilized for the determination of saturation in porous media. First, direct methods of saturation determination are very limited in application and consist of the gravimetric method and the volumetric method. In the gravimetric method saturation is determined by weighing the core sample; whereas, in the volumetric method, saturation is determined by measuring the volume of fluid added to or taken from the core sample. These direct methods are of interest only as a starting point, since they cannot be used under normal test conditions. Second, indirect methods rely upon the observation of changes in a given phenomenon, which is a definable function of the fluid saturation. As the saturation in the core sample changes there is an observable and related change in the given phenomenon.

Since the direct methods are limited in their use, the literature survey was confined to indirect techniques. The indirect techniques are classified as follows:

Radiational

A. X-Ray Absorption
B. Gamma-Ray Absorption and Neutron Bombardment
C. Radioactive Tracers

Electrical

A. Resonant Radio Frequency
B. Resonant Audio Frequency
C. Magnetic Induction
D. Resistance
E. Capacitance

The headings in the above outline are descriptive of the basic principles or phenomena behind each particular method of saturation determination. There is some overlapping in the areas mentioned; however, each topic is distinct enough to merit its own discussion.

Radiational

A. X-Ray Absorption. One of the first applications of x-ray techniques to determine saturation is described by Boyer, Morgan and Muskat (2). The technique which they used depended upon the addition to the oil of a soluable tracer material that is the primary absorber of the x-rays incident upon the core. By using a comparator, the investigators could determine the flowing oil saturation of the core without removing the core from its test cell. It was found that a high concentration of the tracer was needed to produce good results. Addition of the tracer, iodobenzene, appeared to make little change in the general physical characteristics of the oil. The data and results presented by Boyer, Morgan and

Muskat indicated the potentialities of the x-ray methods.

According to Morgan, McDowell and Doty (15) the technique used by Boyer and his colleagues was capable of yielding accurate results; but, the apparatus used was not especially convenient for determining the fluid distribution along the length of a core. Morgan and his colleagues further stated that with Boyer's technique it was necessary to make a point-by-point survey of the material under investigation. Therefore, the possibility existed that sections of the core, having a variable or unusual saturation distribution, would go unobserved. Morgan and co-workers made several modifications and improvements to the work started by Boyer. The improvements consisted of a method and apparatus for recording continuously and automatically the intensity of the x-ray beam transmitted by the core. Consequently, these investigators also developed a method of determining the variation of saturation at a given section of the core with time. Saturation distribution was determined by scanning the core when driving it in synchronism with the recorder. In using this method, as well as the one discussed by Boyer, the core did not have to be weighed, and errors due to gas bubbles expanding or loss of liquid, were avoided.

Further refinement is made of Boyer's work by Laird and Putnam (12), who discussed the theory of x-ray absorption and predicted that it would be possible to extend the x-ray technique to saturation determination for three-fluid components. In a later work Laird and Putnam (11) developed the theory of three component saturation determination by x-ray techniques. The x-ray techniques for saturation determination depended upon the absorption properties of the fluid(s) contained in the core sample. Because of this fact, Laird and Putnam had to limit the three component saturation determination to three specific types of fluids 1) gas, 2) brine, 3) oil.

In the area of x-ray absorption-vs-saturation, the theory is held by some that the relationship is not necessarily a single valued function of saturation, and may be subject to a hystersis effect. However, Geffen and Gladfelter (7) support with experimental evidence, the theory that x-ray absorption-vs-saturation is single-valued regardless of the saturation history.

B. Gamma Ray Absorption and Neutron Bombardment. Snell (22) acknowledged the use of x-ray and gamma-ray techniques in saturation determination. However, according to this author, these techniques were applicable only to the oil phase of the fluid. Also he felt that the absorption methods could not be used effectively in determining gas saturation. He then supported his theory with the fact that oil and water have different absorption characteristics when using either the x-ray or gamma-ray technique of saturation determination.

In view of the above, the investigator suggested the use of neutron bombardment to determine gas phase saturation. Snell described the reaction of oil and water to neutron bombardment as being identical, thus making it possible to obtain a direct plot of gas saturation vs. thermal neutron count. The combined reaction of oil and water to neutron bombardment can be determined because their reactions are identical.

Brunner and Mardock (3), in their paper on a neutron method of measuring saturation, pointed out that the neutron method can be used in measuring oil saturation. This method permitted local saturation to be measured in a core enclosed in a steel pressure vessel, without interrupting the flow. Basis for this method can be found in the fact that there was a very penetrating radiation in a beam of neutrons, and its scattering by substances containing hydrogen, such as oil, was qualitatively different from that caused by other materials. The neutron method described by Brunner and Mardock seemed to be particularly useful in response to local saturation.

C. Radioactive Tracers. Josendal, Sandiford, and Wilson (10), discussed the use of radioactive tracers in determining saturation in a core sample. Cesium 134 Chloride was used as the water phase tracer and Iodo 131 benzene as the oil phase tracer. It was their opinion that the radioactive tracer method has many advantages over the x-ray absorption, the gamma-ray absorption, and the neutron diffraction. The radioactive tracer method required less equipment than the x-ray method. In addition to this, regulation of radiation was not required in the radioactive tracer method. Another advantage of the radioactive tracer method was that only a slight amount of tracer was required whereas in the x-ray method 20 per cent (by weight) absorber was required. Josendal and his colleagues pointed out a possible disadvantage of the radioactivity method, i.e., a disproportionate amount of activity came from the portion of the core nearest to the counter. On the other hand, x-ray gave a true average saturation in the region covered by the beam. With the radioactive method there is a similar counting problem as in the x-ray method.

Electrical

A. Resonant Radio Frequency. Snell (22, 23) discussed the use of resonant radio frequency method for the measurement of conductive liquid saturation in a porous medium. This investigator used in his radio frequency study a series-resonant RCL circuit, which was tuned to its resonant frequency at 100 per cent water saturation in the test core. The actual testing device was a pair of coils mounted diametrically opposite each other across the test core. This resonant radio frequency method depended upon the small change in resonant frequency as the coil impedance changed with a change in the water saturation. It was of interest to note that the variable was found in the inductive branch of the RCL circuit; i.e., the resistance and the capacitance remained constant for all practical purposes, and the inductance, being the variable, changed with the change in the core sample saturation. This change in the inductance affected the resonance of the RCL circuit. A circuit response method was used instead of measuring changes in resonant frequency. Also, Snell used reference cells or cores which eliminated the necessity of dismantling the test core in order to determine the amount of water and/or gas contained under a given set of conditions. The main advantage presented by this technique was the elimination of the handling of bulk radioactive tracer fluids. Another advantage was that it can be used in ordinary laboratories.

B. Resonant Audio Frequency. Gupta and Hills (8) presented a method for determining the conductivity of solutions by utilizing audio frequency levels. Their technique employed a transformer bridge consisting of two toroidal transformers coupled together by a closed loop. This loop consisting of the test fluid was placed in a nonconductive container. By comparing the conductance of the test fluid with a standard conductance, it was possible to determine the value of conductance of the test fluid.

Fatt (6) explored the use of Gupta and Hills' idea in core sample saturation determination. For the test fluid he substituted a reservoir core sample mounted in plastic and as the saturation in the test core changed, the conductance of the fluid loop changed. Any change in the conductance was detected and was related to the saturation of the core.

C. Magnetic Induction. Magnetic susceptibility method was presented by Whalem (26) and was based on the premise that one of the fluid phases contained within a porous material must be sufficiently greater than that of the remaining phases. The fluid content of the material was determined by an induction measurement. Induction measurement was accomplished by making the core sample a part of the transformer's secondary field, and by measuring the induced voltage in the core sample. With this arrangement the core sample and the fluids which it contained were a portion of the magnetic flux path. Since most of the fluids used in core sample testing had a low magnetic susceptibility, it was necessary to use a magnetic tracer in one of the fluid phases. In his work Whalem found that it was necessary to use 20 per cent by weight of Cobaltous Chloride in the aqueous phase. He also pointed out that this method did not require the elaborate instrumentation and calibration techniques that many of the other saturation determination methods required. It was further pointed out by Whalem that the equipment involved was simple to operate and to maintain.

D. Resistance. The resistance method of saturation determination is one of the most frequently used methods because the equipment required is easy to use and is comparatively inexpensive.

Blake (1) discussed the use of tuned resonant circuit utilizing a variable resistance to determine solution concentration and to control flow through a pipe system. From this early application of resistance, many new ideas and modifications have appeared.

De Witte (5) in his paper, discussed work conducted by several people in the area of resistivity and fluid contents. He attempted to present a theory of current conduction in porous materials, which would lead to general formulas applicable in all cases. De Witte also indicated some of the disadvantages of various other theories of current conduction in porous materials. The following factors were considered to be necessary for determining accurate resistivity measurements: 1) the resistivity of interstitial water, 2) the formation factor, 3) water saturation, and 4) conductive solids present in the rock.

Wyllie and Spangler (29) discussed the application of resistivity measurements to fluid flow in porous media. Most of their work was directed toward deriving one of the major parameters in the Kozeny equation. In a section concerned with electrical properties of partially saturated porous media, Wyllie and Spangler pointed out that the resistivity index (a ratio of the apparent formation factor to the formation factor at complete saturation) was equal to a negative exponential function of the wetting phase saturation. The negative exponential function appeared to be independent of the absolute value of saturation. In a porous medium the value of this function depended upon the type of fluid distribution at any saturation.

In his paper Rust (21) covered the area of types and configurations in electrode mounting. Rust discussed the techniques and equipment involved in comparing the two and four electrode mounting methods. In the two electrode method, the electrodes mounted on the ends of the core were used for both passing a current through the core sample and for measuring the potential drop across the core sample. In the four electrode mounting method, two end mounted electrodes were used to pass a current through the core sample; while two electrodes along the sides of the core, were used to measure the potential drop. The author suggested that, in the two electrode method, great care should be taken to insure good electrical contact between the core and the end electrodes. Rust stated that good contact was not as important with the four electrode method as with the two electrode method because separate electrodes were used to measure the potential difference across a portion of the sample. Rust concluded that both the two and four electrode mounting methods gave reliable results. He suggested that both methods be used in saturation determination in order to check one measurement against the other.

Pierce and Lowe (19) discussed static saturation determination. They presented a means of obtaining good electrical contact between the core sample and the two end electrodes using the two electrode method. It is possible that the electrical contact could be improved by painting the ends of the test core with conductive silver paint (21). However, Pierce and Lowe suggested that mercury be used for the end electrodes, thus eliminating the necessity of using silver paint. The experimental work of Pierce and Lowe indicated that mercury provides the electrical contact needed.

Odeh (17) had problems in obtaining repeatable results using the electrical resistance method of saturation determination. The difficulty was created by the method used in attaching the electrodes to the core. Therefore, Odeh's solution to this electrode mounting problem was to scratch a small recess into the surface of the core and then to fill this recess with diatomaceous earth. He then placed the electrode plates, with leads soldered to them, in the filled recessions in direct contact with the diatomaceous earth. After which, the test core was mounted in lucite by compression molding. Odeh reported that this method of electrode mounting resulted in reliable and repeatable resistivity readings as a function of saturation.

Patnode and Wyllie (18) found that conductive solids in reservoir rocks affected the determination of the formation factor. These investigators demonstrated that the presence of conductive solids (such as wet clay), in a reservoir core sample had a very definite effect on the conductivity of the core sample. Results of any effort to determine saturation by the resistance method were affected by the presence of conductive solids. Presence of conductive solids also decreased the electrical resistance of the core, and indicated that there was more conductive fluid present during a saturation test than was actually there.

Another aspect to be considered when using the resistance method was disclosed by Holmes (9) as he discussed the effects of current frequency and conduction of current over the surface of the core. Holmes indicated that the conduction of electrical current over the core surface materially affected the value of resistance measured on cores partially saturated with brine solution. Surface conduction phenomena resulted from the presence of moisture on the core surface and effected a short between the electrodes. This short between the electrodes became more effective as the core became less saturated. Holmes also observed that surface conductance always appreciably affected the measured value of resistance of the core in the range of water saturation below 40 per cent.

Licastro and Keller (14) discussed another aspect which influenced the results of resistance saturation determination, namely, the dynamics of the geometry involved in the resistance method of determining saturation. They indicated that above the critical water saturation for water wet cores, the replacement of water by gas reduced the cross section of the material available to conduct current and at the same time increased the distance the electrical current had to travel. The result of this replacement was a relative uniform increase in resistivity as water saturation decreased. However, Licastro and Keller pointed out that below the critical water saturation an additional factor had to be considered. The increasing unavailability of isolated water deposits which provided a path for electrical current, caused the resistance to increase at a faster rate. On the other hand, for a non-water wet core, these investigators showed that the removal of a small amount of water from the connecting pores caused the resistance to increase rapidly. The increase continued until the critical water saturation was reached. Below the critical saturation the remaining water was contained in the larger pores. At this point, further reduction of water primarily affected the core's cross section, and only to a minor extent did it affect its electrical continuity.

Pressure applied to the core was shown by Wyble (28) to have an affect on several test core properties, one of these properties being conductivity. The conductivity was shown to decrease asymptotically over a pressure range of 0 to 3,500 psi. Wyble found that for most core samples the maximum deviation of the ratio of conductivity at a given pressure to the conductivity at zero pressure was less than 3 per cent.

E. Capacitance. Reilley (20) discussed all three of the electrical phenomena, resistance-capacitance-inductance, in relation to high frequency methods of measurement. Since two of these methods, resistance-inductance, have been previously discussed, Reilley's work will be considered only in respect to capacitance.

Reilley developed some of the theoretical aspects of using a variable capacitance (parallel plates) as a measuring method. According to the theoretical calculation of capacitance with parallel plates, doubling the area of the capacitor plates will double the capacitance response. In addition, large changes in capacitance were obtained by decreasing the thickness of the dielectric material between the plates and the solution. Capacitance can also be changed by increasing the path length through the solution.

Nielsen and Peffer (16) discussed the use of a variable capacitor in conjunction with an oscillometer. The saturation tests were conducted on artificial cores made of glass bead packs, using standard cells as a reference for the test cell. Their system was sensitive enough to differentiate between the interface of the interstitial fluid and injected fluid in the test cell. The results of their experiments indicated that the method of employing an oscillometer shows great promise in saturation determination. Nielsen and Peffer suggested that in order to get the best results, care should be taken to assure that the standard cell is at the same temperature as the test cell; also, the plates should be insulated. In addition they recommended that the plates comprise 25 per cent of the circumference of the test cell.

The following is a summary of the literature survey. Radiation methods of determining core sample saturation consist of two basic types, one in which the radiation source is external to the core, and the other in which the radiation source is internal to the test core. The external source methods are the x-ray, the gamma-ray, and the neutron methods. X-ray and gamma-ray methods are generally applicable to oil saturation determination and the neutron method is most effectively used in gas saturation determination. External radiation source methods are confronted with the problem of extensive instrument calibrations and with the necessity of frequently introducing absorption tracers into the fluid system.

Internal radiation source techniques require the use of radioactive tracers. In this method the radiation source (radioactive isotope) was introduced into one of the flowing phases of fluid which was to be passed through the test core. The resulting radiation was picked up by external instruments and the count was proportional to the saturation of the labeled (activated) fluid. With the radioactive tracer method the instrumentation and calibration were reduced; but, there was a definite problem in equipment contamination and in handling bulk radioactive materials.

In regard to the electrical methods of determining reservoir core sample saturation, it can be said that these methods consist largely of the use of inductance, resistance, or capacitance as indicators of the saturation variation within the core sample. Variation of these methods consist of combining two or more of the above mentioned methods into a tuned circuit whose resonant frequency is sensitive to the change in the core sample saturation. Problems encountered in the electrical methods of saturation determination are in the areas of electrode mounting, electrode spacing, temperature control of reference cells and the use of magnetic tracers. Also, pressure effects, electrical contact between the test core and the electrodes, and the presence of conductive solids, present problems in electrical methods of saturation determination.

CHAPTER III

STATEMENT OF THE PROBLEM

Many problems exist in determination of fluid saturation as exhibited in the literature reviewed in Chapter II. For testing purposes, equipment required should be relatively easy to operate and maintain. Materials involved should be easily acquired and stored, and should be safe for laboratory personnel to handle. Also, techniques employed should be easily followed. In general, the method used should provide reliable and reproducible results, and must be indirect because the flowing system is under pressure.

Requirements established above automatically eliminate several testing methods proposed by many authorities, including the gravimetric and volumetric methods. Also included among those testing techniques eliminated are radiation methods because of the danger of radioactive materials used and because of the complex equipment necessary. This leaves only the broad category of the electrical methods.

After reviewing literature in the area of determination of the fluid saturation in porous media, it was concluded that the variable capacitance method showed the most promise for being developed into a reliable method of determining saturation. It is the purpose and specific problem of this study to modify the existing equations for calculating capacitance using parallel plates so that they can be applied to calculating capacitance using curved plates. Furthermore, the purpose is to experimentally establish that the capacitance method gives reliable and reproducible results for determining fluid saturation.

CHAPTER IV

THEORETICAL DEVELOPMENTS AND EXPERIMENTAL TECHNIQUES

The theoretical equation of capacitance for a capacitor having parallel plates is as follows:

$$C = \frac{KA \times 10^{-11}}{36 \Pi d} f . \tag{1}$$

In order to calculate the capacitance of a capacitor with curved plates, it becomes necessary to modify Equation (1). Curvature of the Plates is such that the plates would be positioned on the surface of a cylinder. The difference in behavior of the curved plates and the parallel plates will be defined as "end effects" and it is assumed that the circular area of the plates is an indication of the "end effects". Using this basic assumption together with Figure 1, several geometrical implications can be derived.

The core volume included between the plates (PV) is

$$PV = W \times F \tag{2}$$

where W equals the plate width.

$$F = \Pi r^2 - 2(E-J), \tag{3}$$

$$E = \Pi r^2 \times \frac{(180 - H)}{360}, \tag{4}$$

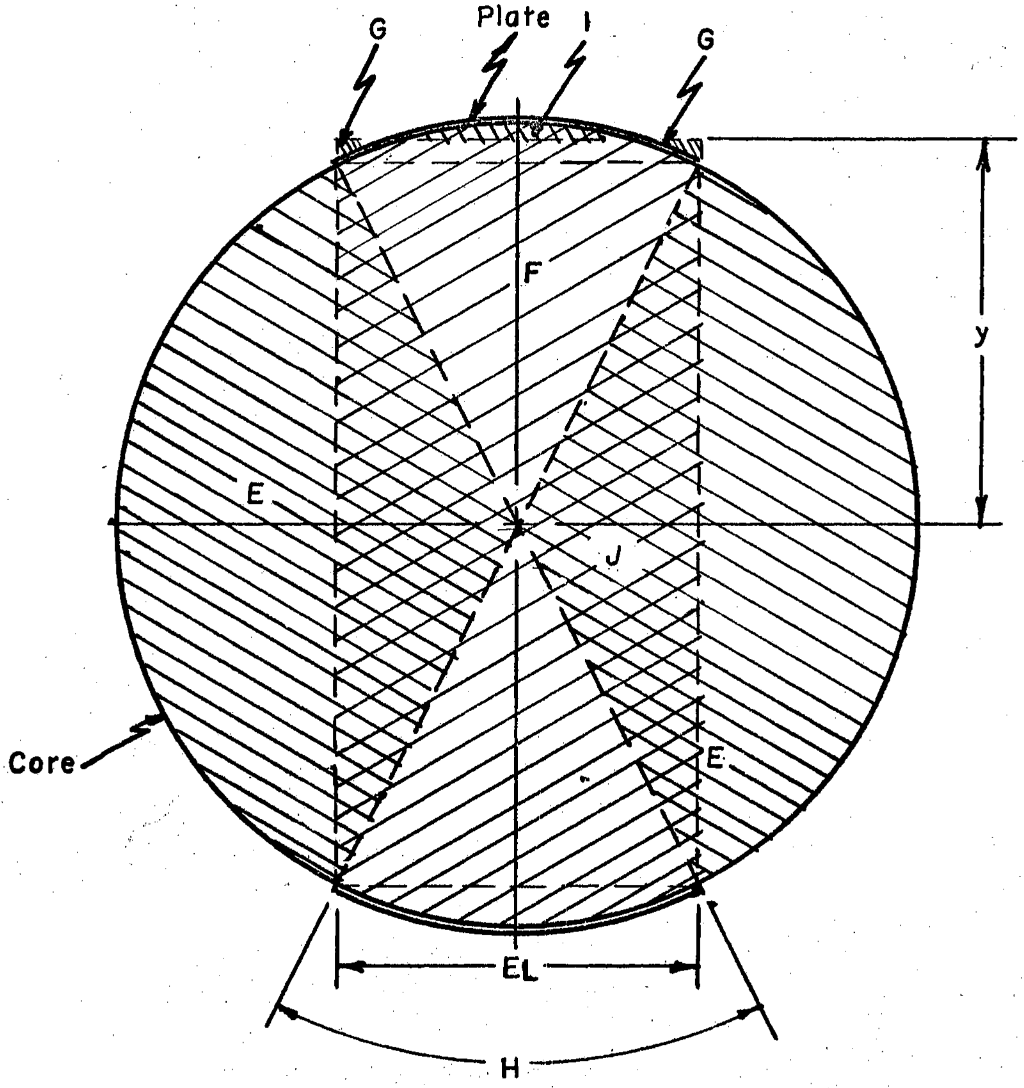

Figure 1. Cross Section of Core and Plates

and

$$J = \frac{1}{2} \left[D \cos \frac{H}{2} \times \frac{1}{2} D \sin \frac{H}{2} \right]. \qquad (5)$$

Then

$$F = \pi \frac{D^2}{4} - \frac{D^2}{4} \left[\pi \left(1 - \frac{H}{180}\right) - \sin H \right] \qquad (6)$$

where

$$\sin H = 2 \sin \frac{H}{2} \cos \frac{H}{2} . \qquad (7)$$

Thus,

$$PV = \frac{D^2 W}{4} \left[\frac{\pi H}{180} + \sin H \right] . \qquad (8)$$

A problem in using curved plates is to determine the distance (d) between the plates. Distance (d) is found by dividing the core area (F) between the plates by the effective length (EL) of the plates. From this division the resultant length is 2y. Now the rectangular area (EL x 2y) is equal to the core area (F) between the plates and the length 2y can be substituted for distance (d) between the plates. Combining Equations (2) and (8) results in:

$$F = \frac{D^2}{4} \left[\frac{\pi H}{180} + \sin H \right] \qquad (9)$$

then

$$EL = D \sin \frac{H}{2} . \qquad (10)$$

Where

$$F = EL \times 2y, \tag{11}$$

thus

$$d = 2y = \frac{D \left[\frac{\pi H}{180} + \sin H \right]}{4 \sin \frac{H}{2}} . \tag{12}$$

Using Equations (10) and (12) another equation to calculate the theoretical capacitance of a capacitor with curved plates may be determined by substituting for A and d in Equation (1).

Thus,

$$CC = \frac{KW \sin^2 \frac{H}{2} \times 10^{-11} f}{9\pi \left(\sin H + \frac{\pi H}{180} \right)}, \tag{13}$$

where

$$A = W \times EL = WD \sin \frac{H}{2} . \tag{14}$$

The above equations suggest a means for determining an optimum plate design. The main objective in the design of the plates is to make them as sensitive as possible to the saturation change within the test core. It becomes apparent that the circular area of the plates is the deciding factor in regard to the sensitivity of the plates.

As the included angle of the plates is increased, the "end effects" become more pronounced. Thus, the plates become less sensitive to the saturation change. On the other hand, as the circular length (with constant W) of the plates is reduced the "end effects" become less pronounced and therefore the plates are more sensitive to the saturation change. Obviously, there is a practical limit to either increasing or decreasing the circular length of the plates.

An optimum plate length was suggested by Nielsen and Peffer (16) when they recommended that the plates should cover 25 per cent of the circumference of the test cell. A circular plate covering 25 per cent of the circumference corresponds to the 90 degree central plate angle. With a central plate angle exceeding 90 degrees there would be a definite reduction in plate sensitivity due to the increase in the circular length of the plates.

Another item of interest at this point is the "plate volume" as described by Equation (8). The "plate volume" is also an indication of the effectiveness of the plate design. It can be seen that the "plate volume" also increases or decreases as the central angle H is increased or decreased. However, the change in the "plate volume" is not a linear function as is the circular area (CA) of the plates.

$$CA = \Pi \; DW \; \frac{H}{360} \qquad (15)$$

In answering the question of the optimum central angle there are two factors involved as previously discussed: 1) maximum "plate volume", 2) minimum circular area.

These factors may be related by use of the following ratio:

$$RA = \frac{PV}{CA} \cdot \qquad (16)$$

The objective then is to determine the central plate angle H which will maximize Equation (16). By substituting for PV and CA in Equation (9) the following results:

$$RA = \frac{D}{2} \div \frac{90D \sin H}{II\ H} . \qquad (17)$$

The ratio can be maximized by setting the first derivitive equal to zero as in the following:

$$\frac{d\ (RA)}{d\ \ (H)} = 0, \qquad (18)$$

then

$$\frac{90D}{II} \left[\frac{\cos H}{H} - \frac{\sin H}{H^2} \right] = 0 \text{ results.} \qquad (19)$$

By solving Equation (19) the following result is found:

$$H = \tan H. \qquad (20)$$

Equation (20) is precisely true only at zero degree central angle; physically this is impossible to obtain. It can be approached because the tangent of an angle 30 degrees or less is approximately equal to the angle, thus satisfying Equation (20) which suggests that best results may be obtained by using a central plate angle of 30 degrees or less. This is an indication that Nielsen and Peffer (16) may be in error in suggesting the use of curved capacitor plates with a central angle of 90 degrees.

The plots of Equations (8) and (15) are shown in Figure 2. The plot of Equation (13) is shown in Figure 3. Figure 3 also includes a plot of experimentally determined capacitance as a function of the central angle.

Data for the experimental capacitance curve was obtained by running a series of tests using distilled water as the dielectric between the plates. The plates were ½ inch wide and were mounted diametrically opposite each other inside a 1 inch diameter hole in a piece of lucite. Initially the central angle of the plates was 90 degrees; it was reduced in a series of steps by shortening the circular length of the plates approximately one tenth inch for each step. Then the measured capacitance for each unique central angle was recorded. Capacitances thus measured were corrected to 68° F. The calculated capacitance curve in Figure 3 was determined by calculating several points along the curve using a plate width of ½ inch and a dielectric constant of 80.

One of the desirable features of the capacitance methods is that it is not necessary to have direct contact with the item tested. Utilizing this idea, the first attempt of saturation determination was made using plates taped inside an aluminum test section sleeve which was a part of the core testing apparatus described by Woods (27). It was immediately noticed that the aluminum sleeve acted as a direct short between the plates. Considering this, a lucite test section

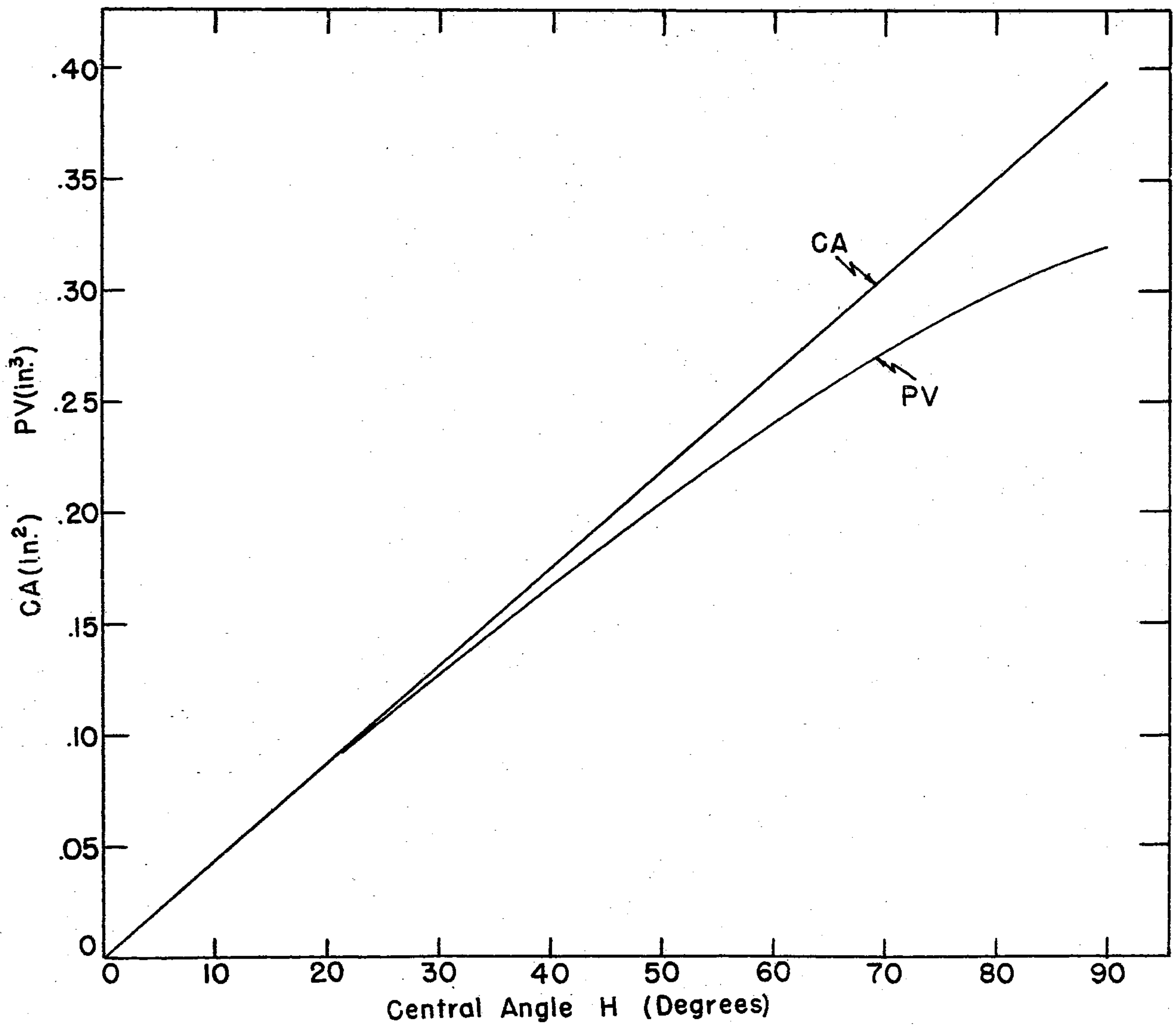

Figure 2. Plate Volume and Circular Plate Area

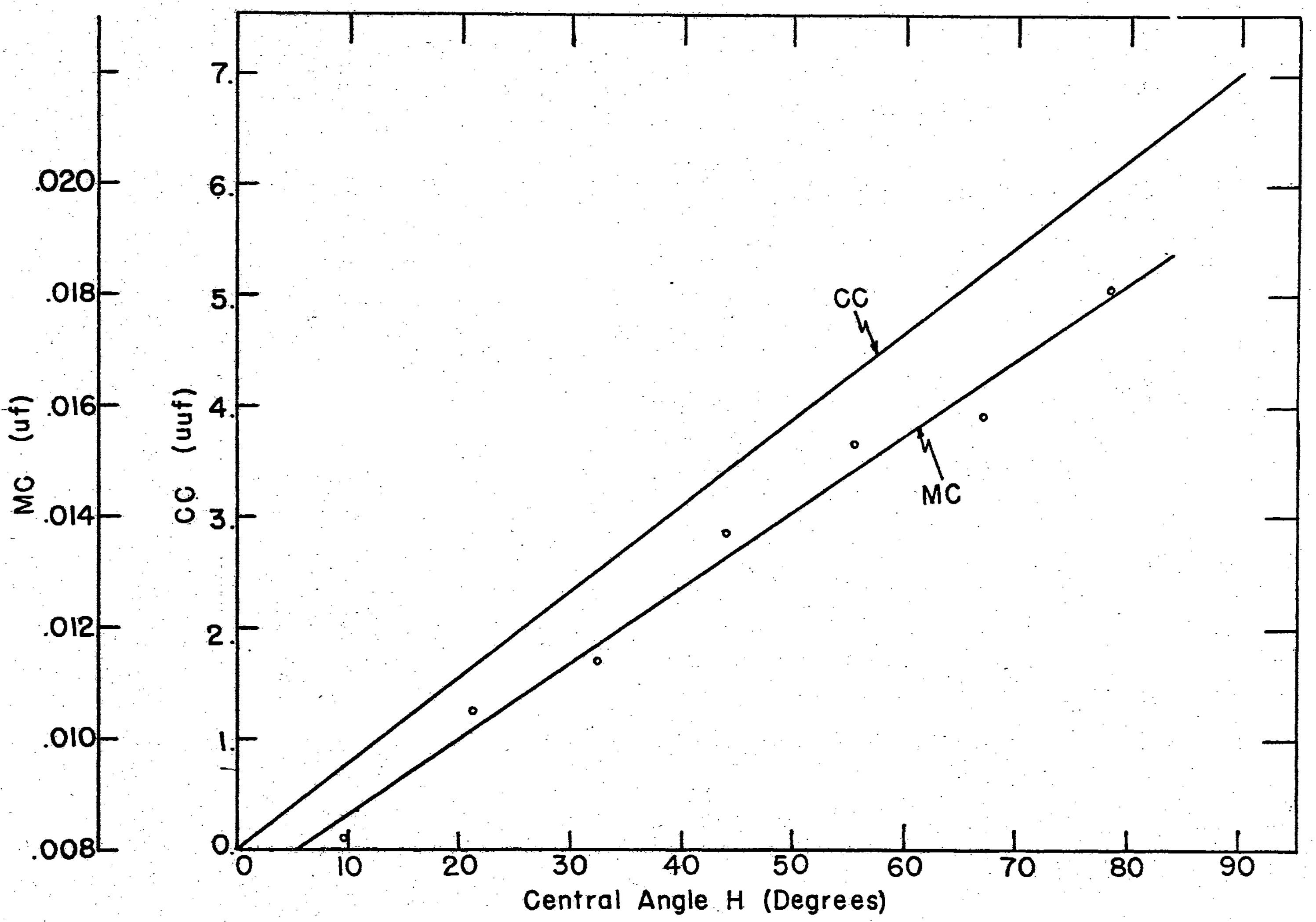

Figure 3. Calculated and Measured Capacitance

was designed and constructed with a 2.1 inch O. D. and a 1.7 inch I. D. for a working pressure of approximately 300 psig and is shown in Figure 4.

Also an attempt was made using plates mounted on spacers inside the lucite test section. Design of the spacers placed the plates as close to the test core as possible. Leads from the plates were passed through the wall of the test section by means of compression fittings; these leads consisted of approximately 18 inches of heavy coaxial cables with solid wire centers. Two problems resulted from this arrangement. First, the coaxial cables introduced large internal fixed capacitances making the system insensitive to small capacitance changes. Second, the rubber sleeve necessary for pressurizing the system and inside which the plates were placed, changed dimensions as the system was pressurized, causing changes in capacitance. These changes were not constant and therefore could not be predicted.

As a result of the above findings, a decision was made to mount the plates directly onto the core. Mounting was accomplished by painting the core with conductive silver paint and then soldering platinum plates to the painted area. This mounting method insured good electrical contact between the plates and the core. Plates constructed of platinum foil were ½ inch wide and covered a 90 degree central angle. In this test the length of the plates was approximately .78 inches. By shrinking a piece of thermal plastic over the core and plate assembly, as shown in Figure 5, the plates were further

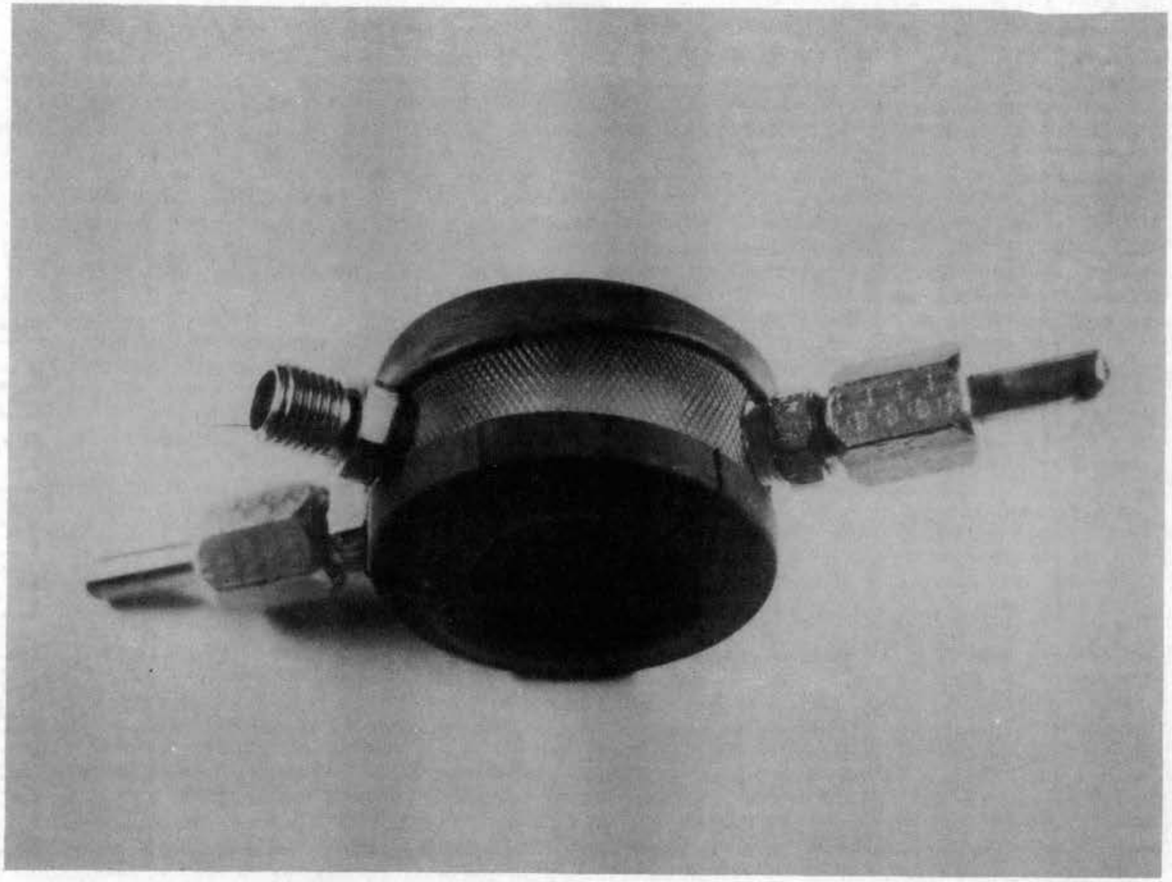

Figure 4. Lucite Test Section

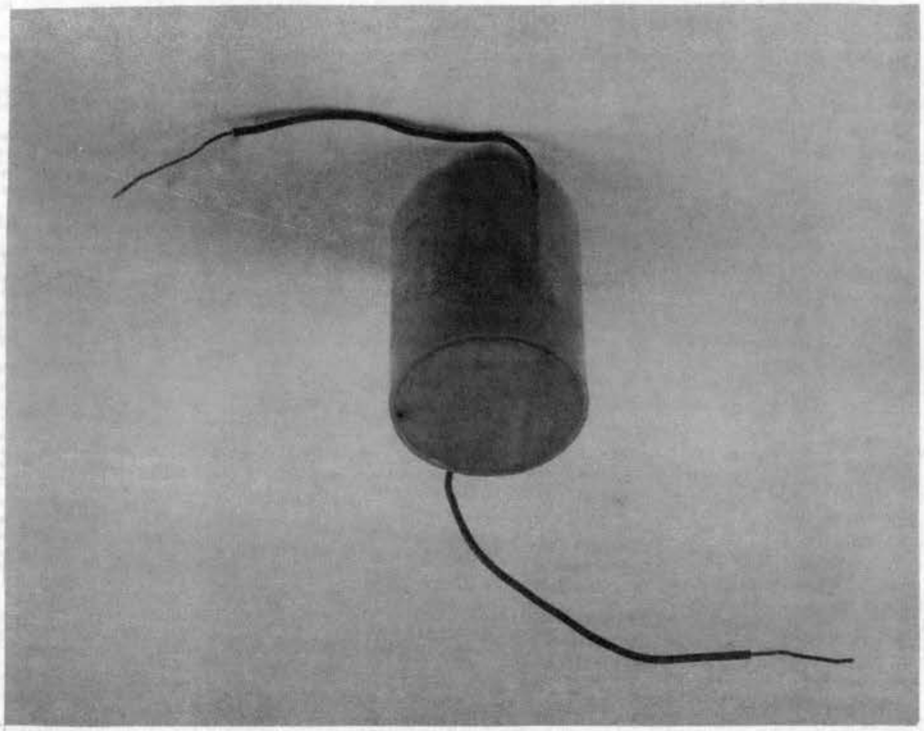

Figure 5. Complete Test Core

secured to the test core. Also, the plastic sleeve facilitated the handling of the core and reduced the number of plate leads broken off.

Coaxial plate leads were discarded and replaced by small insulated wires sufficient in length to extend outside the test section. These leads were connected during a test to an impedance bridge which was used to measure capacitance. In addition, a thermocouple used to detect the test core temperature was located on the wall of the rubber sleeve.

In conjunction with the capacitance-saturation correlation, the resistance method was used to cross check the results. The resistance of the test core was determined by using capacitance plates as electrodes and by using a conductance bridge to measure the resistance. A complete test apparatus assembly is shown in Figure 6.

Making use of the above equipment, the proceeding steps were followed in a typical test run:

1. Determine and record dry weight of test core.
2. Saturate test core, upstream core, downstream core and mixing head.
3. Place cores in test apparatus and apply sleeve pressure.
4. Measure and record the capacitance, resistance and temperature.
5. Release sleeve pressure, remove test core and determine weight.
6. Replace test core, apply sleeve pressure and again follow step 4.
7. Inject gas for a short period of time, stop gas and allow system to stabilize.

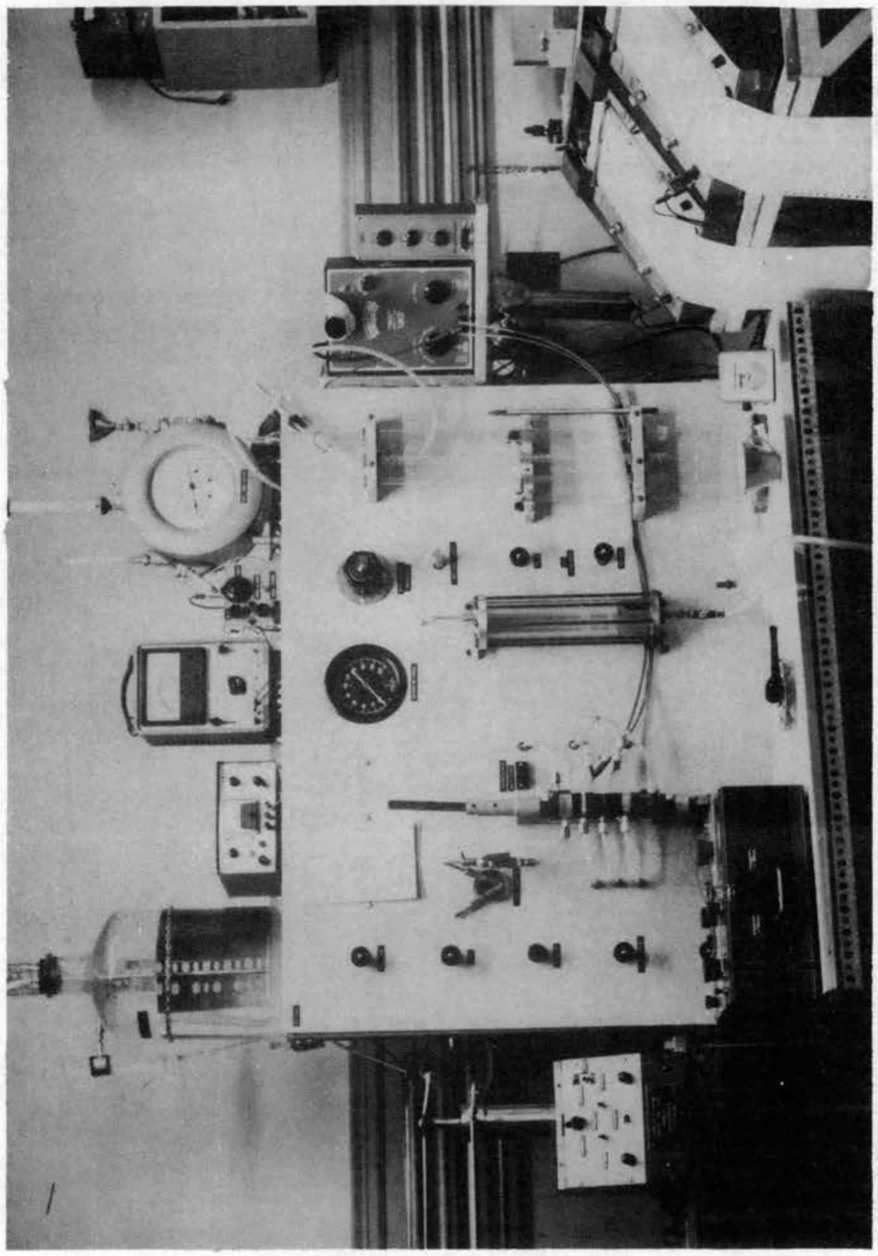

Figure 6. Complete Test Apparatus

8. Repeat steps 4 through 7 injecting more gas each time.

Note: Care should be taken that sufficient time be allowed for the system to reach a state of equilibrium.

Data recorded from resistance-capacitance-saturation test runs were then processed and correlated through the use of an IBM 1620 computer program (4). The computer program consisted of two parts, one part containing the resistance-saturation correlation. Another part was a modified version of the resistance-saturation program consisting of capacitance-saturation correlation.

Fortran listings of the resistance-saturation and the capacitance-saturation programs used in connection with this experiment are shown in Tables I and II respectively. Also, in Table III symbols for both the resistance-saturation and capacitance-saturation programs are identified.

The following is a summary of Comer, et al. (4) IBM 1620 computer program for resistance-saturation correlation:

> The program is based on the fact that a log-log plot of resistance divided by resistance at 100% water saturation vs. water saturation is a straight line. For each core the resistance at 100% water saturation, the temperature at which the resistance was observed, and the number of data points to be processed must be read into the computer. The following data is required for each data point: 1) identification number, 2) resistance, 3) temperature at which the resistance was observed, 4) weight of the partially saturated core, and 5) dry weight of the core. The output data includes the following: 1) resistance when the core contains one gram of water, 2) slope of the curve on log-log axis, 3) weight of water in the core when it is fully saturated, 4) resistance at 100% saturation

TABLE I

RESISTANCE-SATURATION PROGRAM

```
  C      CURVE FITTING PROGRAM FOR SATURATION-RESISTANCE CORRELATION
C       FITS TO FORMS  R=(A*(WT.WTR.)**B)  AND  RR=(WTR.SAT.)**B
        DIMENSION R68L(100),WTRL(100)
   1    READ 24
        READ 2,BR,TBR,N
        DO 3 J=1,N
        READ 4,I,R,T,WT,DWT
C       RESISTANCE CONSTANTS GIVEN FOR 1250 PPM BRINE
        R68=R*(.1593+(.012365*T))
        WTR=WT-DWT
        R68L(I)=LOG(R68)
   3    WTRL(I)=LOG(WTR)
        BR68=BR*(.1593+(.012365*TBR))
        BRL=LOG(BR68)
        SLR=0.
        SLW=0.
        SLWR=0.
        SLWS=0.
        C=N
        DO 5 I=1,N
        SLR=SLR+R68L(I)
        SLW=SLW+WTRL(I)
        SLWR=SLWR+(R68L(I)*WTRL(I))
   5    SLWS=SLWS+(WTRL(I)**2)
        B= ((C*SLWR)-(SLR*SLW))/((C*SLWS)-(SLW**2))
        AL=((SLR*SLWS)-(SLWR*SLW))/((C*SLWS)-(SLW**2))
        A=EXP(AL)
        WBL=(BRL-AL)/B
        WB=EXP(WBL)
        W20=WB/5.
        R20=A*(W20**B)
        RR20=R20/BR68
        IF (SENSE SWITCH 1)11,10
  10    PUNCH 24
        PUNCH 6
        PUNCH 18
        PUNCH 8,A,B,WB,BR68,RR20
        GO TO 22
  11    TYPE 24
        TYPE 6
        TYPE 18
        TYPE 8,A,B,WB,BR68,RR20
  22    IF (SENSE SWITCH 2)20,21
  20    TYPE 14
        GO TO 7
  21    PUNCH 14
   7    DO 9 I=1,N
        RR=EXP(R68L(I)-BRL)
        SW=EXP(WTRL(I)-WBL)
        SW=100.*SW
        IF (SENSE SWITCH 2)12,13
  12    TYPE 16,I,SW,RR
        GO TO 9
  13    PUNCH 16,I,SW,RR
   9    CONTINUE
        GO TO 1
   2    FORMAT (F5.0,F8.1,I7)
   4    FORMAT (I3,3X,F5.0,3X,F4.0,3X,F6.3,F9.3)
   6    FORMAT (7X,1HA,14X,1HB,8X,32HMAX WTR WT   BASE RES     RR (20))
   8    FORMAT (E12.4,E15.6,F12.4,F12.2,F12.3)
  14    FORMAT (38H  IDENT           WTR SAT           RES RATIO)
  16    FORMAT (3X,I3,10X,F5.1,10X,F6.2)
  18    FORMAT (33X,18HGRAMS          KILOHMS)
  24    FORMAT (49H CORE IDENTIFICATION                                 )
        END
```

TABLE II

CAPACITANCE-SATURATION PROGRAM

```
C       JOHN THOMAS WARD RESEARCH
C       CURVE FITTING PROGRAM FOR CAPACITANCE-SATURATION CORRELATION
C       FITS TO FORMS C=(A*(WT.WTR.)**B) AND CR=(WTR.SAT.)**B
        DIMENSION C68L(100),WTCL(100)
5       READ 95
        READ 60,BC,TBC,N
        DO 6 J=1,N
        READ 65,I,C,T,WT,DWT
C       CAPACITANCE CONSTANTS GIVEN FOR 1250 PPM BRINE
        C68=C*(1.391-(.00578*T))
        WTC=WT-DWT
        C68L(I)=LOG(C68)
6       WTCL(I)=LOG(WTC)
        BC68=BC*(1.391-(.00578*TBC))
        BCL=LOG(BC68)
        SLC=0.
        SLW=0.
        SLWC=0.
        SLWS=0.
        D=N
        DO 10 I=1,N
        SLC=SLC+C68L(I)
        SLW=SLW+WTCL(I)
        SLWC=SLWC+(C68L(I)*WTCL(I))
10      SLWS=SLWS+(WTCL(I)**2)
        B=((D*SLWC)-(SLC*SLW))/((D*SLWS)-(SLW**2))
        AL=((SLC*SLWS)-(SLWC*SLW))/((D*SLWS)-(SLW**2))
        A=EXP(AL)
        WBL=(BCL-AL)/B
        WB=EXP(WBL)
        W20=WB/5.
        C20=A*(W20**B)
        CR20=C20/BC68
        IF (SENSE SWITCH 1)20,15
15      PUNCH 95
        PUNCH 70
        PUNCH 90
        PUNCH 75,A,B,WB,BC68,CR20
        GO TO 25
20      TYPE 95
        TYPE 70
        TYPE 90
        TYPE 75,A,B,WB,BC68,CR20
25      IF (SENSE SWITCH 2)30,35
30      TYPE 80
        GO TO 40
35      PUNCH 80
40      DO 55 I=1,N
        CR=EXP(C68L(I)-BCL)
        SW=EXP(WTCL(I)-WBL)
        SW=100.*SW
        IF (SENSE SWITCH 2)45,50
45      TYPE 85,I,SW,CR
        GO TO 55
50      PUNCH 85,I,SW,CR
55      CONTINUE
        GO TO 5
60      FORMAT (F5.0,F8.0,I7)
65      FORMAT (I3,3X,F5.0,3X,F4.0,3X,F6.0,3X,F6.0)
70      FORMAT (7X,1HA,14X,1HB,8X,32HMAX WTC WT   BASE CAP    CR(20) )
75      FORMAT (E12.4,E15.6,F12.4,F12.2,F12.3)
80      FORMAT (38H  IDENT        WTR SAT         CAP RATIO )
85      FORMAT (3X,I3,10X,F5.1,10X,F6.4)
90      FORMAT (32X,18HGRAMS         MF     )
95      FORMAT (49H CORE IDENTIFICATION                           )
        END
```

TABLE III

RESISTANCE, CAPACITANCE-SATURATION PROGRAM SYMBOL LIST

A	Resistance of the core when one gram of water is contained.
B	Slope of the Log-Log plot of Resistance ratio vs saturation
BC	AC Capacitance of core at S_w = 100%
BC68	BC corrected to 68° F
BCL	Logarithm of BC68
BR	AC Resistance of core at S_w = 100%
BR68	BR corrected to 68° F
BRL	Logarithm of BR68
C	Number of data points (floating point form, Resistance)
C	AC Capacitance of core at S_w (Capacitance)
C20	AC Capacitance at S_w = 20%
C68	AC Capacitance corrected to 68° F
C68L	Logarithm of C68
CR	Capacitance Ratio
CR20	Capacitance Ratio at S_w = 20%
DWT	Dry weight of core, grams
I	Identification number
J	A computer indexing number
N	Number of data points (fixed point form)
RR	Resistance Ratio
RR20	Resistance Ratio at S_w = 20%
R20	AC Resistance at S_w = 20%
R	AC Resistance at S_w

TABLE III (Continued)

R68	AC Resistance corrected to 68° F
R68L	Logarithm of R68
SLC	Summation of Logarithms of C68
SLR	Summation of Logarithms of R68
SLW	Summation of Logarithms of weight of water in core
SLWC	Summation of the products of the Logarithms of C68 and weight of water in the core
SLWR	Summation of the products of the Logarithms of R68 and weight of water in the core
SLWS	Summation of the squares of the Logarithms of weight of water in the core
SW	Water saturation of core, %
T	Temperature of core, $^\circ$F
TBC	Temperature at which capacitance BC was observed
TBR	Temperature at which resistance BR was observed
WB	Weight of water in core at $S_w = 100\%$
WBL	Logarithm of WB
WT	Weight of core at S_w
WTC	Weight of water in core (Capacitance)
WTR	Weight of water in core (Resistance)
WTCL	Logarithm of WTC
WTRL	Logarithm of WTR
W20	Weight of water in core at $S_w = 20\%$

corrected to 68° F and 5) resistance ratio at 20% water saturation. For each data point an identification number, water saturation, and resistance ratio is given as output. The major calculations involved in this program are as follows.

1. Temperature compensation, cards 9 and 13

$$R68 = R * (.1593 + (.012365*t)) \qquad (21)$$

This relation was experimentally determined and used to correct resistance readings to 68° F. This relation is for 1250 ppm NaCl brine with 10 ppm $HgCl_2$. The constants change with salinity.

2. Resistance, card 48.

The algebraic form is:

$$RR = e\ (LnR-LnR_{100}) \text{ or } RR = \frac{R}{R_{100}} \qquad (22)$$

3. Slope of Log Resistance vs. Log Water content Plot, card 25. By the method of least squares the slope of the best straight line through a group of points is given by:

$$B = \frac{n\sum_{i=1}^{n} (x_i y_i) - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} (x_i)^2 - \left[\sum_{i=1}^{n} x_i\right]^2} \qquad (23)$$

In this application Log weight of water in core and Log resistance replace x and y respectively. This slope may be shown to also be the slope of a Log Resistance Ratio vs. Log Saturation Plot.

With a few exceptions, the above summary pertaining to the resistance-saturation program apply also to the capacitance-saturation program. The major calculations are the same as the resistance-saturation program except for the temperature correction equation which is as follows:

$$C_{68} = C* (1.391 - (.00578*T)) \tag{24}$$

Equation (24) adjusts a measured capacitance to an equivalent capacitance at 68° F. This equation is correct only for a brine solution of 1250 ppm NaCl and 10 ppm $HgCl_2$.

CHAPTER V

EXPERIMENTAL RESULTS

Theoretical assertions developed in Chapter IV were confirmed by experimental work which utilized the equipment discussed also in Chapter IV. Experiments were designed to show the various aspects involved when determining the saturation of a reservoir core sample by using the variable capacitance method. Also, included in the experiments was a comparison of the resistance and capacitance methods for determining saturation. The same electrodes were used for both the capacitance method and resistance method. It is acknowledged that there are several other electrode configurations which may be used in conjunction with the resistance method of determining saturation. Therefore, the decision to use the same electrodes for both the resistance and capacitance methods was to give a comparison of the two different techniques using as many of the same parameters as was possible.

A series of capacitance-resistance-saturation test runs provided the test data which was taken from two tests using capacitor plates with a central angle of 90 degrees, and from one test using capacitor plates having a central angle of 30 degrees. Two tests using 90 degree plate angles are reported

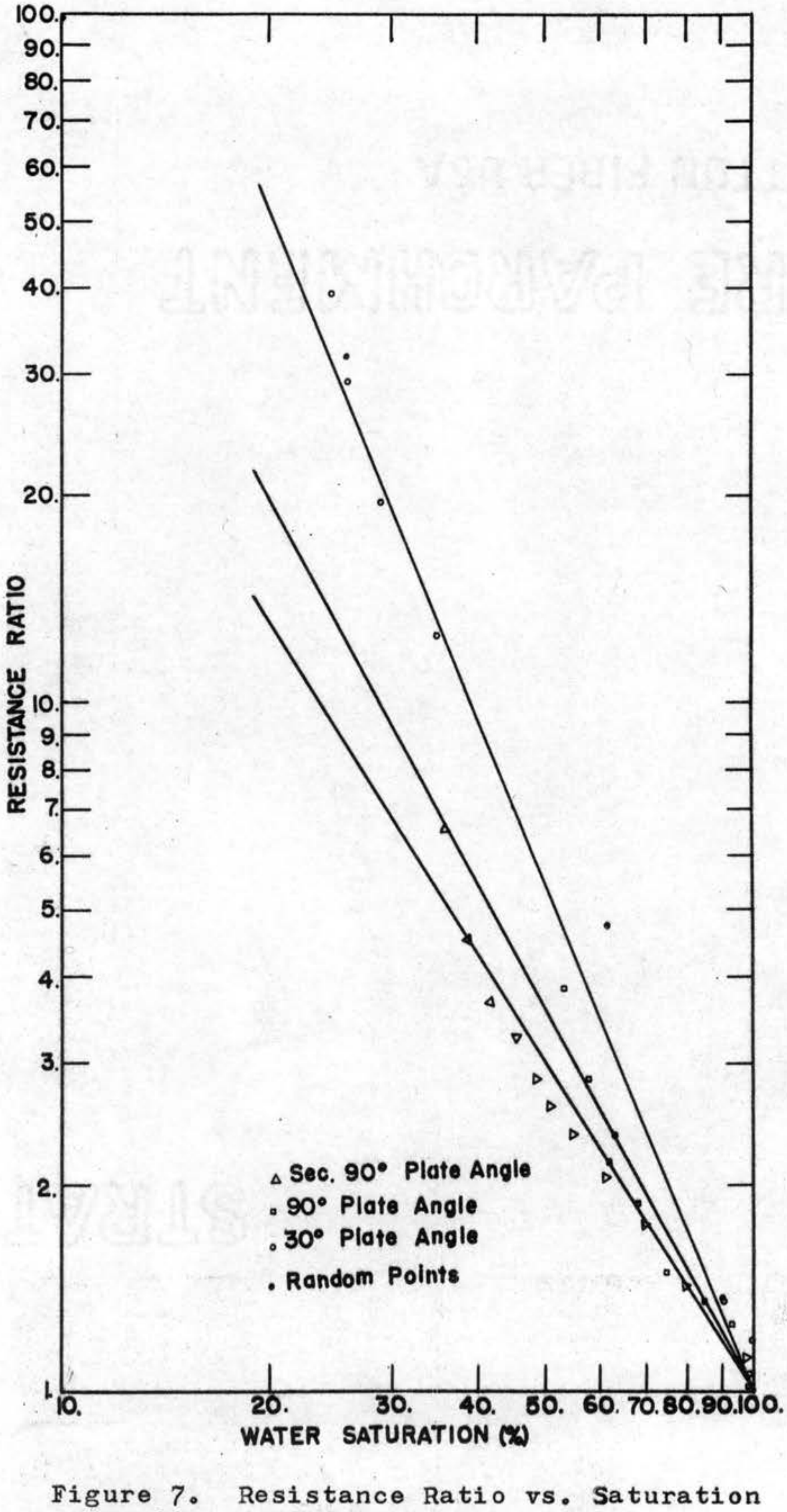

Figure 7. Resistance Ratio vs. Saturation for 90 and 30 Degree Plate Angles

TABLE IV

RESISTANCE-SATURATION TEST FOR 90 DEGREE PLATE ANGLE

```
                        INPUT DATA

                        A-21 PLATE ANGLE 90DEG.
  BR    BT     N
 1.33  78.5   20
IDENT  RES.    TEMP.   WT.       DWT.
       KOH     DEG F   GM         GM
 1     1.42    78.5   69.486    63.562
 2     1.4     78.5   69.486    63.562
 3     1.51    78.5   69.228    63.562
 4     1.52    78.5   69.228    63.562
 5     1.68    78.5   69.071    63.562
 6     1.65    78.5   69.071    63.562
 7     1.80    78.5   68.615    63.562
 8     1.81    78.5   68.615    63.562
 9     2.00    78.2   68.053    63.562
 10    2.00    78.2   68.053    63.562
 11    2.30    78.5   67.634    63.562
 12    2.30    78.5   67.634    63.562
 13    2.50    79.0   67.582    63.562
 14    2.50    79.0   67.582    63.562
 15    2.87    79.0   67.287    63.562
 16    2.87    79.0   67.287    63.562
 17    3.75    79.5   67.028    63.562
 18    3.75    79.5   67.028    63.562
 19    5.10    79.5   66.782    63.562
 20    5.10    79.5   66.782    63.562

                        RESULTS

                        A-21 PLATE ANGLE 90DEG.                                   ‡001
       A                  B            MAX WTR WT   BASE RES    RR (20)           ‡002
                                         GRAMS      KILOHMS                       ‡003
  .4111E 02     -.185707E 01            5.9406        1.50      19.862            ‡004
 IDENT          WTR SAT            RES RATIO                                      ‡005
    1             99.7                1.06                                        ‡006
    2             99.7                1.05                                        ‡007
    3             95.3                1.13                                        ‡008
    4             95.3                1.14                                        ‡009
    5             92.7                1.26                                        ‡010
    6             92.7                1.24                                        ‡011
    7             85.0                1.35                                        ‡012
    8             85.0                1.36                                        ‡013
    9             75.5                1.49                                        ‡014
   10             75.5                1.49                                        ‡015
   11             68.5                1.72                                        ‡016
   12             68.5                1.72                                        ‡017
   13             67.6                1.88                                        ‡018
   14             67.6                1.88                                        ‡019
   15             62.7                2.16                                        ‡020
   16             62.7                2.16                                        ‡021
   17             58.3                2.85                                        ‡022
   18             58.3                2.85                                        ‡023
   19             54.2                3.87                                        ‡024
   20             54.2                3.87                                        ‡025
```

TABLE V

RESISTANCE-SATURATION TEST FOR SECOND 90 DEGREE PLATE ANGLE

```
                  INPUT DATA

      SECOND A-21 PLATE ANGLE 90DEG.
  BR   BT     N
 2.29 76.7    12
IDENT  RES.   TEMP.   WT.       DWT.
       KOH    DEG F   GM         GM
 1     2.35   76.7   69.412    63.394
 2     2.60   76.7   69.322    63.394
 3     3.26   76.5   68.248    63.394
 4     4.00   76.5   67.659    63.394
 5     4.73   76.0   67.116    63.394
 6     5.55   75.7   66.733    63.394
 7     6.10   75.0   66.504    63.394
 8     6.70   75.7   66.346    63.394
 9     7.60   75.7   66.164    63.394
 10    8.72   74.2   65.977    63.394
 11    11.0   74.2   65.774    63.394
 12    15.0   71.5   65.586    63.394

                  RESULTS

      SECOND A-21 PLATE ANGLE 90DEG.                                        ‡001
       A              B         MAX WTR WT    BASE RES     RR (20)          ‡002
                                  GRAMS       KILOHMS                       ‡003
  .4464E 02    -.159633E 01      6.0289         2.53       13.055           ‡004
  IDENT          WTR SAT        RES RATIO                                   ‡005
    1              99.8           1.02                                      ‡006
    2              98.3           1.13                                      ‡007
    3              80.5           1.42                                      ‡008
    4              70.7           1.74                                      ‡009
    5              61.7           2.04                                      ‡010
    6              55.3           2.39                                      ‡011
    7              51.5           2.61                                      ‡012
    8              48.9           2.89                                      ‡013
    9              45.9           3.28                                      ‡014
   10              42.8           3.70                                      ‡015
   11              39.4           4.66                                      ‡016
   12              36.3           6.16                                      ‡017
```

TABLE VI

RESISTANCE-SATURATION TEST FOR 30 DEGREE PLATE ANGLE

```
                        INPUT DATA

                   CAP. A-21 PLATE ANGLE 30DEG.
  BC    BT       N
 .635 73.5      14
IDENT   CAP.    TEMP.    WT.         DWT.
         MF     DEG F    GM           GM
  1     .575    73.5    69.130     62.792
  2     .575    73.5    69.130     62.792
  3     .496    73.5    68.576     62.792
  4     .490    73.5    68.576     62.792
  5     .187    73.5    66.767     62.792
  6     .188    73.5    66.767     62.792
  7     .038    73.5    64.864     62.792
  8     .038    73.5    64.864     62.792
  9     .024    74.0    64.637     62.792
 10     .024    74.0    64.637     62.792
 11     .014    74.5    64.482     62.792
 12     .016    74.5    64.482     62.792
 13     .012    75.0    64.368     62.792
 14     .012    75.0    64.368     62.792
                        RESULTS

                   CAP. A-21 PLATE ANGLE 30DEG.
       A                B             MAX WTC WT    BASE  CAP     CR(20)
                                         GRAMS       MF
   .3935E-02      .273133E 01          6.3507           .61          .012
  IDENT          WTR SAT          CAP RATIO
    1               99.7             .9055
    2               99.7             .9055
    3               91.0             .7811
    4               91.0             .7716
    5               62.5             .2944
    6               62.5             .2960
    7               32.6             .0598
    8               32.6             .0598
    9               29.0             .0376
   10               29.0             .0376
   11               26.6             .0219
   12               26.6             .0250
   13               24.8             .0187
   14               24.8             .0187
```

because their results were inclusive and were representative of the other 90 degree central angle tests. Random points, taken independently of the aforementioned 30 degree plate angle tests, further confirmed the 30 degree curves by falling along the established curve.

Resistance ratio (discussed in Chapter IV) curves for the 90 degree central angle tests and for the 30 degree central angle test have different slopes as observed in Figure 7. Curves in Figure 7 were developed from experimental results shown in Tables IV, V, and VI. Variation in the 90 degree plate angle test results can be explained by the existence of "end effects" which have considerable affect when using large central angles. These "end effects," when using large central angles, were virtually uncontrollable and unpredictable, thus causing discrepancies in the test results.

Random points, as previously mentioned, further established the 30 degree central plate angle Resistance Ratio plot. The difference in the slopes of the 90 degree Resistance Ratio plots and the 30 degree Resistance Ratio plot can also be explained by considering the "end effects". The "end effects" discussed were similar to those described by Holmes in regard to conduction of electrical current over the surface of the test core. At a given saturation, the 90 degree Resistance Ratio curves indicated a lower resistance than the 30 degree curves; this difference became more pronounced as the saturation decreased. The "end effects" were more understandable when considering that the circumferential distance of the core

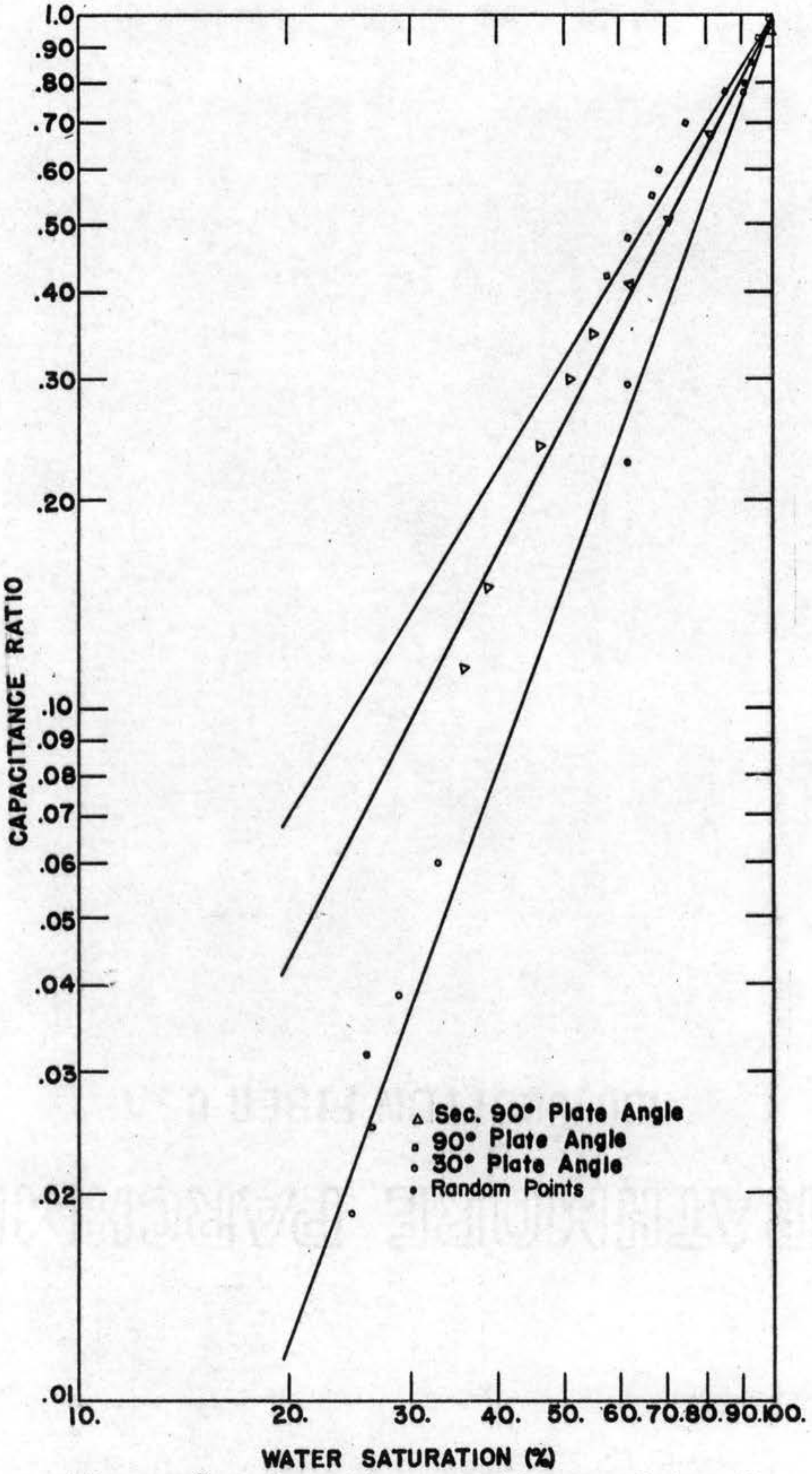

Figure 8. Capacitance Ratio vs. Saturation for 90 and 30 Degree Plate Angles

TABLE VII

CAPACITANCE-SATURATION TEST FOR 90 DEGREE PLATE ANGLE

```
                         INPUT DATA

                 CAP. A-21 PLATE ANGLE 90DEG.
 BC   BT     N
1.13 78.5    20
IDENT CAP.   TEMP.    WT.       DWT.
       MF    DEG F    GM         GM
 1    1.14   78.5   69.468    63.562
 2    .955   78.5   69.468    63.562
 3    1.06   78.5   69.228    63.562
 4    1.05   78.5   69.228    63.562
 5    .87    78.5   69.071    63.562
 6    .97    78.5   69.071    63.562
 7    .88    78.5   68.615    63.562
 8    .88    78.5   68.615    63.562
 9    .79    78.2   68.053    63.562
 10   .79    78.2   68.053    63.562
 11   .675   78.5   67.634    63.562
 12   .68    78.5   67.634    63.562
 13   .625   79.0   67.582    63.562
 14   .628   79.0   67.582    63.562
 15   .55    79.0   67.287    63.562
 16   .55    79.0   67.287    63.562
 17   .483   79.5   67.028    63.562
 18   .483   79.5   67.028    63.562
 19   .341   79.5   66.782    63.562
 20   .341   79.5   66.782    63.562

                         RESULTS

                 CAP. A-21 PLATE ANGLE 90DEG.                                        #001
     A                 B           MAX WTC WT   BASE CAP     CR(20)                  #002
                                     GRAMS      MF                                   #003
 .5633E-01      .164778E 01         5.9327         1.05          .070                #004
IDENT           WTR SAT          CAP RATIO                                           #005
    1             99.5             .10088496E 01                                     #006
    2             99.5             .8451                                             #007
    3             95.5             .9380                                             #008
    4             95.5             .9292                                             #009
    5             92.8             .7699                                             #010
    6             92.8             .8584                                             #011
    7             85.1             .7787                                             #012
    8             85.1             .7787                                             #013
    9             75.6             .7004                                             #014
   10             75.6             .7004                                             #015
   11             68.6             .5973                                             #016
   12             68.6             .6017                                             #017
   13             67.7             .5513                                             #018
   14             67.7             .5540                                             #019
   15             62.7             .4852                                             #020
   16             62.7             .4852                                             #021
   17             58.4             .4247                                             #022
   18             58.4             .4247                                             #023
   19             54.2             .2999                                             #024
   20             54.2             .2999                                             #025
```

TABLE VIII

CAPACITANCE-SATURATION TEST FOR SECOND 90 DEGREE PLATE ANGLE

```
                 INPUT DATA

          SECD. CAP. A-21 ANGLE 90DEG.
 BC   BT    N
.940 76.7   12
IDENT  CAP.   TEMP.   WT.       DWT.
        MF    DEG F    GM        GM
 1     .900   76.7   69.412    63.394
 2     .815   76.7   69.322    63.394
 3     .640   76.5   68.248    63.394
 4     .480   76.5   67.659    63.394
 5     .385   76.0   67.116    63.394
 6     .325   75.7   66.733    63.394
 7     .282   75.0   66.504    63.394
 8     .250   75.7   66.346    63.394
 9     .225   75.7   66.164    63.394
 10    .184   74.2   65.977    63.394
 11    .143   74.2   65.774    63.394
 12    .104   71.5   65.586    63.394

                 RESULTS

          SECD. CAP. A-21 ANGLE 90DEG.                                 ǂ001
     A              B          MAX WTC WT   BASE CAP    CR(20)         ǂ002
                                 GRAMS      MF                         ǂ003
  .2727E-01    .194226E 01      6.0186         .89        .043         ǂ004
  IDENT        WTR SAT       CAP RATIO                                 ǂ005
    1            99.9          .9574                                   ǂ006
    2            98.4          .8670                                   ǂ007
    3            80.6          .6816                                   ǂ008
    4            70.8          .5112                                   ǂ009
    5            61.8          .4113                                   ǂ010
    6            55.4          .3478                                   ǂ011
    7            51.6          .3031                                   ǂ012
    8            49.0          .2675                                   ǂ013
    9            46.0          .2408                                   ǂ014
   10            42.9          .1987                                   ǂ015
   11            39.5          .1544                                   ǂ016
   12            36.4          .1141                                   ǂ017
```

TABLE IX

CAPACITANCE-SATURATION TEST FOR 30 DEGREE PLATE ANGLE

```
                          INPUT DATA

                          A-21 PLATE ANGLE 30DEG.
 BR     BT      N
2.37  73.5     14
IDENT  RES.    TEMP.   WT.       DWT.
       KOH     DEG F   GM         GM
1      2.80    73.5   69.130    62.792
2      2.80    73.5   69.130    62.792
3      3.23    73.5   68.576    62.792
4      3.23    73.5   68.576    62.792
5      5.55    73.5   66.767    62.792
6      5.55    73.5   66.767    62.792
7      29.5    73.5   64.864    62.792
8      29.5    73.5   64.864    62.792
9      46.0    74.0   64.637    62.792
10     46.2    74.0   64.637    62.792
11     68.5    74.5   64.482    62.792
12     68.5    74.5   64.482    62.792
13     90.0    75.0   64.368    62.792
14     90.0    75.0   64.368    62.792

                          RESULTS

                          A-21 PLATE ANGLE 30DEG.                                   #026
      A                   B           MAX WTR WT   BASE RES    RR (20)              #027
                                         GRAMS     KILOHMS                          #028
  .2391E 03    -.246314E 01            6.3380        2.53       52.682              #029
 IDENT            WTR SAT            RES RATIO                                      #030
    1               99.9                1.18                                        #031
    2               99.9                1.18                                        #032
    3               91.2                1.36                                        #033
    4               91.2                1.36                                        #034
    5               62.7                2.34                                        #035
    6               62.7                2.34                                        #036
    7               32.6               12.44                                        #037
    8               32.6               12.44                                        #038
    9               29.1               19.52                                        #039
   10               29.1               19.60                                        #040
   11               26.6               29.23                                        #041
   12               26.6               29.23                                        #042
   13               24.8               38.63                                        #043
   14               24.8               38.63                                        #044
```

between the ends of the 90 degree plates was less than the diametrical distance between the plates. However, the converse of this is true for the 30 degree plates.

Log-Log plots of the Capacitance Ratio vs. Saturation for the two 90 degree plate angle tests and for the 30 degree plate angle test (with random points) are shown in Figure 8. Curves in Figure 8 were developed from experimental results which are recorded in Tables VII, VIII, and IX. The plots of the Capacitance Ratio vs. Saturation were straight lines; however, the slopes of the curves were positive instead of negative as were those in Resistance-Saturation, Figure 7. Difference in the sign of the slopes was a result of the capacitance decreasing and the resistance increasing as the water saturation was decreased. Curves in Figure 8 differ in magnitude of their slopes. Again, this difference can be explained by the presence of "end effects"; however, these "end effects" differ from those related to the tests shown in Resistance-Saturation, Figure 7. "End effects" related to the tests shown for Capacitance-Saturation, Figure 8, were those associated with the use of curved capacitor plates in place of parallel plates. The capacitance theory of parallel plates suggested that in order to neglect the "end effects" the area of the plates must be large in comparison to the distance between the plates. Therefore, when using curved plates, the "end effects" are of some consequence.

From a study of Tables VII, VIII, and IX it was apparent that there is approximately 50 per cent difference in the base capacitance of the 90 degree central plate angle test results and the base capacitance of the 30 degree central plate angle test results. However, the plate area was reduced in excess of 66 per cent, and there was approximately a 60 per cent reduction of the "plate volume". The effects of reducing the plates were shown in Figure 5. A comparison of the plate angle change and the base capacitance change further indicated the presence of "end effects". A difference in the magnitude of the slopes of the curves shown in Figure 8 indicated that the "end effects" became more pronounced as the water saturation of the core decreased.

CHAPTER VI

CONCLUSIONS

Information obtained from this research investigation led to several conclusions. In the resistance method it was evident, by a comparison of the 90 and 30 degree cases, that electrical current was conducted along the surface of the test core as well as through the core when using 90 degree plate electrodes. The use of 30 degree plate electrodes reduced the surface conduction by making the diametrical distance the shortest line of contact between the plates. There is the possibility, however, that a certain amount of surface conduction still existed even with the 30 degree plate electrodes.

By comparing the capacitance-saturation test results of the 90 and 30 degree cases, it was apparent that the capacitor plates with a 30 degree central angle was a definite improvement over the 90 degree central angle plates. The 90 degree central angle plates showed a wide variation by not giving repeatable results, because of the presence of the "end effects" resulting from deviation from the parallel plate assumption. However, the 30 degree plate angle test results showed stability, and the random points further substantiated its reliability. Comparison of the 30 and 90 degree capacitance-saturation test results verified the theoretical implications used to develop Equation (20). General observation of both the resistance-saturation and capacitance-saturation test results indicated that both methods reacted similarly to changes in core saturation, and that the capacitance method was as reliable as the resistance method.

From the research conducted by this author the following conclusions can be drawn:

1. The geometrical shape of capacitor plates was an important factor in obtaining reliable capacitance-saturation test results.
2. Use of modified parallel capacitor plate equations for curved capacitor plates was valid for central plate angles of 30 degrees or less.
3. Use of a 30 degree central plate angle resulted in an improvement over the use of a 90 degree central plate angle and the use of a 30 degree central plate angle produced reliable capacitance-saturation test data under ordinary laboratory conditions.

CHAPTER VII

RECOMMENDATIONS FOR FUTURE STUDY

By the very nature of a research study it is limited in scope; such is true of this particular study. However, this research revealed many important facets of the capacitance method for determining fluid saturation, which are of value to those interested in further developing the capacitance method. The following suggestions for future study are of importance in the resistance method of saturation determination; therefore, it is felt that an investigation of these suggestions might provide information leading to an improved capacitance technique. One aspect for investigation is the effect of current frequency upon test results, when using the capacitance method of saturation determination. Another area is the net effect of conductive solids in the test core. Also, the effect of pressure on capacitance-saturation test results offers another area for future study.

The capacitor plates used in this study were rectangular in shape. The only alteration to the plates was reducing the central plate angle from 90 to 30 degrees. As reported in Chapters V and VI, this reduction of 90 to 30 degrees produced a change in the testing characteristics of the plates. Results indicated above, suggest that capacitor plate design or configuration is an important area for further study. A study of the use of any closed geometrical figure, such as a circle, for the design of the plates could possibly lead to plate designs that would further reduce "end effects", and thus improve the testing sensitivity of the plates. Study and research in the aforementioned areas could result in the improvement of the capacitance method for determining fluid saturation of core samples.

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APPENDIX

LIST OF ABBREVIATIONS AND SYMBOLS FOR THE TEXT

A	Parallel surface area of capacitor plates (cm^2).
C	Capacitance
CA	Circular area of plates
CC	Theoretical calculated capacitance for a capacitor with curved plates
D	Diameter of core
d	Distance between plates (cm)
EL	Effective or projected length of the curved plates
f	Unit of capacitance (farad)
H	Central plate angle
K	Dielectric constant
MC	Measured capacitance
PV	Volume of core covered by plates
r	Radius of core
W	Width of capacitor plates

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