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REPEATED LOAD TRIAXIAL TEST
WITH
PORE PRESSURE MEASUREMENT

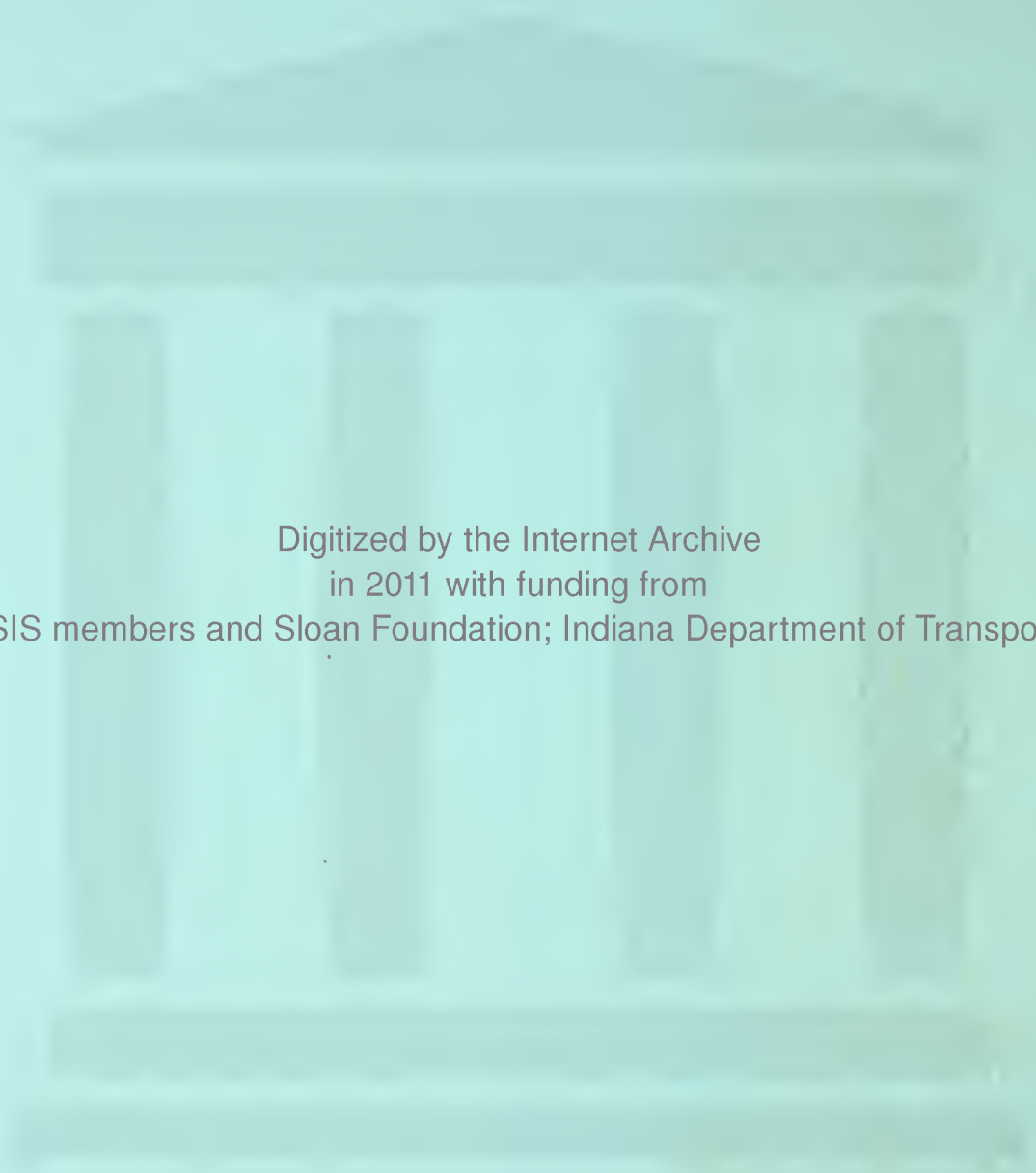
OCT. 1962

NO.24

Joint
Highway
Research
Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

by
R.W. JOHNSON
&
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Technical Paper

REPEATED LOAD TRIAXIAL TEST WITH
PORE PRESSURE MEASUREMENT

TO: K. B. Woods, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

October 31, 1962

File: 6-18-7
Project: C-36-15G

Attached is a technical paper entitled "Repeated Load Triaxial Test With Pore Pressure Measurement" by R. W. Johnson and E. J. Yoder. This paper is a summary of the research performed by Mr. Johnson under the direction of Professor Yoder and previously presented to the Board.

The paper was presented at the Fourth Pacific Area National Meeting of the American Society for Testing and Materials held in Los Angeles October 1-5, 1962.

The paper is presented for the record and action granting permission to submit the paper for publication in the Proceedings of this meeting is requested.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:kmc

Attachment

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R E P E A T E D L O A D T R I A X I A L T E S T W I T H
P O R E P R E S S U R E M E A S U R E M E N T

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INTRODUCTION

Examination of the literature concerned with the testing of soils reveals at once that the development of related equipment, methods and procedures has progressed parallel with the development and evolution of soil mechanics itself together with technological developments in areas quite unrelated to soil testing. This fact presents at once a great challenge to the laboratory investigator attempting to duplicate as realistically as possible, the actual in situ conditions which represent the soil problem under investigation as well as a barrier in terms of complex equipment fabrication. As the amount of effort expended in soils research increases, the degree of complexity of unsolved problems mounts likewise, accompanied by a demand for better test equipment. This trend leads inevitably to a decision to break big problems down into smaller pieces and so approach a solution in a piece-wise manner. No stigma attaches to this method by any standard of evaluation, providing the problem can be solved by this approach. Occasions arise however, when such techniques will not suffice due to a requirement to evaluate inter-related test data; in this case the test equipment becomes much more complex.

A recently concluded program of research (1) required rather complex test equipment which was not commercially available and which

insofar as was then known had not been produced elsewhere in quite the same form. This paper describes the equipment designed and constructed as a part of the research program as well as methods and procedures developed to accompany the testing of certain soil specimens included in the program.

DYNAMIC TRIAXIAL LOADING EQUIPMENT

Prior to initiation of any work on the equipment design, considerable thought was given to the specific objectives of the research program. While it was recognized which general areas of research would be investigated, it was also recognized that certain limitations in scope would have to be observed.

With the purpose and scope defined, the research program divided more or less naturally into three distinct phases as follows:

- a. Equipment design and construction,
- b. Development of testing techniques and procedures,
- c. Testing program and data analysis.

Equipment design and construction was probably the most difficult phase of the program since it was desired to construct equipment which afforded maximum flexibility of operation and which would be adaptable to future research. It was determined that in general a dynamic triaxial testing apparatus permitting measurement of pore pressures in the sample was necessary. It was further determined that this apparatus must be designed and constructed locally after inquiry revealed that it was not commercially available. The test equipment thus comprised two elements; the repetitive dynamic

triaxial loading apparatus and the pore pressure measuring apparatus together with related appurtenances. The equipment was designed by the author and fabricated in the Civil Engineering machine shop of Purdue University.

The dynamic loading equipment used for the triaxial tests is shown schematically in Figures 1 and 2. This equipment is based generally on a quite successful earlier design used by Havers (2) in his study of subgrade pumping. The loading energy is provided by compressed air actuating a piston type air cylinder. The magnitude of the load carried to the soil sample by the piston can be controlled by regulating the air line pressure. Compressed air is supplied by a 3 H.P. air compressor operating at 120-160 psi outlet pressure. From the air compressor the air passes into an accumulator tank of 0.9 cubic feet capacity and through a combination 40 micron filter, pressure regulator and oiler. As indicated in Figure 2 the line branches to the dual loading units which can be operated either singly or in unison. The system is designed for maximum flexibility of loading and calibrating operations in that the piston can be made to operate either single or double acting under dynamic loading, or maintain continuous variable static loads. The desired dynamic or static loading condition is controlled by the manually operated air line valves together with the

four-way Bellows-Valvair pilot-operated solenoid valves. (Fig. 2.)

To energize the system the line switch is closed maintaining current through the normally closed contacts of the switch in the counter to the normally closed contacts in timer. This impulse energizes the solenoid valve causing the port which is normally closed, to open for the down or pressure stroke of the piston. After the controlled delay in the timer has elapsed, the contacts in the counter open, causing one count to be recorded and de-energizing the time which de-energizes the pressure stroke of the piston. The timer controls both the duration of load as well as the interval between load applications for any desired number of repetitions as set on the counter. An adjustable micro-switch set on the loading piston of the tri-axial cell will shut off the entire apparatus after the sample fails or the deformation reaches a pre-determined magnitude. The foregoing sequence is that which takes place for a single-acting movement in which it is desired that the loading piston remain in continuous and complete contact with the soil sample. For operation as a double-acting system, the manual control valves are opened or closed as necessary to obtain the desired action; no change in the timing sequence is required.

Controlled Temperature Room

Accurate determination of pore pressures and volume changes which are temperature dependent, requires that the testing be performed in a temperature controlled environment. This was achieved by use of a controlled temperature chamber in which the loading apparatus and electronic gear was installed. In addition to the obvious advantage obtained by use of the chamber for fluid measurements, a secondary, though important benefit was that of a stabilized temperature for all electronic sensing and recording elements thus improving the performance and reliability.

The chamber is described as a controlled environmental room manufactured by the Electric Hotpack Company of Philadelphia, Pennsylvania, Model 8316. The chamber dimensions are 6 feet wide, 8 feet long and 7 feet high. Control of temperature is obtained through heating coils and a refrigeration unit coupled to a Partlow thermostatic control unit. The temperature of the unit can be adjusted to operate from 0 degree centigrade to 40 degrees centigrade at a temperature differential of plus or minus one-half degree centigrade. Current characteristics are 230 V AC and 4800 watts. An important feature of the chamber is the diffusion of the conditioned air by mechanical convection which assures uniform temperature and

humidity at all locations in the room. The movement of air in the chamber tends to cause some discomfort to personnel during prolonged periods of testing and in addition the recirculated air tends to become musty. Corrosion of metal is also somewhat accelerated in such an environment.

It was important to provide a firm anchored support for the loading apparatus entirely free of contact with the chamber. This was achieved by carrying the weight of the apparatus through the floor of the chamber on six anchor rods. These anchors are not in contact with the chamber at any point and thus extraneous disturbances by personnel in the room are also avoided (Figure 3).

Electronic Recording Equipment

The electronic recording equipment used in this study consisted, for the most part, of modified components designed and used on an earlier investigation of subgrade support characteristics (3). A block diagram of the components is shown in Figure 4 and the bridge and calibration unit in Figure 5. The sensing elements are numerically keyed to the specimen, Figure 6.

The system is composed of a power supply unit, a seven channel amplifying and control unit, a six channel recording galvanometer unit and the various electronic pick up devices. The amplifying and control unit contains seven amplifiers, seven frequency modulating units, seven power amplifiers for driving galvanometers, oscillators generating voltages at 30,000 cps and 2,000 cps and two power amplifiers. The amplifying unit was modified by removing one amplifier and inserting another power amplifier to provide additional energy for the sensing elements. In addition a bridge and calibration unit (Figure 5) was designed and constructed to permit use of strain gages with this unit since its original design was specifically for use with Schaevitz 040L and 125L linear variable transformers. The bridge unit was inserted in the position formerly occupied by the top-most amplifier. The

rectified 30 kc voltage is filtered and used as a bias for the power amplifier; the 2 kc voltage is amplified by the two power amplifiers which serve as the energy source for the transducers. The power for the transducers either goes directly to the transducer as in the case of LVDT's or it is isolated from ground when used with Wheatstone bridge strain gage units.

The galvanometer unit consists of six BL-902 Brush Electronics Company pen motors (input impedance 1450 ohms) and one event marker. All channels may be used with either ink writing or electric writing pens on sensitized paper. In this study the electric stylus was used. All galvanometer units are mounted in a single unit, Brush Model BL-276.

For further detailed information on the principle of operation, reference (3) can be consulted.

Sensing Elements and Calibration

Referring to Figure 6, the relationship of the sensing elements to the test specimen is shown.

A Baldwin Type C, 0-5000 ^{pound}~~pounds~~ load cell (1) was used to

measure the magnitude of the applied load including its own weight and that of the moving piston. The load cell utilizes four active ^{SR}~~SR~~-4 strain gages wired in a Wheatstone bridge circuit and has a precision of plus or minus one-fourth percent full scale calibration accuracy. Calibration of the load cell was accomplished by loading the cell in the environmental chamber against an accurate proving ring. Galvanometer and proving ring deflections were recorded for varying magnitudes of applied load. The amplifier gain was brought into proper adjustment and the galvanometer pen zeroed. Simultaneously the power amplifier output voltage was adjusted to operating voltage as noted on a voltage meter. Recordings were taken for several cycles of load and unload and the mean of the values taken as the most probable value. With the cell completely unloaded, i.e., the dead load of the piston removed, the calibration resistance was switched on and the galvanometer pen deflection was noted and recorded.

From the work of Whitman, et al (4), it was determined that measurement of the pore pressure using a Dynisco PT-25, 0 - 100 psia pressure transducer as shown in Figure 6 was possible. The cell employs a miniature strain gage in the configuration of a four-active-arm Wheatstone Bridge. Performance characteristics include a maximum non-linearity of 0.5 percent full scale and repeatability maximum of 0.1 percent full scale.

Calibration of the pressure cell was accomplished in much the same manner as the load cell. A closed pressure chamber was constructed of about one liter capacity. The transducer adapter was threaded into the base and the chamber filled one-half with de-aired water. The pressure cell was then screwed into the adapter, its base being in and below water such that no air bubbles were present in the system. Air was admitted to the top of the chamber and its pressure recorded on an accurate laboratory pressure gage. As the pressure was varied, galvanometer deflections were recorded for each increment of pressure change, over a series of several cycles of loading and unloading. The mean of these values was taken as the most probable value. Power amplifier output voltage and calibration resistance deflection were also noted and recorded. A high degree of linearity was obtained for both of these devices, particularly at the middle and upper ranges of the calibration curve.

Deformation was measured by a Schaevitz Type 125SL linear variable transformer. This was mounted in an adjustable holder which, in turn, was mounted in a bracket attached to the loading ram of the triaxial cell. The transformer core with a brass extension was permitted to react against the top of the cell. Thus, even though the cell deformed very slightly under load, the LVDT measured only the true deformation of the ram and hence of the soil sample. Calibration of the LVDT followed standard procedures and is described in reference (3). The calibration procedure was simplified by using a micrometer attachment fitted with an adaptor on the shaft which screwed into the transformer core. Thus, once the null position was found, the range could be set on the galvanometer by raising the core an exact amount (.1250 inch) with the micrometer. After calibration, the adaptor was screwed out of the core, the micrometer removed and the transformer was ready for use.

Volume Change

Although the importance of the relationship between pore pressure and volume change was recognized in this research program, the technique of measuring volume change was the last to be successfully accomplished. This delay was caused primarily by attempting, during the early development period, to measure volume changes rapidly with respect to time instead of the volume change taking place during the conduct of the entire test. Accordingly, the first volume change device shown in Figure 6 was based on a float principle which recorded the change in cell fluid level as the test progressed. By relating the incremental increase in fluid with the deformation, and knowing the area of the cap, the volume increase or decrease could be computed. This device was eventually perfected and used for one test. It was successful in principle but unsuccessful from the test standpoint because its range was not great enough. This, in turn, was directly the result of being forced to use a 040 LVDT due to space requirements which did not have the necessary range.

The failure of the float device required that other techniques be investigated. An earlier research project by Schaub (5) on volume changes in bituminous mixes during the triaxial test,

made use of the technique used at Imperial College of Science, University of London and described by Bishop and Henkel (6). This device was adapted to this research and is shown schematically in Figure 7.

In partly saturated soils, a volume change occurs due to densification of the soil and compressibility of the air in the pore space. This change is determined by measuring the volume of fluid entering or leaving the cell as the test is conducted. The measurement is made by observing the displacement of a free surface between the water supply to the cell and some other fluid such as mercury. Any change in volume of the soil ^{causes} ~~caused~~ a change in volume of the liquid in the cell which, in turn, is reflected by a change in the level of the mercury in the measuring tube. A differential head of mercury between the mercury reservoir and the measuring tube is avoided by suspending the reservoir on a calibrated spring which ^{changes} ~~changed~~ length directly as the mercury level ^{changes.} ~~changed~~ in the measuring tube ~~changed~~.

Referring to Figure 7, the mechanism of the device is shown in detail. With application of pressure to the cell, a decrease in volume of the sample takes place which causes the volume of the cell liquid to increase and the level of mercury in the measuring

tube to rise. For the soils studied in this research program, a decrease in volume of the soil took place rapidly at the beginning of the test. This caused the mercury level to rise further until the volume change stabilized or reached an equilibrium value. In those tests where failure did not occur and the sample was tested statically to failure, the mercury level was lowered in the measuring tube as volume expansion took place. By reading the metric scale adjacent to the measuring tube, the changes in level of the mercury were read to the nearest millimeter. For this device, a change in level of one millimeter corresponded to a volume change of .030321 cubic inch.

The observed displacements in mercury level must be corrected for temperature differentials, expansion of the lucite cylinder under confining pressure and for volume changes reflected by movement of the loading ram. In the case of temperature changes, the use of a controlled temperature chamber prevented any volume changes arising from this source. During an increase in cell pressure the cell itself expands, causing a volume change which must be deducted from the observed displacement of water. This change was established by conducting calibration tests at various confining pressures. An exact dummy was machined to dimensions of 4,000 inches diameter and 8,000 inches in height. This was placed in

the cell and the confining pressures applied. It was noted that the change recorded for the various confining pressures occurred almost instantly and did not increase appreciably with time after the first 10 minutes. Accordingly, the confining pressure was applied for the period of 10 minutes at least before each test so that this correction did not need to be calculated out. During loading of the sample, water is displaced by the penetration of the loading ram into the cell causing a volume change which must be added to the observed decrease in volume. This change can be calculated based on the area and penetration of the ram. Data on calibration of the cell for various confining pressures as well as tabulations of volume changes resulting from penetration of the ram are normally computed to show the magnitude of the correction.

There are several sources of error to be avoided in using a device of this type to measure volume change. One of these is the possibility of entrapment of air in the top of the triaxial cell. This air will be compressed at high confining pressures and eventually enter into solution causing erroneous volume changes. Another source of error is that arising from water leakage in the cell and volume change apparatus. Thus all joints must be tight and leakproof. In early tests using this apparatus, some errors resulted in the measured volume changes due to both sources.

In addition, for tests of long duration, errors may arise from creep in the Lucite cylinder and leakage through the rubber membrane.

TEST CONDITIONS

Prior to commencing design, or purchase of any equipment, considerable thought and planning was given to the conditions of test since these would control the size of the equipment which was necessary.

The first consideration was given to sample size. A granular material was to be used although of small diameter. In addition, the sample would be compacted, after laboratory mixing in such a manner as to permit the specimen to be handled. For such samples, the 4 inch diameter sample is customary, since the the same compaction equipment can be used as is used for the standard compaction test. Furthermore, the measurement of pore pressure utilizing a probe indicated a sample as large as practicable. Normally an l/d ratio of 2:00 to 2.5 is used, thus the sample should be at least 8 inches high.

As was mentioned earlier, the accurate measurement of pore pressure can only be accomplished under conditions where the ambient temperature differential is zero or close to zero, so that no pore pressure changes can be suspected as being derived from changes in temperature. Thus the equipment was placed in a

controlled temperature environment where a constant temperature from 0 degrees to 40 degrees centigrade could be obtained. The decision as to what temperature to use in testing was mainly one of comfort for the personnel and economy of operation. The value of 68 degrees fahrenheit (20 degrees ^{centigrade} ~~centigrade~~) was thus selected as meeting the above conditions in addition to being a standard reference temperature for many materials.

The matter of rate of load application was quite difficult to reconcile. Factors to consider were equipment capability, pore pressure build-up and dissipation, relation to field conditions and continuity with previous work. The limitation on equipment was imposed chiefly by the port size of the reducing valve on the main air line and the volume of air necessary to build up the load to its maximum value. From previous experience (2), it was known that some time delay could be expected. In order to keep this to a minimum, the air cylinder and valves should be as close to each other as possible and the cylinder as small as possible, consistent with the expected loads. Timers were not a problem. The possible range for equipment design purposes was 0.1 to 0.10 seconds interval between load applications and 0.5 to 10 seconds load duration.

From the standpoint of pore pressures, the rate had to be slow enough so that the pore pressure build-up during load would

have time to dissipate prior to the next load application, and fast enough to prevent redistribution of the pore pressures in the sample with load application. If performed too fast, on the other hand, the response of the equipment might not indicate the true magnitude of the pore pressure change.

Seed, Chan and Monismith (7) found that for compacted clays the frequency of load application was not related to total deformation. Haynes (8) in his study of the ^{AASHO}~~AASHTO~~ Test Road base course materials, used a frequency of 40 repetitions per minute; Larew (9) used 20 cycles per minute. Although some of the early pilot tests were run at 30 cycles per minute, it was found that the equipment performed very well at 40 cycles per minute with one second load duration and one-half second interval between load applications. This rate was used for all tests except where indicated otherwise.

No program of research on soils should attempt to fix limits on or assign values to all the variables under consideration. On the other hand, some intuitive reasoning must be used to set some of the boundary conditions. This was particularly true of the deviator stress used for the specimens. If the stress selected was too high, the specimen would fail under few load applications, and

conversely if too low, would result in low strains and pore pressure values. Accordingly, the decision was made to fix the deviator stress on some percentage of the peak compressive strength of the soil sample as determined from a static triaxial (UU) test. All other test conditions were to remain the same. This was done and the deviator stress fixed at 30, 40 and 50 percent of the peak compressive strength at each confining pressure.

Lastly, the confining pressures were selected. These had to be high enough so that the pore pressure changes would always be positive during the test yet not be dangerous to the personnel (6). Although early tests were run as high as 50 psi lateral pressure, this was changed during the test programming to 30, 35 and 40 psi.

SOILS AND MIX DESIGN

The soils used in the study were selected on the basis of research continuity. A number of research projects at Purdue, both past and present, have used local soils of essentially the same properties. Indeed, the source is usually in the same general area. The desire to expand this research in the area of dynamic testing of soils, led to the early decision to work with these soils. For correlation purposes and because of its known properties, Ottawa sand was selected for the aggregate. Ottawa sand has a high degree of sphericity and smoothness in sizes above the No. 100 sieve. Since little amount of the fractions below this size exist in situ, the smaller fractions are produced by crushing. These small sizes are composed of grains having a high degree of angularity and low degree of smoothness. The maximum vibrated dry density of the test sand was found to be 102 pcf. with a corresponding porosity of 0.35. The binder, considered for this study to be the minus No. 200 sieve fraction was chosen on the basis outlined above and is known locally as the "Crosby-B" soil.

The Crosby, B horizon is a soil very common in Indiana derived from glacial drift and can be described as a silt loam. Total clay content averages 35 percent of which the majority of the clay mineral is illite and chlorite. Less than 10 percent is

coarser than silt size (.05mm) and 100 percent passes the No. 10 sieve. Tests show the liquid limit to average about 34 percent and the plastic limit 20 percent.

Of the very large number of variables to consider in such a test program, it was recognized that the binder content was one of the most important. Accordingly, the sand gradation was held constant based on a design gradation computed from Talbot and Richarts' expression $p = 100 \left(\frac{d}{D}\right)^n$ where $n = 0.5$ as shown by Fuller for maximum density. The computations, using D equal to the No. 10 sieve size resulted in a binder content which was varied as follows:

- a. Maximum binder required for maximum density,
- b. Excess binder,
- c. Minimum binder.

Referring to Table 1, the percent by weight passing each sieve size can be noted ($n = 0.5$).

Thus the percent binder, or the minus No. 200 sieve fraction is seen to be 19 percent. This value of 19 percent established the binder content for the A series for which maximum density was the criterion.

TABLE 1

Summary of Mixture Gradation Data

<u>Sieve Number*</u>	<u>Opening Inches</u>	<u>Percent Passing A Mix</u>	<u>Percent Passing B Mix</u>	<u>Percent Passing C Mix</u>
10	0.0787	100	100	100
16	0.0469	77.2	80.0	75.8
20	0.0331	65.0	69.3	62.8
30	0.0232	54.4	60.0	51.5
40	0.0165	45.8	52.4	42.3
50	0.0117	38.6	46.1	34.6
70	0.0083	32.6	40.8	28.2
100	0.0059	27.4	36.2	22.7
200	0.0029	19.0	29.0	14.0

* U.S. Bureau of Standards

From the work of Miller and Sowers (10), the amount of binder required for nearly cohesive behavior was fixed at 10 percent more than for maximum density or 29 percent. In the tests conducted during the aforementioned research, Miller and Sowers found that if the volume of voids in the compacted aggregate is assumed to be just filled with compacted binder, the resulting amount was 22 percent. Similarly they found that the mix exhibited pure cohesive behavior at binder contents above 33 percent. Applying this relationship to this research led to the decision to use 10 percent more binder or a total of 29 percent in an attempt to obtain data for the boundary condition of almost pure cohesive behavior.

Similarly the lower range of 14 percent binder was arbitrarily fixed as a reasonable lower value for which more nearly cohesionless behavior would be obtained and which at the same time would be high enough to permit relatively uniform saturation of the specimen and handling stability.

Once the elements of the test specimen had been established, the matter of compaction was considered. This was a problem of more than ordinary interest since several factors had to be considered when pore pressures were to be measured which were not applicable to ordinary compaction procedures.

One of these factors was that of placement of a probe in a sample containing aggregate compacted to a high density. Obviously this could not be accomplished after compaction was completed. Thus it must be accomplished at the time the specimen was compacted, yet the specimen must admit of high or desired density, and 100 percent (essentially) saturation in order to obtain valid test data.

Chamberlin (11) found that vibration of the mold for 60 to 90 seconds on the upper tray of a Gilson mechanical sieving apparatus produced maximum density for open graded base course materials. For open graded mixes this method is not only satisfactory but is nearly mandatory if degradation is to be avoided. When binder is added in any proportion such that the mix is no longer open graded, two possibilities exist. Either the mold and soil can be vibrated together or dynamic loads can be applied to the soil alone to achieve compaction. The first procedure cannot be effectively utilized for dense graded mixes, hence the latter must be used. The greatest difficulty in applying vibration to the soil lies in evaluating the compactive effort or energy imparted to the soil sample.

Kneading compaction was given some consideration, primarily from the standpoint of the clay mineral structure formed in a

kneading compactor as well as the similitude with field compaction methods. The clay structure is more oriented in kneading compaction than that produced by impact compaction tests. Again in the latter, the clay particles are more oriented than those in a static test. Since the binder soil averaged about 35 percent clay, a total of approximately 6.7 percent (A Series) of the sample by weight was composed of particles in which the surface forces predominated and the remainder composed of particles in which the gravity forces predominated. Evidently clay structure contributed relatively little to the strength properties of the sample.

A considerable body of respected opinion holds that impact compaction techniques no longer serve for laboratory tests. This fact and the foregoing discussion notwithstanding, it was determined in a comprehensive series of tests that the impact compaction method conducted in accordance with ASTM Specification D698-42T produced resulting densities highly consistent in molding water content as well as dry density; this method of compaction was used throughout.

Furthermore, in view of the intent to measure pore pressures, it was felt that a less oriented clay structure would improve the degree of saturation obtained as well as reduce the tendency of

the sample to swell, particularly during the period when the sample was being readied for testing and the lateral pressure was not yet applied.

The modified AASHO densities and optimum moisture contents are reported below:

<u>Mix</u>	<u>Maximum Density pcf</u>	<u>Optimum m.c. percent</u>	<u>Binder Content, percent</u>
A	136.5	6.35	19.0
B	140.5	6.45	29.0
C	135.5	6.25	14.0

Hygroscopic moisture in the binder was determined and the added water then computed. Densities were computed from oven dry weight of the sample after test; specific gravity of the soil grains averaged 2.67 and for the Ottawa sand 2.65. It will be noted that the compacted moisture contents tended to average about one-half percent below optimum.

TEST PROCEDURE

This section of the report details the procedures followed in preparing a sample for testing, testing the sample in the repeated load apparatus and data recording procedure. Specific problems of probe design are described.

Sample Preparation

The proportion of each fraction making up the design mix being used was weighed out carefully and thoroughly mixed in the dry state. The amount of water (less hygroscopic moisture in the binder) necessary for compaction was boiled, cooled to room temperature and mixed into the dry soil.

After mixing was completed, the soil was compacted in the 4 inch diameter by 8 inch high split mold. In each case it was desired that the sample be compacted to maximum density at optimum moisture for the design mix in question. During compaction a brass dummy of the same dimensions as the probe was placed in the soil at mid-depth. The dummy had a threaded screw hole in the base to facilitate removal when compaction was completed. After carefully leveling the top surface and filling voids from loosened sand grains, the specimen was removed and weighed. As quickly as possi-

ble the dummy was removed and the probe which had been de-aired by boiling for 15 minutes was inserted. The top of the probe minus the cap was covered with a one centimeter square piece of filter paper to restrain sand grains from entering the small orifice and screw holes. Insertion of the probe was easily accomplished since the diameter of the dummy was made 0.005 inch greater than the diameter of the probe. In addition, the round and semi-round grain shape of the Ottawa sand permitted a relatively smooth surface of sliding. The use of a dummy during compaction and removal afterwards was considered to be reasonable on the basis of a remolded soil sample. Subsequent saturation in the saturation cell permitted the probe and soil to reach complete contact throughout.

When the probe had been inserted, the sample was transferred from the base of the split compaction mold to the base of a split aluminum saturation mold (Plate 4). This mold was designed and fabricated for use during a previous research project by Haynes (8). It is composed of a split thin wall aluminum tube to which a recessed aluminum top and bottom plate has been fitted and fastened by three $3/8$ inch diameter brass rods. Holes $1/8$ inch in diameter were drilled at regularly space intervals over the periphery of the tubing to permit flow of water into the sample.

The interior dimensions of the mold are exactly 4 inches in diameter and 3 inches high when assembled.

Previously prepared damp filter paper was wrapped around the sample, smoothed and the mold clamped tightly around it. The saturation mold containing the sample was then lowered into the saturation tank and covered with de-aired water. The cover of the tank was positioned, the gasket wetted and the nuts turned tight. A vacuum was then applied for 15 minutes after which the hoses were clamped securely closed and the tank replaced in the controlled temperature room for 24 to 48 hours.

Testing

After considerable trial and error, modifications to equipment as well as experimentation, a testing technique evolved which was followed during the majority of the tests conducted in the research program. These procedures are, in general, unique to these test conditions; doubtless they could be improved upon in several ways.

Every piece of equipment, apparatus or appurtenance used in conducting a test was kept in the controlled temperature room at all times. When space requirements demanded, these were removed only for as long a period of time as necessary to preclude the effect of temperature differentials and thus introduce a source of error in the results.

Certain other routine procedures were consistently followed such as:

- a. The base of the triaxial cell was kept in the controlled temperature chamber. Prior to use it was submerged in de-aired water and freed of air bubbles in the system by passing de-aired water through the lines repeatedly until no air bubbles remained. All joints were made up under water.

- b. De-aired water was prepared in advance and stored under vacuum in a 20 liter jar in the controlled temperature room.
- c. A beaker of water containing the two submerged membranes for the next test was kept in the chamber.
- d. Chamber temperatures were checked daily by a laboratory thermometer.
- e. The Norton Stone used for the probe was kept in a beaker of water at all times except when in use. Prior to use it was boiled for 15 minutes to remove any trapped air. Cooling under vacuum in a desiccator jar was attempted and rejected since air was present in the sample.
- f. De-aired water was used as the cell fluid in the tests, except where volume change measurements were made.
- g. High vacuum grease was used as a lubricant on the triaxial cell piston. All mechanical joints were sealed with suitable compound.

Prior to placing the triaxial cell in the loading apparatus, adjustment of the equipment for the requirements of the test being run was made. The deviator stress or magnitude of applied vertical load was first adjusted by placing an accurate load ring under the load cell and adjusting the dial indicator of the load ring to correspond to the dead load of the piston, ram and load cell. This total weight amounted to 53.48 pounds and contributed 4.256 pounds to the total stress difference. By adjustment of the main air line regulator valve, the load was increased or decreased to correspond to the calculated load ring dial indicator reading with the apparatus cycling at test condition. Fine adjustments to the cycling and timing controls were made at this time by observing the load cell oscillogram. With time, (i.e., after several days of testing), minor readjustments to the timer were sometimes necessary. When the deviator stress adjustment was completed, the power switch was turned to the off position and the override plunger on the 4-way valve was pushed in and locked. This removed the air from the top of the piston and permitted later lifting of the piston and load cell during placement of the triaxial cell. Finally the counter was set to zero, and the confining pressure for the test in question adjusted using the pressure tank calibrator, Plate 5, and laboratory air gage.

The base of the triaxial cell was next removed from the environmental chamber and the pore liquid tubing filled with de-aired water as described previously and weighed.

Removing the saturation cell from the chamber, the vacuum was released and the test specimen removed. The screws of the saturation mold were removed and the mold withdrawn. The filter paper was also peeled off. As rapidly as possible, the sample was transferred to the base of the triaxial cell and weighed. The pore water line was pushed into the close fitting probe hole and the cap screwed on making a tight mechanical joint which did not leak. It must be emphasized that extreme care must be taken to assure that no air bubbles are trapped in the probe when this connection is made, or the pore pressure measurements will be either much in error or non-existent. During this process some grains of sand were removed in order to get the probe cap fitted and secured. This left a void in the mixture around the probe which would permit air to enter the sample. To avoid this possibility, plaster of paris slurry was spread over the probe end. This slurry hardened around the probe and in the small voids adjacent to it, eliminating the voids when the membrane was placed. In some latter tests a soil slurry was used with equally good results.

Using a vacuum pump and a brass membrane stretcher, the two wet membranes were placed over the sample and secured top and bottom with two O-rings. If the test was to be of short duration, i.e. less than eight hours, the membranes were not separated by silicone grease. If the test was to be longer than eight hours, grease was used, although little benefit was noted.

Next, the inside of the Lucite cylinder and the inner side of the top plate of the triaxial cell were smeared with a wetting agent. This was done to prevent air bubbles from forming as the cell was filled and was a great aid in ensuring complete removal of air from the cell. Using the four stainless steel bolts, the cell was assembled. The LVDT calibration micrometer was attached beneath two of the bolts during assembly (Plate 3).

The cell was now taken into the chamber and set carefully beneath the loading ram. Connections to the volume measuring device, Figure 7, and to the pressure transducer, Figure 6, were made up. The cell was now filled with liquid using extreme care to assure that no air was trapped under the top plate of the cell.

Extra tapped holes were located around the top to aid in removing all air. Note that confining pressure was not applied yet, unless compression desired. In early tests this was the usual case until the effect of volume change became known.

a ~~consolidation~~ period was ~~desired~~.

The LDVT for deformation recording was calibrated next according to the procedure described in reference (3). Similarly the pressure transducer was calibrated as described earlier, using the loading cell method shown in Plate 4. At this time the volume change device was read prior to pressurizing the cell. The cell was then pressurized. A reading was again taken on the measuring tube scale. The zero reading on the dial indicator for vertical deformation was also read and recorded. Chart feed for the galvanometer recorder was set at 10 mm/sec. and the over-ride plunger on the 4-way valve pulled out simultaneously, turning the timer switch to "on" position. The test was then in operation and readings were taken as quickly as possible for all measuring devices. After 30 cycles or so, readings were taken at every 10 cycles up to 100 cycles and thereafter at every 100 cycles to 1,000 cycles. As the test progressed, readings were taken at intervals increasing up to 4 to 6 hours towards the end of the test (Figure 8).

The procedure described above, although rather straightforward appearing, was not developed at once, but represents rather the evolution of procedure as the tests were run and refinements to both equipment and technique incorporated.

In this regard, it is considered pertinent to describe the evolution of the pore fluid sensing element, the probe. Referring

to Plate 6, a series of four probes are seen. The early tests, i.e. those on A-mixes, used probes Type B and C. Type B, the very first one used and that shown in Figure 6 was not very successful due to difficulty in preventing leakage around the membrane. Further, since the stem protruded out nearly one-half inch from the socket, the probe could not be placed in the sample and saturated with the sample. This meant that complete contact of the probe with the soil grains was not assured even with care in removing the dummy. Too, the membranes could not be re-used after each test and lastly, much time was lost in placing and connecting the probe. As a result it was decided to place the probe and pore water tube completely under the membranes. Plate 5 shows how this was accomplished. At the same time a new probe was used employing a mechanical joint at the socket. A No. 56 hole was drilled in the center of the socket along the longitudinal axis. Another No. 56 hole was then located at the exact joint between the cap and socket and 90 degrees to the first hole. The tube was then inserted and secured with two 0-80 N.F. screws. This entailed some rather refined machine work but produced a leakproof joint. Now the dummy could be withdrawn after compaction and the probe inserted during the saturation period. This technique did not produce a single failure in making pore pressure measurements.

In running the tests on the B-mixes, it became apparent rather early that considerable swell was taking place prior to application of the cell confining pressure. Therefore probe Type D was developed which permitted only the pore fluid pressure in the exact center of volume of the sample to be measured. At the same time due to the short ceramic portion on the probe, it could and was compacted into the sample. It worked very well for the B mixes (29 percent) binder but not as well as the Type C did for the A and C mixes. Various grits were tried but due to the partial saturation problem caused by swell, the 120 grit probe gave the best results. Additional developmental tests were conducted, using a very fine "India" stone produced by Norton Abrasives which is harder and more durable than those used in the test programs. This ceramic shows great promise as a probe element.

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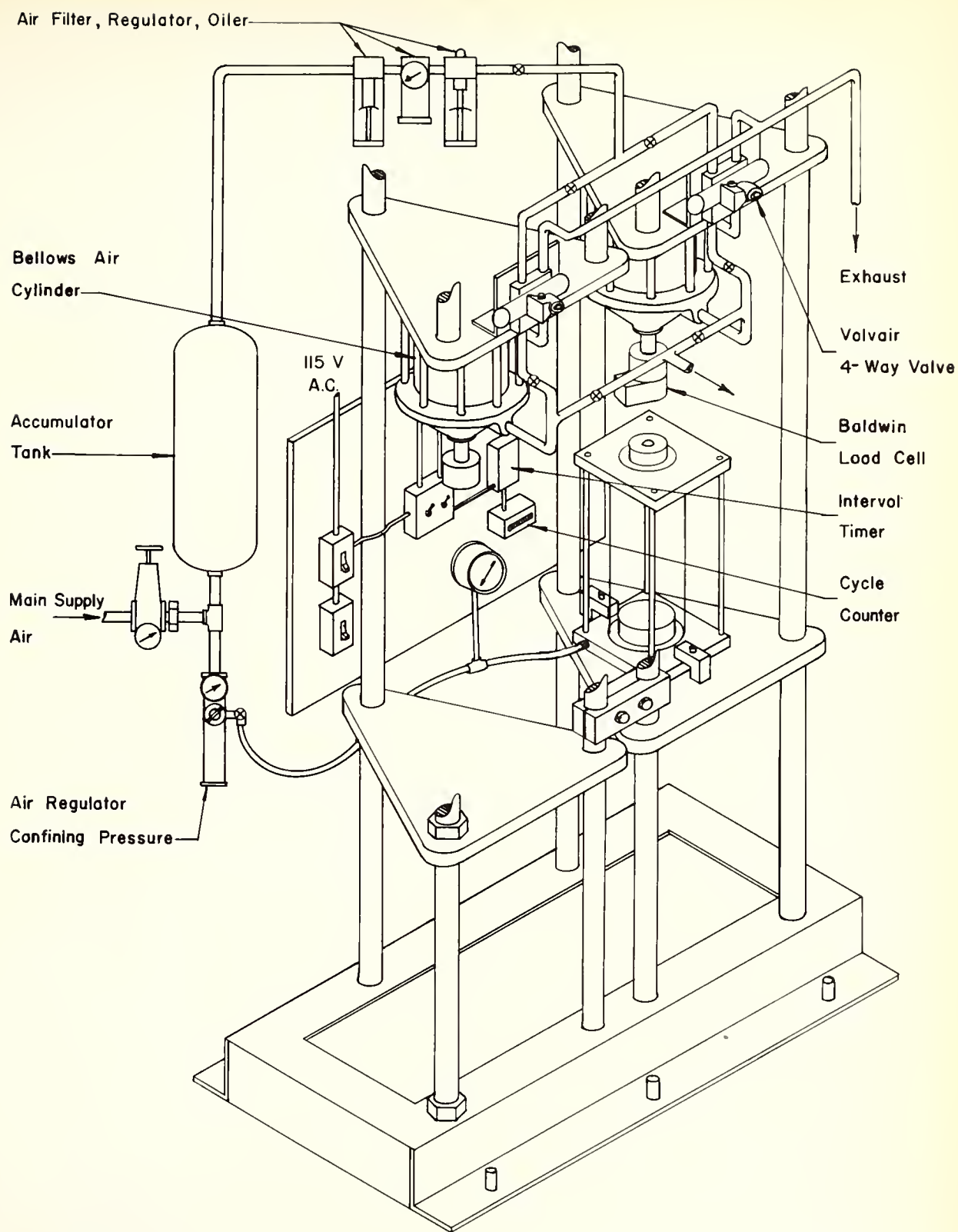


FIGURE 1.

REPETITIVE

LOADING

APPARATUS

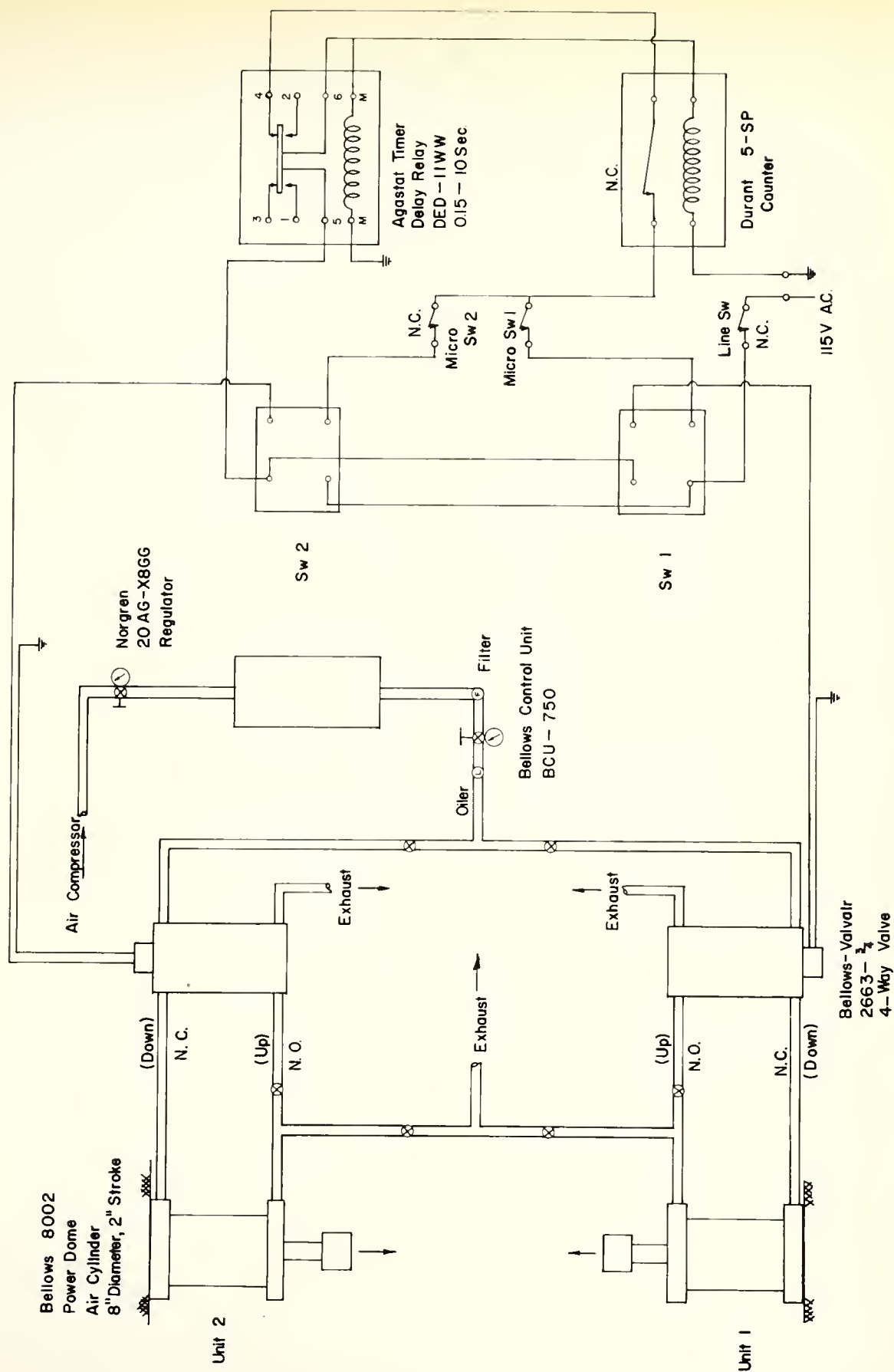


FIGURE 2 . SCHEMATIC DIAGRAM OF AIR AND ELECTRICAL DISTRIBUTION SYSTEM

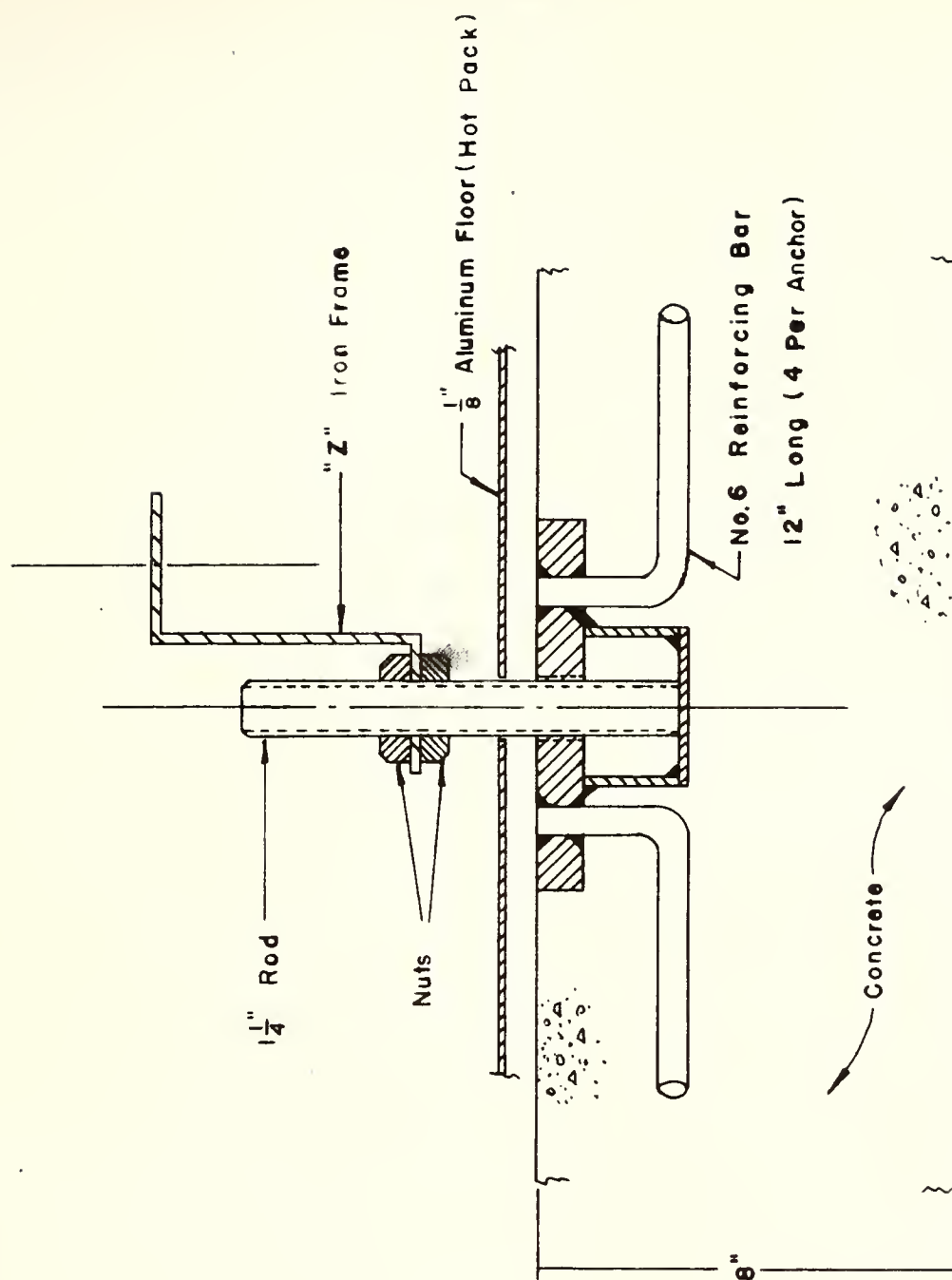


FIGURE 3. DETAIL OF LOADING FRAME ANCHOR

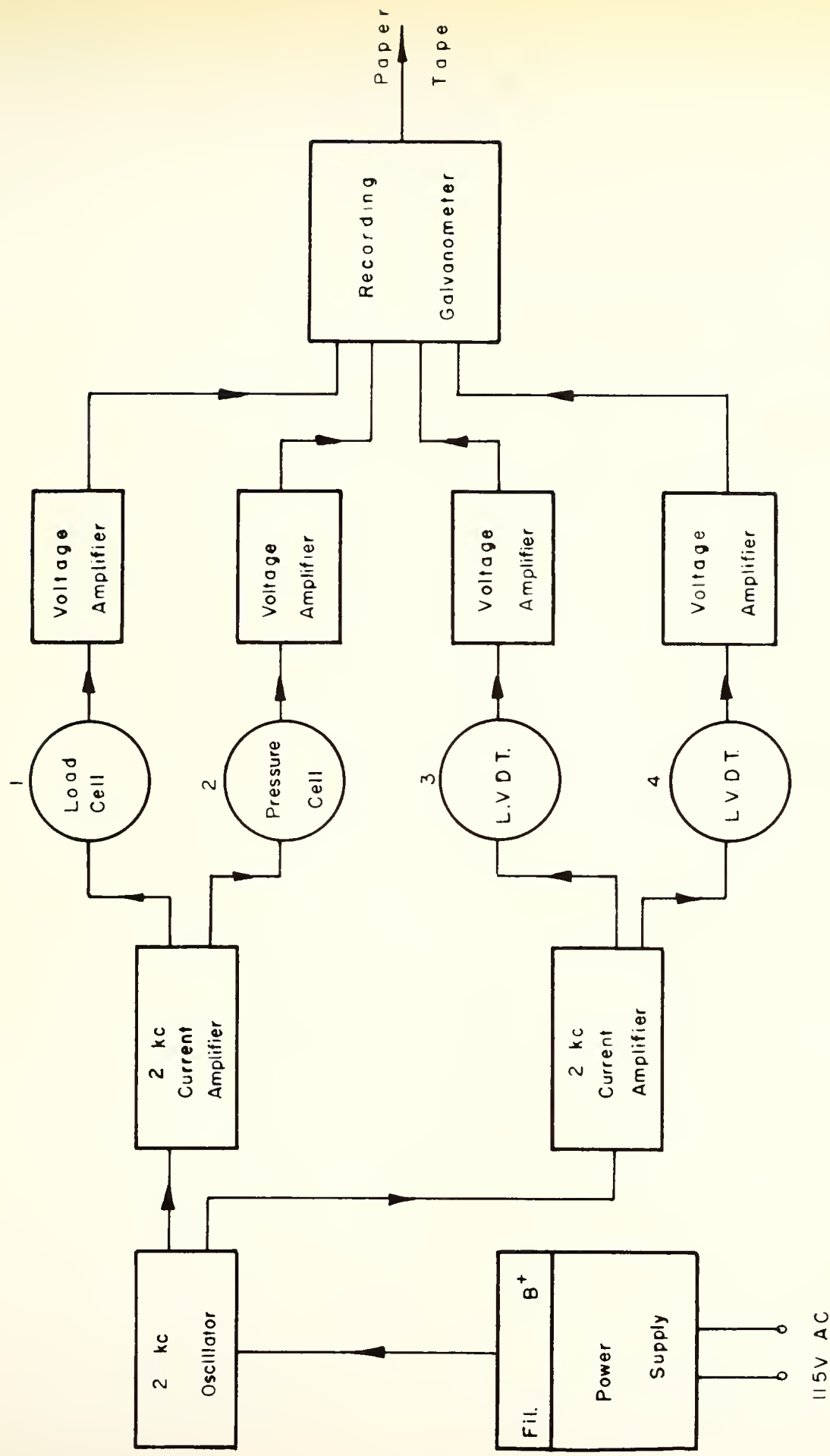


FIGURE 4. BLOCK DIAGRAM OF ELECTRONIC SENSING AND RECORDING EQUIPMENT

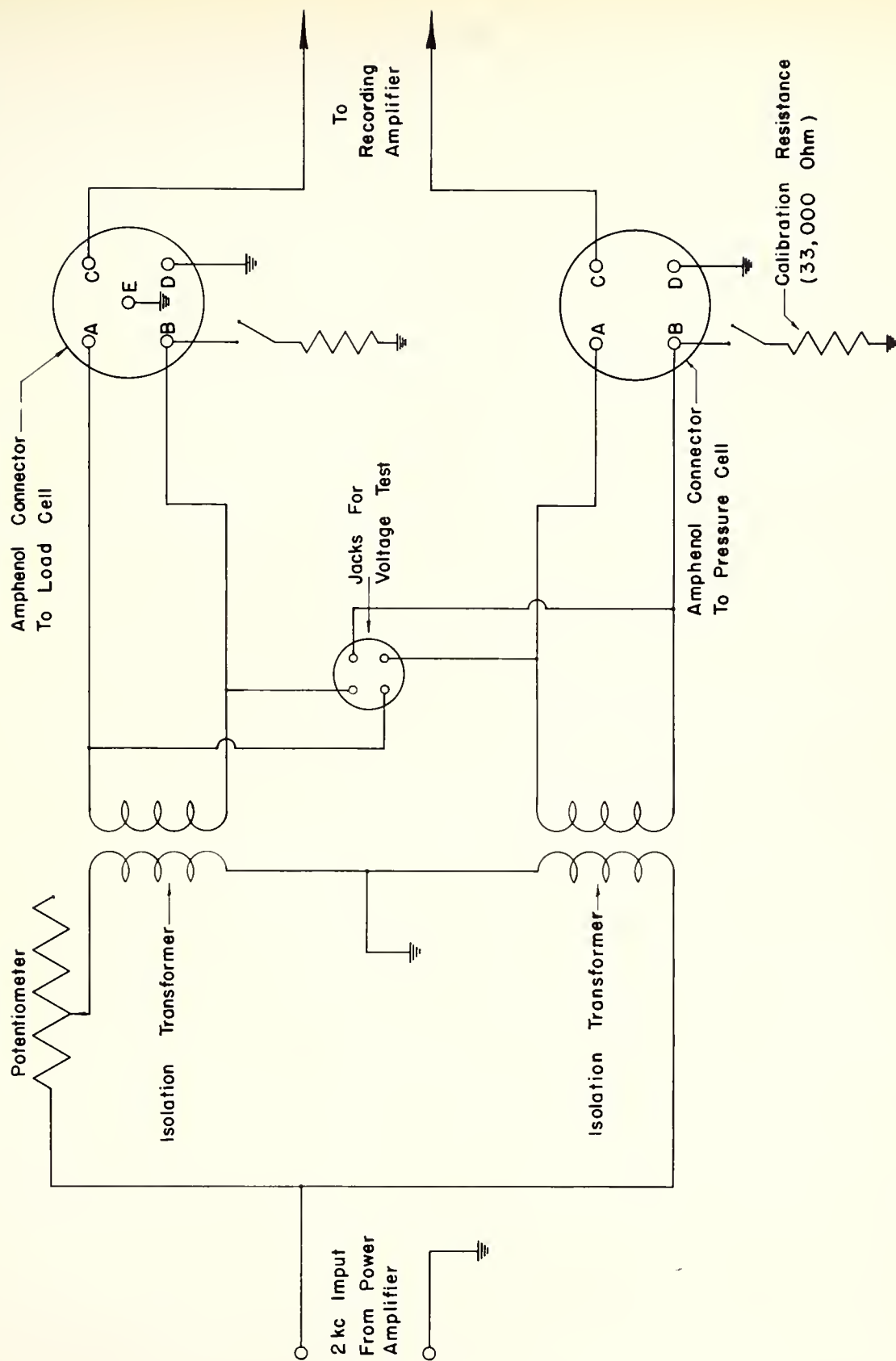


FIGURE 5. STRAIN GAGE BRIDGE UNIT

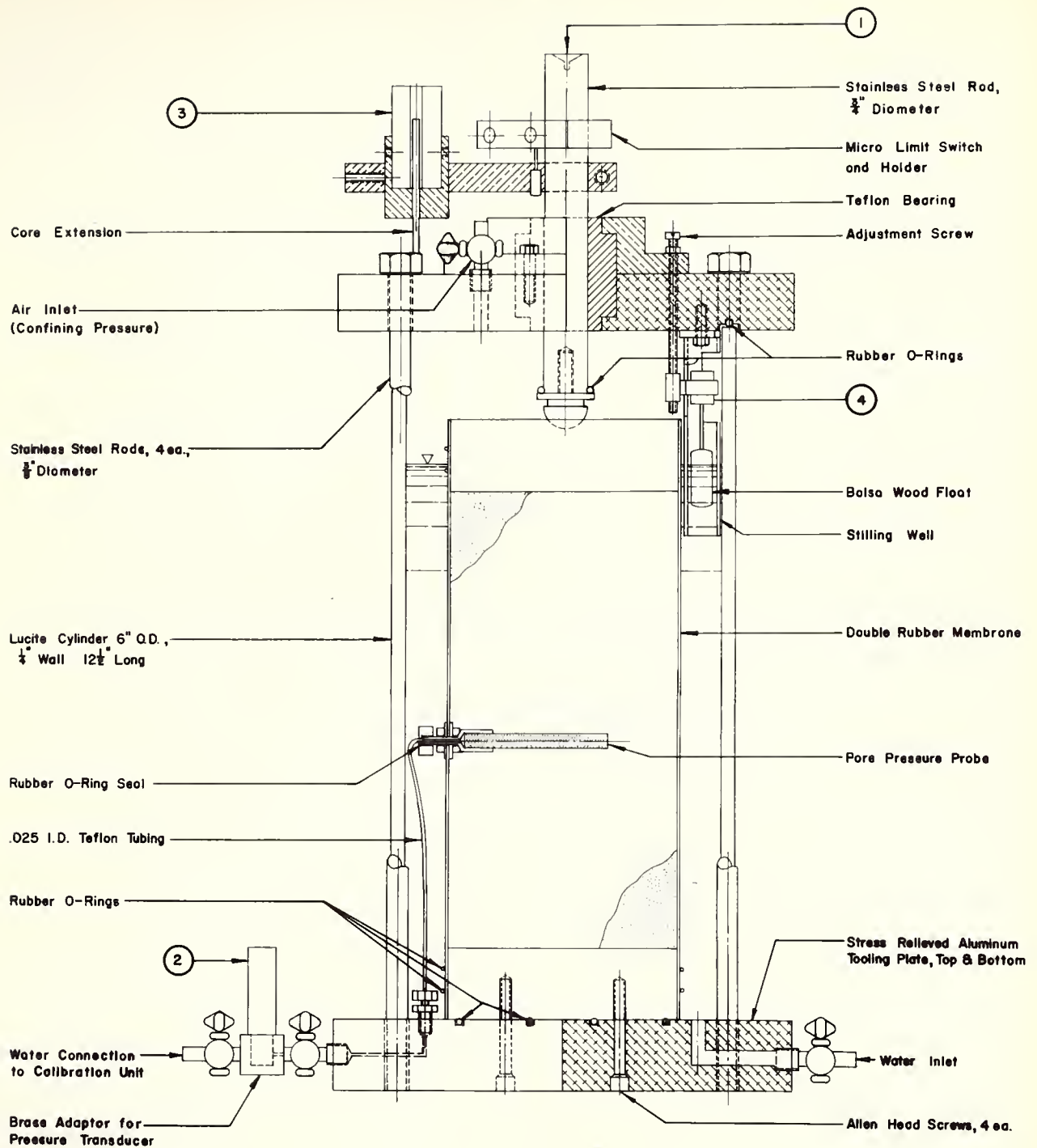


FIGURE 6. TRIAXIAL CELL SHOWING ELECTRONIC PICKUP DEVICES

NOTE:

1. During Filling Of Cell, Valve A, D, & E Open; B & C Closed.
2. With Valve D & E Closed, Valve A Is Closed And B & C Opened.
3. Valve D Opened, Cell Is Pressurized.

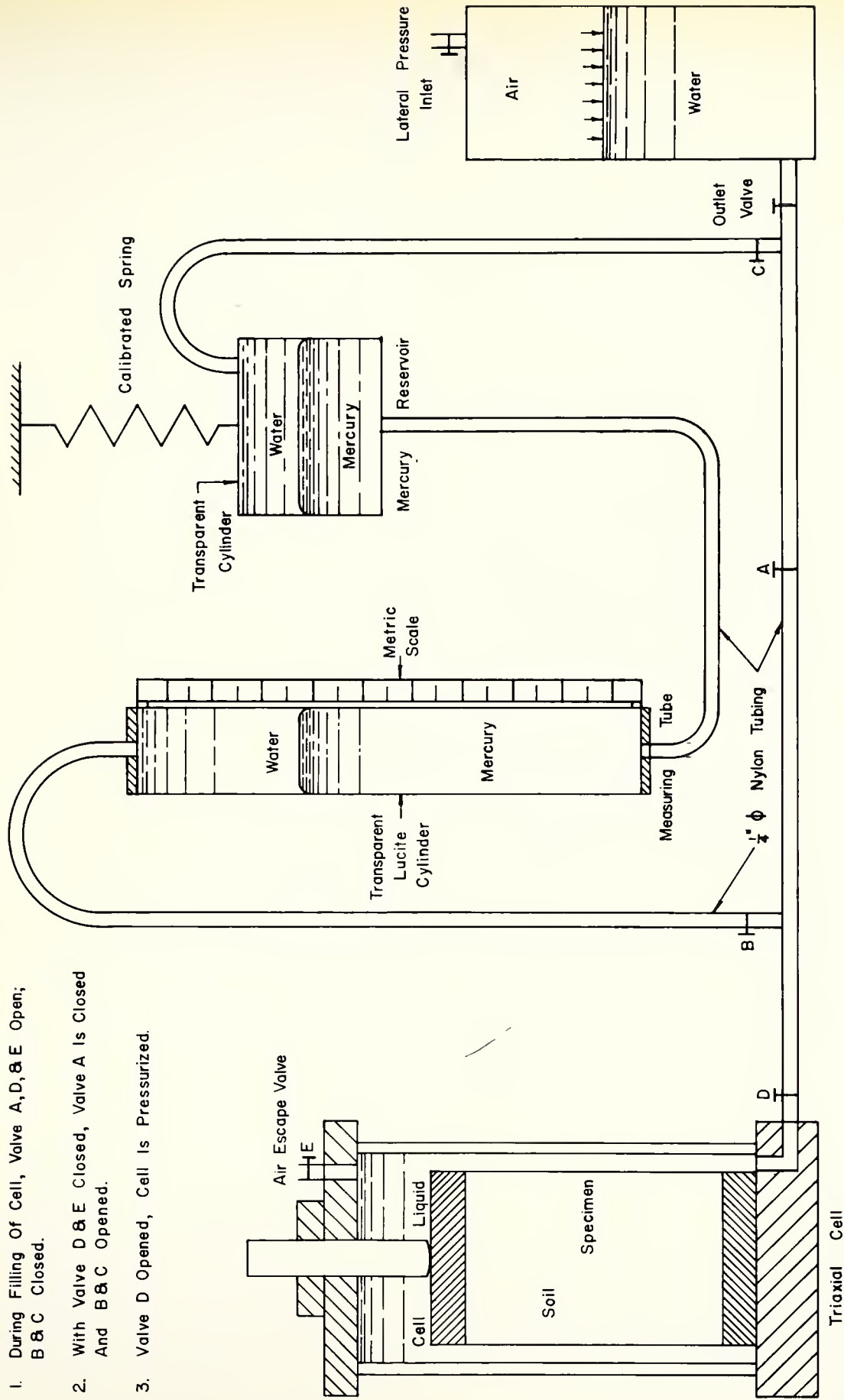


FIGURE: 7 APPARATUS FOR MEASURING VOLUME CHANGE UNDER PRESSURE

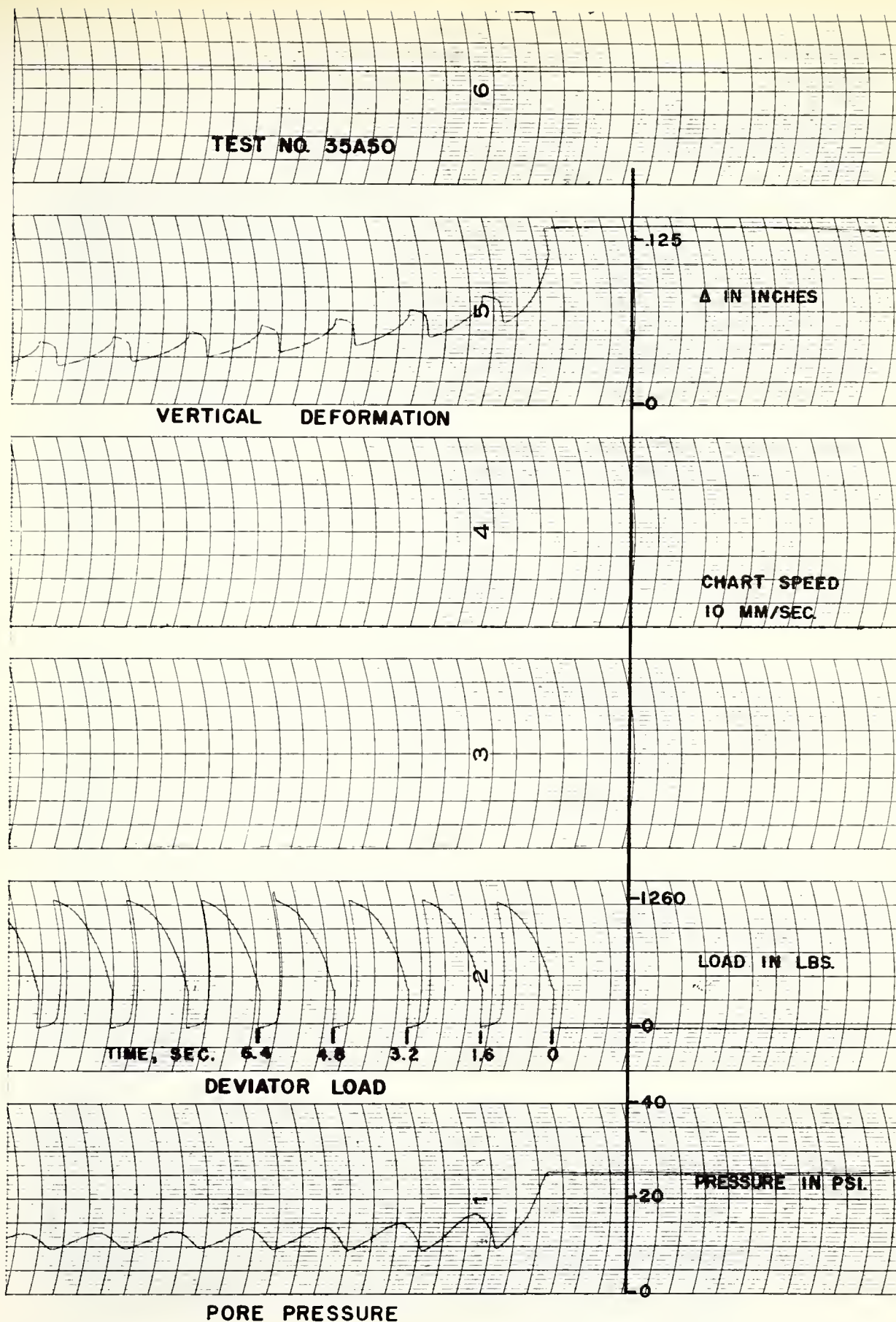


FIGURE 8. TYPICAL OSCILLOGRAM SHOWING RECORDED TEST RESULTS

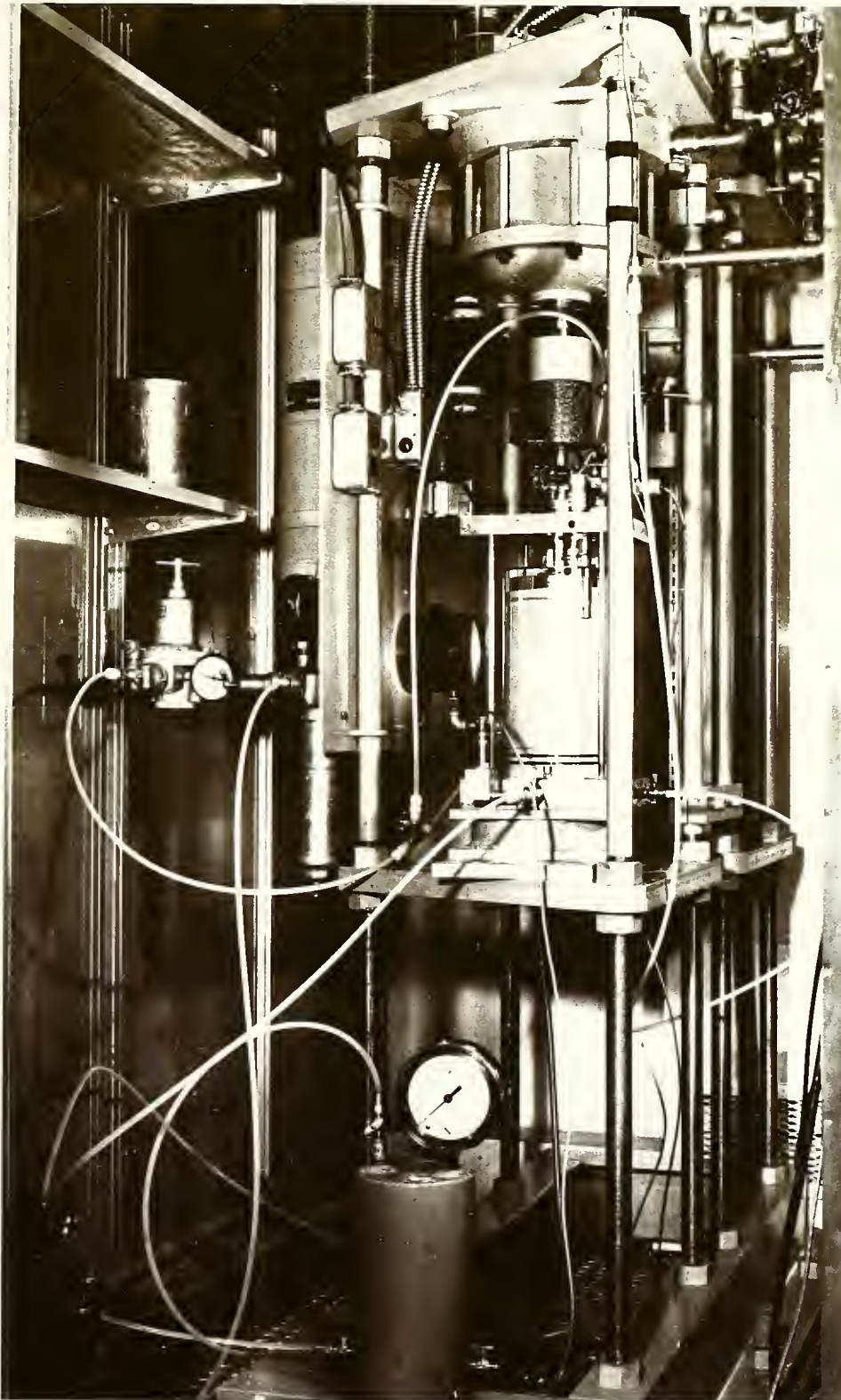


PLATE I. TRIAXIAL REPEATED LOAD APPARATUS

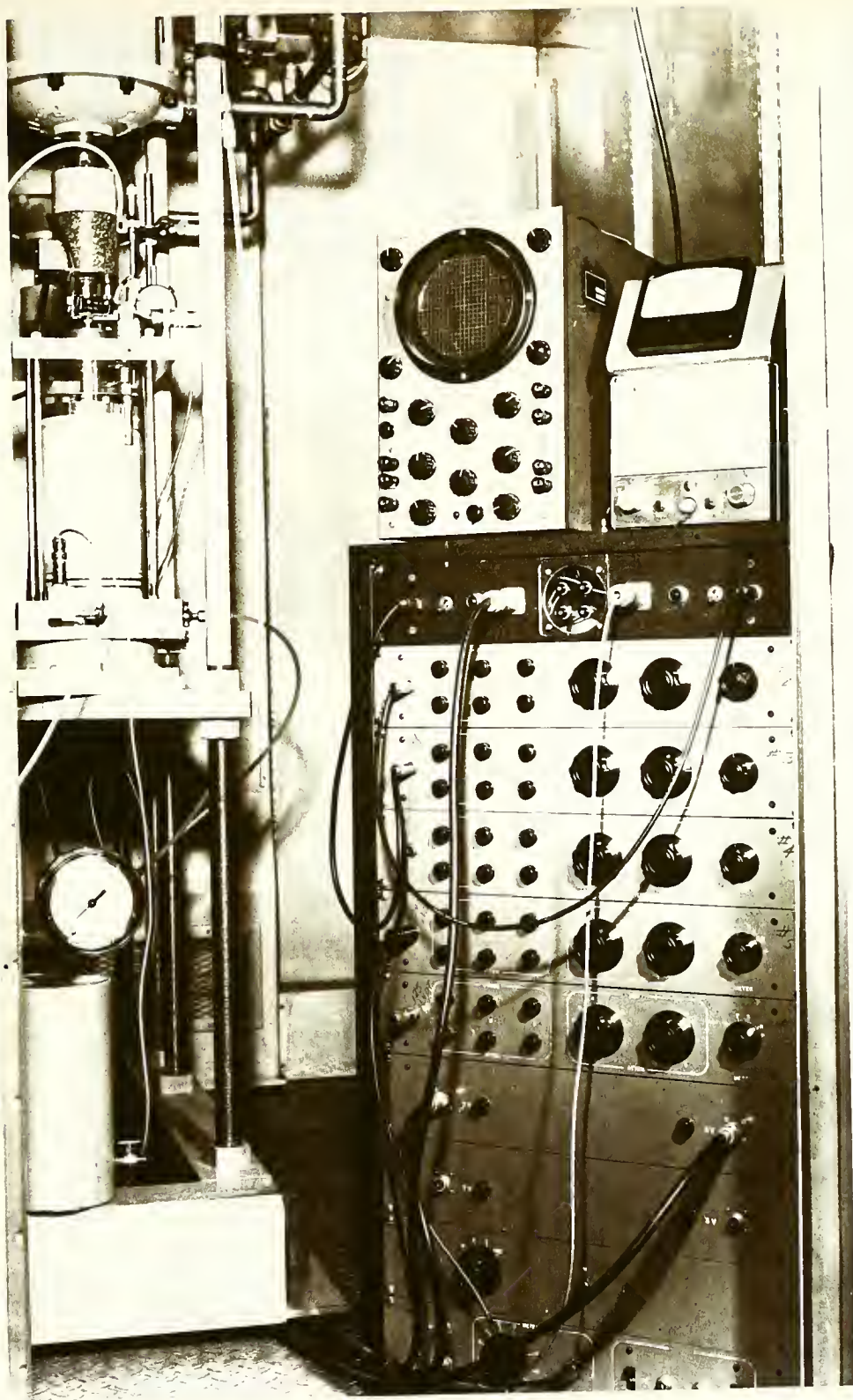


PLATE 2. ELECTRONIC EQUIPMENT IN CONTROLLED TEMPERATURE CHAMBER

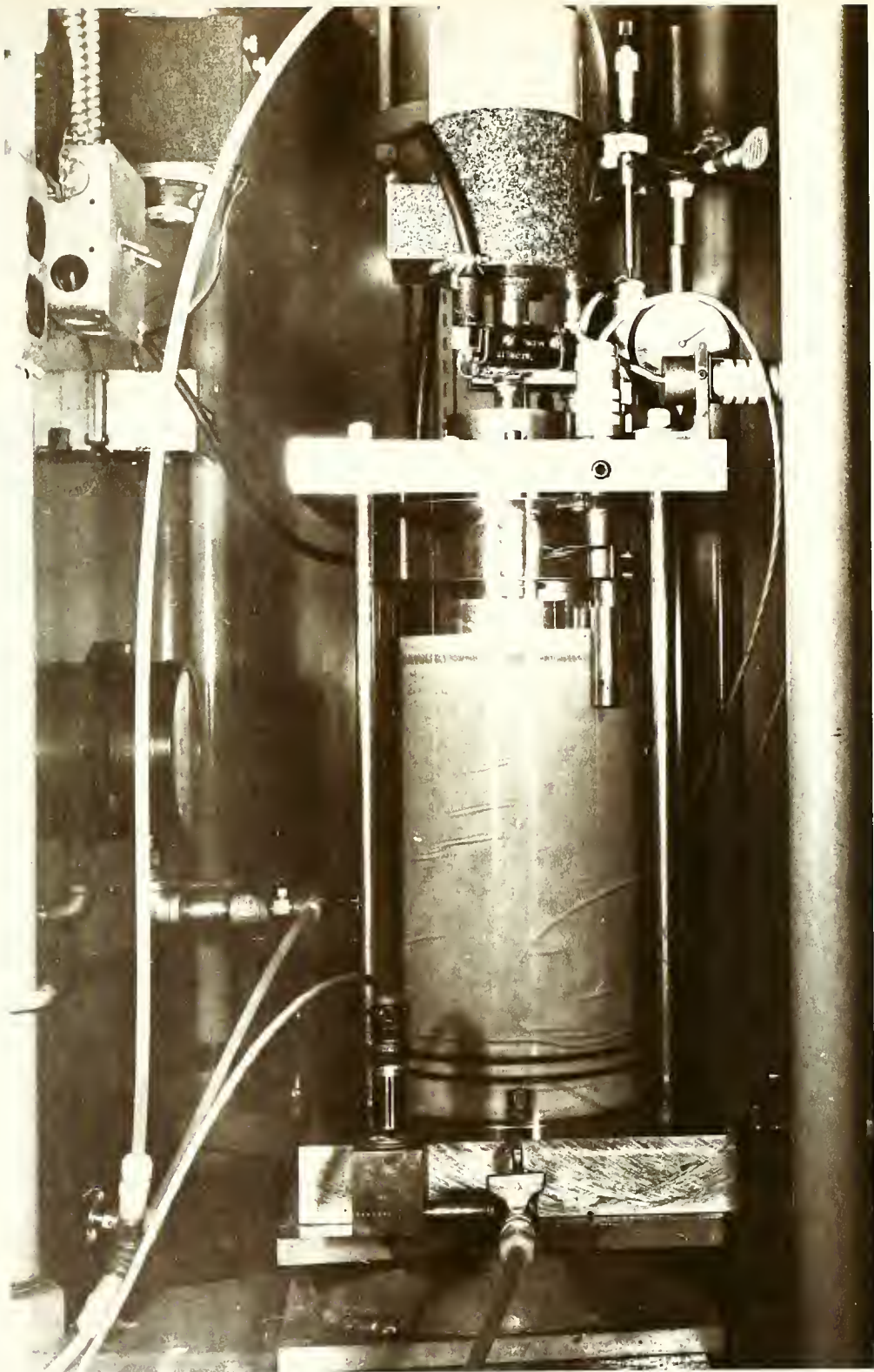


PLATE 3. TRIAXIAL CELL WITH SPECIMEN.
NOTE FAILURE PLANE DEVELOPED IN TEST.



PLATE 4 SPLIT SATURATION MOLD & SATURATION CELL

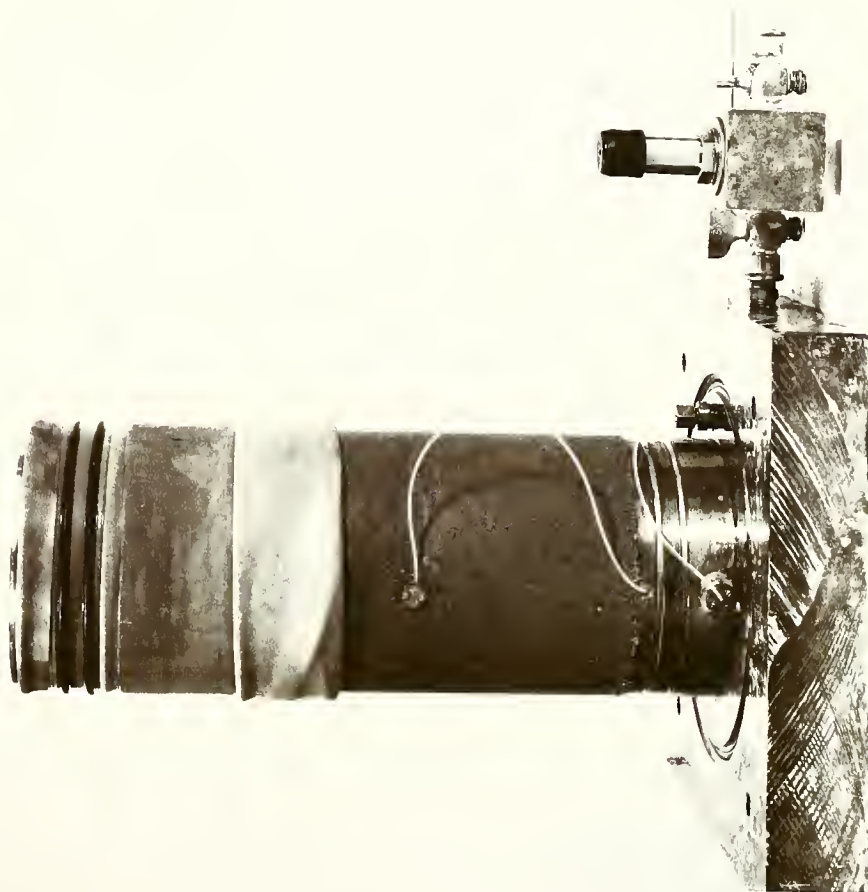
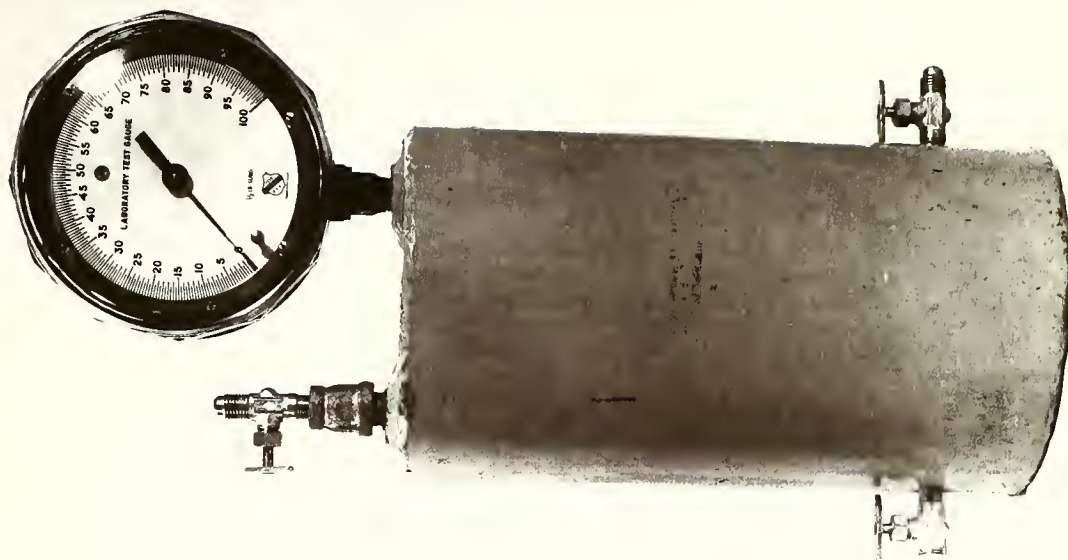
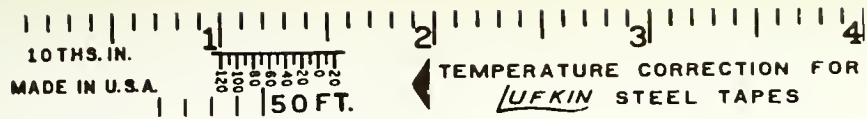


PLATE 5 PORE PRESSURE SENSING SYSTEM SHOWING CALIBRATION TANK



A. DUMMY PROBE



B. PROBE THROUGH MEMBRANE



C. PROBE UNDER MEMBRANE
USED WITH DUMMY



D. PROBE UNDER MEMBRANE
COMPACTED IN SPECIMEN

