COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES
GEOLOGY AND GEOPHYSICS

CORE ANALYSIS IN AUSTRALIA METHODS EMPLOYED AND FACILITIES AVAILABLE

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RECORD 1965.193

ECONOMIC COMMISSION FOR ASIA AND THE FAR EAST
COMMITTEE ON INDUSTRY AND NATURAL RESOURCES

Symposium on the Development of Petroleum Resources of Asia and the Far East

Third Session: 10th—20th November 1965
TOKYO, JAPAN

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CORE ANALYSIS IN AUSTRALIA

(METHODS EMPLOYED AND FACILITIES AVAILABLE)

by

M.C. Konecki(1), P.G. Duff(2), and B.A. McKay(3)

INTRODUCTION

There are two main organizations in Australia which currently carry out core analysis and associated investigations in connection with petroleum exploration and development. One of these organizations is the Bureau of Mineral Resources, Geology and Geophysics, a Division of the Department of National Development of the Federal Government; the other, Core Laboratories Australia Limited, a subsidiary of Core Laboratories, Inc. of U.S.A., is a private service company operating on a commercial basis.

This latter service organization operates three kinds of laboratories:

- A permanent, fully equipped laboratory to which the preserved core material is sent in from the field for analysis. Such a laboratory has been set up in Brisbane, Queensland.

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(1) Supervising Petroleum Technologist
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- Mobile, skid-mounted or trailer-mounted laboratories at remote well locations.
- "Suit case" core analysis laboratories, fully portable, which can be quickly set up in any suitable place at the well location, including skid or trailer-mounted mud and cuttings logging units. In this operation core analysis is usually performed on random core samples throughout the progress of the drilling, including in particular, any hydrocarbon-bearing sections.

The core analysis laboratory of the Bureau of Mineral Resources forms part of the permanent petroleum technology laboratory located in Australia's capital city, Canberra. This laboratory, like other laboratories of the Bureau, provides routine and research support for its operations in the field of exploration of mineral resources of the country and carries out, if required, laboratory investigations for the industry or individuals. This service to the public is free of charge.

In carrying out core analysis both these organizations follow procedures recommended by the American Petroleum Institute.

Two types of core analysis are performed in Australia, viz. the conventional and special core analysis. Sidewall core analysis is included in the conventional core analysis, although the interpretation of the results of sidewall core analysis presents specific difficulties due to the coring technique and well-bore conditions.

The techniques of core analysis involve the use of small core plugs and of the whole cores and the corresponding apparatus.

A. CONVENTIONAL CORE ANALYSIS

1. Definitions:

The conventional core analysis involves the determination of the Effective Porosity, Permeability and Residual Fluid Saturation.

(a) Effective Porosity of a rock is the total volume of intercommunicating voids available for the storage of fluids and is expressed as the percentage of the bulk volume of the rock, the formula being:

$$\phi = \frac{Vv}{Vb} \times 100$$

(b) Permeability of a rock is simply defined as its capacity to transmit fluids under a pressure gradient.

In conventional core analysis this rock property is determined in respect of a single-phase fluid, either gas or liquid. Quantitatively, permeability is defined by the empirical, linear-flow formula of Darcy:

$$K = \frac{\mu QL}{A \Delta P}$$

μ is the viscosity in centipoise units of the flowing fluid;

Q is the average rate of flow of fluid in cm^3/sec;

L is the length of rock sample in cm;

A is cross-sectional area of rock sample in cm^2;

ΔP is the pressure gradient along the length of rock sample L in atm.

The unit of permeability is the darcy: it is defined as that value of rock permeability when a fluid of one centipoise viscosity will flow through a porous medium under conditions of a "viscous flow" at a rate of one cm^3/sec. through the cross-sectional area of one cm^2 at a pressure gradient of one atm per one cm. It is a large unit, and normally one-thousandth of a darcy, or one millidarcy is used.

Gas permeability values of rocks, particularly those with capillary-size channels, are always greater than liquid permeability values to the extent of from 1% to 70%. This capillary effect, producing gas slippage or slip-flow, must be taken into account by way of the Klinkenberg correction, in order to convert the gas permeability value to the equivalent liquid permeability value; the liquid is assumed to be non-reactive, i.e., inert in respect of the rock material.

(c) Equivalent Liquid Permeability to non-reactive liquids, then, equals the gas permeability reduced by the amount due to the slip-flow effect.

Accordingly, Klinkenberg's formula for the equivalent liquid permeability is:

$$K_\infty = \frac{K_g}{1 + \frac{b}{P_m}}$$, where -

K_g = Gas permeability.

P_m = Mean pressure during flow through the rock.

b = Constant depending on the average capillary size distribution.

If Pm is large, $Kg \rightarrow K_\infty$. This statement is the basis for Klinkenberg's method of determining K_∞ by measuring Kg at several pressures Pm and plotting the respective Kg values against the corresponding values of $\frac{1}{Pm}$ and extrapolating the plot to $\frac{1}{Pm} = 0$ (or $Pm = \infty$), where $Kg = K_\infty$. (See Fig. 1).

Liquid permeability may be determined in a liquid permeameter by passing a particular liquid of known viscosity through a rock sample and using Darcy's formula for calculation as in the determination of gas permeability. However, the use of liquids which may chemically react with the rock material should be avoided if the results of permeability determination are to be correct and reliable, as they should be. For the same reason, liquid permeability determined with fresh water on rocks containing clay material may be severely reduced when compared with that determined with kerosene, oil or brine.

(d) Residual Fluid Saturation is that fraction of the effective porosity which is occupied by reservoir fluids remaining in the core when brought to the surface and at the time of extraction or retorting in a suitable apparatus.

The values of the residual fluid saturation are useful for comparative purposes rather than for quantitative evaluation. It is possible by these means to determine the presence of oil and/or gas, to determine the gas-water or oil-water interfaces, and to make inferences as to which fluids will be produced.

It is obvious that, for greater accuracy and closer approximation to actual saturation conditions, special precautions should be taken while coring, in order to avoid or reduce flushing and contamination with drilling fluid. When brought to the surface the core should be sealed to preserve all fluids present therein.

Seldom, if ever, will the sum of the residual oil and water saturations amount to 100 percent of the effective porosity; the difference is assumed to represent the gas fraction. This assumption is not entirely correct, because gas expansion results not only in the loss of volatile components but also of liquids (oil and water); gravity and evaporation losses of liquids also occur. Gas saturation of a core can also be determined by means of a mercury pump.

2. Procedures and Measurements

When the core is removed from the core barrel on the well site, the drilling mud adhering to the core is carefully wiped off with a dry rag. The core is then placed in a core box, and top of each core segment is suitably marked. Three to four-inch pieces (7.6 cm. to 10 cm) are then selected for analysis at the discretion of the wellsite geologist or petroleum engineer; the hydrocarbon-bearing sections are sampled at regular intervals, usually of one foot (30.5 cm).

If the analysis is to be performed on the spot, the suitably marked samples are wrapped up in aluminium foil or plastic bags and transferred to the laboratory. For analysis in more distant laboratories, the foil-wrapped samples are either canned in sealed tins or sealed in a layer of wax or placed in dry ice-filled, insulated freeze boxes.

The laboratory procedures and measurements are carried out either on small plugs or whole-core samples.

(a) *Small-plug Analysis*

Variant A: After unwrapping, the core sample is broken into two pieces, one about $1\frac{1}{2}$ inches and the other $2\frac{1}{2}$ inches long, (about 4 cm and 6 cm). The shorter piece is used for permeability determination and the longer-one for porosity and fluid saturation tests.

(i) *Permeability* is determined on a "horizontal" cylindrical plug $\frac{3}{4}$ inch in diameter and $\frac{3}{4}$ inch long (1.9 cm in diameter and 1.9 cm long) drilled out with a diamond core drill in the direction parallel to the bedding (if visible) or perpendicular to the core axis. When both "horizontal" and "vertical" permeabilities are required, they are determined on a $\frac{1}{4}$ inch (1.9 cm) cube cut out of the (smaller) core piece with a double-blade diamond saw. Care must be taken to mark the cube for the "horizontal" and "vertical" directions.

The plugs or cube are then extracted at 180°F (59°C) for 30 minutes or longer in a variable-speed, contrifugal extractor, using speeds from 850 to 6000 R.P.M. depending on the degree of sample consolidation. Extraction completed, the samples are oven-dried at 250°F (121°C); lower temperature is used for drying of samples with a high clay content.

After drying, the plug or cube is placed in a modified Fancher holder in the permeameter. Air is then allowed to flow from a null-balance regulator through the sample and then through a calibrated orifice. A mercury manometer indicates the differential pressure across the sample and a water manometer the differential across the orifice. The mercury manometer scale is so calibrated that its reading, when multiplied by the air flow-rate through the sample and by the length-to-area ratio of the sample, will give the air permeability value in millidarcy. (Fig.2).

This value is then converted to the equivalent liquid permeability value using a suitable table. (Work-sheet A.2a) - A).

(ii) <u>Fluid Saturation and Effective Porosity</u>. These are obtained by the "fluid summation" method. This entails the determination of the oil and water contents of the core sample in an electric retort still and of the gas content in a mercury pump.

For this, the 2½ inch (4 cm) piece of core is split in half along the core axis.

The half-piece selected for gas content determination is shaped into a rough sphere of about 20 cm^3, weighed and then placed in the reservoir of a calibrated mercury pump, and the bulk volume of the sample is correctly determined. The gas volume is obtained by injecting mercury into the sample to a standard reference pressure and reading from the pump scale the volume of injected mercury.

The other half-piece of core sample is broken up into small pieces and 120 gm of them are charged into the retort, where oil and water contents are determined.

The sum of the gas, oil and water volumes thus obtained, and expressed in percentages of the bulk volume, are assumed to equal the effective porosity. The retorting is carried out at a temperature of some 700°F (371°C) at which the free water in the core sample can be distilled out in 10 to 20 minutes. (The actual distilling time of free water in any particular formation is predetermined through measurement of a water plateau over several time intervals). This water is recorded as "initial water", and the retort is then heated to 1200°F (649°C) to drive off the heavy oil fractions. The "water of crystallization" (recorded as "final water") driven off at this elevated temperature is not included in the fluid saturation calculation. A small correction has to be made in the calculations to account for coking and cracking of oil in the retorting process. (Work-sheet A.2a) -A).

Variant B: From the four-inch (10 cm) sample a piece of about 1 to 1½ inches (2.5-4 cm) is broken off and the exposed surfaces are examined under the U.V. light.

(i) Oil and Water Saturation is determined on this piece, in the following manner:-

The outer skin is chipped away to a depth of about ½ inch (1.3 cm) and the remaining kernel crushed and sieved on a B.S.S. No.14 sieve, so that only pieces larger thatn 1.2 mm remain on the wire. They are, then, transferred to a previously weighed glass thimble with a sintered glass base. After weighing, the loaded thimble is placed in the boiling flask of a Soxhlet extraction apparatus and is supported above the level of the solvent, usually toluene.

The extraction is normally carried out for a period of eight hours, but it may be necessary to extend it to 24 hours.

The weight of water is determined from the volume reading in the graduated water receiver; when subtracted from the total loss of weight of sample, it gives the weight of extracted oil. (This oil fraction remains in the solvent in the boiling flask).

Oil and water saturations may be calculated on the weight basis relative to the sample before extraction, or on the volume basis in percent of porosity, determined on the adjacent piece of core and using assumed or determined values of the formation oil and water densities. (Work-sheet A.2a) - B (i)).

This method of simultaneous determination of oil and water saturation is a modification of the method described by Rall and Taliaferro of U.S. Bureau of Mines in December, 1946, Paper R.I. 4004.

The most obvious error in this method will be due to an insufficiently long time of extraction. Fine-grained, low-permeability rock samples require long periods of extraction, while for the highly permeable rocks with intergranular porosity the time of extraction may be cut to one or two hours.

Another source of error in water estimation, particularly of rocks with low water content, is due to the limitations in reading the water receiver scale, as well as to the condensation of water vapour of air in the condenser tube.

Gypsum, some zeolites and other hydrous minerals of the rock sample, if present, are likely to contribute to the errors through the addition of their water of crystallization to the "total water" extracted. Moreover, it has been noticed that not all of this water of crystallization is driven off on refluxing, and that further "loss" occurs on drying the sample in the oven at 110°C after extraction. As the oil saturation is obtained by subtracting the sum of the weight of extracted water and that of extracted dry rock sample from the weight of the "original" rock sample, the resulting value of oil saturation will be in excess of the true value. This error may be considerable when the oil content of sample is low.

Finally, an error in calculation of oil saturation may be introduced by the assumption of incorrect value of oil density.

(ii) Permeability and Effective Porosity, including bulk volume and grain volume, are determined on the remaining (7.5-6 cm) piece of core.

For this purpose, three plugs are drilled out of the core piece with a diamond core drill. Depending on the length and diameter of the core piece available, the plugs drilled may be of $\frac{3}{4}$ inch, 1 inch or $1\frac{1}{4}$ inch (1.9 cm, 2.54 cm, 3.2 cm) diameter. The length of plugs, after trimming of both ends with a diamond saw, is either 1 inch or $1\frac{1}{2}$ inch (2.54 cm or 3.81 cm), again depending on the size of core piece available.

One of these plugs is drilled out parallel to the core axis, and the other two are drilled horizontally at right angles to each other. If bedding or lamination is evident in the core, the "horizontal" plugs are taken along the strike and dip respectively.

After suitable marking for reference, the plugs are extracted in the apparatus as for water and oil saturation determination described above, and then oven-dried at 110°C.

Permeability, vertical and horizontal, is then determined on these three plugs in a permeameter using a single-phase fluid (dry air or nitrogen) for the flow through them.

The plug under test is held firmly along its entire length in a rubber sleeve, so that the flowing fluid may pass only lengthwise through the plug.

The calculation of permeability is made using the measured rate of fluid flow, temperature, inlet and outlet pressure (the latter is atmospheric), and plug dimensions. (Work-sheet A.2a) - B (ii) - 1).

The permeameter used in the Petroleum Technology Laboratory of the Bureau of Mineral Resources is "Ruska Gas Permeameter" Cat. No. 1011 manufactured by Ruska Instrument Corporation, Houston, Texas, U.S.A. (Fig.3).

Single-phase liquid permeability, if required, is determined in the "Ruska Liquid Permeameter", Cat. No. 1013. (Fig.4). The plug under test is first evacuated and then saturated with the particular liquid prior to the inducement of flow. For obvious reasons the determination of liquid permeability is carried out following the gas permeability and porosity determinations. (Work-sheet A.2a) - B (ii) - 2).

Effective Porosity determination involves either the measurement of bulk and grain volumes (Kobe or Boyle's Law method) or of the bulk and pore space volumes (direct method). The instrument used is "Ruska Universal

Porometer" Cat. No. 1053E, which is essentially an accurate mercury pump with the attached large steel pycnometer. (Fig.5).

The bulk volume of the core plug under test is obtained by displacement method as follows:

- Mercury is withdrawn from the pycnometer until empty and the volume scale set.
- The plug is placed in the empty pycnometer, the lid locked in position and the valve opened.
- Mercury is injected into the pycnometer until it is full (as indicated by the appearance of a mercury bead in the valve seat).
- The volume of the plug is read directly on the volume scale and the hand-wheel dial in cubic centimeters to the third decimal place.

The solids or gain volume measurement is effected by a preliminary calibration to determine the response of the porometer to various grain volumes at a constant pressure of 30 p.s.i.g. (2 atm), so that future grain volume measurements may be facilitated through the use of the resulting compression volume-to-grain volume graph. This is done by adding various accurately measured volumes of mercury (solids) to the pycnometer by means of the mump. For each volume of mercury added (or equivalent volume of air removed) the pycnometer is sealed, the pump piston advanced to give a pressure of 30 p.s.i.g. (2 atm) and the volume scale and dial readings noted. These readings are plotted against the corresponding mercury (grain) volumes. This plot gives a straight line.

When the actual grain volume determination is to be made, the core plug is placed in the empty pycnometer, which is then sealed and the air is forced into interconnected pore spaces, by advancing the pump piston until the pressure of 30 p.s.i.g. (2 atm) is reached.

When a steady pressure of 30 p.s.i.g. (2 atm) is obtained, the volume scale and dial are read. The corresponding grain volume is read directly on the graph.

The effective pore colume, then, is the difference between the bulk and grain volumes. (Work-sheet A.2a) - B (ii) - 3).

The direct determination of effective pore space volume in the Ruska porometer is carried out by mercury injection at high pressure, immediately following bulk volume measurement. With core plug and mercury remaining in the pycnometer, the pycnometer valve is closed and the system pressurised to 750 p.s.i.g. (51 atm). The volume of mercury that enters the pore spaces of the core plug is then read directly on the pore space scale and the hand-wheel dial. A 2% correction is made to the reading to account for the compression from 1 to 51 atm. (750 p.s.i.g.) of air entrapped in the core plug. Another correction must also be made for the expansion of the porometer system when raising pressure from atmospheric to 750 p.s.i.g. This correction factor, which should not exceed 0.50 cm^3, is determined prior to the bulk volume measurement. For the pore volume measurement, the hand-wheel dial is adjusted to the value of correction factor, so that direct reading of pore volume will be provided. (Work-sheet A.2a) - B (ii) - 4).

The mercury injection method of porosity determination is less accurate, but much faster than the Kobe method.

(iii) Other Tests include -
the determination of "dry" bulk and grain densities, core water salinity, and acetone and fluorescence tests.

"Dry" bulk and Grain Densities are useful in log interpretation and geophysical work. These densities are simply calculated from dry bulk and grain volumes measured for porosity determination, and the additional work involved is the weighing of the extracted and oven-dried core plugs.

Core Water Salinity is determined on the extracted and oven-dried core sample, by boiling it for four hours in a known volume of distilled water. After cooling and filtration, a measured aliquot of the clear filtrate is titrated with standard silver nitrate and the chloride content determined. The result is expressed in ppm of NaCl equivalent.

Acetone and Fluorescence Test for detection of hydrocarbon in the core is made on the core material that passed through the BSS No. 14 sieve while preparing for the extraction test for the core fluid saturation determination.

Sufficient of the powder is transferred to a test tube so that it is half-filled; the remaining space in the test tube is almost-filled with acetone and the mixture is well shaken.

After one or two hours, during which the tube is periodically shaken, the mixture is filtered and the filtrate examined for colour and fluorescence. As a check, distilled water is added to the filtrate; white precipitate will occur when hydrocarbons are present. The precipitate is recorded as trace, fair, strong and very strong, as the case may be.

(b) Sidewall-core Analysisinvolves the following operational procedure: The core sample is placed, at the well site, in a tightly-sealed jar and delivered to the laboratory, where, upon removal from the jar, it is cleanly wiped of mud etc. and then cut into two pieces. One piece, after extraction and drying, is mounted in wax in a brass bushing and permeability determined. The mercury is then injected into the sample and its gas content measured. The injected sample is then placed in a small, specially designed retort for fluid content determination; mercury, water and oil are retorted from the sample and condensed into a graduated collecting tube; they are then separated by centrifuging, and their respective volumes read directly on the graduated scale. Effective porosity is calculated by the summation-of-fluids method.

Alternatively, the sidewall core sample, properly trimmed at both ends, may be extracted for fluid content determination by the modified Rall and Taliaferro method as previously described, and permeability and porosity of this extracted and dried sample may be measured in the same manner as on the core-plugs drilled out of the conventional cores; it is also possible to drill a $\frac{1}{2}$ inch diameter core-plug out of a well consolidated sidewall core for permeability and porosity determinations. Obviously, the permeability measured on the sidewall core samples is the "horizontal" permeability.

Considering the method of obtaining sidewall cores (by percussion) and the fact that they represent mostly the flushed well-bore zone, it is obvious that the results of sidewall core analysis are bound to differ significantly from those of conventional cores. At best, therefore, the measured fluid saturations will be those of the flushed zone; water saturation will be significantly higher and oil and gas saturations lower when compared both with the true reservoir saturations and with those obtained from conventional cores. The extent of the increased water saturation of sidewall cores is greater the more porous and permeable is the reservoir rock. Coarse-grained rocks are particularly affected in this way. It also appears that gas-bearing sands are more prone to water flushing than oil-bearing sands. Generally, in the interpretation of sidewall core fluid saturations, the same considerations will apply as those used in the electric log interpretation of the invaded and flushed well-bore zones.

The permeability measured on sidewall cores is affected by the compaction (compression) and fracturing during sidewall sampling of the formation. Compaction will result in the reduction, and the fracturing in the increase of measured permeability. Sidewall cores from the well-consolidated formation will tend to show an increased measured permeability, while the less consolidated and cemented rocks will have their permeability significantly reduced. Permeability and porosity of sidewall cores may be further impaired by the invasion of drilling mud solids.

(c) Whole-core Analysis

There are many formations in which the presence of fractures, vugs or very erratic intergranular porosity makes it impossible to obtain reliable average data from measurements on any number of small-size core plugs; in some instances the fractures or vugs may be larger than the size of the core plug. Utilizing the full-diameter samples and the specially developed techniques and equipment, the core analysis of fractured, vugular or conglomerate formations is made effective and reliable. Moreover, the whole-core analysis may be also used to verify the results of small-plug analysis of the intergranular porosity-type formations, particularly when this porosity, and permeability, is irregular.

The following is a description of equipment and procedures used in the whole-core analysis by the Petroleum Technology Laboratory of the Bureau of Mineral Resources in Canberra.

(i) Residual Fluid Saturation is determined in a specially designed Dean and Stark whole-core distillation unit or in a vacuum-type retort unit. (Work-sheet A.2c)- (i) - 1 and Work-sheet A.2c) - (i) - 2). Toluene is used as a refluxing agent in the Dean and Stark distillation unit. The bulk volume of the "whole-core" sample is obtained by a careful measurement with calipers.

(ii) Effective Porosity is determined by the gas expansion method in the whole-core porosimeter which consists of a $4\frac{1}{2}$ inch (10.4 cm) I.D. chamber for receiving core and blanks, a mercury manometer, an expansion vessel and a vacuum pump. The air volume, contained at atmospheric pressure in an isolated core chamber with core and steel blanks, is flashed to a calibrated mercury manometer with an adjustable scale, and to the expansion vessel at a reduced reference pressure (Fig.6).

Initially, before the equipment can be put into service, a volume scale must be developed for the mercury manometer. This ensures that a true measurement of all air volumes flashed from the core chamber to the manometer and expansion vessel will be represented by the manometer scale at all equalization pressures. This calibration is effective throughout the useful life of the equipment.

Each core test must be preceded by a "dead" volume determination of the system. This is accomplished by completely filling the core chamber with the accurately measured non-porous metal blanks, lowering the manometer and expansion vessel pressure by vacuum pump to a standard reference, and reading the system's "dead" volume after "flashing" and pressure equalization.

This reference pressure, which is controlled at 2 centimetres of mercury below the prevailing atmospheric pressure is set by the operator for each test run on a group of cores.

Sufficient metal blanks are now removed from the core chamber to admit the core sample, and the bulk volume of the core and removed blanks are separately noted on the data sheet. The core chamber and contents are then isolated at atmospheric pressure, whereupon the manometer and expansion vessel are evacuated to the reference pressure. The core chamber is then slightly opened and the pressure across the system allowed to stabilize; the manometer volume reading is recorded.

Effective Porosity of the core sample is then calculated as follows: The bulk volume of the core is first subtracted from the sum of the system's "dead" volume and the blanks which were removed to admit the sample. This volume, which represents the volume of air space outside the core in the chamber, is then subtracted from the final reading of the volume of the system containing the core sample. This difference is a true measure of the core pore volume. (Work-sheet A.2c) - (ii) & (iii)).

(iii) Permeability is determined in the whole-core permeameter consisting of a 4-inch steel Hassler cell with an inside rubber sleeve and steel end-plugs. The cell is connected by a pressure hose to a manometer-type flow measurement device. Inlets are provided on opposite sides of the cell and at the end-plugs, so that air or nitrogen flow in the horizontal and vertical directions may be obtained. (Fig.7).

For the measurement of vertical permeability, the trimmed core sample used previously in porosity determination is placed inside the cell in the rubber sleeve and the end-plugs are secured against each of the end faces of the sample. Air pressure is applied between the inside cell wall and the sleeve, so that an effective seal around the core is obtained. By means of a null-balance regulator, air is allowed to pass through the length of the sample from one end-plug to the other and through the calibrated orifice of the flow measuring device. The pressure differential across the sample is measured by a calibrated mercury manometer, while the differential across the orifice is measured by a water manometer.

The rate of flow through the core is determined by the relation between orifice size and fluid position in the water manometer. The mercury manometer is so calibrated that its reading gives the product of gas (air or nitrogen) viscosity, differential pressure and the constant of Darcy's equation. The length and cross-sectional area of the core sample are obtained by caliper measurement. The permeability, in millidarcy, is calculated as follows:

$$K = \frac{\text{Reading on mercury column x rate of flow x sample length}}{\text{Cross-sectional area of sample}}$$

For the measurement of horizontal permeability, screens of a predetermined size are placed on opposite quadrants of the cylindrical surface of the core sample. Each screen covers a 90° segment of the core sample circumference, so that good distribution of gas over the inlet section and removal of gas from the opposite side are assured. Rubber plugs are then firmly attached to the end-faces of core sample which is placed in a rubber sleeve, so that the screens are centrally located opposite gas inlets in the Hassler cell.

Gas is allowed to pass through the screens and across the sample and the rate of flow and the pressure drop across the sample are measured with an orifice-manometer system.

Horizontal gas permeability is calculated using the following equation:

$$K = \frac{1.2\ CQ}{L\ l} \quad ; \quad \text{where:}$$

C = the reading taken from a specially calibrated scale on a differential pressure mercury manometer;

Q = rate of gas flow measured by the orifice - water manometer system;

L = length of core;

l = length of the screen;

1.2 = empirical factor determined by electrolytic model studies.

(The factor $\frac{1.2}{L\,l}$ replacing the $\frac{L}{A}$ factor in the standard permeability equation is called the "shape factor").

Horizontal permeability is measured in two directions at right angles to each other. For the initial determination the analyst tries to ascertain the direction of the principal fracturing or, where possible, of vug interconnection; the second test is then made at right angles to the first. (Work-sheet A.2c) - (ii) & (iii)).

B. SPECIAL CORE ANALYSIS

While data on basic reservoir rock properties determined by the conventional core analysis methods and techniques are useful largely for the well completion and formation evaluation, particularly when used in conjunction with data from log interpretation and formation testing, they are inadequate for the reservoir engineering studies involved in development and production of reservoirs. Special laboratory core analysis tests have, therefore, been developed for quantitative determinations for use in accurate engineering calculations. These determinations concern mainly the distribution of fluids in the reservoir, the pore distribution and the two-phase flow characteristics of the reservoir.

1. <u>Capillary Pressure Determination</u>. The test results usually take the form of a capillary pressure curve, and can be used in the following:

- Determination of the average irreducible water saturation in a reservoir;
- determination of water saturation above the free water table in the reservoir;
- determination of pore-size distribution of a reservoir rock;
- determination of the threshold or entry pressure of the reservoir rock;
- determination of permeability of irregular shape rock samples, including drill cuttings.

The Petroleum Technology Laboratory of the Bureau of Mineral Resources operates two types of equipment for capillary pressure studies by two methods respectively, viz. the restored state method and the mercury injection method.

(a) <u>The Restored State Method</u> equipment consists of a stainless steel cell with a semi-permeable diaphragm (normally porcelain) mounted in the base. The cell is connected by a pressure hose with a system of null-balance regulators and pressure gauges, so that a precise air displacement pressure of up to 35 p.s.i.g. (about 2.4 atm) can be applied to the cell. (Fig.8).

The core plug to be tested is extracted, dried and weighed. It is then saturated with an aqueous solution of a salinity similar to that of the reservoir from which the core plug was selected. After weighing, it is placed on a wetted tissue on the semi-permeable plate, which is also saturated with the same aqueous solution. The cell is then closed and humidified air is applied to the cell at constant pressure not exceeding 1 p.s.i.g. (about 0.07 atm) by means of the null-balance regulator. The pressure is held constant until no more aqueous solution is displaced into the graduated cylinder; this may take several days for low-permeability samples. The core plug is then removed and re-weighed, and the weight of the displaced solution determined by the weight difference at the beginning and the end of displacement process.

In a similar manner stabilized weight values are obtained at 2, 4, 8, 15 and 35 p.s.i.g. (about 0.14, 0.27, 0.55, 1.5 and 2.5 atm). The volume of aqueous solution displaced from the core is determined at each of these points by dividing the respective weight difference values by the solution density. When friable samples are being used, grain losses from the sample during testing can have a noticeable effect on the brine saturation determinations. Although the actual loss throughout the test is somewhat difficult to delegate, it is generally considered that the maximum portion is lost during handling in the first desaturation step. Therefore, 90% of the calculated grain loss is apportioned to the first desaturation step, and the balance of 10% is evenly distributed among the remaining desaturation points, and all are noted in column 15 of the data sheet. (Work-sheet B. 1a).

The capillary pressure curve is obtained by plotting the volumes of aqueous solution remaining in the core plug (saturation) at the end of each pressure step, against the respective pressures. The connate saturation (irreducible water) is then the value where the curve becomes near vertical, that is, negigible or no water is produced with the increased pressure. A capillary pressure curve may also be obtained as a plot of water saturation vs. the height above the reservoir water table (100% water saturation or zero capillary pressure).

A similar capillary pressure curve may be obtained for an oil-water system, using oil instead of air as a displacing phase around the core plug in the cell. Although the test is somewhat more difficult and slower, the results are more directly applicable to oil reservoir conditions.

The following are the advantages of the restored state capillary method:

- The core sample can easily be used for additional tests after connate water extraction;
- a number of samples can be tested at the same time in the same cell:

The disadvantages of the method include:

- Length of time involved; samples may require two or more weeks to complete the test;

- the ultimate useful test pressure is limited by the threshold pressure of the semi-permeable membrane (about 40 p.s.i.g. or 2.7 atm);
- grain and fluid losses during weighing may create errors in calculating saturation volumes;
- irregular-shape samples, including drill cuttings, cannot be used.

(b) The Mercury Injection Method of capillary pressure determination is carried out in apparatus consisting of a mercury reservoir, a precision high-pressure mercury pump, a manifold system of control valves and pressure gauges, a vacuum pump and a high-pressure nitrogen source. (Fig.9).

A capillary pressure curve, similar to that of the restored state method, is obtained by incrementally applying pressure and noting the corresponding volumes of mercury forced into a dried and extracted core sample.

The procedure involves, firstly, a calibration of the mercury pump and the manifold system without a core sample, in order to measure the "dead volume", which must be subtracted from the mercury injection volume readings at each incremental pressure.

The extracted and dried sample on which the bulk volume and effective porosity have been determined is placed in the reservoir of the mercury pump, the reservoir lid is firmly secured and vacuum applied until a desired absolute pressure of 20 microns absolute is established in the system.

The pump piston is then advanced until the mercury level in the reservoir appears at the upper reference mark of the reservoir sight-glass, whereupon the scale and vernier on the mercury pump are set at "zero".

The vacuum is then disconnected and the atmospheric pressure is allowed to slowly bleed into the system until the low-pressure manifold gauge reads 3 p.s.i.g. (0.20 atm) absolute. The entry of mercury into the pores of the sample will cause a mercury meniscus to drop below the upper reference mark in the sight-glass, and the volume of mercury that entered the sample is determined by returning the meniscus to the reference mark by advancing the mercury pump piston.

The procedure is repeated for each successive pressure of 6, 9, 12, 15, 30, 60, 100, 200, 500, 1,000 and 2,000 p.s.i.g. and the cumulative mercury injection volumes noted during each pressure step. These readings must now be corrected by subtracting each cumulative calibration volume ("dead volume") of the system from the cumulative mercury injection volume obtained at each of the pressure steps. The corresponding void volumes are then expressed as percentages of the core-sample porosity and plotted against the respective pressure values to obtain the capillary pressure curve. (Worksheet B. 1b).

In comparing the mercury injection with air/water capillary pressure results, consideration must be given to the differences in surfaces tensions and contact angles between the rock and the fluids used. Purcell* has shown

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* Petroleum Transactions, AIME T.P. 2544, February, 1949.

that a reasonably close agreement between the results from the two methods can be obtained by dividing the mercury injection pressures by 5 to obtain pressures similar to those during the air/water test. This figure is a ratio of the product of the surface tension of mercury and its contact angle with a solid to the product of the same parameters for water or -

$$\frac{480 \text{ (dynes per cm) x cos } 140^{\circ}}{70 \text{ (dynes per cm) x cos } 0^{\circ}} = 5$$

Advantages of mercury injection method are as follows:

- Pressures can be carried to very high limits, so that the range of capillary pressures available for observation is large;
- samples for testing need not be of regular shape and even drill cuttings may be used;
- time involved is short, a matter of few hours rather than weeks;
- permeability of samples can be determined from the capillary pressure curve by the method described in Purcell's paper.

The method also has disadvantes, inasmuch as the samples cannot be used for any other tests, because of their impregnation with mercury; also, the indicated "non-wetting phase" saturation of clayey samples may be too high because of the partial wetting of clay by mercury.

2. Other Special Core Analysis Facilities in Australia

Since the discovery of the first commercial oil production in Australia in 1961, the search for new reserves has taken place on an ever increasing scale. Drilling is being done in many areas of the continent and the continental shelf and several widely separated significant discoveries have been made.

In view of these developments the Petroleum Technology Laboratory of the Bureau of Mineral Resources is presently being equipped for carrying out the following tests and investigations:

- Gas/oil and water/oil relative permeability to provide data for engineering calculations of recoverable primary and secondary reserves under gas cap, solution-gas and water drives. (Figs. 10 and 4);
- water flood susceptibility of reservoirs;
- electrical resistivity of cores to assist with electric log interpretation.

Fig. 1

KLINKENBERG CORRECTION PLOT OF

K_g vs. $\frac{1}{P_m}$

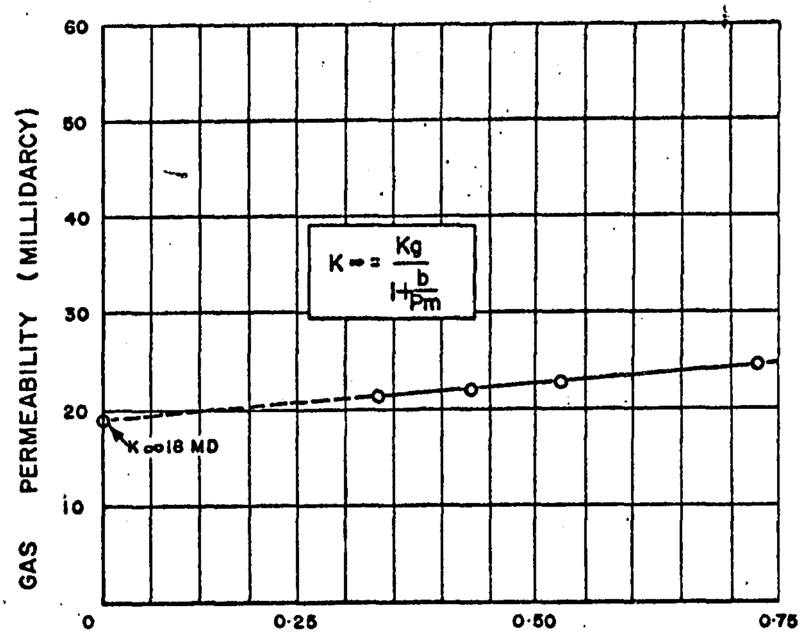
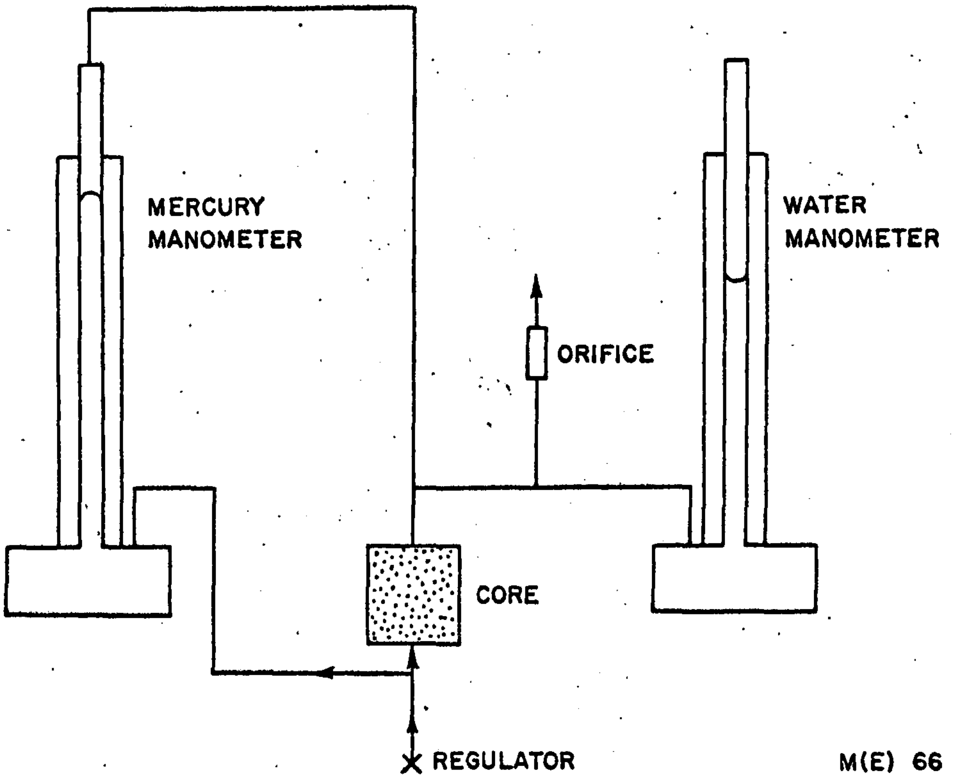


Fig. 2

FLOW DIAGRAM CORE LABORATORY TYPE PERMEAMETER.



M(E) 66

Fig. 3

CONVENTIONAL CORE ANALYSIS PERMEAMETER

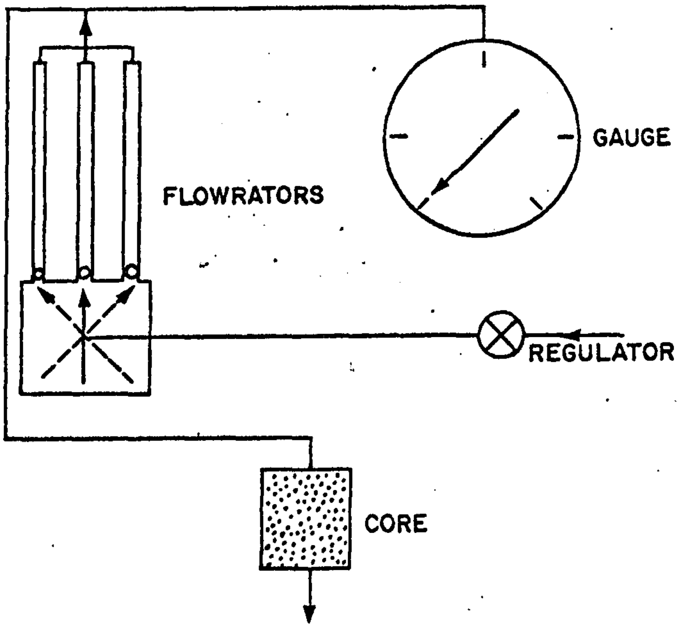
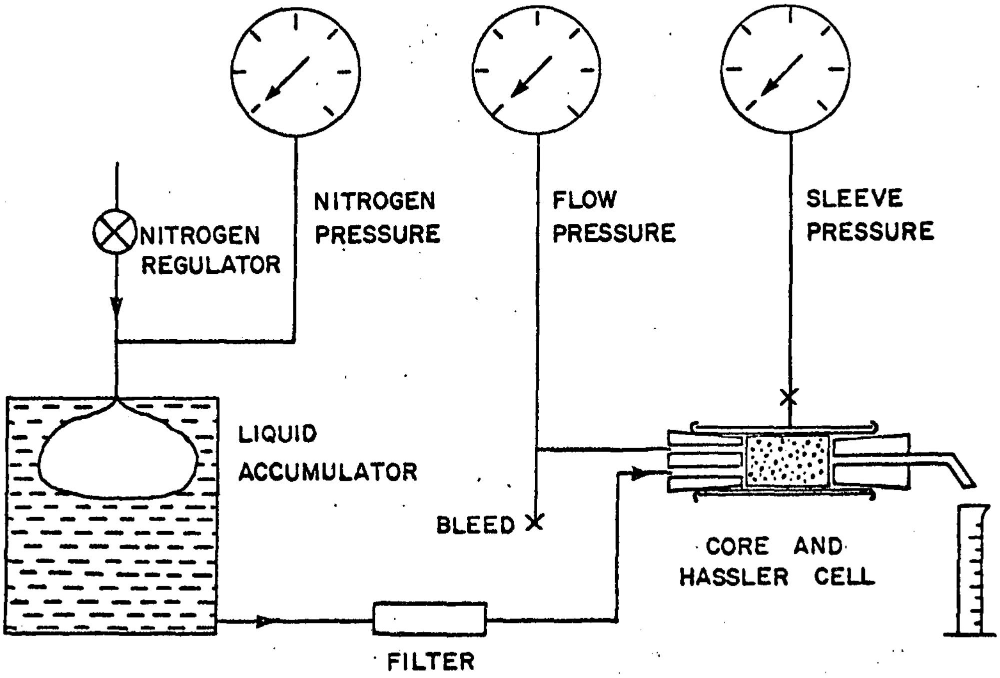


Fig. 4

LIQUID PERMEABILITY APPARATUS SHOWING HASSLER CELL AND LIQUID TRANSFER ACCUMULATOR



M(E) 68

Fig. 5

CONVENTIONAL CORE ANALYSIS POROSIMETER

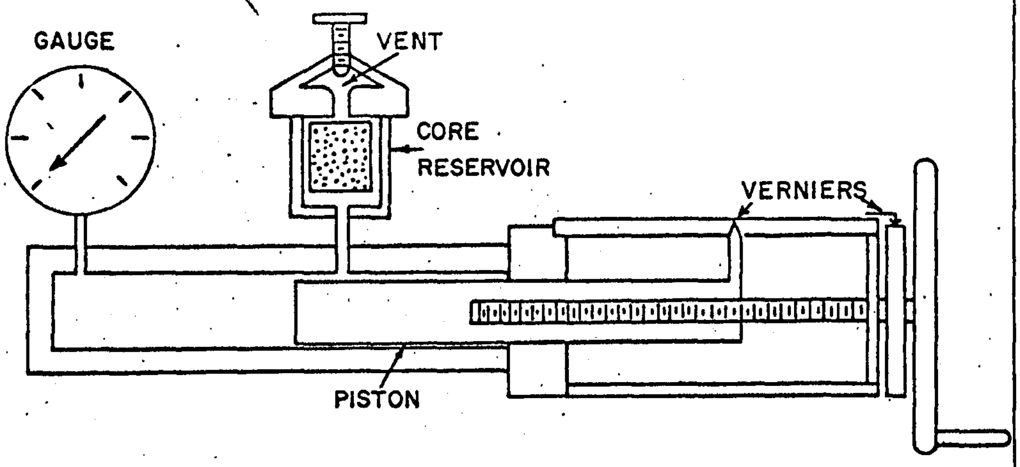
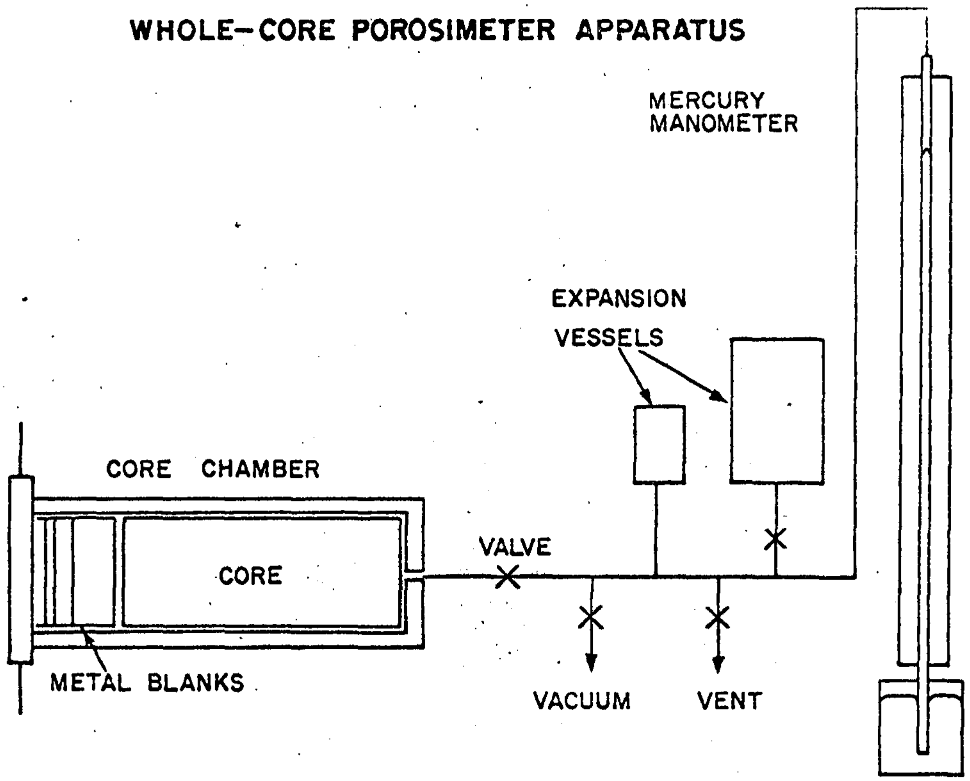


Fig. 6

WHOLE-CORE POROSIMETER APPARATUS



M(E) 65

Fig. 7

WHOLE-CORE PERMEAMETER APPARATUS IN VERTICAL FLOW CONFIGURATION

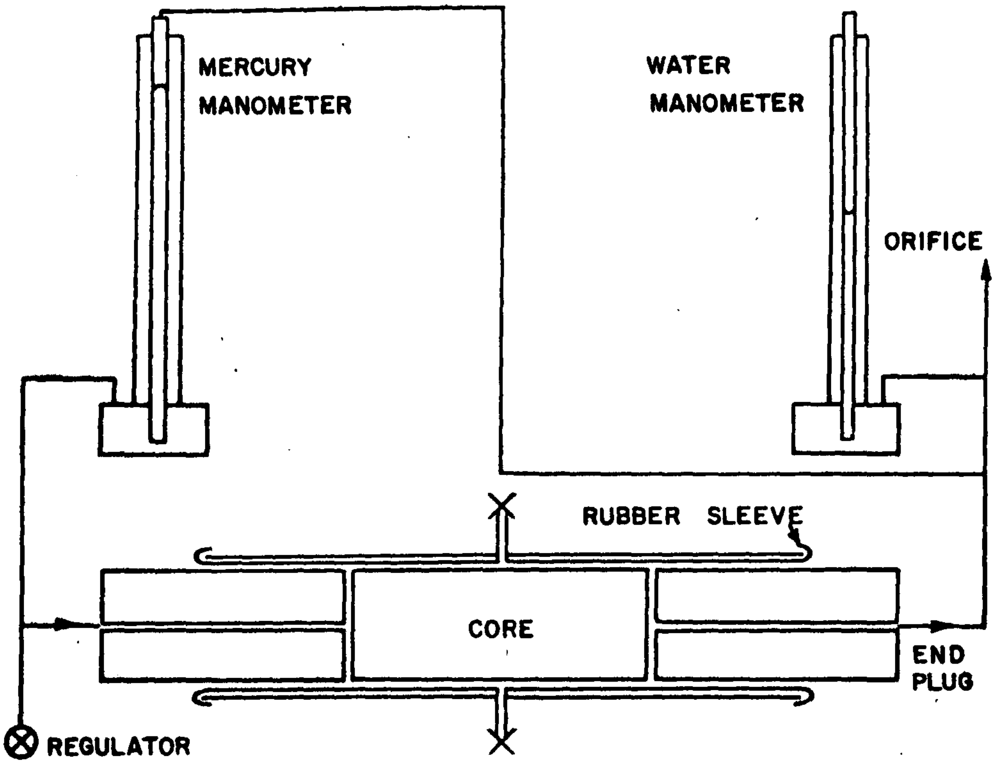


Fig. 8

RESTORED STATE POROUS DIAPHRAGM CAPILLARY PRESSURE APPARATUS

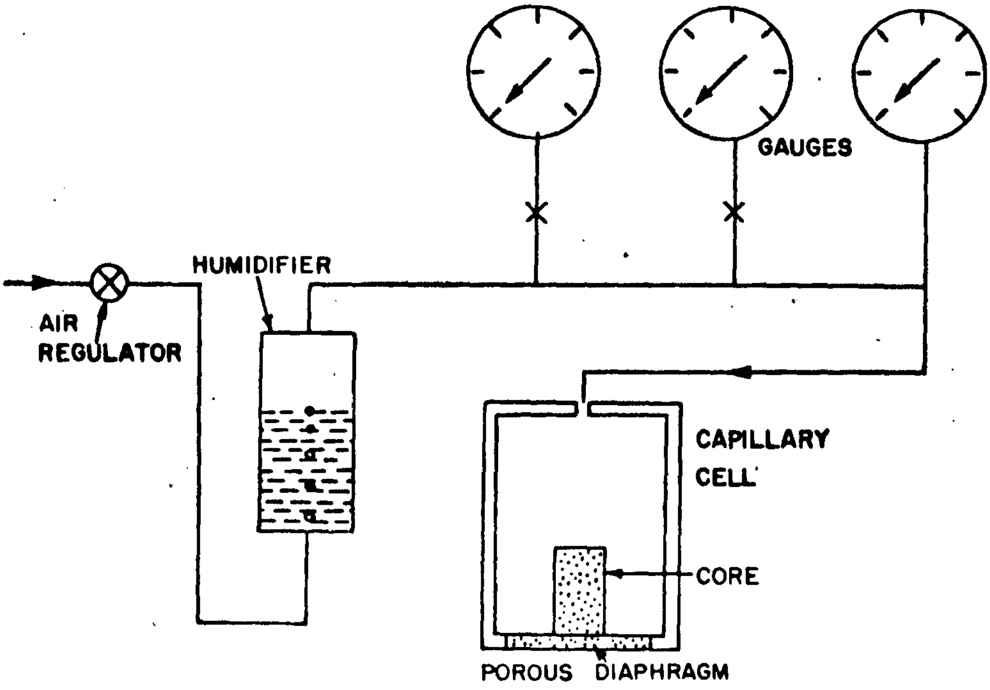


Fig. 9

MERCURY INJECTION CAPILLARY PRESSURE APPARATUS

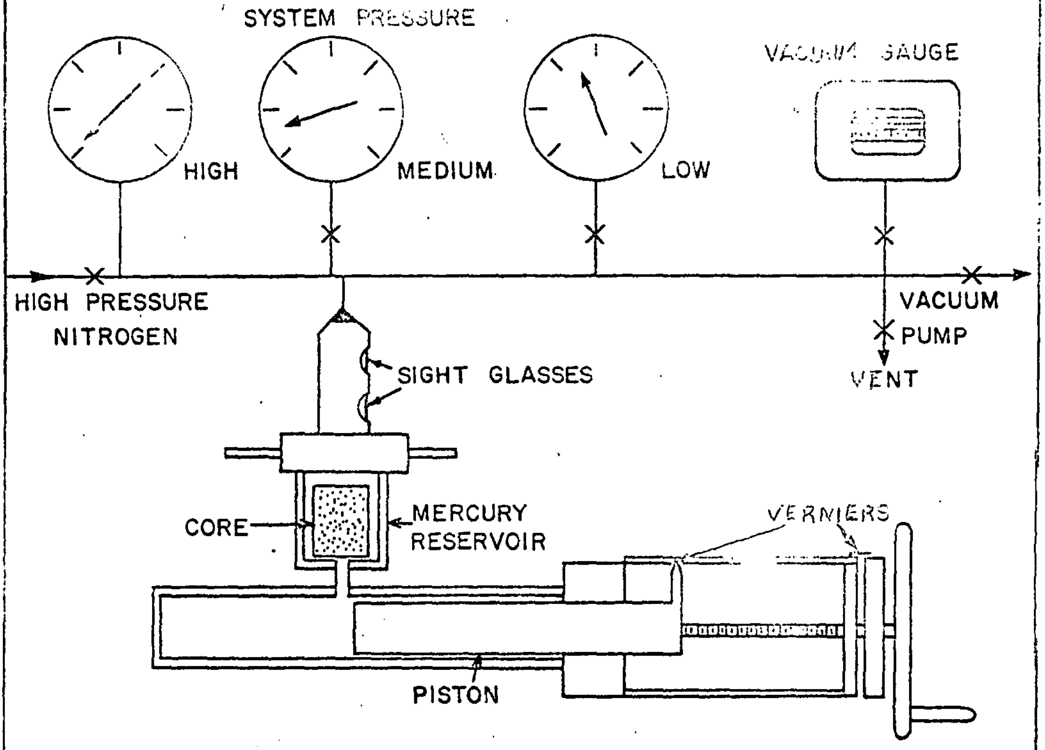
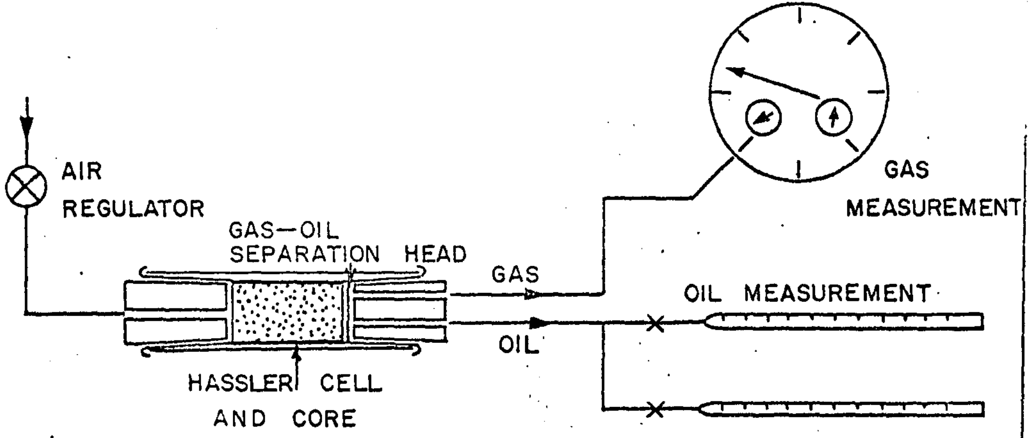


Fig.10

GAS-OIL RELATIVE PERMEABILITY APPARATUS



WORK-SHEET A. 2a)-A.

CORE ANALYSIS - PERMEABILITY, FLUID SATURATION (RETORT) AND POROSITY (FLUID SUMMATION)

DATE OF TEST:

SAMPLE NUMBER	DEPTH (FT)		PERMEABILITY DATA M·x Q x (L÷A)								MERCURY PUMP DATA			NATURAL DENSITY (Gm/cc)	RETORT DATA						% BULK VOL			POROSITY (% B.V)	PORE SATURATION (% B.V)		PROBABLE PRODUCTION	LITHOLOGY AND REMARKS
	From	To	ORIFICE TYPE	WATER MANOMETER	MERCURY MANOMETER	"Q"(cm³/sec)	SAMPLE LENGTH (cm)	SAMPLE AREA (cm²)	PERMEABILITY TO AIR (md)	EQUIVALENT LIQUID PERMEABILITY (md)	BULK VOLUME (cm³)	WEIGHT (Gm)	MERCURY VOLUME INJECTED (cm³)		SAMPLE WEIGHT (Gm)	BULK VOLUME (cm³)	OBSERVED OIL (cm³)	FINAL WATER (cm³)	CORRECTED OIL (cm³)	INITIAL WATER (cm³)	OIL	WATER	GAS		OIL (% Pore Vol.)	WATER (% Pore Vol.)		
1	*4819*	*21*	*4.00*	*130*	*60*	*2.60*	*2.00*	*4.00*	*78*	*69*	*19.20*	*43.23*	*2.10*	*2.24*	*120*	*53.4*	*0.0*	*3.5*	*0.0*	*3.1*	*0.0*	*5.9*	*11.0*	*16.9*	*0.0*	*34.3*	*GAS*	*FINE TO MEDIUM GRAIN SANDSTONE*
2	*21*	*23*	*4.00*	*200*	*117*	*4.00*	*2.00*	*4.00*	*235*	*215*	*17.33*	*73.59*	*2.43*	*2.17*	*120*	*55.3*	*0.0*	*3.9*	*0.0*	*3.5*	*0.0*	*6.3*	*14.0*	*20.3*	*0.0*	*31.1*	*GAS*	*"*
3	*23*	*25*	*4.00*	*200*	*120*	*4.00*	*2.00*	*4.00*	*241*	*220*	*18.54*	*41.89*	*2.41*	*2.25*	*120*	*53.3*	*0.0*	*1.2*	*0.0*	*1.1*	*0.0*	*2.1*	*13.0*	*15.1*	*0.0*	*13.9*	*GAS*	*"*
4	*25*	*27*	*4.00*	*200*	*139*	*4.00*	*2.00*	*4.00*	*278*	*238*	*17.65*	*40.05*	*1.96*	*2.27*	*120*	*52.8*	*0.0*	*2.6*	*0.0*	*2.4*	*0.0*	*4.4*	*11.1*	*15.6*	*0.0*	*28.8*	*GAS*	*"*
5	*27*	*29*	*4.00*	*200*	*175*	*4.00*	*2.00*	*4.00*	*350*	*320*	*19.40*	*41.71*	*2.55*	*2.18*	*120*	*55.0*	*0.4*	*3.6*	*0.65*	*2.7*	*1.2*	*4.9*	*13.3*	*19.4*	*6.2*	*25.3*	*TRANSITIONAL*	*"*
6	*29*	*31*	*4.00*	*200*	*123*	*4.00*	*2.00*	*4.00*	*245*	*225*	*16.41*	*37.20*	*1.61*	*2.26*	*120*	*53.1*	*1.1*	*2.2*	*1.5*	*2.0*	*2.8*	*3.8*	*9.8*	*16.4*	*17.7*	*22.5*	*OIL*	*"*
7	*31*	*34*	*4.00*	*200*	*177*	*4.00*	*2.00*	*4.00*	*354*	*324*	*17.40*	*37.87*	*2.17*	*2.18*	*120*	*55.0*	*1.4*	*2.8*	*1.8*	*2.5*	*3.3*	*4.5*	*12.4*	*20.2*	*16.3*	*22.3*	*OIL*	*"*
8	*34*	*37*	*4.00*	*200*	*265*	*4.00*	*2.00*	*4.00*	*529*	*499*	*18.04*	*40.29*	*2.00*	*2.23*	*120*	*53.8*	*1.3*	*2.1*	*1.7*	*1.9*	*3.1*	*3.5*	*11.1*	*17.7*	*17.5*	*19.8*	*OIL*	*"*
9	*37*	*40*	*4.00*	*200*	*95*	*4.00*	*2.00*	*4.00*	*191*	*171*	*17.65*	*41.25*	*1.38*	*2.34*	*120*	*51.3*	*0.9*	*1.8*	*1.2*	*1.6*	*2.4*	*3.1*	*7.8*	*13.3*	*18.1*	*23.3*	*OIL*	*"*
10	*40*	*43*	*6.00*	*200*	*246*	*6.00*	*2.00*	*4.00*	*739*	*699*	*18.41*	*42.32*	*1.66*	*2.30*	*120*	*52.2*	*1.1*	*1.9*	*1.5*	*1.7*	*2.9*	*3.2*	*9.0*	*15.1*	*19.2*	*21.2*	*OIL*	*"*
11	*43*	*45*	*4.00*	*200*	*181*	*4.00*	*2.00*	*4.00*	*362*	*332*	*18.33*	*41.96*	*1.59*	*2.28*	*120*	*52.6*	*0.9*	*2.8*	*1.2*	*2.5*	*2.3*	*4.7*	*8.7*	*15.7*	*15.3*	*29.7*	*TRANSITIONAL*	*"*
12	*45*	*47*	*4.00*	*200*	*214*	*4.00*	*2.00*	*4.00*	*428*	*398*	*17.65*	*39.88*	*1.51*	*2.26*	*120*	*53.0*	*1.0*	*4.0*	*1.4*	*3.6*	*2.6*	*6.8*	*8.4*	*17.8*	*13.4*	*39.6*	*WATER*	*"*
13	*47*	*49*	*4.00*	*195*	*60*	*3.9*	*2.00*	*4.00*	*117*	*104*	*18.19*	*40.25*	*1.59*	*2.21*	*120*	*54.0*	*0.95*	*5.6*	*1.3*	*5.1*	*2.4*	*9.4*	*8.7*	*20.5*	*11.6*	*45.7*	*WATER*	*"*
14	*49*	*51*	*0.10*	*0.0*	*60*	*0.0*	*2.00*	*4.00*	*0.0*	*0.0*	*18.04*	*48.36*	*0.03*	*2.67*	*120*	*45.0*	*TRACE*	*0.5*	*0.1*	*0.38*	*0.1*	*0.8*	*0.2*	*1.1*	*9.5*	*75.2*	*NO FLOW*	*SANDSTONE WITH NUMEROUS SHALE LAMINATIONS*

M(Pt) 75

WORK - SHEET A. 2a) - B(i)

CORE ANALYSIS - FLUID SATURATION (DEAN AND STARK) AND CORE WATER SALINITY

DATE OF TEST:

WELL NAME AND NUMBER	CORE NUMBER	DEPTH	LITHOLOGY	① WEIGHT OF EMPTY GLASS THIMBLE (gm)	② WEIGHT OF THIMBLE PLUS SATURATED SAMPLE (gm)	③ WEIGHT OF SATURATED SAMPLE ②-① (gm)	④ WEIGHT OF THIMBLE PLUS EXTRACTED SAMPLE (gm)	⑤ WEIGHT OF EXTRACTED SAMPLE ④-① (gm)	⑥ WEIGHT DIFFERENCE ③-⑤ (gm)	⑦ INITIAL WATER IN TRAP (cm^3)	⑧ FINAL WATER IN TRAP (cm^3)	⑨ WATER EXTRACTED ⑧-⑦ (cm^3)	⑩ CORRECTED WATER ⑨+⑬ (cm^3)
KANGAROO No1	*7*	*8762' 4"*	*SANDSTONE*	*24.62*	*52.98*	*28.36*	*50.48*	*25.86*	*2.50*	*1.26*	*3.06*	*1.80*	*1.83*

CORE WATER SALINITY: Using N/20 $AgNO_3$ 250 ml. water for leaching 50 ml. for titration				⑮ DRY SAMPLE VOLUME ⑤ / Dry B.D. (cm^3)	⑯ WATER SATURATION ⑩ x 10^4 / ⑮ x Ave Poros (% of Pore Space)	⑰ OIL WEIGHT ⑥ - ⑩ (gm)	⑱ OIL VOLUME ⑰ / 0.80(assumed) (cm^3)	⑲ OIL SATURATION ⑱ x 10^4 / ⑮ x Ave Poros (% of Pore Space)	GAS SATURATION 100-(⑯+⑲) (% of Pore Space)	REMARKS
⑪ AVERAGE TITRATION (cm^3)	⑫ SALINITY 14600 x ⑪ / ⑨ p.p.m. NaCl	⑬ VOL. OF SALT LEFT IN SAMPLE ⑫ x ⑨ / *2.17 x 10^6 (cm^3)	⑭ CORRECTED SALINITY ⑫ x ⑨ / ⑩ p.p.m. NaCl							
5.00	*40,600*	*0.03*	*39,900*	*12.49*	*67*	*0.67*	*0.84*	*31*	*2*	

* *2.17= S.G. of Salt.*

Note: For dry bulk density and average porosity values use results in porosity work-sheet.

M(Pt) 76

WORK-SHEET A. 2a)-B(ii)-1

CORE ANALYSIS - GAS PERMEABILITY

DATE OF TEST:

WELL NAME AND NUMBER	CORE NUMBER	DEPTH	LITHOLOGY	SAMPLE ORIENTATION	① L SAMPLE LENGTH (cm)	② D SAMPLE DIAMETER (cm)	③ A CROSS SECTION AREA $\frac{\pi D^2}{4}$ (cm²)	④ $\frac{L}{A}$ LENGTH / AREA (cm⁻¹)	⑤ PRESSURE (atm)	⑥ FLOW-RATOR SIZE (S-M-L)	⑦ FLOW-RATOR READING (cm)	⑧ "Q" FROM SAMPLE FLOW RATE GRAPH (cm³)/sec	⑨ T TEMP. (°C)	⑩ μ GAS VISCOSITY (cp)	⑪ PERMEABILITY ④x⑧x⑩x1000 / ⑤ (md)	REMARKS
EMU No 1	*16*	*6922*	*FINE GRAIN HOMOGENEOUS SANDSTONE*	*H_1*	*3.57*	*3.16*	*7.85*	*.455*	*0.50*	*M*	*13.7*	*11.5*	*23°*	*.0176*	*184*	
				H_2	*3.59*	*3.16*	*7.85*	*.457*	*0.50*	*M*	*13.8*	*11.8*	*23°*	*.0176*	*190*	
				V	*3.58*	*3.16*	*7.85*	*.456*	*0.50*	*M*	*12.4*	*10.2*	*23°*	*.0176*	*164*	
"	*17*	*7212*	"	*H_1*	*3.55*	*3.16*	*7.85*	*.452*	*0.25*	*L*	*1.5*	*8.8*	*24°*	*.0176*	*280*	
				H_2	*3.50*	*3.16*	*7.85*	*.446*	*0.25*	*L*	*1.4*	*8.3*	*24°*	*.0176*	*261*	
				V	*3.56*	*3.14*	*7.75*	*.460*	*0.50*	*M*	*8.3*	*5.8*	*25°*	*.0177*	*94*	
"	*18*	*7539*	*FINE GRAIN SANDSTONE WITH SHALE LAMINATIONS*	*H_1*	*3.51*	*3.14*	*7.75*	*.453*	*1.00*	*S*	*6.0*	*0.28*	*16°*	*.0173*	*2*	
				H_2	*3.34*	*3.15*	*7.80*	*.428*	*1.00*	*S*	*3.4*	*0.18*	*17°*	*.0173*	*1*	
				V	*3.47*	*3.15*	*7.80*	*.445*	*1.00*	*S*	*0.0*	*0.0*	*17°*	*.0173*	*0*	*VERY SHALY*

M(PT)77

WORK-SHEET A.2 a)-B(ii)-2

CORE ANALYSIS. - LIQUID PERMEABILITY $\left[K_L = \frac{V \cdot L \cdot \mu \cdot 1000}{T \cdot A \cdot \Delta p}\right]$

DATE OF TEST:

① WELL NAME AND NUMBER	② TOTAL DEPTH (FT.)	③ CORE NUMBER	④ DEPTH (FT.)	⑤ LITHOLOGY	⑥ LIQUID TYPE	⑦ LIQUID TEMP. (°C)	⑧ LIQUID VISCOSITY μ (c.p.)	⑨ PRESSURE DROP ACROSS SAMPLE Δp (atm.)	⑩ LIQUID VOLUME MEASURED V (cm³)	⑪ TIME TO MEASURE LIQUID VOLUME T (sec)	⑫ SAMPLE LENGTH L (cm)	⑬ SAMPLE DIAMETER D (cm)	⑭ SAMPLE CROSS SECTIONAL AREA A (cm²)	⑮ $\frac{\text{LENGTH}}{\text{AREA}}$ $\frac{L}{A}$ (cm⁻¹)	⑯ LIQUID PERMEA-BILITY (md)	⑰ REMARKS
KOALA No 1	*10000*	*10*	*6742*	*SANDSTONE FINE GRAIN*	*KEROSENE*	*20°*	*1.28*	*2.042*	*5*	*19.4*	*3.50*	*3.14*	*7.75*	*.452*	*73*	
KOALA No 1	"	*10*	*6747*	"	"	"	"	"	*5*	*16.2*	*3.47*	*3.15*	*7.77*	*.447*	*86*	
KOALA No 1	"	*10*	*6752*	"	"	"	"	*1.361*	*5*	*15.5*	*3.41*	*3.14*	*7.73*	*.442*	*89*	
KOALA No 1	"	*10*	*6757*	*AS ABOVE SLIGHTLY SHALY*	"	"	"	*2.721*	*5*	*38*	*3.50*	*3.15*	*7.78*	*.450*	*28*	

WORK - SHEET A. 2a) - B(ii) - 3

CORE ANALYSIS — POROSITY (KOBE METHOD)

DATE OF TEST:

WELL NAME AND NUMBER	CORE NUMBER	DEPTH (FT.)	LITHOLOGY	SAMPLE ORIENTATION	① DRY WEIGHT (Gm)	② SAMPLE BULK VOLUME (cm^3)	③ PUMP READING AT 30 PSI (cm^3)	④ SAMPLE GRAIN VOLUME (GRAPH) (cm^3)	⑤ SAMPLE PORE VOLUME ②-④ (cm^3)	⑥ APPARENT GRAIN DENSITY ①/④ (Gm/cm^3)	⑦ DRY BULK DENSITY ①/② (Gm/cm^3)	⑧ POROSITY ⑤/② x 100 (% OF B.V.)	REMARKS
EMU No 1	20	8230	SANDY SL. PYRITIC SHALE	H_1	65.62	25.99	29.41	22.16	3.83	2.96	2.52	15	
				H_2	52.45	20.93	25.98	17.19	3.74	3.05	2.51	18	
				V	69.25	27.79	29.88	22.84	4.95	2.94	2.42	18	
"	21	8541	MEDIUM GRAIN SANDSTONE	H_1	54.78	26.48	28.29	20.54	5.94	2.67	2.07	22	
				H_2	55.05	26.72	28.38	20.67	6.05	2.66	2.06	23	
				V	57.40	27.38	29.08	21.69	5.69	2.65	2.10	21	

M(Pf) 79

WORK-SHEET A. 2a)-B(ii)-4

CORE ANALYSIS – POROSITY (MERCURY INJECTION METHOD)

PUMP CORRECTION VOLUME AT 750 PSI = 0.27 (cm^3) *DATE OF TEST:*

WELL NAME AND NUMBER	CORE NUMBER	DEPTH (FT.)	LITHOLOGY	SAMPLE ORIENTATION	① DRY SAMPLE WEIGHT (Gm)	② SAMPLE BULK VOLUME (cm^3)	③ SAMPLE PORE VOLUME INJECTION AT 750 PSI (cm^3)	④ SAMPLE GRAIN VOLUME ②-③ (cm^3)	⑤ DRY BULK DENSITY ① / ② (Gm/cm^3)	⑥ APPARENT GRAIN DENSITY ① / ④ (Gm/cm^3)	⑦ POROSITY ③ / ② x 100 (% OF BV)	REMARKS
EMU No 1	*25*	*9452*	*SANDSTONE FINE TO MEDIUM GRAIN*	*H_1*	*54.60*	*26.60*	*5.40*	*21.20*	*2.05*	*2.58*	*20*	
				H_2	*57.24*	*27.50*	*5.40*	*22.10*	*2.08*	*2.59*	*20*	
				V	*55.12*	*26.61*	*5.22*	*21.39*	*2.07*	*2.58*	*20*	
"	*26*	*9812*	*SILTSTONE SANDY AND SHALY*	*H_1*	*61.34*	*25.75*	*2.80*	*22.95*	*2.38*	*2.67*	*11*	
				H_2	*59.19*	*25.30*	*3.29*	*22.01*	*2.34*	*2.69*	*13*	
				V	*63.23*	*26.41*	*2.94*	*23.47*	*2.39*	*2.69*	*11*	

M(Pf)80

WORK-SHEET A.2c)-(i)-1

(WHOLE-CORE) CORE ANALYSIS — FLUID SATURATION-DEAN AND STARK

DATE OF TEST:

WELL NAME AND NUMBER	CORE NUMBER	DEPTH (FT.)	LITHOLOGY	① UNTRIMMED SATURATED SAMPLE WEIGHT (Gm)	② WATER EXTRACTED (cm^3)	③ UNTRIMMED DRY SAMPLE WEIGHT (Gm)	④ LOSS IN WEIGHT ①-③ (Gm)	⑤ ACTUAL OIL WEIGHT ④-② (Gm)
BOOMERANG 1	*12*	*5240*	*LIMESTONE-VUGGY*	*2210*	*35.3*	*2163*	*47*	*11.7*
"	*12*	*5244*	*"*	*1832*	*27.9*	*1796*	*36*	*8.1*
"	*12*	*5248*	*"*	*1319*	*19.9*	*1291*	*28*	*8.1*
"	*12*	*5252*	*"*	*1455*	*18.2*	*1433*	*22*	*3.8*

⑥ TRIMMED DRY SAMPLE WEIGHT (Gm)	⑦ TRIMMED SAMPLE BULK VOLUME (cm^3)	⑧ DRY BULK DENSITY $\frac{⑥}{⑦}$ (Gm/cm^3)	⑨ VOLUME OF UNTRIMMED DRY SAMPLE $\frac{③}{⑧}$ (cm^3)	⑩ ACTUAL OIL VOLUME $\frac{⑤}{0.8}$ (cm^3)	⑪ OIL SATURATION $\frac{⑩ \times 10^4}{⑨ \times \text{POROSITY}}$ (% OF PORE SPACE)	⑫ WATER SATURATION $\frac{② \times 10^4}{⑨ \times \text{POROSITY}}$ (% OF PORE SPACE)	REMARKS
1959	*764*	*2.56*	*846*	*14.6*	*20*	*49*	
1646	*636*	*2.59*	*693*	*10.1*	*20*	*56*	
1179	*461*	*2.54*	*508*	*10.1*	*22*	*44*	
1317	*505*	*2.60*	*552*	*4.7*	*13*	*48*	

M(Pf) 81

WORK-SHEET A.2c)-(i)-2

(WHOLE-CORE) CORE ANALYSIS — FLUID SATURATION-VACUUM RETORT

DATE OF TEST:

WELL NAME AND NUMBER	CORE NUMBER	DEPTH (FT.)	LITHOLOGY	① UNTRIMMED SATURATED SAMPLE WEIGHT (Gm)	② WATER EXTRACTED (cm^3)	③ OIL EXTRACTED (cm^3)	④ CORRECTED OIL READING (cm^3)	⑤ UNTRIMMED DRY SAMPLE WEIGHT (Gm)
BOOMERANG 1	*12*	*5240*	*LIMESTONE-VUGGY*	*2210*	*35.3*	*11.4*	*14.1*	*2163*
"	*12*	*5244*	*"*	*1832*	*27.9*	*7.4*	*9.6*	*1796*
"	*12*	*5248*	*"*	*1319*	*19.9*	*7.5*	*10.0*	*1291*
"	*12*	*5252*	*"*	*1455*	*18.2*	*3.6*	*4.8*	*1433*

⑥ TRIMMED SAMPLE DRY WEIGHT (Gm)	⑦ TRIMMED SAMPLE BULK VOLUME (cm^3)	⑧ DRY BULK DENSITY $\frac{⑥}{⑦}$ (Gm/cm^3)	⑨ UNTRIMMED DRY SAMPLE VOLUME $\frac{⑤}{⑧}$ (cm^3)	⑩ OIL SATURATION $\frac{④ \times 10^{4}}{⑨ \times \text{POROSITY}}$ (% OF PORE SPACE)	⑪ WATER SATURATION $\frac{② \times 10^{4}}{⑨ \times \text{POROSITY}}$ (% OF PORE SPACE)	REMARKS
1959	*764*	*2.56*	*846*	*20*	*49*	
1646	*636*	*2.59*	*693*	*19*	*56*	
1179	*461*	*2.54*	*508*	*22*	*44*	
1317	*505*	*2.60*	*552*	*13*	*48*	

M (Pf) 82

WORK-SHEET A.2c)-(ii) AND (iii)

(WHOLE-CORE) CORE ANALYSIS - POROSITY AND PERMEABILITY

DATE OF TEST:

WELL NAME AND NUMBER	CORE NUMBER	DEPTH (FT)	LITHOLOGY	① TRIMMED CORE LENGTH (cm)	② CORE AREA (cm²)	③ TRIMMED SAMPLE BULK VOLUME ① x ② (cm³)	④ TRIMMED SAMPLE DRY WEIGHT (Gm)	⑤ POROMETER DEAD VOLUME (cm³)	⑥ VOLUME OF PLUGS REMOVED (cm³)	⑦ MANOMETER READING WITH CORE (cm³)	⑧ AIR VOLUME ⑤ + ⑥ (cm³)
BOOMERANG No I	*12*	*5240*	*LIMESTONE - VUGGY*	*12.65*	*60.40*	*764*	*1959*	*143*	*802*	*244*	*944*
"	*12*	*5244*	*"*	*10.50*	*60.55*	*636*	*1646*	*143*	*663*	*213*	*805*
"	*12*	*5248*	*"*	*7.61*	*60.55*	*461*	*1179*	*143*	*486*	*208*	*628*
"	*12*	*5252*	*AS ABOVE WITH TRACES VERTICAL FRACTURES*	*8.38*	*60.25*	*505*	*1317*	*143*	*508*	*180*	*651*

⑨ CORRECTED CALIBRATION ⑧ - ③ (cm³)	⑩ PORE VOLUME ⑦ - ⑨ (cm³)	⑪ GRAIN VOLUME ③ - ⑩ (cm³)	⑫ GRAIN DENSITY ④ ÷ ⑪ (cm³)	⑬ DRY BULK DENSITY ④ ÷ ③ (Gm/cm³)	⑭ EFFECTIVE POROSITY $\frac{⑩}{③}$ x 100 (% OF BULK VOL)	VERTICAL PERMEABILITY DATA ⑮ ORIFICE TYPE	⑯ WATER MANOMETER (mm)	⑰ MERCURY MANOMETER (mm)	⑱ "Q" (cm³/sec)	⑲ $\frac{L}{A} = \frac{①}{②}$	⑳ VERTICAL PERMEABILITY (md)
180	*64*	*700*	*2.80*	*2.56*	*8.5*	*0.100*	*190*	*60*	*0.095*	*.2095*	*1.2*
167	*46*	*590*	*2.79*	*2.59*	*7.2*	*0.100*	*0.0*	*60*	*0.00*	*.1731*	*0.0*
167	*41*	*420*	*2.81*	*2.54*	*9.0*	*0.250*	*96.0*	*60*	*0.120*	*.1258*	*0.9*
146	*34*	*471*	*2.80*	*2.60*	*6.8*	*0.250*	*163*	*60*	*2.04*	*.1390*	*17*

HORIZONTAL PERMEABILITY DATA										HORIZONTAL PERMEABILITY (md)	
㉑ ORIFICE TYPE		㉒ WATER MANOMETER (mm)		㉓ MERCURY MANOMETER		㉔ "Q" (cm³/sec)		㉕ SCREEN LENGTH (cm)	SCREEN FACTOR $\frac{1.2}{\sqrt{① \times ㉕}}$	POSITION 1	POSITION 2
POSITION 1	POSITION 2	POSITION 1	POSITION 2	POSITION 1	POSITION 2	POSITION 1	POSITION 2				
6.00	*6.00*	*105*	*126*	*60*	*60*	*3.14*	*3.80*	*7*	*.1271*	*24*	*29*
6.00	*6.00*	*68*	*56*	*60*	*60*	*2.03*	*1.55*	*7*	*.1395*	*17*	*13*
6.00	*6.00*	*123*	*141*	*60*	*60*	*3.69*	*4.22*	*5*	*.1938*	*43*	*49*
6.00	*6.00*	*180*	*87*	*60*	*60*	*5.40*	*2.61*	*5*	*.1850*	*60*	*29*

WORK-SHEET B.1a)

SPECIAL CORE ANALYSIS
CAPILLARY PRESSURE – RESTORED STATE METHOD

DATE OF TEST:

FIELD AND WELL NUMBER....... *TOTAL DEPTH..........* *BRINE DENSITY................ Gm/cm³*
CORE NUMBER..........DEPTH........FT. *SATURATING BRINE SALINITY.............ppm.* *SALT WT/Gm OF BRINE.......... Gm*
SAMPLE NUMBER........DEPTH........FT.

① SATURATED SAMPLE WEIGHT . . . . Gm
② DRY SAMPLE WEIGHT . . . . Gm
③ BRINE SATURATION IN SAMPLE ①-② . . . . Gm
④ PORE VOLUME x BRINE DENSITY . . . . Gm
⑤ DIFFERENCE ④-③ . . . . Gm
⑥ WEIGHT AFTER DRYING AND CAPILLARY PRESSURE TEST . . . . Gm
⑦ APPARENT GRAIN LOSS ②-⑥ . . . . Gm
⑧ BRINE WEIGHT AFTER FINAL STEP . . . . Gm
⑨ SALT WEIGHT IN ⑧. . . . . Gm
⑩ CORRECTED GRAIN LOSS ⑨-⑦. . . . . Gm

⑪ DATE EACH PRESSURE STEP COMMENCED	⑫ PRESSURE DURING EACH DESATURATION STEP (P.S.I.)	⑬ SAMPLE WEIGHT AFTER EACH DESATURATION STEP (Gm)	⑭ APPARENT BRINE WEIGHT IN SAMPLE AFTER EACH STEP ⑬-② (Gm)	⑮ PROPORTIONATE CUMMULATIVE GRAIN LOSS OF SAMPLE DURING EACH STEP (FROM ⑩) (Gm)	⑯ CORRECTED BRINE WEIGHT DURING EACH STEP ⑭ + ⑮ (Gm)	⑰ BRINE SATURATION % OF PORE VOLUME DURING EACH STEP ⑯/④ x 100	REMARKS

WORK-SHEET B.1b)

SPECIAL CORE ANALYSIS
CAPILLARY PRESSURE – MERCURY INJECTION METHOD

DATE OF TEST:

WELL NAME AND NUMBER..... *TOTAL DEPTH.........FT.* *PORE VOLUME.............(cm^3)*
CORE NUMBER........DEPTH......FT. *SAMPLE NUMBER........DEPTH......FT.*

① PRESSURE DURING EACH STEP (PSIA)	② PUMP "DEAD VOLUME" (cm^3)	③ PUMP VOLUME READING WITH SAMPLE (cm^3)	④ VOLUME OF MERCURY INJECTED ③–② (cm^3)	⑤ % OF PORE VOLUME PENETRATED $\frac{④}{P.V.} \times 100$ (%)	⑥ EQUIVALENT WATER SATURATION 100 – ⑤ (%)	REMARKS

M(Pf) 85