RTH 114-93

PROPOSED METHOD OF TEST FOR GAS PERMEABILITY OF ROCK CORE SAMPLES

1. Scope

1.1 This method describes procedures for determining gas permeabilities of rock core samples. Test procedures are described for both large-diameter cores (NX size--5.4 cm and larger) and small-diameter cores which include plugs taken from larger diameter cores. Samples are normally right cylinders although cube samples may be used with a suitably modified sample holder.

1.2 The permeability measurement will be made according to standard procedures with dry air as the permeant. The value obtained with this fluid may then be corrected to a corresponding value for a nonreacting liquid using a standard table of Klinkenberg corrections.[1] The use of such corrections should be specifically noted in reporting results. Determination of permeability of rock specimens may be made with other gases or with a liquid as the permeant. However, measurements of liquid permeability are difficult to standardize because of potential interaction between rock constituents and the liquid.

1.3 Permeability measurements made parallel to the bedding planes of sedimentary rocks shall be reported as horizontal permeability while those measured perpendicular to the bedding shall be reported as vertical permeability. Structural features other than bedding may be used to describe the direction of flow during measurement. These shall be specifically noted in reporting results.

1.4 Samples of hard, consolidated rock may be cut to shape and tested without artificial support. Friable, soft, shaly, or otherwise weak rock may require additional support to resist deformation or alteration during testing. Deformation or alteration will affect test results. Such samples shall be supported by mounting in a suitable potting material (i.e. cement slurry) exercising care not to alter the surfaces through which fluid flow will occur.

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[1] "Recommended Practice for Determining Permeability of Porous Media," 3rd ed., American Petroleum Institute RP 27 (1952).

Testing procedures are the same for both unsupported and artificially supported samples.

1.5 The conventional direction of permeability measurement for small cylindrical samples is parallel to the axis of the cylinder. Large-diameter core samples are conventionally measured by one of two methods. In one method, referred to as the "linear permeability measurement," gas flow is either across the core perpendicular to a plane formed by a diameter of the core and the vertical axis or parallel to the core axis as with the small-diameter samples. When flow is across the sample, screens are used over diametrically opposite quadrants of the core circumference to uniformly distribute the gas flow. The second method is referred as a "radial permeability measurement" in which gas flows from the outside surface of the core radially through the core to a small-diameter hole drilled concentric with the axis of the core sample.

1.6 The permeability test is applicable to a wide range of rock types with a correspondingly wide range of permeabilities. With proper selection of test equipment components, permeabilities as low as 0.01 millidarcys and as high as 10 darcys can be measured accurately.

2. Summary of Method

2.1 The method for small samples consists of (a) placing the prepared sample in a Hassler- or Fancher-type core holder, Figs. 1 and 2, (b) applying the air pressure required to seal the sleeve around the core for the Hassler-type holder or loading the rubber compression ring for the Fancher holder, and (c) initiating dry gas flow through the sample. Because of the sensitivity of permeability to minor changes in lithology, no prescribed number of samples can be recommended to define the permeability of a given rock stratum. Reproducibility of approximately ±2 percent for samples of 0.1 millidarcy or greater permeability should be obtained for a given sample.

2.2 The method used to measure permeability for large-diameter cylindrical samples with vertical gas flow is the same as that described in 2.1.

2.3 The method for large-diameter samples with horizontal flow consists of (a) positioning appropriate-size screens diametrically opposite each other, (b) attaching the screens to the sample by light rubber bands, (c) placing the

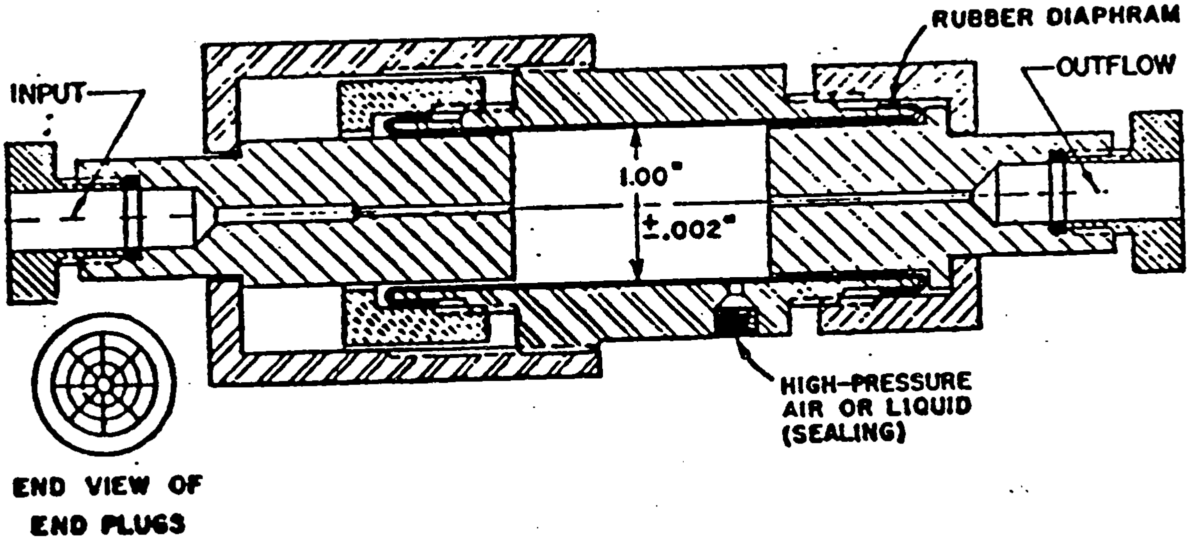

Fig. 1. Hassler-type permeability cell.

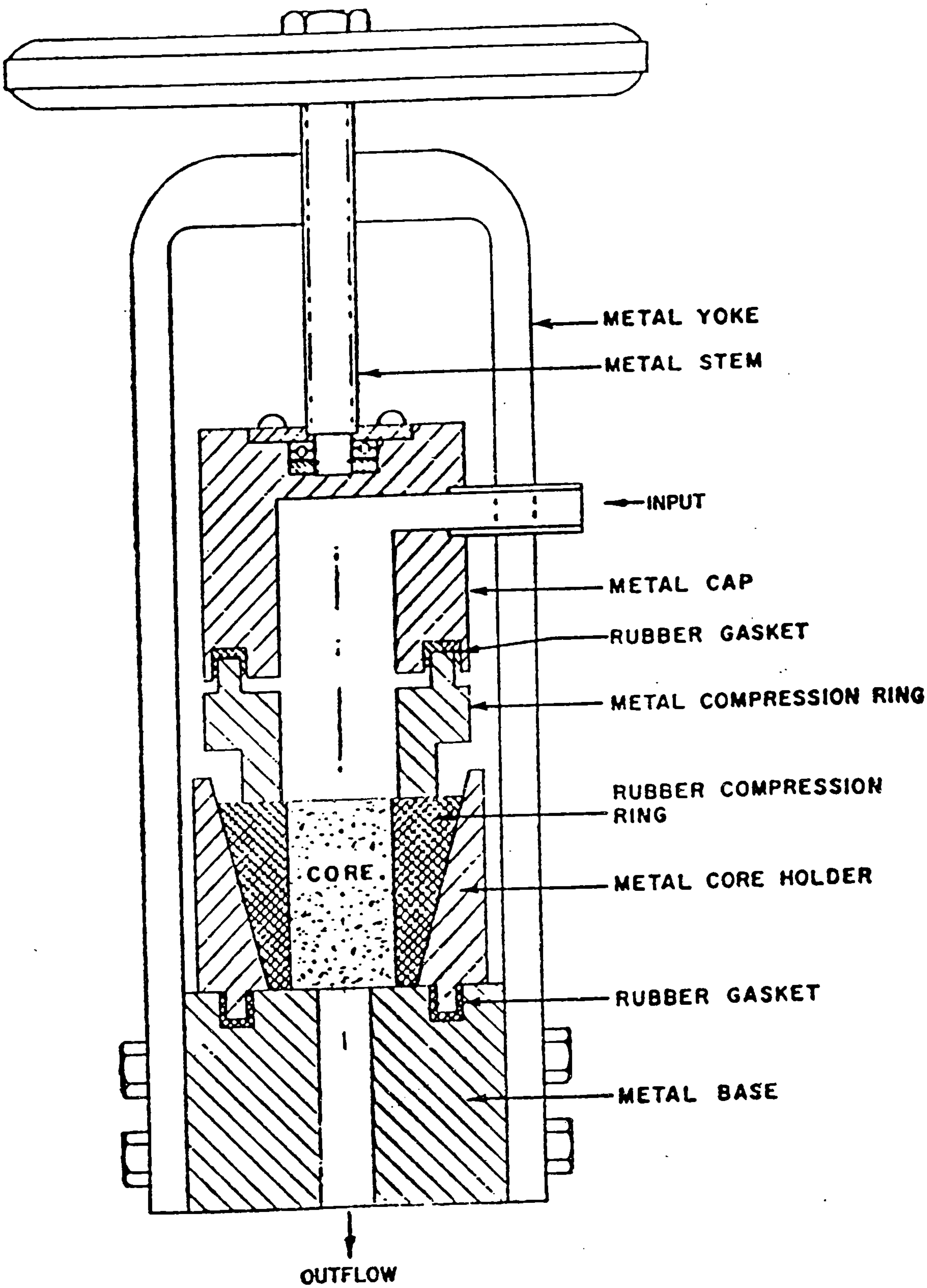

Fig. 2. Fancher-type core holder.

prepared sample in a Hassler-type or compression (ram) core holder, Figs. 3 and 4, (d) compressing the rubber gaskets which seal the ends of the samples in the Hassler-type holder (the ends of the samples used in the compression holder are presealed with plastic which is overlapped by the compression halves), (e) applying the air pressure (Hassler-type) or hydraulic force (compression) necessary to seal the sides of the sample except the area covered by the screens, and (f) initiating dry gas flow through the sample. Permeability is normally measured in two directions across the core: one is in the direction of apparent maximum permeability and the other is perpendicular to the first.

2.4 The method for large-diameter specimens with radial flow consists of (a) positioning the prepared sample in the radial flow core holder, Fig. 5, (b) raising the core against the closed lid by means of a piston, and (c) initiating dry gas flow through the sample.

3. <u>Apparatus</u>

3.1 <u>Components</u> - The apparatus used in dry air permeability testing consists of the following major components:

(a) A source of dry air
(b) Pressure regulator
(c) Inlet-pressure measuring device
(d) Core holder
(e) Outlet-pressure measuring device
(f) A dry air flow-rate metering device

3.2 <u>Source of Air</u> - The source of air for permeability measurements can be either the normal laboratory air supply or cylinders. Provisions should be made to filter particulate matter, absorb oil vapor, and remove water vapor. These devices should be periodically checked to insure proper operation.

3.3 <u>Pressure Regulator</u> - A suitable pressure regulator should be provided for the source of dry air. This regulator should apply air at a constant pressure and should be capable of doing so over a range of pressures between 1 and 80 cm of mercury (Note 1) which will produce the desired flow rate

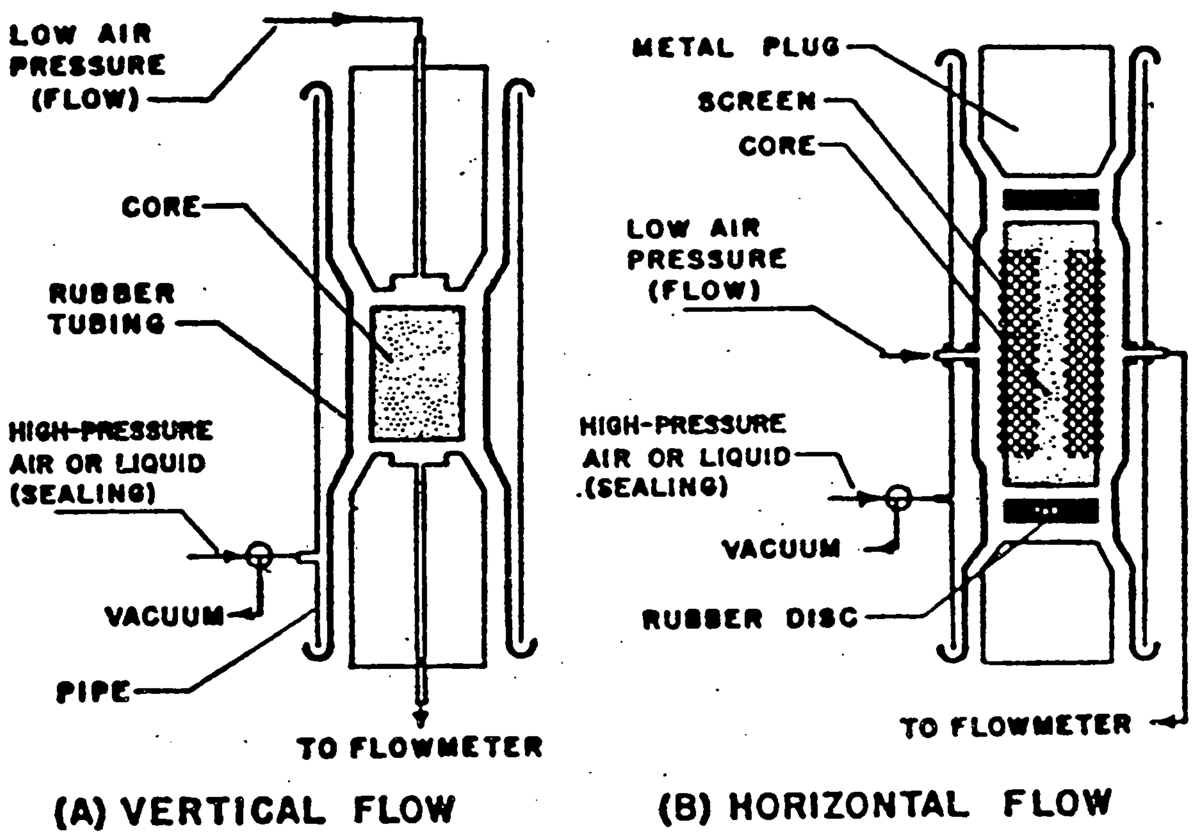

Fig. 3. Hassler-type permeameter.

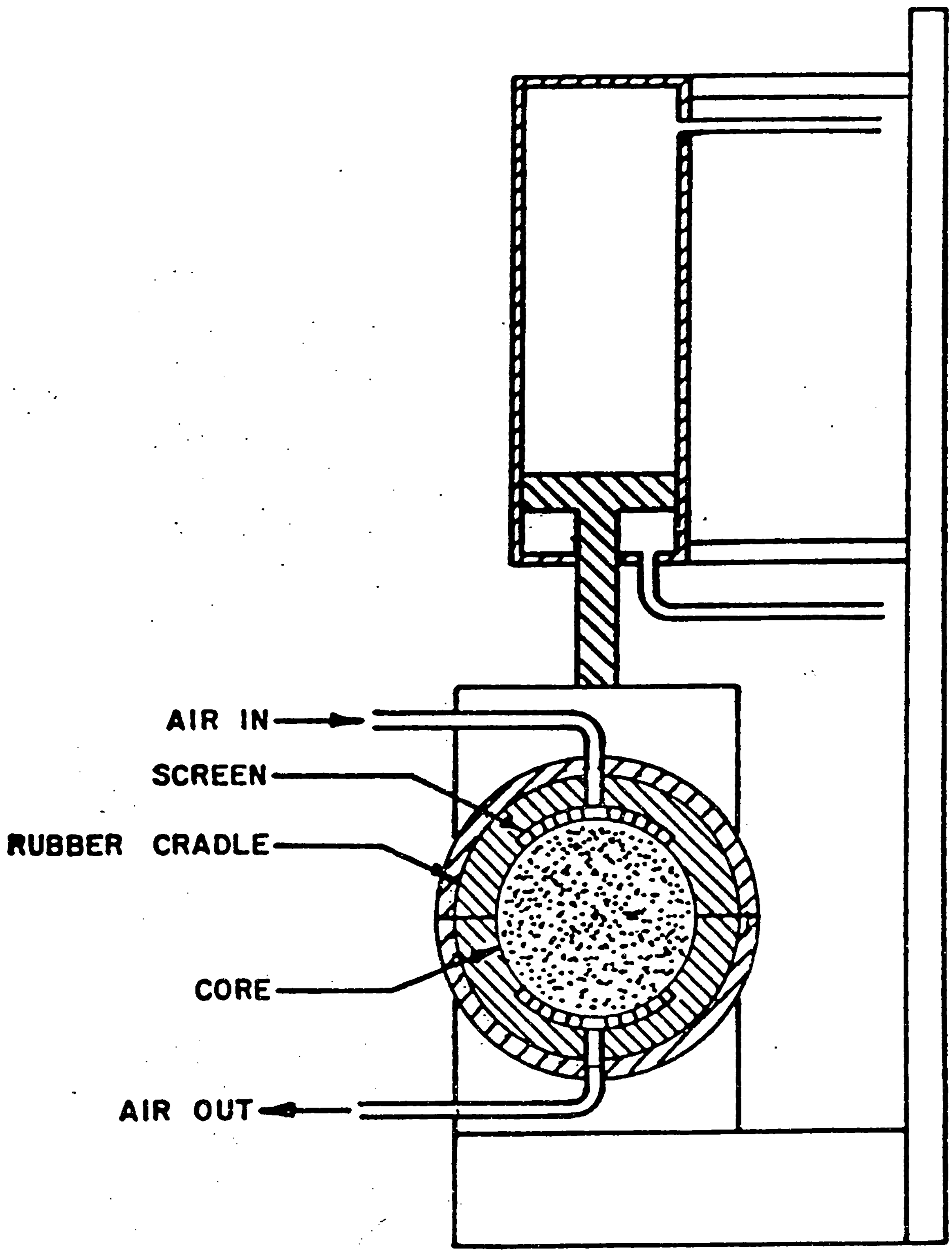

Fig. 4. Compression (RAM) permeameter.

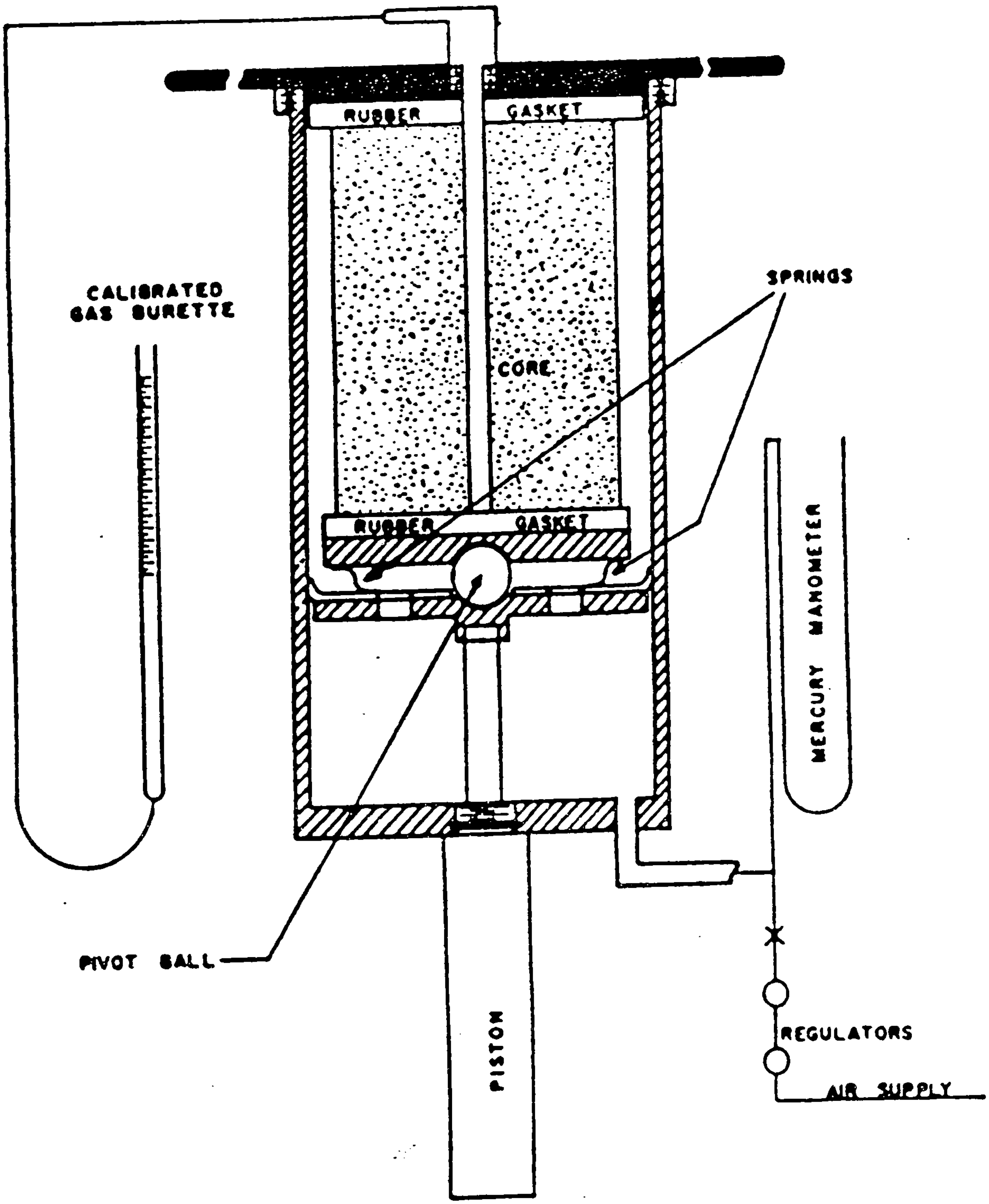

Fig. 5. Full-diameter radial permeameter.

(Note 1) of approximately 1 cu cm per second. Regulators of the pneumatic type are suitable for this purpose.

NOTE 1--The pressures required to produce the desired flow rate (1 cu cm per second) depend on the permeability and dimensions of the rock sample. Since the dimensions and permeability range of samples are not specified, the range of pressures over which pressure control is required cannot be specified. Equipment in common use operates over the pressure range of 1 to 80 cm of mercury. This pressure range is capable of producing laminar flow. This is the flow region required for permeability measurements. It is usually observed at flow rates up to 1 cu cm per second.

3.4 Pressure Measuring Devices - Inlet- and outlet-pressure measuring devices are manometers. These are water-, oil-, or mercury-filled and of a convenient length, usually 80 cm or less, with selection of length and fluid depending upon pressures to be measured. Manometers may be used in parallel to obtain the necessary accuracy over a range of pressures. Manometers are either open to the atmosphere or connected across the core. Connected across the core, they measure "differential" pressure. Where the pressure is in excess of 80 cm of mercury, a bourbon-type gage may be employed. This type of gage is normally only used in measuring extremely low permeabilities where high inlet pressures are required.

3.5 Core Holders

3.5.1 Three types of core measurements are commonly made:

(a) Axial flow in both small- and large-diameter cores

(b) Diametric flow in large-diameter cores

(c) Radial flow in large-diameter cores

3.5.2 Except for radial flow, more than one type of core holder may be used for permeability determinations. Irrespective of direction of gas flow or type of core holder used, the core holder must be such that when pressure is applied to one end of the system, all flow is through the sample. Care must be taken that no fluid bypasses the sample either through an imperfect seal between the core holder and sample or between the sample and the supporting material if the sample is mounted. Holders which accommodate several cores for simultaneous or sequential testing using matched pairs of inlet-outlet valves must be designed so that no fluid can leak between samples.

3.5.3 Selection of the type of core measurement is based on both the size of the sample available and the desired representativeness of the permeability value. For uniform, homogeneous rock small-diameter cores taken parallel and perpendicular to the bedding should provide representative permeability values. Measuring permeability of large-diameter cores is recommended for rock which is nonhomogeneous, vugular, fractured, or laminated. The radial method provides more representative data than the horizontal flow method since the entire diameter surface area of the core rather than a concentrated section of the diameter surface area of the core is involved in flow.

3.6 Screens to Distribute Gas Flow - When flow is across the core parallel to a diameter, screens should be of a wire diameter and mesh size such that a uniform gas distribution is obtained. Care should be exercised in positioning the screens prior to placing the sample in the holder to ensure that they maintain their proper position while the core is being seated.

3.7 Air Flow-Rate Metering Device- Three types of dry air flow-rate metering devices may be used:

(a) Calibrated orifices (a capillary tube which is calibrated for the conditions of testing, so that the pressure drop across the orifice is small compared to the core)

(b) Soap bubble in a calibrated burette

(c) Water-displacement meters

The calibrated orifice is the most commonly used type of flow metering device. Timing the movement of a soap bubble in a burette is also frequently used. Differential pressures across the core are adjusted to minimize turbulence in the flow of gas through the sample. Flow rates of 1 cu cm per second or less are used.

3.8 Sample Preparation Equipment - Sample preparation equipment shall include the following:

3.8.1 Diamond coring equipment for taking small-diameter cylinders from larger samples.

3.8.2 Diamond saw for trimming ends of samples. Ends should be sufficiently flat and parallel for leakage seating of rubber end seals.

3.8.3 Drill press and diamond drill for drilling axial holes for radial flow measurement samples. The holes should be concentric with the axis of the cylindrical sample. Care should be exercised in drilling to prevent cracking of the sample.

3.8.4 Sample cleaning to remove original fluids from the cores, external coatings such as drilling muds, and, in the case of highly saline original fluid, deposited salts. Where the original fluids are hydrocarbons, cleaning may be accomplished by solvent extraction, gas-driven solvent extraction, distillation-extraction, or other suitable method.[2] Drilling muds may be removed from the surface with water washing. If the interstitial water is very saline, several thorough freshwater washing should remove deposited salts.

3.8.5 Drying oven that can be maintained at 110 ± 5 °C.

3.8.6 Micrometer or vernier caliper for measuring length and diameter of test specimen. Micrometer or caliper should be direct reading to 1/50 mm.

3.8.7 Equipment as required for mounting samples of weak rock in optical pitch or suitable potting plastic.

3.8.8 Miscellaneous equipment such as timing devices, magnifying lenses, etc., used in preparing the sample and measuring pressures and gas flow rates.

4. Calibration

4.1 The permeameter should be calibrated regularly by means of capillary tubes of various known permeabilities or with standard plugs.

4.2 Orifices used to measure gas flow rates should be calibrated by allowing air to flow from the orifice to a burette containing a soap bubble.

4.3 Micrometers or vernier calipers used to measure sample dimensions should be checked against length standards.

5. Sample Preparation

5.1 There are no standard sample sizes. Small-diameter samples are commonly 1.9 to 3.8 cm in diameter. Large-diameter cores are arbitrarily 5.4 cm

[2]Darcy, H., The Public Fountain of the Village of Dijon. Paris: Victor Dalmont, 1856 (French text).

in diameter (equivalent to NX core) and larger. Cores as large as 15.2 cm in diameter are commonly tested. Core holders are designed for a specific size or sizes of cores. The core holders are designed for a specific size or sizes of cores. The core holder may be modified to accommodate a smaller sized sample by placing the core in a rubber sleeve whose inner diameter is that of the core and whose outer diameter is that for which the permeameter was designed. Thus a 1.9-cm-diam sample can be tested in a permeameter designed for 2.54-cm samples. Sample length is also not standardized. Sample lengths vary from 2.54 cm for small-diameter samples to 60.96 cm for large-diameter cores. Core holding devices are designed to accept different length samples. Where a sleeve is used to adapt a core, differences in sleeve and sample length may be compensated for by means of spacer rings placed on top of the sample.

5.2 Ratio of sample length to diameter also is not standardized. A ratio of 1:1 is recommended as a minimum for small-diameter samples. For large-diameter samples, a minimum L/D ratio of 1:2 is recommended.

5.3 The diameter of the test specimen is measured to the nearest 0.1 mm by averaging two diameters measured at right angles to each other at about midlength of the specimen. This average diameter is used for calculating the cross-sectional area. The length of the test specimen is determined to the nearest 0.1 mm by averaging three length measurements taken at third points around the circumference.

5.4 If the sample requires artificial support, the mounting material and method of mounting should be such that penetration into the sample is minimized, the sample does not extend beyond the surface of the mounting material, and mounting material does not cover any surface perpendicular to the direction of flow. Specific details of the mounting procedures, as well as mounting materials, are given in reference 1.

5.5 In cleaning and mounting the sample prior to testing, care should be used to prevent any alteration of the minerals comprising the rock sample which may produce changes in permeability. Samples containing clays or other hydratable minerals are especially susceptible.

5.6 Before measuring permeability any sample which is suspected of being cracked should be tested by coating with a liquid while air is passing through the sample. A row of bubbles on the downstream surface will serve to indicate the presence of a crack parallel to the direction of flow. Such samples should either be discarded as nonrepresentative or, if retained, note should be made of the crack in reporting permeability values.

6. Procedure

6.1 The prepared sample is mounted in the specified core holder as follows:

6.1.1 Hassler-type Holder - Retract rubber diaphragm or sleeve, Fig. 1, by applying a vacuum to the space between the diaphragm and the body of the core holder. (Note 2)

NOTE 2--A vacuum source of 5 cm of mercury is sufficient to retract the diaphragm.

Remove one end of the core holder and insert the cylindrical sample. Reinsert the end of the core holder, applying sufficient force to seat the sample. Remove the vacuum from the space between the body and the diaphragm, thus allowing the diaphragm to constrict around the sample. (Note 3)

NOTE 3--Fine-grained, smoothly formed samples can be effectively sealed at 690 N/m^2 pressure. Coarse-grained samples will require from 1035 to 1370 N/m^2 sealing pressure.

The pressure between the diaphragm and core holder body is maintained during the permeability measurement.

6.1.2 Fancher-type Holder - Select a rubber stopper drilled to the diameter and length of the sample. Carefully push the sample plug into the tapered stopper base until it is flush with the small end surface. Remove all loose sand grains. Place the stopper containing the test sample inside the tapered material core holder, Fig. 2. Turn the ram hand wheel to move the upper ram plug down to seal tightly against the top of the holder. Compress the tapered rubber stopper with the ram to effect a seal around the sample perimeter.

6.1.3 Compression (Ram) Holder - Place the sample in the lower half of the rubber cradle, Fig. 4, making certain that the screen is centered over the air outlet and the ends of the sample are overlapped by the rubber cradle. Lower the upper compression half by applying air or hydraulic pressure above the piston. After seating the two halves, apply sufficient pressure to compress the rubber cradle with the ram to effect the seal around the sample perimeter. (See Note 3).

6.1.4 Radial Flow Holder - Place the core on a (2.54-cm) solid rubber gasket which is attached to the lower floating plate, Fig. 5. Raise the core by means of the piston against the closed lid with the center hole of the core matching that of the upper gaskets. After the core contacts the upper gasket, increase the piston pressure slightly to adjust the lower floating plate if the core ends are not parallel. Sufficient piston pressure is then applied to effect a seal of the upper and lower core surfaces. (Note 4)

NOTE 4--With gas flowing through the core at a constant rate, the piston pressure is increased. Decreased flow rate with increasing piston pressure indicates a leak at the rubber gasket. Repeat the test until no change in the flow rate is noted.

6.2 Connect the source of dry gas and inlet pressure measuring devices to the inlet fitting on the core holder. Connect the outlet pressure measuring devices and flow rate metering device to the outlet fitting on the core holder.

6.3 Initiate dry gas flow through the sample. Control the flow rate to minimize turbulence. Measure the flow rate through the sample intermittently for a period of 3 to 10 minutes until the flow becomes constant. Record the constant flow rate and pressures.

7. Calculations

7.1 The calculation of permeability is based on the empirical expression of Darcy known as Darcy's law.[2] The coefficient, k, of proportionality is the permeability.

7.2 The unit of the permeability coefficient, k, is the darcy. For convenience the subunit millidarcy may be used where 1 millidarcy equals 0.001 darcy. A porous medium has a permeability of one darcy when a single-phase fluid of one centipoise viscosity that completely fills the voids of the medium will flow through it under "conditions of viscous flow" at a rate of 1 cu cm per second per square centimetre of cross-sectional area under a pressure gradient of one atmosphere per centimetre. "Conditions of viscous flow" mean that the rate of flow is sufficiently low to be directly proportional to the pressure gradient. The permeability coefficient so defined has the units of length squared or area.

7.3 Vertical Flow Parallel to Core Axis - Darcy's law in differential form for linear flow is

$$q = \frac{k}{\mu} \frac{dp}{dL}$$

where

- q – macroscopic velocity of flow, in centimetres per second
- k – permeability coefficient, in darcys
- μ – viscosity of the fluid that is flowing, in centipoises
- dp/dL – pressure gradient in the direction of flow, in atmospheres per centimetres

Relating the velocity of flow to the volume rate of flow through the cross-sectional area and performing the indicated integration produces the following working equation for permeability coefficient in millidarcys:

$$k = (2000\ Q_o O_o\ L\ \mu)/\left(P_i^2 - P_o^2\right)$$

where

- Q_o = rate of flow of outlet air, in cubic centimetres per second
- P_o = outlet pressure, in atmospheres (absolute)
- P_i = inlet pressure, in atmospheres (absolute)
- L = length of sample, in centimetres
- A = cross-sectional area perpendicular to direction of flow, in square centimetres

Several methods of simplification exist for calculating the permeability coefficient. Two such methods are given below:

7.3.1 Method 1 - For this method inlet pressure and pressure drop across the rate measuring orifice during the test are selected so that the outlet pressure is essentially one atmosphere. The working equation then reduces to

$$k = Q\ CL/A$$

where

$C = (2000\ \mu)/(P_i^2 - 1)$

μ = viscosity of air under the conditions used to calibrate the orifice

C then is a constant for each fixed inlet pressure since the fact that the same air flows through both the core and the orifice means that any change in air viscosity resulting from temperature changes or water vapor will have no effect on the relative pressure readings.

7.3.2 Method 2 - For this method calibration charts or tables of permeance (Note 5) versus outlet pressure for given inlet pressures and orifices are prepared based on the following equation

$$k_c = \frac{L_c}{A_c}\left(\frac{k_{or}}{L_{or}/A_{or}} \cdot \frac{\Delta P_{or} Q_c}{\Delta P_c Q_{or}}\right)$$

where

k_c, k_{or} = permeability of the core and the equivalent permeability of the orifice, respectively, in millidarcys

L_c, L_{or} = length of core and orifice, respectively, in centimetres

A_c, A_{or} = cross-sectional area of core and orifice, respectively, in square centimetres

ΔP_c, ΔP_{or} = pressure drop across the core and orifice, respectively, in atmospheres

Q_c, Q_{or} = flow rate through the core and orifice, respectively, in cubic centimetres per second

NOTE 5--Permeance or apparent permeability is the proper term for flow capacity. The term as used is analogous to the term conductance for the flow of current through an electrolyte solution. Permeance and permeability, therefore, are related in the same way as conductance and conductivity.

This working equation can be simplified to

$$k_c = \frac{L_c}{A_c} \frac{Q_c}{\Delta P_c} \cdot L$$

where

L = orifice constant

L may be determined directly by use of a known permeability plug. When tables or nomographs are used to calculate the permeability coefficient from measured outlet pressure for given inlet pressures and orifices, the working equation reduces to

$$k_c = \frac{L_c}{A_c} k_c^{\theta}$$

where

k_c^{θ} = permeance of the core

The permeance as calculated when multiplied by the L/A ratio gives the core permeability coefficient, k_c.

7.4 Horizontal Flow Parallel to Core Diameter - The same differential form of Darcy's law and working equation as used for vertical flow are applied. The working equation is modified by a factor for shape to the following form:

$$k = (Q_m \mu / L \Delta P)(1000)(G)$$

where

k = permeability, in millidarcys

Q_m = volume rate of air flow at mean core pressure, in cubic centimetres per second

μ = viscosity of flowing fluid, in centipoises

L = length of sample, in centimetres

ΔP = pressure drop across the core, in atmospheres

G = shape factor,[3] Fig. 6

7.5 Radial Flow - The radial permeability is calculated directly from the integrated form of Darcy's law for radial flow. The equation in terms of permeability coefficient is

$$k = (\mu Q_a)\,(\ln d_e/d_w)\,(P_o)/(\pi h)\,(P_i^{\,2} - P_o^{\,2}) \cdot 1000$$

where

k = permeability, in millidarcys

μ = viscosity of flowing fluid at test temperature, in centipoises

Q_a = measured flow rate at test temperature and pressure = P_o, in cubic centimetres per second

ln = logarithm to the base e

d_e = outside diameter of sample, in centimetres

d_w = inside diameter of inner hole, in centimetres

P_o = outlet pressure, in atmospheres (absolute)

h = height of sample, in centimetres

P_i = inlet pressure, in atmospheres (absolute)

As with vertical flow, if the outlet pressure is atmospheric and the orifices are calibrated over the range of inlet pressures, the working equation simplifies to

$$k = \mu Q_m\,(\ln d_e/d_w)/2\pi h\Delta \cdot 1000$$

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[3]Collins, R. E., "Determination of the Transverse Permeabilities of Large Core Samples from Petroleum Reservoirs," Journal of Applied Physics 23, 681-84 (1952).

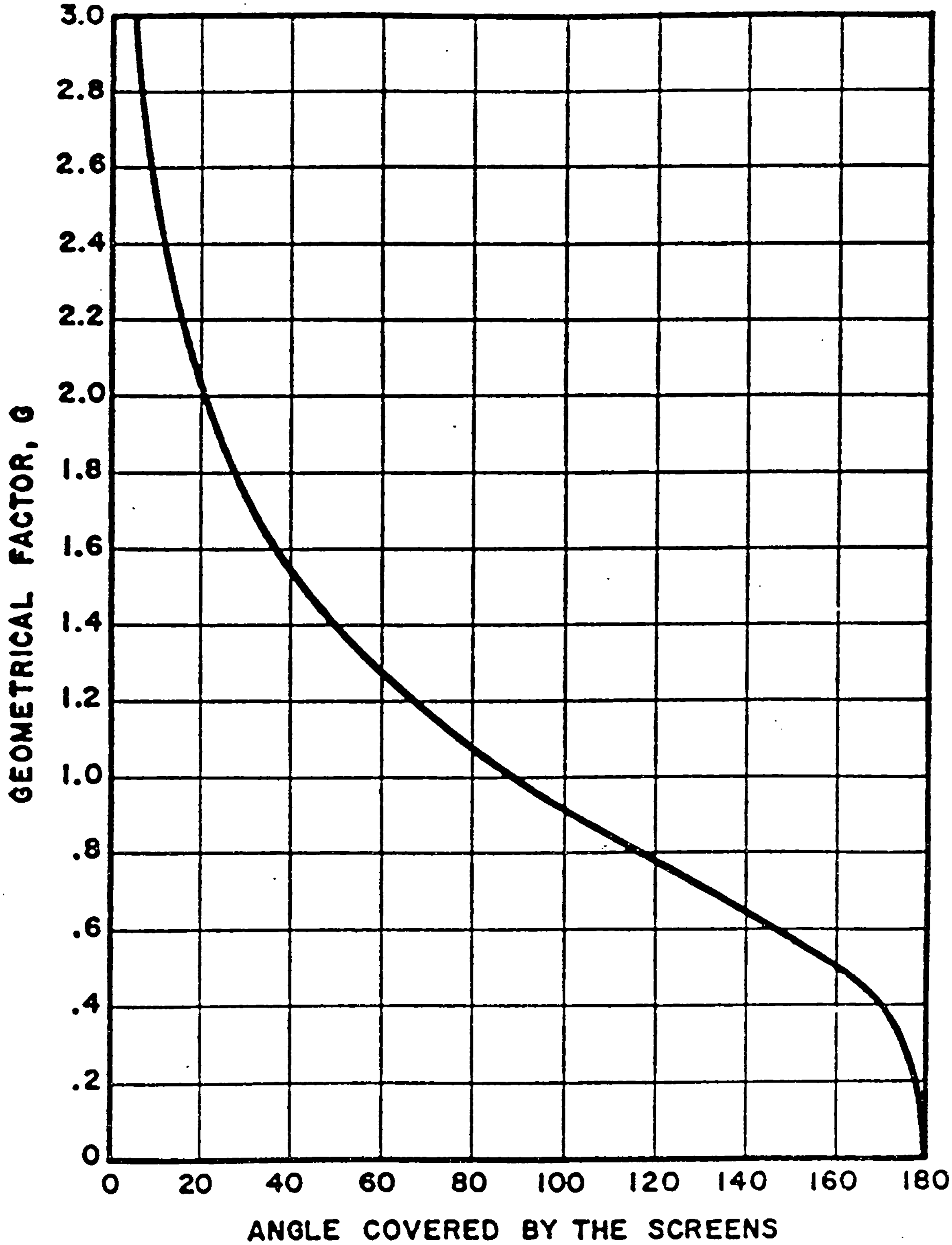

Fig. 6. Theoretical curve relating the geometric factor and the angular segment of the core covered by the screens (Collins, 1952).

where

Q_m = volume rate of air flow at mean core pressure, in cubic centimetres per second

ΔP = pressure drop across sample, in atmospheres (absolute)

8. Report

8.1 The report shall include the following:

8.1.1 A lithologic description of the rock tested.

8.1.2 Source of sample including depth and orientation, dates of sampling and testing, and storage environment.

8.1.3 Methods used for sample cleaning.

8.1.4 Methods used for sample support, capping, or other preparation such as sawing, grinding, or drilling.

8.1.5 Specimen length and diameter.

8.1.6 Type of core holder used.

8.1.7 Pressures used to seal core surfaces in core holder.

8.1.8 Flowing fluid used and direction flow.

8.1.9 Method used for calculating permeability coefficient.

8.1.10 Results of other physical tests, citing the method of determination for each.

8.1.11 Permeability corrections used.

8.2.12 Description of air source.

8.1.13 Calculation of permeability, with values defined for all variables.