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RECOMMENDED PRACTICE

for

DETERMINING PERMEABILITY

of

POROUS MEDIA

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RECOMMENDED PRACTICE FOR DETERMINING PERMEABILITY OF POROUS MEDIA

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Note

This edition supersedes the 2nd edition dated April, 1942. Adopted in May, 1935, *Standard Procedure for Determining Permeability of Porous Media* was originally designated as *API Code No. 27*. In conformance with present publication policy, the designation and title have been changed to *API RP 27: Recommended Practice for Determining Permeability of Porous Media*.

API RECOMMENDED PRACTICE FOR DETERMINING PERMEABILITY OF POROUS MEDIA

Foreword

a. This revised *Recommended Practice* has been prepared by the Special Project Committee on Permeability. It is published under the auspices of the Central Committee on Drilling and Production Practice, as were the original* and previously revised† editions.

*Adopted May, 1935, after formulation by the Topical Committee on Development and Production Research.

†Amendments of May and Nov., 1941, incorporated in a revision prepared by the Topical Committee on Production Technology.

b. The purpose of this recommended practice is to facilitate comparisons and coordination of permeability measurements on porous media as made in various laboratories by the adoption of uniform notation and dimensionally equivalent units. It is the further purpose to define the conditions of test and to point out sources of error commonly encountered, not with the view to standardize the detailed technique of measurement but rather to insure that reported values are free from inaccuracies caused by faulty methods and improper conditions of test.

SECTION I

DEFINITIONS

Introduction

1. Permeability is a property of a porous medium and is a measure of the capacity of the medium to transmit fluids. The measurement of permeability of a porous rock, or stratum, is a measurement of the fluid conductivity of the particular material. Consequently, permeability represents the reciprocal of the resistance which the porous medium offers to fluid flow. Reference to the relation of the resistance and conductance properties of electrical conductors to the flow of electrical current and of the resistance and conductance properties of thermal conductors to the flow of heat suggests an analogous interpretation of the phenomena of fluid flow. The permeability of a homogeneous medium is considered to be the same everywhere, although in a heterogeneous medium the permeability may be anisotropic.

2. The experiments and studies of Darcy¹⁰ many years ago led to an empirical expression of the relationship among the variables involved in the flow of liquids through porous media. This expression is known now as Darcy's law. Briefly, Darcy's work showed that the volume rate of flow of a liquid per unit cross-sectional area of permeable medium was directly proportional to the pressure gradient and inversely proportional to the viscosity of the liquid for a condition of flow which customarily is called "viscous flow." The coefficient of proportionality is the permeability (see Appendix B for further details).

Unit of Permeability

3. In order to make practical use of the general concept that porous media possess the measurable property of permeability, an arbitrary standard unit must be defined. For the purpose for which this recommended practice is intended, the standard unit of permeability shall be the "darcy," the definition and discussion of which follow.

4. 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 one cubic centimeter per second per

square centimeter of cross-sectional area under a pressure or equivalent hydraulic gradient of one atmosphere (76.0 cm of Hg) per centimeter. "Conditions of viscous flow" shall mean simply that "the rate of flow be sufficiently low to be directly proportional to the pressure or hydraulic gradient." Consideration of this definition indicates that the unit of permeability (the darcy) as a coefficient of proportionality between pertinent, although admittedly arbitrary, physical quantities possesses dimensions. Specifically, the permeability, so defined, has the dimensions of length squared (L^2), or those of an area. It should be emphasized that the permeability coefficient has these dimensions because it is desired that it represent a property or attribute of the medium alone and not of the fluid except as herein-after qualified, and that the selection of a definition and hence of the dimensions has been done through choice. For convenience the following sub-unit may be used:

$$\text{Millidarcy} = 0.001 \text{ darcy} \dots \dots \dots (1)$$

5. The use of other sub-units such as the centidarcy or microdarcy is not recommended because practical considerations eliminate the necessity for additional sub-multiples of the standard unit. The same statement can be made for multiples of the darcy. *The spelling of the plural form of the unit has been standardized and established in the literature as "darcys" and "millidarcys."*

Terminology

6. Symbols. A complete list of symbols, with definitions as used herein, has been prepared (Table 11).

7. Permeability. The definition of the *standard unit* of permeability requires that the porous medium contain only one homogeneous, single-phase fluid. Although the property of the medium so determined properly might be termed the *specific permeability*, for practical reasons sanctioned by custom, it shall be called simply *permeability*, and shall be denoted by the symbol k . It should be emphasized that by this definition the unqualified term, *permeability*, becomes solely the property of the porous medium; and the particular numerical value of the permeability is

constant and independent of the fluid used in the measurement. It is to be realized, however, that whenever certain minerals and fluids are brought in contact and interaction results or material is deposited from the fluid, this phenomenon, in effect, produces a *new medium* the permeability of which may differ from that of the unaltered medium. This phenomenon in no way vitiates the application of the principles herein stated (cf. Ref. 2, 12, and 23). Whenever this phenomenon is experienced, the fact should be indicated clearly by appropriate references to both medium and particular fluid, e.g., "the permeability of Woodbine sand to salt water (fresh water, crude oil, heptane, air, nitrogen, as the case may be)."

8. Effective Permeability. The *effective permeability*³⁴ of a porous medium is a measure of the conductance of the medium to one fluid phase of a multi-phase fluid system existing in the medium. The medium can have a distinct and measurable *effective permeability* to each such fluid phase present. In addition to being a function of the porous medium, the effective permeability to each fluid phase clearly is a function of the quantity or percentage saturation and of the distribution of each phase in the medium. The effective permeability to a particular phase has a constant value only for "certain necessary conditions of flow" and for a constant percentage saturation and a unique distribution of the fluid phases present (see Sect. III). The possible range for values of effective permeability lies, therefore, between the limit of zero at some definite percentage of the phase under consideration and the permeability† of the medium. The effective permeability to a particular fluid phase at 100 per cent saturation of the medium will be equal to the permeability (except as pointed out in Par. 7). The fluid phases of major significance to the petroleum production industry and hence properly the concern of this recommended practice are *oil*, *water*, and *gas*. The amount or *saturation* of each phase present in a porous medium shall be expressed as a *percentage of the total pore volume*.

9. The effective permeability should be expressed in standard units and can be denoted symbolically as k_o , k_w , or k_g . If the percentage saturation of the various phases is known, it is suggested that the percentage saturation of oil and water (*always in this order of succession*) be indicated by an appropriate designation. For example, $k_o(60, 13)$ is read: "The effective permeability of the medium to oil when the percentage fluid saturation of the medium is 60 per cent oil, 13 per cent water, and 27 per cent gas (millidarcys or darcys)." The gas concentration (27 per cent) obviously is derived by difference. Likewise, $k_w(50, 40)$ is read: "The effective permeability of the

medium to water when the percentage fluid saturation is 50 per cent oil, 40 per cent water, and 10 per cent gas is (millidarcys or darcys)." Take note that $k_g(o, o)$, which is effective permeability to gas, ordinarily would be expected to equal the permeability and hence could just as well be written k .

10. As more experimental data are obtained, evidence is increasing of the importance of the immediate past history in arriving at a particular saturation and distribution of fluids in a porous medium on which it is desired to conduct flow studies. For example, a particular gas saturation may be arrived at by dynamic methods,⁴ capillary pressure methods,^{5, 18, 29} or by pressure depletion from a gas-saturated liquid phase. For each method the final gas saturation may be the same, but the distribution of the gas within the porous medium may be quite different. In some regions of saturation a pronounced hysteresis develops in the measurement of effective permeability, depending upon the method of changing the saturation. The reproduction within a core of the same condition of saturation and distribution of fluids which may prevail in an underground reservoir of equal percentage saturation is essential to successful experimental work and interpretation of results; this same condition to be brought about by the use of methods and mechanisms which approximate those by which fluid saturation becomes changed in underground reservoirs by the production of reservoir fluids. *No specific nomenclature applicable to this problem is suggested here, but the suggestion is made that when reporting effective permeability data the methods used in experimentation be stated clearly.*

11. Relative Permeability. The *relative permeability* of a porous medium to one fluid phase of a multi-phase fluid system existing in the medium at any definite percentage saturation of the fluid phases is defined as the ratio of the effective permeability to the permeability. In accordance with the discussion under Par. 7, 8, and 9, the terminology required is illustrated and defined with the following examples:

$$k_{ro}(50, 30) = \frac{k_o(50, 30)}{k} \dots\dots\dots (2)$$

$$k_{rw}(50, 30) = \frac{k_w(50, 30)}{k} \dots\dots\dots (3)$$

$$k_{rg}(50, 30) = \frac{k_g(50, 30)}{k} \dots\dots\dots (4)$$

12. As a practical expedient, any effective permeability [e.g., $k_w(o, 100)$] can be used as a reference or base permeability instead of the permeability k , so long as the particular one used is stated clearly. In reporting relative permeability the effective permeability also should be reported so that any desired conversion of relative permeability base can be made.

†The way in which the fluids are arranged in the medium has a bearing on the resultant effective permeability.⁴

‡For exceptions to the upper limit, see Appendix B, references 2, 11, 13, 25, and 26.

SECTION II

THEORY

Summarized Theory of Permeability Determination

13. Darcy's law for the viscous flow of fluids through permeable media may be stated in general terms as

$$v_s = - \frac{k}{\mu} \left[\frac{dp}{ds} - \rho g \frac{dz}{ds} \right] \quad (5)$$

wherein:

s = distance along the direction of flow.

v_s = volume flux (rate of flow) across a unit area of the porous medium in unit time.

z = vertical coordinate directed downward.

ρ = the density of the fluid.

g = acceleration of gravity.

$\frac{dp}{ds}$ = pressure gradient along s at the point to which v_s refers.

μ = viscosity of the fluid.

k = permeability of the medium.

Take note that

$$v_s = \frac{Q}{A} \quad (6)$$

wherein:

Q = volume rate of flow.

A = average cross-sectional area perpendicular to lines of flow.

14. The convention adopted here and that which is the basis for placing the minus sign in front of the right side of Equation (5) is that v_s should be positive if the fluid is flowing toward increasing values of the coordinate s (see Par. 18).

Liquids

15. Special Cases for Steady State Flow of Incompressible Liquids. Equation (5) may be reduced to simpler forms under special conditions of flow. Some of the more important of these are as follows.

(NOTE: The absolute value of dz/ds as a derivative always is used together with the definition of s as given in Par. 13 and Table 11 to determine the algebraic sign, plus or minus, in equations.)

A. Horizontal flow:

$$s \rightarrow x: \frac{dz}{ds} = 0 \quad (7)$$

$$v = - \frac{k}{\mu} \frac{dp}{dx} \quad (8)$$

$$k = - \frac{\mu v}{\frac{dp}{dx}} \quad (9)$$

B. Vertical flow:

$$s \rightarrow z: \frac{dz}{ds} = 1 \quad (10)$$

(a) Free downward flow (see Fig. 1):

$$\frac{dp}{ds} = 0 \quad (11)$$

$$v = \frac{k}{\mu} \rho g \quad (12)$$

$$k = \frac{\mu v}{\rho g} \quad (13)$$



FIG. 1

See B (a)

(b) Downward flow with a driving head "h" (see Fig. 2):

$$\frac{dp}{ds} = - \frac{\rho g h}{L} \quad (14)$$

$$v = \frac{k}{\mu} \rho g \left[\frac{h}{L} + 1 \right] \quad (15)$$

$$k = \frac{\mu v}{\rho g \left[\frac{h}{L} + 1 \right]} \quad (16)$$

L = length of flow column.



FIG. 2

See B (b)

(c) Upward flow with driving head "h" (see Fig. 3):

$$\frac{dp}{ds} = \frac{\rho gh}{L} + \rho g \quad (17)$$

$$v = -\frac{k}{\mu} \frac{\rho gh}{L} \quad (18)$$

$$k = -\frac{\mu v}{\frac{\rho gh}{L}} \quad (19)$$

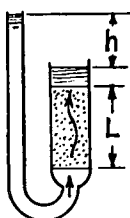


FIG. 3

See B (c)

C. Radial flow (inward) (see Fig. 4):

$$s \rightarrow r: \frac{dz}{ds} = 0 \quad (20)$$

$$v_r = -\frac{k}{\mu} \frac{dp}{dr} \quad (21)$$

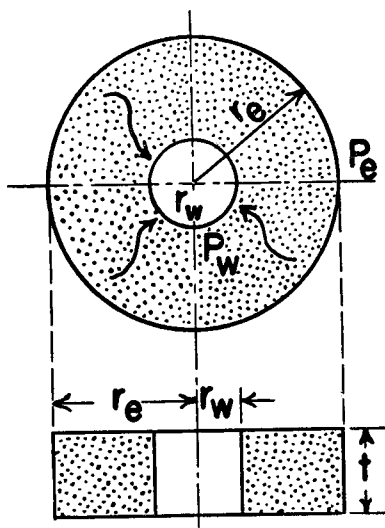


FIG. 4

See C

16. With inward radial flow, the total flux will be:

$$Q = -2\pi r t v_r \quad (22)$$

$$Q = \frac{2\pi k t r}{\mu} \frac{dp}{dr} \quad (23)$$

On integration:

$$Q = \frac{2\pi k t (p_e - p_w)}{\mu \ln \frac{r_e}{r_w}} \quad (24)$$

and

$$k = \frac{Q \mu \ln \frac{r_e}{r_w}}{2\pi t (p_e - p_w)} \quad (25)$$

wherein: t is the axial thickness of the sample.

17. If the flow should be outward, exactly the same formula should be used with p_e again referring to the inflow pressure and p_w to the outflow pressure, and Q representing the positive numerical value of the total flux rate.

18. It should be realized that the minus sign in the permeability formula for the case of horizontal flow arises from the fact that inasmuch as the flow is assumed to be directed toward increasing values of x , the pressure gradient dp/dx will be negative. The resultant numerical value of the permeability will therefore come out to be positive. In the vertical flow case B (c), the volume flux v will be negative because the flow will be directed toward decreasing values of the coordinate z . The resultant numerical value of the permeability will thus again be positive.

Gases

19. If the fluid used in any measurement is a gas, the peculiar properties of the gas must be considered in formulating an exact and appropriate expression for any one of the special geometrical cases developed for liquids. Like Darcy's law for the flow of liquids, the empirical formulation of a law for the flow of gases through permeable media rests solely upon experimental observations. It has been found experimentally* that, for certain ranges of velocity, the rate of mass flow of a gas per unit cross-sectional area of a porous medium is directly proportional to the difference between the square of the inlet pressure and the square of the outlet pressure and also inversely proportional to both the viscosity of the gas and the distance the gas has traveled. In the preceding sentence the phrase "certain ranges of velocity" is analogous to "conditions of viscous flow" as this latter phrase is used throughout this recommended practice.

20. With a gas, the flux v_s is not constant, but increases as the outlet of the flow channels through the medium is approached because of the expansion of the gas. Likewise, the pressure gradient dp/ds increases simultaneously, but in such a way that the ratio of this expression to v_s remains constant. The mass velocity (v_s multiplied by the density ρ) and the gradient of the square of the pressure remain constant along the path of the flow channel. In the foregoing, the flow of gas at constant temperature has been assumed. If this is not the case, appropriate correction for temperature change must be made. The gas is assumed to behave as a perfect gas, but if this should not be true in a particular situation, appropriate correction must be made.

*See references in Appendix B.

21. The equations appropriate for the calculation of the permeability from data obtained for the flow of gas through permeable media may be derived as shown in the following paragraphs.

Special Cases for Isothermal Steady-State Flow of Gas

A. Horizontal flow:

Darcy's law, Equation (5), may be rewritten for the flow of gas as:

$$v_x = - \frac{k}{\mu} \frac{dp}{dx} \quad (26)$$

The direction of flow in Equation (26) has been denoted by x . As previously indicated, neither the flux v_x nor the quantities on the right-hand side of Equation (26) will be constant along the x -axis. However, if each side of the equation is multiplied by the density of the gas ρ , the left side becomes the mass velocity which is constant as indicated in Par. 20. Thus:

$$\rho v_x = \text{constant} = - \frac{k\rho}{\mu} \frac{dp}{dx} \quad (27)$$

The mass velocity may be expressed as:

$$\rho v_x = \frac{Q_b \rho_b}{A} \quad (28)$$

wherein:

Q_b = volume rate of flow measured at the base pressure p_b .

ρ = density at pressure p_b , and

A = cross-sectional area perpendicular to the direction of flow of the gas.

For an ideal gas and isothermal flow, ρ may be expressed as:

$$\rho = \rho_b \frac{p}{p_b} \quad (29)$$

Inserting Equations (28) and (29) into (27), the latter becomes:

$$\frac{Q_b}{A} = - \frac{k}{\mu} \frac{p}{p_b} \frac{dp}{dx} \quad (30)$$

the integral of which is:

$$\frac{Q_b}{A} = \frac{k(p_1^2 - p_2^2)}{2\mu L p_b} \quad (31)$$

wherein: p_1 and p_2 are the terminal pressures. Finally, Equation (31) may be solved for k :

$$k = \frac{2\mu Q_b p_b L}{A(p_1^2 - p_2^2)} \quad (32)$$

Equation (32) provides a direct expression for the calculation of the permeability from experimental data and is convenient to use for many purposes. Equation (32) may be transformed to simulate Equation (9) for liquids to illustrate the analogy between the flow of a liquid and a gas through porous media.

Thus, because Q_b is proportional to the mass velocity, [compare with Equation (28)]:

$$Q_b p_b = Q_{av} p_{av} \quad (33)$$

wherein: p_{av} is the algebraic mean pressure, $\frac{p_1 + p_2}{2}$;

and Q_{av} is the volume rate of flow at the mean pressure. Factoring the denominator of Equation (32) shows that:

$$k = \frac{\mu Q_{av} L}{A(p_1 - p_2)} \quad (34)$$

Consequently the permeability k may be computed from experiments involving the flow of gas at constant temperature in exactly the same way as in the flow of liquids, provided only that in accordance with the foregoing equations the volume outflow rate at base conditions or conditions of measurement be reduced to the equivalent volume at the algebraic mean pressure and constant temperature, and further provided that conditions arbitrarily defined as *viscous flow* also prevail during the experiment.

B. Vertical flow:

Similar arguments apply to cases B(a), B(b), and B(c) (Par. 15) for situations wherein the fluid flowing vertically is a gas rather than a liquid. The consideration of these cases is pointless for laboratory work with gas because, except for conditions of pressure so great that the density of the gas becomes appreciable, the correction for density and head is trivial. Either Equation (32) or (34) can be used for practical purposes in virtually all cases involving rectilinear flow.

C. Radial flow (inward) (see Fig. 4):

Likewise, special geometrical case C can be analyzed with the following result:

$$k = \frac{\mu Q_b p_b \ln \frac{r_e}{r_w}}{\pi t (p_e^2 - p_w^2)} \quad (35)$$

which is equivalent to:

$$k = \frac{\mu Q_{av} \ln \frac{r_e}{r_w}}{2\pi t (p_e - p_w)} \quad (36)$$

22. The purpose of the discussion and of the classification which has been made is to provide a basis for the measurement of the permeability of sands and similar porous media. Consideration of the special cases presented, and particularly of the definition of k for each case, demonstrates that a measurement of permeability involves only the setting up of a suitable experiment falling under one of the special cases and the accurate measurement of the particular variables pertinent to the problem.

Variation of the Permeability of a Porous Medium with the Nature of the Test Fluid

23. The development of Equations (9), (13), (16), (19), (25), (32), (34), (35), and (36) has been based upon the hypothesis of non-interaction between the

medium and the fluid. Furthermore, Equations (32), (34), (35), and (36) have been based also upon the idea of complete analogy between the mechanism of flow of a gas and a liquid whenever conditions of viscous flow prevail. Experiments have shown that although frequently the permeability of a porous medium to a liquid is independent of the nature of the liquid, nevertheless, the permeability of some porous media may vary with the liquid employed in making the test. Likewise, the permeability of a porous medium to a gas may exceed the permeability of the same medium to a liquid which does not react with the medium unless compensation for the phenomenon of *slip* is made, particularly if the medium is tight and the mean pressure of the gas low. Only in the event of complete analogy and of non-reaction to the medium with the test fluid could the permeability of a porous medium be a unique and single-valued property of the medium, regardless of whether the test fluid were liquid or gas.

24. The variation in the permeability of a medium to a single liquid with the nature of the liquid apparently depends upon either chemical or physical reaction between the medium and the liquid or upon electro-kinetic effects, or upon both phenomena. Obviously, electro-kinetic effects may be minimized by reduction of fluid velocity in experimental work, whereas the former cannot be controlled. Ionic reactions such as those between clay minerals and aqueous ionic solutions are common causes of anomalies in permeability measurements, anomalies which are unpredictable in magnitude.

25. The difference between the permeability of a porous medium to liquid and to gas in the absence of complicating chemical reactions or electro-kinetic effects, is due almost entirely to the phenomenon known as *slip*, a fact first pointed out to the oil industry by Klinkenberg²⁵ which had been overlooked or ignored by prior investigators of permeability despite theory and experimental data for slip in the flow of gases through small capillary tubes in scientific literature as early as 1875.²⁸ Klinkenberg developed, on the basis of theory and experimentation,

the relation between the permeability of a porous medium to gas and to a non-reactive liquid, viz.:

$$k_L = \frac{k_G}{\left[1 + \frac{b}{p_m}\right]} \quad (37)$$

wherein:

k_L = permeability of the medium to a single liquid phase completely filling the pores of the medium at constant temperature.

k_G = permeability of the medium to gas completely filling the pores of the medium at constant temperature.

p_m = mean pressure at which the gas is flowing.

b = constant (Klinkenberg) for a given gas and a given porous medium.

According to Equation (37) a plot between k_G and $1/p_m$ should result in a straight line with an intercept of k_L and a slope of bk_L (see Fig. 5). The absolute validity or the theoretical basis for Equation (37) is discussed extensively in the literature.^{6, 16, 19, 25, 28, 29, 38, 42, 50, 51} Practically, Equation (37) may be used to calculate the permeability to a liquid (in the absence of the complications mentioned) from measurements of the permeability to gas at several different values of the mean pressure as accurately as it can be measured directly.

26. The phenomenon of slippage when a gas passes through a porous medium is related to the mean free path of the gas molecules. Consequently, the permeability of a porous medium to gas should be a function of the factors controlling the mean free path, viz., the temperature, pressure, and the nature of the gas. Slip is maximum when mean free path is maximum; and, consequently, permeability to a gas is highest under such conditions. Thus permeability to a gas is greater at lower pressure, and at a minimum at maximum pressure of flow.

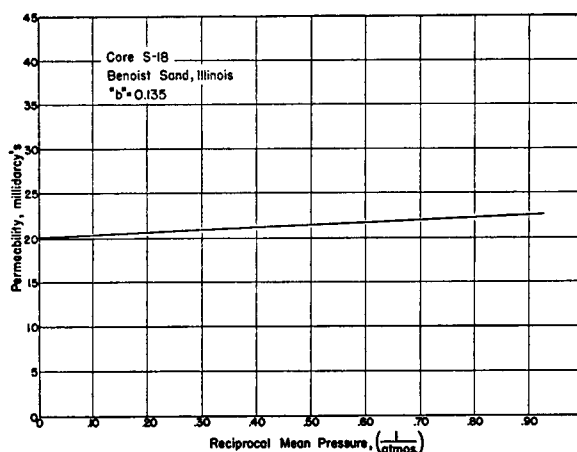


FIG. 5

Relationship between the Permeability to Gas and the Mean Pressure at which Gas Flows through a Medium, a Relationship Making Possible the Determination of the Permeability of the Medium to a Non-Reacting Liquid

27. The absolute value of the Klinkenberg factor b varies with the porous medium. In general, b increases as permeability decreases. Apparently, the numerical value of the factor b is a measure of the difference between the permeability of a particular porous medium to a non-reacting liquid and the permeability to a gas at unit pressure. Consequently, the factor b becomes a measure of the fractional error involved in assuming that the permeability of a porous medium to a gas at low pressure (the usual laboratory determination) is equivalent to the single-valued permeability k . Fortunately, an approximate linear relationship exists between b and k_L when plotted on log-log graph paper (Fig. 6). Furthermore, extensive tests¹⁹ conducted especially for this recommended practice on 11 synthetic cores and 164 cores of oil sands from various localities throughout

the United States indicated that the relation

$$b = 0.777 k_L^{-0.39} \dots\dots\dots (38)$$

reproduces the experimental data fairly well. Consequently, a graph of Equation (38) (Fig. 6) is useful in estimating the probable error involved in making use of permeability data determined in the usual way in the laboratory, i.e., with air (or gas) as the test fluid. This error may be considerable for porous media of low permeability. For example, a core having a low permeability may be in error by as much as 30 per cent if the determination is made at low mean pressure of the gas. Fig. 6 is not to be used to determine the permeability of the medium to a non-reacting liquid, however, but simply to estimate the probable magnitude of the permeability to be expected.

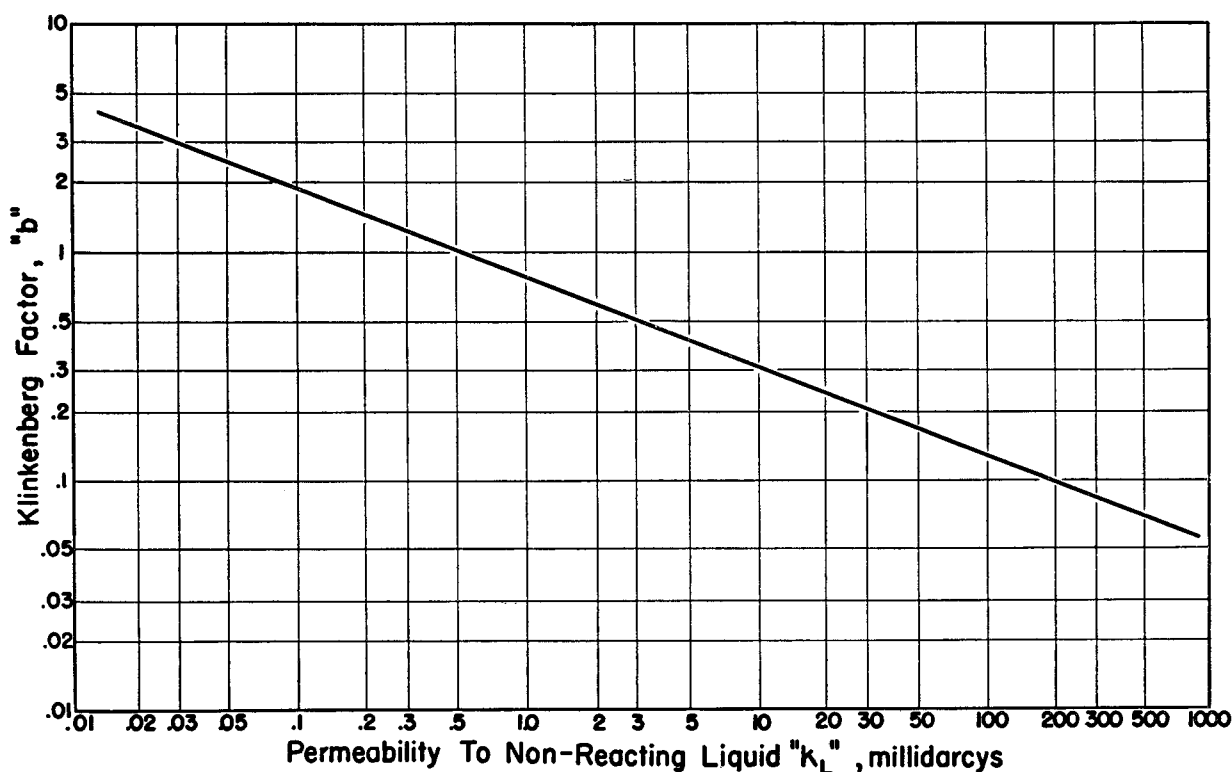


FIG. 6

THE EFFECT OF THE PERMEABILITY OF U. S. OIL WELL CORES ON THE KLINKENBERG
EXTRAPOLATION FACTOR

(API Special Research Project at the Pennsylvania State College)