CALCULATION OF FORMATION COMPRESSION
from CORE and WELL-TEST DATA

by

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ABSTRACT

Rock compaction due to reduction of fluid pressure in subsurface strata causes reduction of rock permeability, porosity, and thickness. Flow relationships in the rock are affected by these changes as well as changes of fluid viscosity and density. Where these changes are negligible, they are assumed constant and flow is described with a differential equation known as the diffusivity equation:

$$\nabla^2 P = \frac{\phi \mu c}{k} \frac{\partial P}{\partial t} .$$

Solutions to this equation are used to predict pressure behavior or to infer various rock characteristics from measured pressure behavior and to predict the amount of rock compaction resulting from fluid withdrawals. When variation of the above properties is not negligible an equation of the form

$$\nabla \cdot (\rho_f \frac{k}{\mu} \nabla P) = \rho_f \phi c \frac{\partial P}{\partial t}$$

is obtained. This equation may be put in the same form as the diffusivity equation with a variable which is defined

$$K (P) \triangleq \int_{P_i}^{P} \rho_f \frac{k}{\mu} dP' .$$

The differential equation is then

$$\nabla^2 K(P) = \frac{\phi \mu c}{k} \frac{\partial K(P)}{\partial t} .$$

Standard solutions to the diffusivity equation in terms of pressure may be used for the equation in terms of $K(P)$ if the quantity $\frac{\phi\mu c}{k}$ may be considered constant. Data from the Wilmington Field verify this assumption. With these solutions, rock compaction may be predicted and well flow tests analyzed for flow in rocks in which permeability, thickness, porosity, fluid viscosity, and fluid density vary significantly as functions of pressure. Core data may be used to describe these variations or they may be determined from analysis of pressures measured during flow tests. With these results reservoir transmissibility and storage coefficients may be determined as functions of pressure.

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INTRODUCTION

Compaction of rock due to withdrawal of fluids from subsurface sediments is a phenomenon accompanied in various parts of the world by land-surface subsidence, reduction of aquifer and/or petroleum reservoir storage capacities and transmissibilities, and compaction of well equipment.

Several techniques are used to predict the amount of rock compaction which can be expected from withdrawal of fluid. These techniques generally fall into two categories:

1. Field observations of some effect caused by fluid withdrawal, such as land-surface subsidence, correlation of that effect with amount of fluid withdrawn, and extrapolation to future time.
2. Sampling and measurement of rock characteristics which can be used with analytical techniques for prediction.

Techniques in most widespread use are in the first category. A disadvantage of such techniques is that accurate predictions are possible only after a history has been accumulated; in other words, compaction must be permitted in order to make a prediction.

Terzaghi(1) and Terzaghi and Peck(2) presented solutions for the head within a layer of rock as a function of time and distance. By relating rock compaction to head with a coefficient of compressibility, rock compaction as a function of time is described. This

paper presents a method for determining in situ variation of rock properties as a function of pressure with flowing tests in wells. Terzaghi's method of calculating rock compaction is modified to account for variation of permeability, viscosity, and fluid density with pressure.

ANALYSIS

In this paper, rock compaction is considered to be due only to reduction of fluid pressure within the pores of confined subsurface sediments. Reduction of fluid pressure is caused by removal of fluid from the pores without a reduction of saturation; namely, fluid removal is accomplished by fluid expansion associated with pressure reduction. Fluid-pressure reduction causes compaction of the rock and results in reduction of vertical rock dimensions only. There is no change of horizontal rock dimensions. Overburden and tectonic forces on the subject rock stratum are constant.

As rock compaction results from fluid-pressure reduction associated with a flowing fluid the flow system of the fluid is examined.

Consider a finite volume of porous material large compared to the size of an individual pore or rock grain and yet small compared to the size of the rock unit we wish to analyze. Such a cube is designated a representative elementary volume by Bear(3) and is defined as of size such that increases or decreases of the size of the volume cause an increase of fluctuations of the porosity of the volume. As such, "its largest dimensions must be much smaller than those of the flow domain, yet it must be large enough to contain a representative group of samples of the void space in the neighborhood of the considered point. The representative elementary volume as defined above is the smallest volume such that adding to it or subtracting from it one or several flow channels has a negligible effect on the value of volumetric porosity, ϕ". The pore space of the rock is assumed to be completely saturated with fluid.

A function, f, is defined such that

$$f\ (x,y,z,t) = 1 \text{ in pore space,} \qquad = 0 \text{ in rock,} \quad \ldots(1)$$

ρ^{μ} is density, and

v^{μ} is particle velocity.

Rock porosity, ϕ, is defined

$$\phi \triangleq \frac{1}{V} \int_{V} f dV, \quad \ldots(2)$$

where V is the representative elementary volume.

ρ_f and ρ_r are defined such that

$$\phi \rho_f \triangleq \frac{1}{V} \int_{V} \rho^{\mu} f\ dV, \quad \ldots(3)$$

$$(1-\phi)\ \rho_r \triangleq \frac{1}{V} \int_{V} (1-f)\ \rho^{\mu}\ dV\ . \quad \ldots(4)$$

$\vec{v}_f$ and $\vec{v}_r$ are also defined

$$\vec{v}_f \triangleq \frac{1}{V} \int_{V} \vec{v}^{\mu}\ f\ dV \quad \ldots(5)$$

$$\vec{v}_r \triangleq \frac{1}{V} \int_{V} (1-f)\ \vec{v}^{\mu}\ dV\ . \quad \ldots(6)$$

$\vec{M}$ is the mass flux density and

$$\vec{M} \triangleq \frac{1}{V} \int_V \vec{v}^{\mu} \rho^{\mu} \, dV . \qquad \ldots(7)$$

From conservation of mass,

$$\nabla \cdot \vec{M} = - \frac{\partial \rho_{\Sigma}}{\partial t} \qquad \ldots(8)$$

where

$$\rho_{\Sigma} \triangleq \frac{1}{V} \int_V \rho^{\mu} \, dV \qquad \ldots(9)$$

$$= \frac{1}{V} \int_V \rho^{\mu} \, [(1-f) + f] \, dV \qquad \ldots(10)$$

$$= (1-\phi)\rho_r + \phi\rho_f . \qquad \ldots(11)$$

Likewise, equation (7) may be written

$$\vec{M} = \frac{1}{V} \int_V \vec{v}^{\mu} \, [(1-f)+f] \, \rho^{\mu} \, [(1-f) + f] \, dV \qquad \ldots(12)$$

$$= \frac{1}{V} \int_V \vec{v}^{\mu} \, \rho^{\mu} \, (1-f)^2 \, dV + \frac{1}{V} \int_V \vec{v}^{\mu} \, \rho^{\mu} \, f^2 \, dV . \qquad \ldots(13)$$

with $f(1-f) \equiv 0$.
For the fluid,

$$\vec{v}_f \rho_f = \frac{1}{V} \int_V \vec{v}^{\mu} \, f \, dV \cdot \frac{1}{V\phi} \int_V \rho^{\mu} \, f dV . \qquad \ldots(14)$$

If $\rho^{\mu} f = 0$ or

$= \rho^{\mu}_1$, a constant,

$\rho^{\mu} f = \rho^{\mu}_1 f$.

By substituting in (14),

$$\vec{v}_f \rho_f = \frac{1}{V} \int_V \vec{v}^{\mu} \, f dV \cdot \frac{1}{V\phi} \, \rho^{\mu}_1 \int_V f dV . \qquad \ldots(15)$$

From (2)

$$\vec{v}_f \rho_f = \frac{1}{V}\int_V \vec{v}^{\mu}\, \rho^{\mu}_{1}\ f\ dV = \frac{1}{V}\int_V \vec{v}^{\mu} \rho^{\mu}\ f\ dV. \qquad ..(16)$$

Similarly, $(1-f)\rho^{\mu} = (1-f)\rho^{\mu_2}$ where ρ^{μ_2} is a constant if grain density is uniform.

Therefore

$$\vec{v}_r \rho_r = \frac{1}{V}\int_V \vec{v}^{\mu}\ \rho^{\mu}\ (1-f)\ dV \qquad ..(17)$$

and, substituting in (13) and noting that $f = f^2$ and $(1-f) = (1-f)^2$,

$$\vec{M} = \vec{v}_r \rho_r + \vec{v}_f \rho_f\ . \qquad ..(18)$$

With (18) and (11) equation (8) becomes

$$\nabla \cdot (\rho_r \vec{v}_r + \rho_f \vec{v}_f) = -\frac{\partial}{\partial t}\left[(1-\phi)\rho_{\underset{r}{\textcircled{f}}} + \phi\rho_f\right]. \qquad ..(19)$$

Φ is designated fluid potential and

$$\Phi \triangleq gh \qquad ..(20)$$

where h is fluid head above a datum.

The equation of motion is postulated in the following form.

$$\vec{v}_f = -\frac{k}{\mu}\rho_f\ \nabla\Phi\ . \qquad ..(21)$$

Equation (21) is a modified form of Darcy's experimental results in which the fluid density and viscosity are noted explicitly and the constant of proportionality includes only the extensive qualities of the rock and rock-fluid system which affect flow. Equation (21) is therefore the defining equation for the constant of proportionality, k, which is designated permeability.

Dilatation, θ, is

$$\theta \triangleq \nabla \cdot \vec{\xi}_r, \qquad ..(22)$$

where $\vec{\xi}_r$ is the displacement of a point in the rock system from its initial position.

$$\vec{v}_r = \lim_{\Delta t \to o} \frac{\vec{\xi}_r}{\Delta t} . \qquad . . (25)$$

Therefore,

$$\nabla \cdot \vec{v}_r = \lim_{\Delta t \to o} \frac{\theta}{\Delta t} . \qquad . . (26)$$

It is assumed that the rock material does not change in volume,

$$\theta = \Delta\phi \qquad . . (27)$$

and

$$\nabla \cdot \vec{v}_r = \frac{d\phi}{dt} . \qquad . . (28)$$

The porosity is a function of fluid pressure and stress in the rock system.

$$\phi = \phi \; (p,\tau) . \qquad . . (29)$$

$$\nabla \cdot \vec{v}_r = \frac{\partial\phi}{\partial P} \; \frac{\partial P}{\partial t} + \frac{\partial\phi}{\partial\tau} \; \frac{\partial\tau}{\partial t} . \qquad . . (30)$$

With the assumption that overburden and tectonic forces are constant, ϕ is a function of pressure only and equation (30) becomes

$$\nabla \cdot \vec{v}_r = \frac{\partial\phi}{\partial P} \; \frac{\partial P}{\partial t} . \qquad . . (31)$$

With rock grain density a constant, ρ^{μ}_{2} , in space and time, equation (4) may be written

$$(1-\phi)\, \rho_r = \rho^{\mu}_{2} \; \frac{1}{V} \int_V (1-f)\, dV \qquad . . (32)$$

or

$$(1-\phi)\rho_r = \rho^{\mu_2}\ (1-\phi). \qquad ..(33)$$

Therefore, $\rho_r = \rho^{\mu_2}$ and expanding equation (19),

$$\rho_r\ \nabla\cdot\vec{v}_r + \nabla\cdot(\rho_f\vec{v}_f) = -\left[\rho_r\left(-\frac{\partial\phi}{\partial t}\right) + \frac{\partial(\rho_f\phi)}{\partial t}\right]. \qquad ..(34)$$

Substituting from (31)

$$\rho_r\ \frac{\partial\phi}{\partial P}\ \frac{\partial P}{\partial t} + \nabla\cdot(\rho_f\vec{v}_f) = \rho_r\ \frac{\partial\phi}{\partial t} - \frac{\partial(\rho_f\phi)}{\partial t} \qquad ..(35)$$

and

$$\nabla\cdot(\rho_f\vec{v}_f) = -\frac{\partial(\rho_f\phi)}{\partial t}\ . \qquad ..(36)$$

The right side of equation (36) is

$$-\frac{\partial(\rho_f\phi)}{\partial t} = -\rho_f\frac{\partial\phi}{\partial t} + \phi\ \frac{\partial\rho_f}{\partial t} \qquad ..(37)$$

$$= -\rho_f\phi\left(\frac{1}{\phi}\ \frac{\partial\phi}{\partial P} + \frac{1}{\rho_f}\ \frac{\partial\rho_f}{\partial P}\right)\frac{\partial P}{\partial t} \qquad ..(38)$$

$$= -\rho_f\phi c\ \ \frac{\partial P}{\partial t} \qquad ..(39)$$

where

$$c \triangleq \frac{1}{\phi}\ \frac{\partial\phi}{\partial P} + \frac{1}{\rho_f}\ \frac{\partial\rho_f}{\partial P} \qquad ..(40)$$

and is designated the isothermal coefficient of compressibility. Equation (23) is substituted in the left side of equation (36),

$$\nabla\cdot(\rho_f\vec{v}_f) = \nabla\cdot(-\rho_f\ \frac{k}{\mu}\ \rho_f\nabla\Phi), \qquad ..(41)$$

and equation (36) becomes

$$\nabla\cdot(\rho_f{}^2\ \frac{k}{\mu}\ \nabla\Phi) = \rho_f\phi c\ \ \frac{\partial P}{\partial t}\ . \qquad ..(42)$$

From our definition of Φ, equation (20),

$$\nabla\Phi = \nabla(gh) = g\nabla h. \qquad ..(43)$$

For horizontal flow,

$$\nabla\Phi = g \ \nabla\left(\int_{P_o}^{P} \frac{dP'}{\rho_f(P')\ g}\right) = \frac{1}{\rho_f}\nabla P. \qquad ..(44)$$

By substitution of (44) in (42),

$$\nabla \cdot (\rho_f \frac{k}{\mu} \nabla P) = \rho_f \phi c \ \frac{\partial P}{\partial t} . \qquad ..(45)$$

Defining a variable K (P) such that

$$K(P) \triangleq \int_{P_i}^{P} \rho_f \frac{k}{\mu} \ dP' \qquad ..(46)$$

then

$$\nabla \ K(P) = \rho_f \frac{k}{\mu} \ \nabla P \qquad ..(47)$$

and

$$\frac{\partial K(P)}{\partial t} = \rho_f \frac{k}{\mu} \ \frac{\partial P}{\partial t} \qquad ..(48)$$

and equation (45) is

$$\nabla \cdot (\nabla K) = \frac{\phi\mu c}{k} \ \frac{\partial K}{\partial t} \qquad ..(49)$$

which is the standard diffusivity equation if the quantity $\frac{\phi\mu c}{k}$ may be considered a constant for the pressure range of interest.

Table 1 presents results of measurements of core properties for the Wilmington Oil Field, Ranger Zone, California. The Wilmington Oil Field underlies part of the downtown and port area of Long Beach, California. Withdrawal of fluids during oil production operations in the area has been accompanied by considerable

Table 1

AVERAGE WILMINGTON FIELD DATA

PRESSURE, P_g psig	PERMEABILITY, k md	Porosity, ϕ Percent	COMPRESSIBILITY COEFFICIENT OF PORE VOLUME, c_f, Vol/Vol/psi	COMPRESSIBILITY COEFFICIENT OF BULK VOLUME c_B, Vol/Vol/psi	Calculated $\frac{k}{\phi\mu c}$, $\frac{ft^2}{day}$
250	1467	39.7	4.74×10^{-4}	1.89×10^{-4}	6.3×10^{-6} 158×10^3
500	944.7	37.7	2.66×10^{-4}	0.99×10^{-4}	5.8×10^{-6} 172×10^3
750	682.4	36.3	2.12×10^{-4}	0.77×10^{-4}	6.1×10^{-6} 163×10^3
1000	552.1	35.2	1.87×10^{-4}	0.66×10^{-4}	7.0×10^{-6} 164×10^3
1250	473.0	34.2	1.73×10^{-4}	0.59×10^{-4}	6.2×10^{-6} 161×10^3
1500	417	33.2	1.62×10^{-4}	0.53×10^{-4}	6.3×10^{-6} 158×10^3

NOTES:

Pressure, permeability, and porosity from experimental data.(4)

c_f, c_B calculated from definitions, p. 32.

$$c \triangleq \frac{1}{\phi}\frac{d\phi}{dP} + \frac{1}{\rho_f}\frac{\partial\rho_f}{dP} = c_f - c_B + \frac{1}{\rho_f}\frac{d\rho_f}{dP}$$

land-surface subsidence. Resultant damage to port facilities and work to prevent encroachment of the Pacific Ocean in industrial areas where the land surface subsided below sea level has caused Wilmington to be greatly publicized and extensively studied and monitored.

Results of the core data for Wilmington indicate that assumption the quantity $\frac{\phi \mu c}{k}$ is a constant is reasonable for the average of the available samples.

Equation (49) is based on the assumption that the time-dependence of total stress equals zero. Biot(5) presented general equations which include the effect of static mechanical equilibrium as well as conservation of mass. The difference between the two developments is discussed by Verruijt(6). The effect of static mechanical equilibrium is not included in this thesis.

FLOW TESTS IN WELLS

With equation (49) in terms of K(P), standard solutions for the diffusivity equation may be used with modification to describe pressure behavior during flow tests of wells through which fluid is removed from compacting subsurface strata.

An example application is to a well-reservoir system assumed to have the following characteristics.

1. Reservoir stratum of infinite horizontal extent and initial thickness equal at all points.
2. Stratum completely penetrated by a vertical well bore through which fluid is withdrawn.
3. Fluid flow is single-phase, isothermal, horizontal, and along a radial path toward the well bore.

For this example, equation (49) is written in polar coordinates,

$$\frac{\partial^2 K}{\partial r^2} + \frac{1}{r}\frac{\partial K}{\partial r} = \frac{\phi \mu c}{k}\frac{\partial K}{\partial t} \quad . . (50)$$

where r is the distance from the center of the well bore. An example solution to this equation is the one for a test with a constant rate of fluid withdrawal during the test period. Boundary conditions are as follows.

1. Initial pressure constant as function of r.

   For all r and $t = o$,

   $P = P_i$; $K(P) = 0$.

2. Infinite reservoir.

$$\lim_{r\to\infty} P = P_i; \quad \lim_{r\to\infty} K(P)=0; \text{ for all time.}$$

3. Constant fluid-withdrawal rate from well. Well of negligible radius.

$$\lim_{r\to 0} \left(\frac{kJ}{\mu} r \frac{\partial P}{\partial r} \right) = - \frac{Q}{2\pi}$$

or

$$\lim_{r\to 0} \left(\frac{kJ}{\mu} r \frac{\mu}{k\rho_f} \frac{\partial K(P)}{\partial r} \right) = - \frac{Q}{2\pi}$$

$$\lim_{r\to 0} \left(r \frac{\partial K(P)}{\partial r} \right) = \frac{Q\rho_f}{2\pi J} = \text{constant for all time} \quad . \; .(51)$$

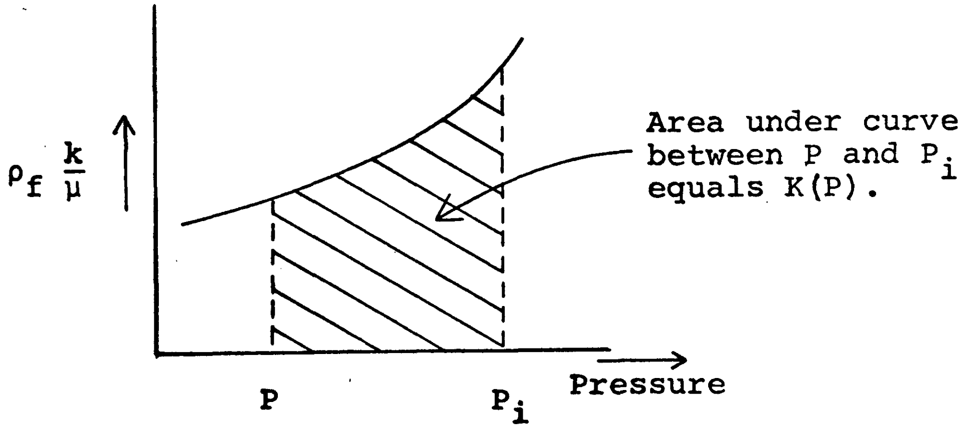
The solution to equation (50) for the boundary conditions (51) is $K(P) = \frac{Q\rho_{f,w}}{4\pi J_w} \text{Ei} \left(- \frac{\phi\mu c r^2}{4kt}\right)$ . .(52)

where the quantity $\frac{Q\rho_{f,w}}{4\pi J_w}$ is a constant.

Use of this equation to determine pressure behavior in a reservoir with pressure-dependent rock and fluid properties requires knowledge of the relation between K(P) and P. To relate K(P) to pressure, the quantity $\rho_f \frac{k}{\mu}$ is plotted as a function of pressure and integrated between P_i and P (see Figure 1).

FIGURE 1

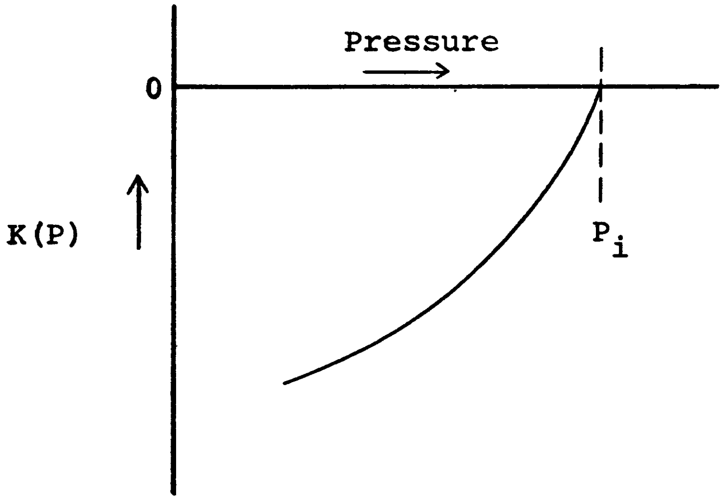
Determination of K(P) as Function of Pressure



If K(P) is determined for several pressures, a plot of K(P) versus P may be constructed:

FIGURE 2

K(P) as a Function of Pressure



With a relation established between K(P) and P, P may be obtained as a function of time and distance with calculated values of K(P) from equation (52).

The calculation procedure outlined above requires $\rho_f \frac{k}{\mu}$ be known as a function of pressure in order to calculate pressure behavior. In well testing, the pressure behavior may be measured in the well bore as a function of time. By reversing the above procedure, the transmissibility coefficient and storage coefficient may be determined as functions of pressure.

Solutions to equation (49) are available for various boundary conditions and the solution for the boundary conditions which most accurately describe the physical test conditions should be used or the test conducted with a procedure as close to that described by the boundary conditions as possible. As an illustration, in order to use the example solution given, the test should have a constant fluid withdrawal rate and be in a large reservoir with static fluid conditions before the test. The pressure is continuously measured in the well bore from a time before flow begins as the well is opened and produced. With pressure measured in the well bore, equation (52) is

$$K(P)\Big|_{r=r_w} = \frac{Q\rho_{fw}}{4\pi J_w}\,\mathrm{Ei}\left(-\frac{\phi\mu c r_w^2}{4kt}\right). \qquad ..(53)$$

With $r = r_w$, the argument of the exponential integral is less than 0.01 within a few seconds. The exponential integral may then be approximated with the following expression to an accuracy greater than is available with most well-test pressure- and flow-measuring devices.

$$\mathrm{Ei}\,(-x)\Big|_{x<0.01} \cong \ln x + 0.5772\,. \qquad ..(54)$$

With equation (54) substituted in (53),

$$K(P)\Big|_{r=rw} = \frac{Q\rho_{fw}}{4\pi J_w}\left[\ln\frac{1}{t} + \ln\frac{\phi\mu c r_w^2}{4k} + 0.5772\right]. \qquad .(55)$$

By taking the derivative of (53) with respect to time and noting that $\frac{Q\rho_{fw}}{4\pi J_w}$ is constant,

$$\frac{\partial K(P)}{\partial t}\Big|_{r=r_w} = \frac{Q\rho_{fw}}{4\pi J_w}\left(-\frac{e^{-\left(\frac{\phi\mu c r_w^2}{4kt}\right)}}{t}\right) \qquad ..(56)$$

From equation (48)

$$\frac{\partial K(P)}{\partial t}\Big|_{r=r_w} = \rho_f \frac{k}{\mu}\frac{\partial P}{\partial t}\Big|_{r=r_w} . \qquad ..(57)$$

Equating the right sides of equations (56) and (57) gives

$$\frac{Q\rho_{fw}}{4\pi J_w}\left(-\frac{e^{-\frac{1}{4t_{Dw}}}}{t}\right) = \rho_{fw}\frac{k}{\mu}\frac{\partial P}{\partial t}\Big|_{r=r_w} . \qquad ..(58)$$

Solving for $\frac{kJ}{\mu}\Big|_w \triangleq T_w$, transmissibility,

$$T_w \triangleq \frac{kJ}{\mu}\Big|_w = \frac{Q}{4\pi}\frac{1}{\frac{dP}{dt}\Big|_w}\left(-\frac{e^{-\frac{1}{4t_{Dw}}}}{t}\right) \qquad ..(59)$$

Within a few seconds time, for typical values of ϕ, μ, c, r_w, and k,

$$-\frac{e^{-\frac{1}{4t_{Dw}}}}{t} \simeq -\frac{1}{t} \qquad ..(60)$$

with greater accuracy than is available for measurement of reservoir and well conditions for test analysis. With $\alpha \triangleq \frac{dP}{dt}\Big|_w$, equation (59) becomes

$$T_w \triangleq \frac{kJ}{\mu}\Big|_w = -\frac{Q}{4\pi}\frac{1}{\alpha}\frac{1}{t} \qquad ..(61)$$

for which α is slope of pressure-time behavior in the well bore at time t. With equation (61), the transmissibility may be calculated as a function of pressure from the data obtained from a constant-rate draw-down type of well flow test. With a rearrangement of equation (58) and equation (61) values of $\rho_f \frac{k}{\mu}$ may be determined as a function of pressure.

$$\rho_f\frac{k}{\mu} = -\frac{Q\rho_{fw}}{4\pi J_w}\frac{1}{\alpha}\frac{1}{t} . \qquad ...(62)$$

The relationship between K(P) and P may be established as described previously by plotting $\rho_f \frac{k}{\mu}$ as a function of pressure and integrating. See Figures 1 and 2.

With K(P) established as a function of pressure, the measured pressure may be converted to K(P) and equations (53) or (55) solved for the constant $\eta \overset{\Delta}{=} \frac{k}{\phi\mu c}$. With the value of η thus obtained, the storage coefficient, S, may be calculated for a given pressure with the already determined value of transmissibility at that pressure.

$$\eta \overset{\Delta}{=} \frac{k}{\phi\mu c} = \frac{kJ}{\phi c\ J\mu} = \frac{kJ}{\mu}\ \frac{1}{\phi c\ J} = \frac{T}{S} \qquad ..(63)$$

where $S \overset{\Delta}{=} \phi c_e J$ is the storage coefficient.

Another technique for well testing and analysis is based on measuring the pressure behavior during flow at two different rates. Again the solution of equation (52) is used for illustrative purposes. The equations for K(P) at two rates are:

$$K_1(P) = \frac{Q_1\rho_{fw}}{4\pi Jw}\ Ei\left(-\frac{\phi\mu c\ r_w^2}{4kt_1}\right) \qquad ..(64)$$

$$K_2(P) = \frac{Q_2\rho_{fw}}{4\pi J_w}\ Ei\left(-\frac{\phi\mu c\ r_w^2}{4kt_2}\right) \qquad ..(65)$$

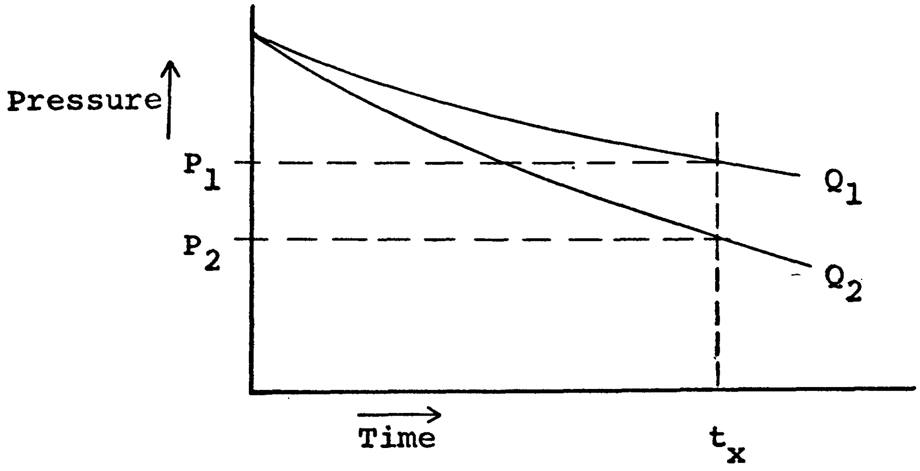
If pressure is measured at the same time from the beginning of production for both rates, $t_1 = t_2 = t_x$ is the time of observation. Subtraction of equation (64) from equation (65) gives:

$$K_2(P) - K_1(P) = \frac{(Q_2-Q_1)}{4\pi}\ \frac{\rho_{fw}}{J_w}\ Ei\ (-\frac{\phi\mu c r_w^2}{4kt_x}) \qquad ..(66)$$

with the ratio $\frac{\rho_{fw}}{J_w}$ constant.

FIGURE 3

Use of Pressures Recorded at Two Different Flow Rates



$$\frac{K_2(P) - K_1(P)}{Q_2 - Q_1} = \frac{\Delta K(P)}{\Delta Q} = \frac{\rho_{fw}}{4\pi J_w} \text{Ei}\left(-\frac{\phi\mu c r_w^2}{4kt_x}\right) \quad ..(67)$$

$$\frac{\frac{\Delta K(P)}{\Delta Q}}{\frac{\Delta P}{\Delta Q}} = \frac{\Delta K(P)}{\Delta P} \quad ..(68)$$

At the time of observation

$$\frac{\Delta P}{\Delta Q}\bigg|_{t_x} = \frac{P_2 - P_1}{Q_2 - Q_1}\bigg|_{t_x} \quad ..(69)$$

as shown in Figure 3. With

$$\frac{dK(P)}{dP} = \rho_f \frac{k}{\mu}$$

and the definition $\frac{\Delta P}{\Delta Q} \triangleq \beta$ equation (68) becomes

$$\frac{\rho_{f_w}}{4\pi J_w \beta} \text{ Ei } \left(-\frac{\phi \mu c\, r_w^{\,2}}{4kt_x}\right) = \rho_f \frac{k}{\mu} \qquad ..(70)$$

from which

$$T \triangleq \frac{kJ}{\mu} = \frac{1}{4\pi\beta} \text{ Ei } \left(-\frac{\phi \mu c\, r_w^{\,2}}{4kt_x}\right) . \qquad ..(71)$$

From calculations at several different times and knowledge of the corresponding pressures, T is known as a function of pressure. Determination of T by equation (71) requires knowledge of the quantity $\frac{1}{t_{Dw}} \triangleq \frac{\phi \mu c\, r_w^{\,2}}{4kt_x}$. If $\eta \triangleq \frac{k}{\phi \mu c}$ is known, t_{Dw} may be calculated from its definition. If η is not known, it may be calculated from the data for a single flow rate as described previously. An alternate method is to equate the right sides of equations (71) and (61):

$$T_w \triangleq \left.\frac{kJ}{\mu}\right|_w = \frac{Q}{4\pi} \frac{1}{\alpha} \frac{1}{t_x} = \frac{1}{4\pi\beta} \text{ Ei } \left(-\frac{1}{t_{Dw}}\right) \qquad ..(72)$$

from which

$$\text{Ei } \left(-\frac{1}{t_{Dw}}\right) = Q \frac{\beta}{\alpha} \frac{1}{t_x} . \qquad ..(73)$$

With knowledge of t_{Dw}, η may be calculated, and with T, the storage coefficient, S, can be obtained from equation (63).

Assumption of constant η means that only one determination of η is theoretically necessary. A determination of η by independent means, e.g., core analysis, may be possible at one pressure from which η is known for all pressures. With a value of η, S may be calculated from knowledge of T with equation (63). Use of laboratory and well-test data for determination of η may include experimental, procedural, analytical, or equipment errors, however, and it is recommended that several such determinations be used to establish η.

In the above development, Q has been considered positive if it represents a rate of production, or fluid removal, from the zone of interest. If the pressures are measured during periods of fluid injection at constant rate, the solutions and interpretive procedures described above are valid if Q is assigned a negative value for calculation with the equations.

From the example analysis of a flow test, Appendix II, it is noted that the calculated values of η show no trend to increase or decrease with pressure changes, thus verifying the assumption of constant η. Variations of the calculated values of η are erratic and are therefore believed the result of lack of precision in the calculation procedure.

PREDICTION OF ROCK COMPACTION DUE TO FLUID WITHDRAWAL

Another application of equation (49) is for boundary conditions describing vertical drainage of an extensive horizontal aquifer. This is an application to the situation where the compacting layer is draining into an over - or underlying layer from which fluid is removed. Such conditions are present in many instances of significant land-surface subsidence. For illustrative purposes the modified analytical procedure is presented for the same conditions as used in the classic Terzaghi solution.

Fluid is flowing vertically in the compacting layer which is of thickness J throughout, the top and bottom boundaries are horizontal, one is sealed and the fluid head is maintained constant at the other.

Equation (42) is

$$\nabla \cdot (\rho_f{}^2 \frac{k}{\mu} \nabla \Phi) = \rho_f \phi c \frac{\partial P}{\partial t}, \qquad \ldots (74)$$

which is written in terms of head with equation (43) and the relation

$$h = \int_{P_o}^{P} \frac{dP'}{\rho_f(P')g} + z \qquad \ldots (75)$$

from which

$$\frac{dh}{dt} = \frac{1}{\rho_f g} \frac{dP}{dt} . \qquad \ldots (76)$$

Therefore, equation (74) may be written in terms of head.

$$\nabla \cdot (\rho_f{}^2 \frac{k}{\mu} \nabla (gh)) = \rho_f \phi c \ (\rho_f g) \frac{dh}{dt} . \qquad . . (77)$$

If K(h) is defined

$$K(h) \triangleq \int_{h_o}^{h} \rho_f^2 \frac{k}{\mu} g \, dh' , \qquad . . (78)$$

then

$$\nabla K(h) = \rho_f^2 \frac{k}{\mu} g \nabla h , \qquad . . (79)$$

and

$$\frac{d\,K(h)}{dt} = \rho_f^2 \frac{k}{\mu} g \frac{dh}{dt} . \qquad . . (80)$$

When equations (79) and (80) are substituted in equation (77),

$$\nabla \cdot (\nabla K(h)) = \frac{\phi \mu c}{k} \frac{\partial K(h)}{\partial t} . \qquad . . (81)$$

The boundary conditions for the problem described above are

(1) At $t=0$; $h=h_i$; $0<z\leq J$; $K(h) = K(h_i)$.

(2) At $z=0$; $h=h_o$; $t\geq 0$; $K(h) = 0$.

(3) At $z=J$; $\frac{\partial h}{\partial z} = 0$; $t\geq o$; $\frac{\partial K(h)}{\partial z} = 0$.

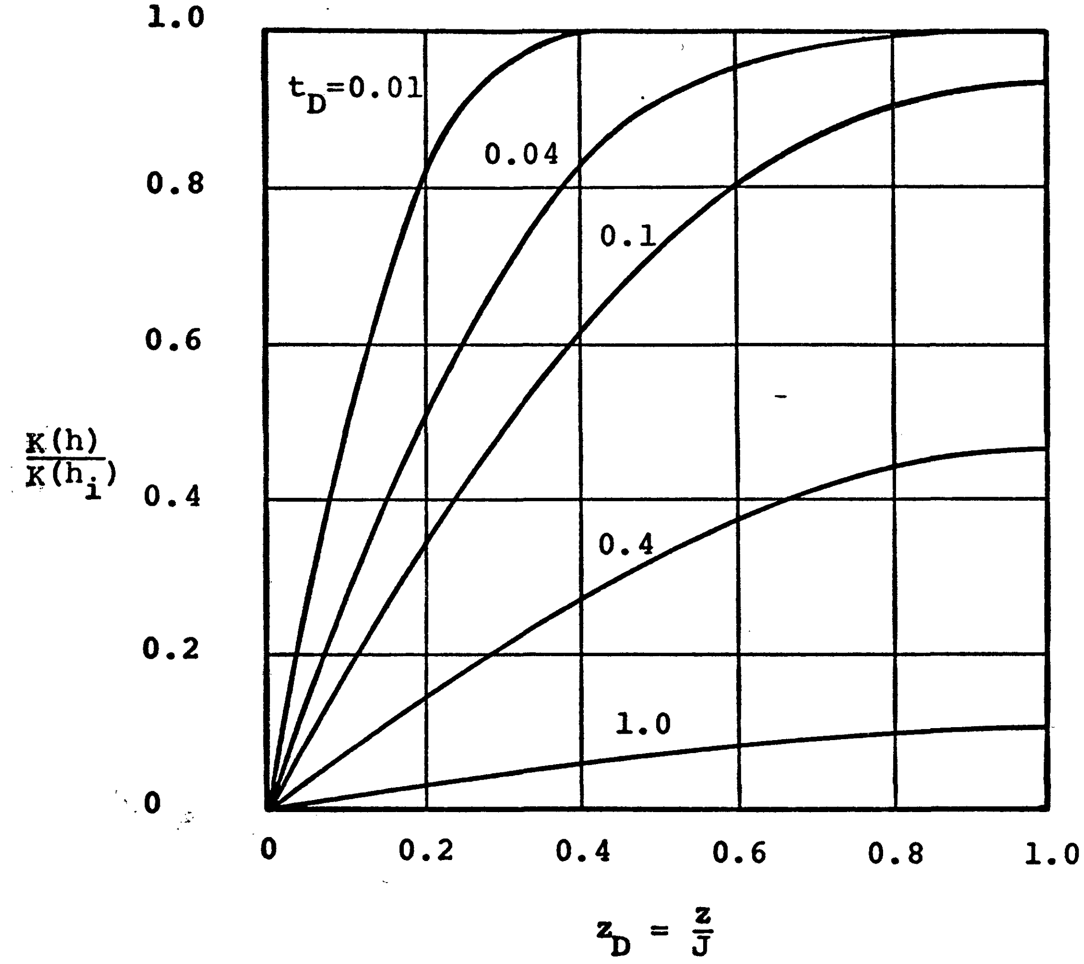
(4) $\lim_{t\to\infty} h=h_o$; $0\leq z\leq J$; $\lim_{t\to\infty} K(h) = 0$. . . (82)

The solution of equation (81) with the boundary conditions (82) is:

$$K(h) = \frac{4K(h_i)}{\pi} \sum_{n=0}^{\infty} e^{-\lambda_n^2 t_D} \frac{1}{2n+1} \sin (\lambda_n z_d) \ . (83)$$

Figure 4

K(h) AS A FUNCTION OF DIMENSIONLESS TIME, t_D, AND DIMENSIONLESS DISTANCE, z_D



(After Carslaw and Jaeger[7])

where

$$\lambda_n \triangleq \frac{2n+1}{2} \pi . \qquad . . (84)$$

$$t_D \triangleq \frac{kt}{\phi \mu c \, J^2} . \qquad . . (85)$$

$$z_D \triangleq \frac{z}{J} . \qquad . . (86)$$

Plots of K(h) as a function of z_D are presented in Figure (4) for various values of t_D. Shrinkage is determined from values of K(h) calculated with equation (83). If c_{Bh} is defined,

$$c_{Bh} \triangleq \frac{1}{V_B} \frac{dV_B}{dh} \qquad . . (87)$$

then

$$V_B = V_{Bi} \exp\left(\int_{h_i}^{h} c_{Bh} \, dh' \right) . \qquad . . (88)$$

With horizontal dimensions constant,

$$\Delta x \, \Delta y \, \Delta z = V_B \text{ and } \Delta x_i \, \Delta y_i \, \Delta z_i = V_{Bi} .$$

Therefore,

$$\Delta z = (\Delta z)_i \exp\left(\int_{h_i}^{h} c_{Bh} \, dh' \right) . \qquad . . (89)$$

With the shrinkage $\Delta s \triangleq \Delta z_i - \Delta z$

$$\Delta s = \Delta z_i \left[1 - \exp\left(\int_{h_i}^{h} c_{Bh} \, dh \right) \right] \qquad . . (90)$$

Total Shrinkage, S_T, of the layer is given by

$$S_T = \int_{o}^{S_T} ds = \int_{o}^{J} \left[1\text{-exp} \int_{h_i}^{h} c_{Bh} dh' \right] dz . \qquad . . (91)$$

With this relation between shrinkage and head, the relation between K(h) and head (equation 78), and the relation between K(h) and distance and time (equation 83), shrinkage can be determined as a function of time.

With equation (83) K(h) is determined for a given time and distance. Equation (78) is then solved to relate K(h) to h. The integration may be done graphically as illustrated in Figure 5.

FIGURE 5a

Determination of K(h) as Function of Head

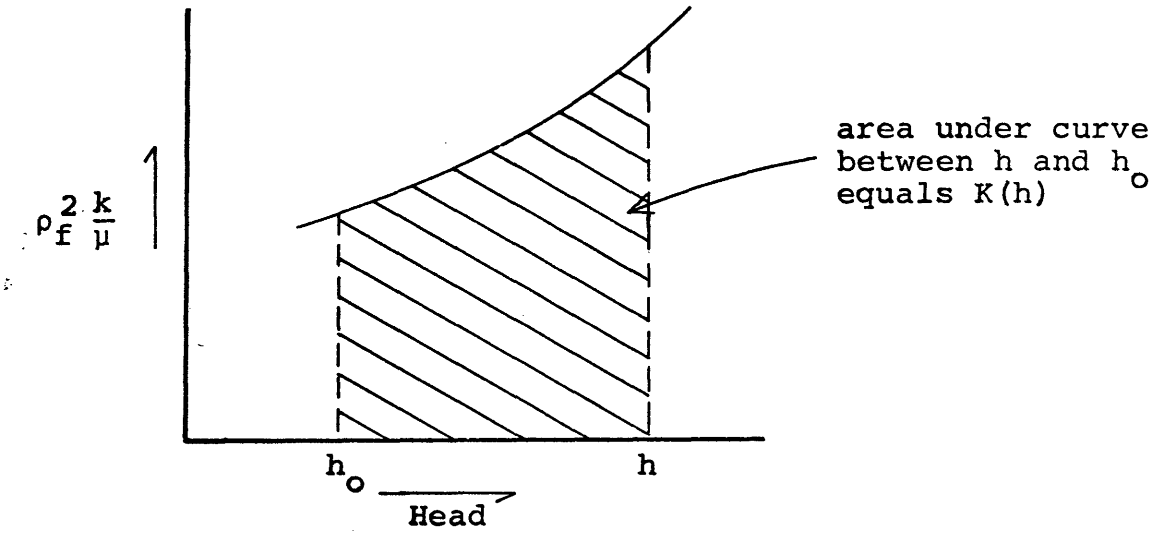
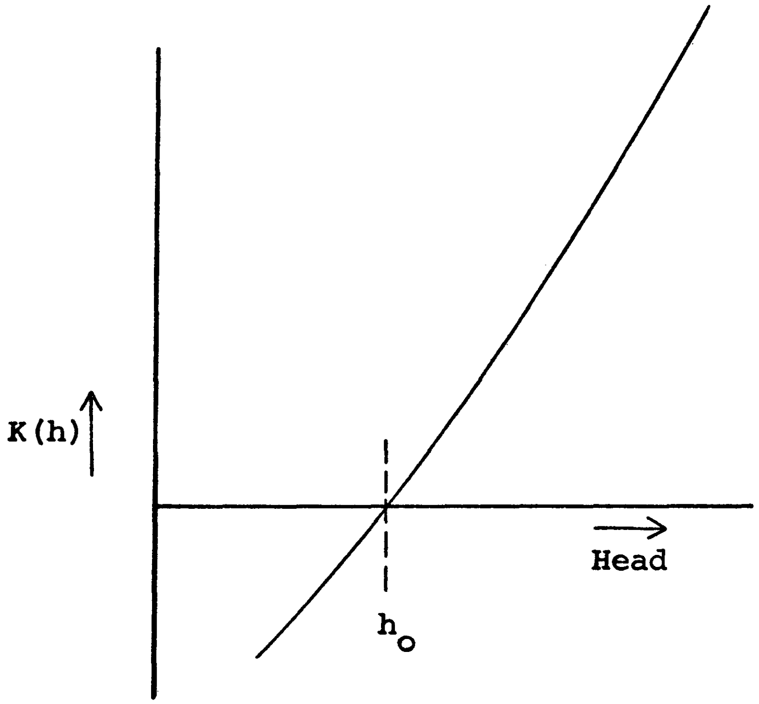


FIGURE 5b

K(h) as Function of Head



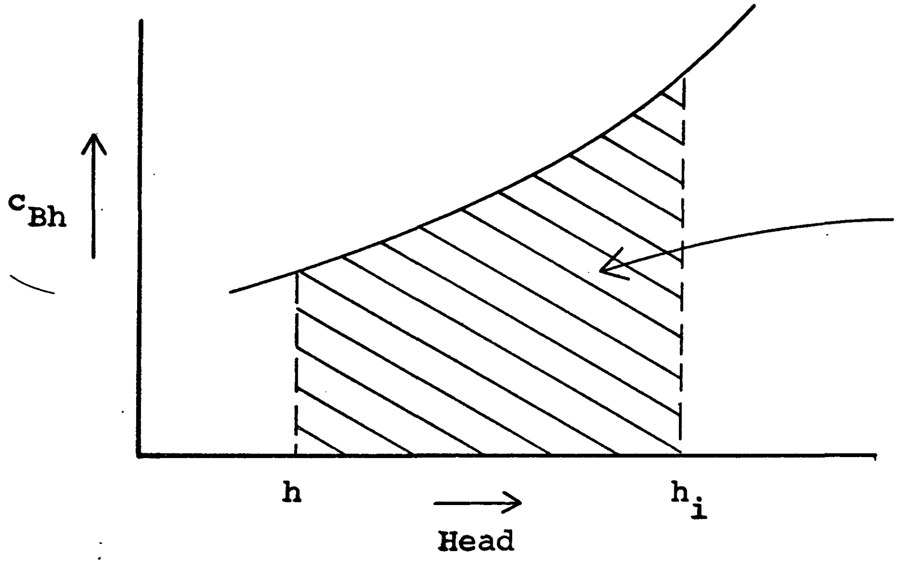
Values for K(h) are determined for several values of h as shown in Figure 5a and plotted as a function of h as shown in Figure 5b. With a plot such as Figure 5b and the calculated value for K(h), h may be obtained for the time and distance of interest. This value of h is to determine the quantity

$$\int_{h_i}^{h} c_{Bh} dh' \text{ of equation (91).}$$

This quantity also may be determined by graphical integration. A plot of c_{Bh} versus h is constructed and the area under the curve between h_i and h is the value of the term. See Figure 6.

FIGURE 6

Bulk Compressibility vs Fluid Head



Area under curve between h and h_i equals $-\int_{h_i}^{h} c_{Bh}dh'$.

At a given time, this process is repeated for several distances. The values of

$$1 - \exp\left[\int_{h_i}^{h} c_{Bh}dh'\right] \text{ are plotted as}$$

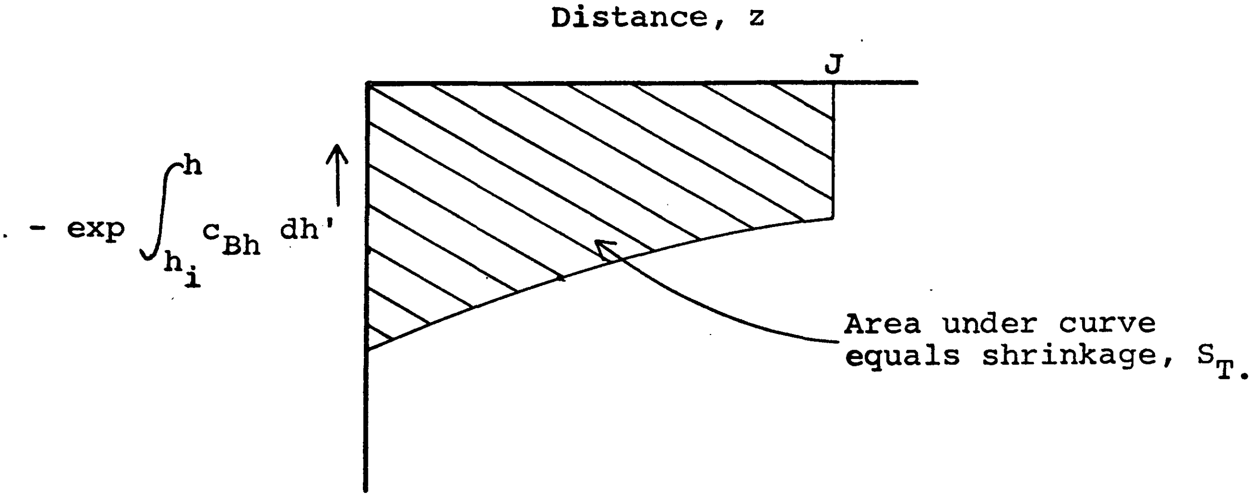
a function of distance. By determination of area under the curve of

$$1 - \exp\left[\int_{h_i}^{h} c_{Bh}dh'\right] \qquad \text{versus } z_i$$

the integration of s_i in equation (91) may be performed graphically. See Figure 7.

FIGURE 7

Plot for Determination of Shrinkage



The above process is repeated for various times to determine shrinkage as a function of time.

If the exponential term is expanded the shrinkage may be evaluated from a plot of $-\int_{h_i}^{h} c_{Bh}\, dh$ versus z where the high-order terms are neglected.

SUMMARY AND CONCLUSIONS

The differential equation describing fluid flow in a subsurface sediment with permeability, porosity, thickness, fluid viscosity, and fluid density as significant functions of pressure has been linearized with a variable transformation to give an equation similar to the standard diffusivity equation:

$$\nabla^2 K(P) = \frac{\phi\mu c}{k} \frac{\partial K(P)}{\partial t} .$$

Solutions to the standard diffusivity equation may be used to solve this equation if the quantity $\frac{\phi\mu c}{k}$ may be considered constant. Core data from the Wilmington Field verify this assumption. Use of core data for prediction of rock-property variation as a function of pressure requires extensive sampling for accurate prediction of large-scale behavior. Variation of these quantities may be obtained in situ from analysis of pressures measured during well flow tests.

Detailed descriptions of application of the modified equation to rock-compaction prediction and flow-test analysis have been presented with an example of each type. The example rock-compaction calculation is for the classic Terzaghi problem: vertical drainage of an infinite horizontal aquifer. The example flow test is for production at a constant flow rate from a reservoir of infinite horizontal extent. Other problems could be solved with application of appropriate boundary conditions. It was noted that the value of $\frac{\phi\mu c}{k}$ calculated from the flow-test results verified the assumption that this quantity may be considered constant.

From this work it is concluded:

1. A transformation reduces the non-linear differential equation describing fluid flow in a subsurface sediment to a linear equation which can be solved with standard techniques if the diffusivity coefficient may be considered constant. Where the coefficient may not be considered constant, the transformation should not be used.
2. Available data, though limited, indicate the assumption of a constant diffusivity coefficient is reasonable for compaction pressures from 0 to 1500 psia for unconsolidated sediments.
3. The linearized equation permits solution of rock compaction and pressure behavior problems for rocks in which porosity, permeability, compressibility, fluid viscosity, and fluid density are significant functions of fluid pressure.
4. Reservoir storage and transmissibility coefficients may be determined as functions of pressure from pressure drawdown or buildup well tests.
5. When fluid withdrawal is planned beneath areas where land-surface subsidence could have undesirable effects, rock properties should be obtained as a function of pressure with a sufficient number of core samples to permit description of large-scale behavior of the rock from which fluid is to be withdrawn.

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LIST OF SYMBOLS

c_B	isothermal coefficient of bulk compressibility in terms of pressure, $c_B \triangleq \frac{1}{V_B} \frac{dV_B}{dP}$.
c_{Bh}	isothermal coefficient of bulk compressibility in terms of head, $c_{Bh} \triangleq \frac{1}{V_B} \frac{dV_B}{dh} = \rho_f g \frac{1}{V_B} \frac{dV_B}{dP} = 0.433\, c_B$.
c	isothermal coefficient of total compressibility, $c \triangleq \frac{1}{\phi} \frac{d\phi}{dP} + \frac{1}{\rho_f} \frac{d\rho_f}{dP}$; equation (40).
c_f	isothermal coefficient of pore volume compressibility, $c_f \triangleq \frac{1}{V_P} \frac{dV_P}{dP}$.
f	function, see equation (1).
g	gravitational constant.
h	fluid head, see equation (75).
J	Total layer thickness.
k	permeability
$K(P)$; $K(h)$	-transormed variables in terms of pressure and head, respectively, see equations (46) and (78).
m	mass flux rate of fluid.
P, P_f	fluid pressure.
P_g	grain-to-grain pressure.
Q	volumetric flow rate at reservoir conditions.
r	radius.
r_w	well radius

s	shrinkage, elemental
S_T	total shrinkage
S	storage coefficient, $S \triangleq \phi cJ$.
t	time
t_D	dimensionless time, $t_D \triangleq \frac{kt}{\phi \mu c J^2}$.
t_{Dw}	dimensionless time, $t_{Dw} \triangleq \frac{kt}{\phi \mu c r_w{}^2}$.
T	transmissibility coefficient, $T \triangleq \frac{kJ}{\mu}$.
v	velocity.
V	representative elementary volume.
V_B	bulk volume.
V_P	pore volume.
x,y	horizontal-distance coordinates
z	vertical-distance coordinate.
z_D	dimensionless distance, $z_D \triangleq \frac{z}{J}$.

Greek Symbols:

ϕ	porosity.
Φ	potential, see equation (20).
λ	$\frac{2n+1}{2} \pi$.
ξ	displacement.
θ	dilatation
ρ	density.
τ	stress.
μ	viscosity.

α	$\alpha \triangleq \frac{dP}{dt}$; see equation (61).
β	$\beta \triangleq \frac{\Delta P}{\Delta Q}$
η	$\eta \triangleq \frac{k}{\phi \mu c}$; see equation (63)

Subscripts:

D	dimensionless
f	fluid
i	initial
o	original, or base, condition
r	rock
w	well
x	observation point
Σ	total

Superscript:

μ	microscopic

APPENDIX I

EXAMPLE ROCK COMPACTION CALCULATION

The following example calculation is for compaction of a sand with average Wilmington Sand properties due to a head reduction from 9,000 feet to 6,000 feet. Fluid contained and withdrawn assumed to be water.

DEVELOPMENT OF UNIT CONSTANT:

$$\frac{k\ (\text{md}) \times \frac{1\text{d}}{1000\ \text{md}} \times 0.9869 \times 10^{-8}\ \frac{\text{cm}^2}{\text{d}} \times \rho_f^2 (\frac{\text{gm}}{\text{cm}^3})^2 \times dh(\text{ft}) \times 30.48\ \frac{\text{cm}}{\text{ft}}}{\mu(\text{cp})\ \frac{1\ \frac{\text{gm}}{\text{cm-sec}}}{1\text{p}}\ \frac{1\text{p}}{100\ \text{cp}}}$$

$$= 30.08 \times 10^{-9}$$

$$K(h),\ (\frac{\text{gm sec}}{\text{cm}^2}) = \int_{h_o}^{h} 30.08 \times 10^{-9}\ \rho_f^2\ (\frac{\text{gm}}{\text{cm}^3})^2\ \frac{k(\text{md})}{\mu(\text{cp})}\ dh'(\text{ft})$$

AVERAGE WILMINGTON DATA

PRESSURE, P_G psig	AVG. PERM, k, md.	AVG. POROSITY $\bar{\phi}$, %	AVG. COEFFICIENT OF:	
			FORMATION COMPRESSIBILITY c_f, psi^{-1}	BULK COMPRESSIBILITY c_B, psi^{-1}
250	1467	39.7	4.74×10^{-4}	1.889×10^{-4}
500	944.7	37.7	2.66 "	0.992 "
750	682.4	36.3	2.12 "	0.769 "
1000	552.1	35.2	1.87 "	0.656 "
1250	473.0	34.2	1.73 "	0.590 "
1500	417.0	33.2	1.62 "	0.529 "

CALCULATION OF SHRINKAGE - TIME RELATIONSHIP

AVERAGE WILMINGTON DATA - RANGER ZONE

GRAIN-TO-GRAIN^2 PRESSURE, P_G, psia	AVG. k, md.	$\rho_f^2 \frac{k}{\mu}$,		h, ft.	BULK COEFF. OF COMP., c_B vol/vol/psi
		$\left(\frac{gm}{cm^3}\right)^2 \frac{md}{cp}$	$\frac{gm\ sec}{cm^2 ft}$		
(a)	(b)	(c)	(d)	(e)	(f)
265	1467	2673	80.40×10^{-6}	9247	1.889×10^{-4}
515	945	1722	51.80×10^{-6}	8670	0.992×10^{-4}
765	682	1242	37.36×10^{-6}	8092	0.769×10^{-4}
1015	552	1006	30.26×10^{-6}	7515	0.656×10^{-4}
1265	473	862	25.93×10^{-6}	6938	0.590×10^{-4}
1515	417	760	22.86×10^{-6}	6360	0.529×10^{-4}

NOTES:

(a), (b), (c), From laboratory data, averaged.

$\rho_f = 1.002 \frac{gm}{cm^3}$ at 124°F.

$\mu_w = 0.55$ cp at 124°F.

(d) $30.08 \times 10^{-9} \times$ (c). (see Development of Unit Constant)

(e) Average Depth = 4269 feet.
Max. P = 4269 psi.

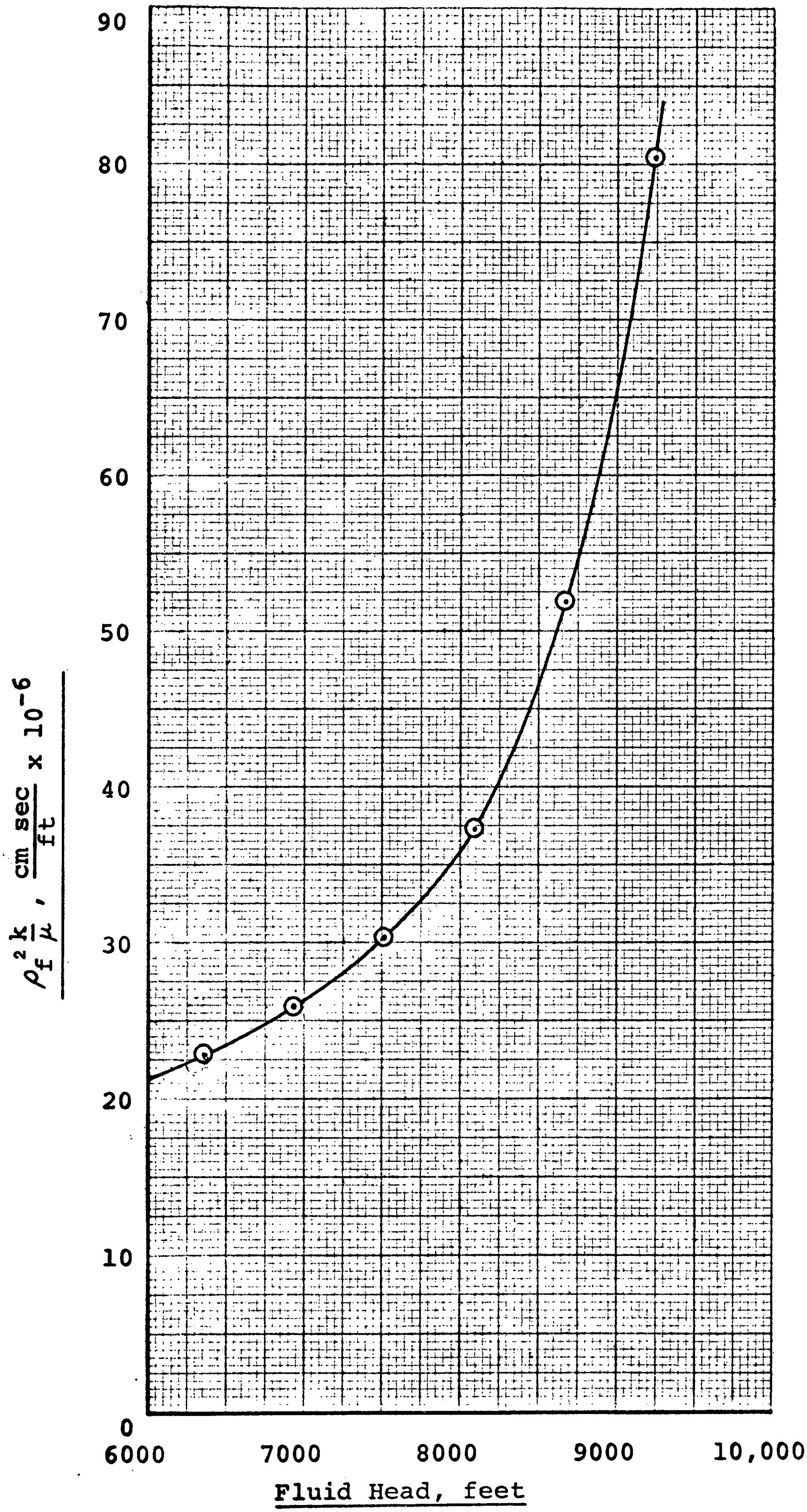
$$\text{Head} = \frac{4269 - P_G}{0.433}$$

(f)

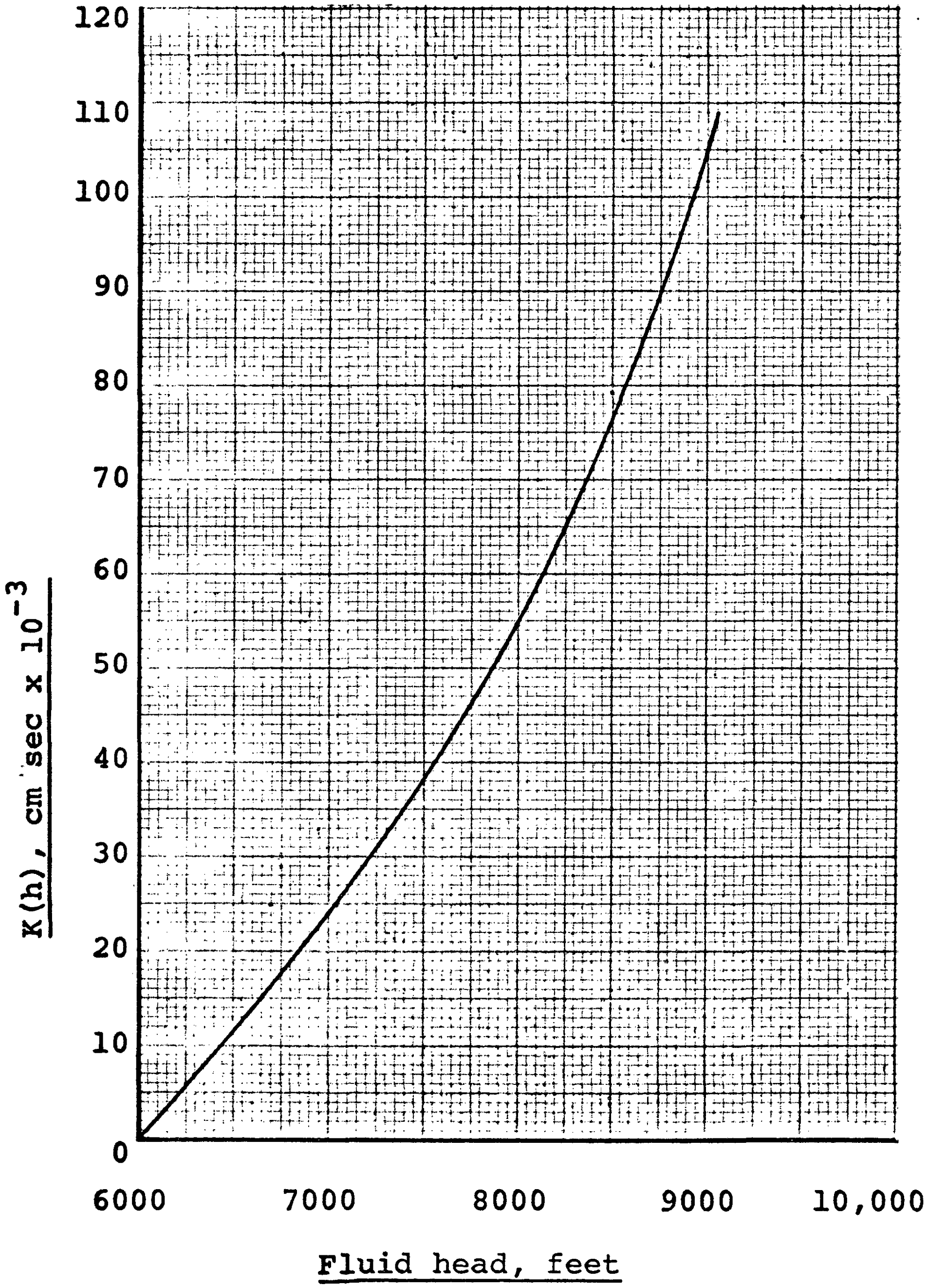
$$c_B \triangleq \frac{1}{V_B} \frac{\partial V_B}{\partial P_f} = \frac{1}{V_p/\phi} \frac{dV_p}{dP_f} = \phi c_f$$

Determine c_f and ϕ from lab data. Multiply, then average.

CHART FOR DETERMINATION OF K(h) AS A FUNCTION OF h



CORRELATION BETWEEN K(h) AND h



CALCULATION OF SHRINKAGE - TIME RELATIONSHIP

AVERAGE WILMINGTON DATA - RANGER ZONE

(1) j/J	(2) $\frac{K(h)}{K(h_i)}$	(3) $K(h)$ cm-sec	(4) h, ft.	(5) $0.433 \int_{h_i}^{h} c_B dh'$
$t_D = 0.01$				
0.4	0.995	104,475	8990	5.6×10^{-4}
0.35	0.980	102,900	8970	16.8×10^{-4}
0.30	0.950	99,750	8920	43×10^{-4}
0.25	0.905	95,025	8840	83×10^{-4}
0.20	0.825	86,625	8690	157×10^{-4}
0.15	0.680	71,400	8390	273×10^{-4}
0.10	0.505	53,025	7950	422×10^{-4}
0.05	0.280	29,400	7190	641×10^{-4}
0	0	0	6000	930×10^{-4}
$t_D = 0.04$				
0.8	0.992	104,160	8990	5.6×10^{-4}
0.7	0.978	102,690	8960	17×10^{-4}
0.6	0.952	99,960	8920	43×10^{-4}
0.5	0.908	95,340	8840	83×10^{-4}
0.4	0.830	87,150	8700	150×10^{-4}
0.3	0.695	72,975	8420	260×10^{-4}
0.2	0.510	53,550	7960	420×10^{-4}
0.1	0.290	30,450	7220	639×10^{-4}
0	0	0	0	930×10^{-4}

CALCULATION OF SHRINKAGE - TIME RELATIONSHIP

AVERAGE WILMINGTON DATA - RANGER ZONE

(1) j/J	(2) $\frac{K(h)}{K(h_i)}$	(3) K(h) cm sec	(4) h, ft.	(5) $0.433 \int_{h_i}^{h} c_B dh'$
$t_D = 0.1$				
1.0	0.935	98,175	8890	56×10^{-4}
0.9	0.925	97,125	8875	63×10^{-4}
0.8	0.905	95,025	8840	83×10^{-4}
0.7	0.865	90,825	8770	116×10^{-4}
0.6	0.800	84,000	8640	178×10^{-4}
0.5	0.720	75,600	8480	242×10^{-4}
0.4	0.615	64,575	8230	333×10^{-4}
0.3	0.490	51,450	7900	442×10^{-4}
0.2	0.345	36,225	7430	576×10^{-4}
0.1	0.185	19,425	6820	737×10^{-4}
0	0	0	6000	930×10^{-4}
$t_D = 0.4$				
1.0	0.470	49,350	7840	460×10^{-4}
0.9	0.460	48,300	7820	465×10^{-4}
0.8	0.440	46,200	7750	486×10^{-4}
0.7	0.415	43,575	7670	510×10^{-4}
0.6	0.375	39,375	7530	548×10^{-4}
0.5	0.330	34,650	7375	592×10^{-4}
0.4	0.275	28,875	7175	644×10^{-4}

CALCULATION OF SHRINKAGE - TIME RELATIONSHIP

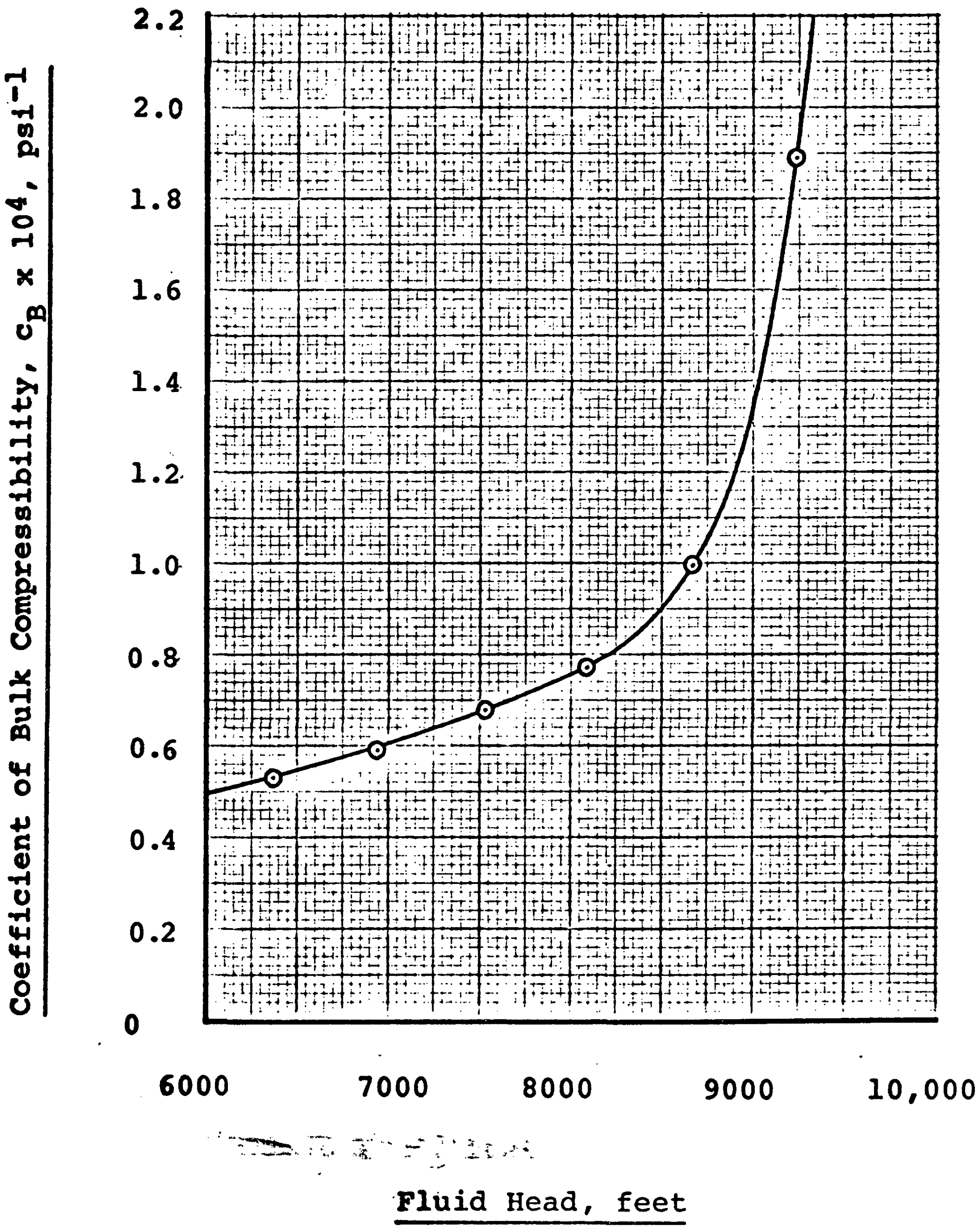
AVERAGE WILMINGTON DATA - RANGER ZONE

(1) j/J	(2) $\frac{K(h)}{K(h_i)}$	(3) K(h) cm sec	(4) h, ft.	(5) $0.433 \int_{h_i}^{h} c_B dh'$
t_D = 0.4 (continued)				
0.3	0.210	22,050	6925	711×10^{-4}
0.2	0.145	15,225	6650	780×10^{-4}
0.1	0.075	7,875	6380	843×10^{-4}
0	0	0	6000	930×10^{-4}
t_D = 0.1				
1.0	0.110	11,550	6500	815×10^{-4}
0.8	0.100	10,500	6460	823×10^{-4}
0.6	0.080	8,400	6365	845×10^{-4}
0.4	0.055	5,775	6250	875×10^{-4}
0.2	0.030	3,150	6130	902×10^{-4}
0	0	0	6000	930×10^{-4}

NOTES:

(1), (2)	From Fig. 3.
(3)	$\frac{K(h)}{K(h_i)} \cdot K(h_i) = (2) \times 105{,}000.$
(4)	From graph K(h) vs h.
(5)	From graph, $0.433 \int_{h}^{h_i} c_B dh'$ vs h .

CORRELATION BETWEEN COEFFICIENT OF BULK COMPRESSIBILITY AND FLUID HEAD



INTEGRAL OF c_B dh'

AS A FUNCTION OF FLUID HEAD

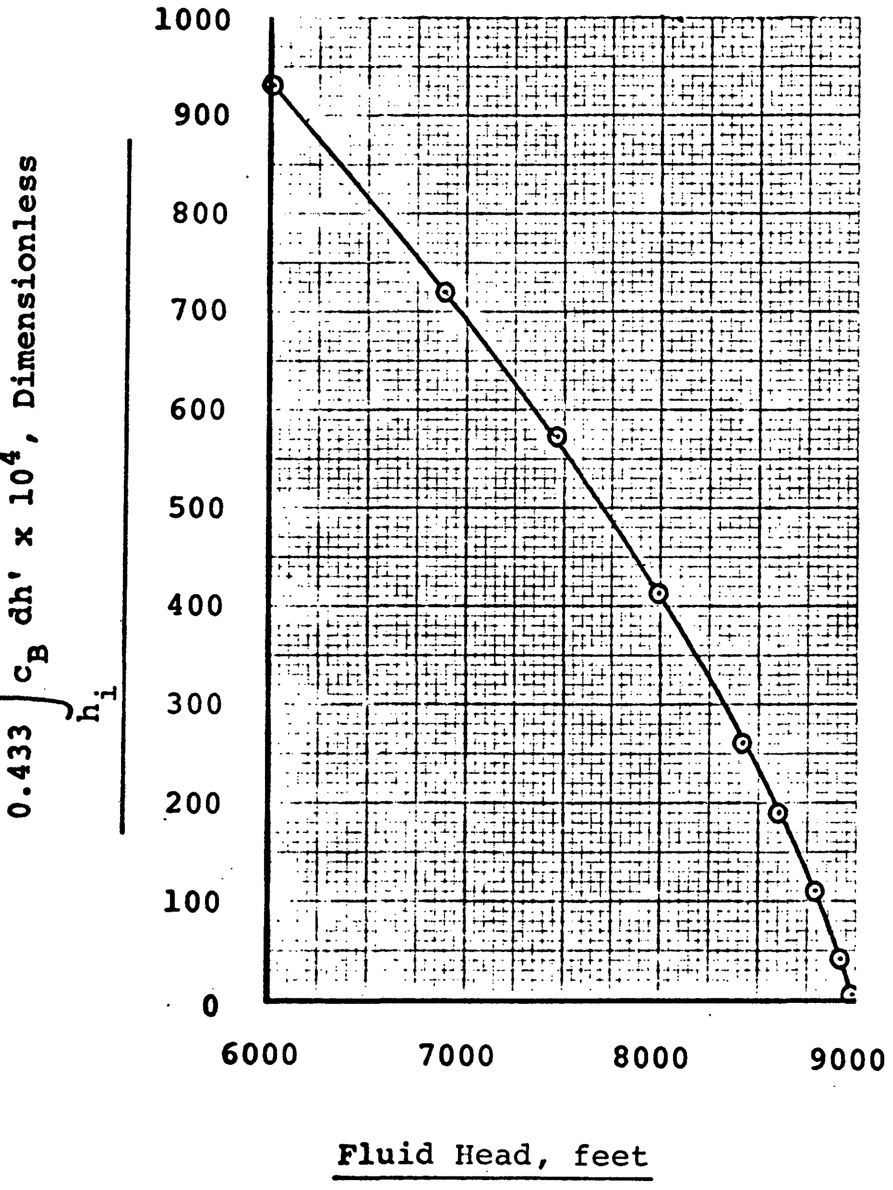
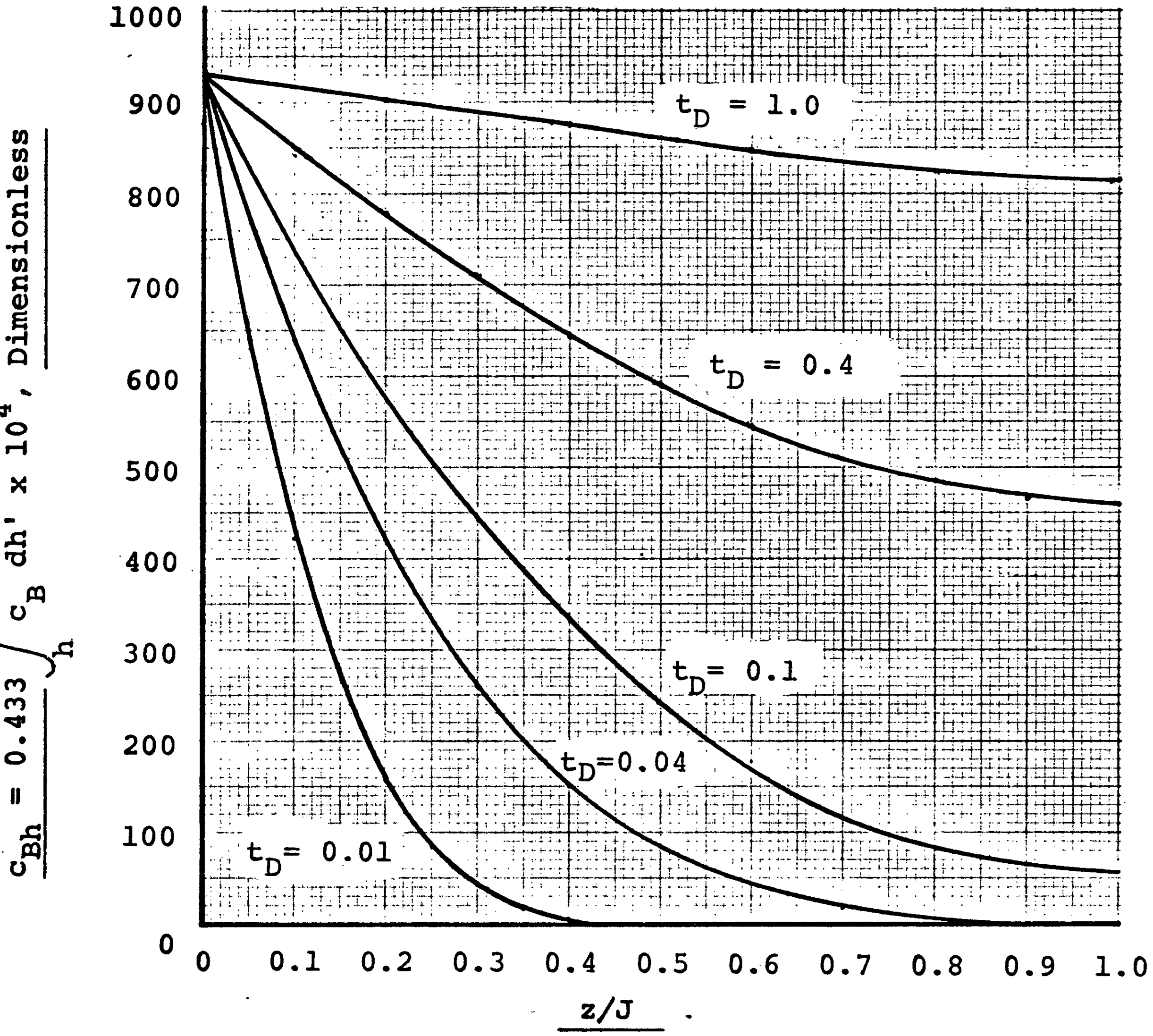


CHART FOR DETERMINATION OF SHRINKAGE AS A FUNCTION OF TIME



INTEGRATING UNDER LAST CURVE

t_D, DIMENSIONLESS TIME	SHRINKAGE, S, ft/ft	DEGREE OF CONSOLIDATION, $U = S/S_\infty$
0.01	104×10^{-4}	0.112
0.04	204.8×10^{-4}	0.220
0.1	321.6×10^{-4}	0.346
0.4	624.0×10^{-4}	0.671
1.0	859.2×10^{-4}	0.924

$S_\infty = 930 \times 10^{-4}$ ft/ft

APPENDIX II

EXAMPLE

PRESSURE DRAWDOWN TEST

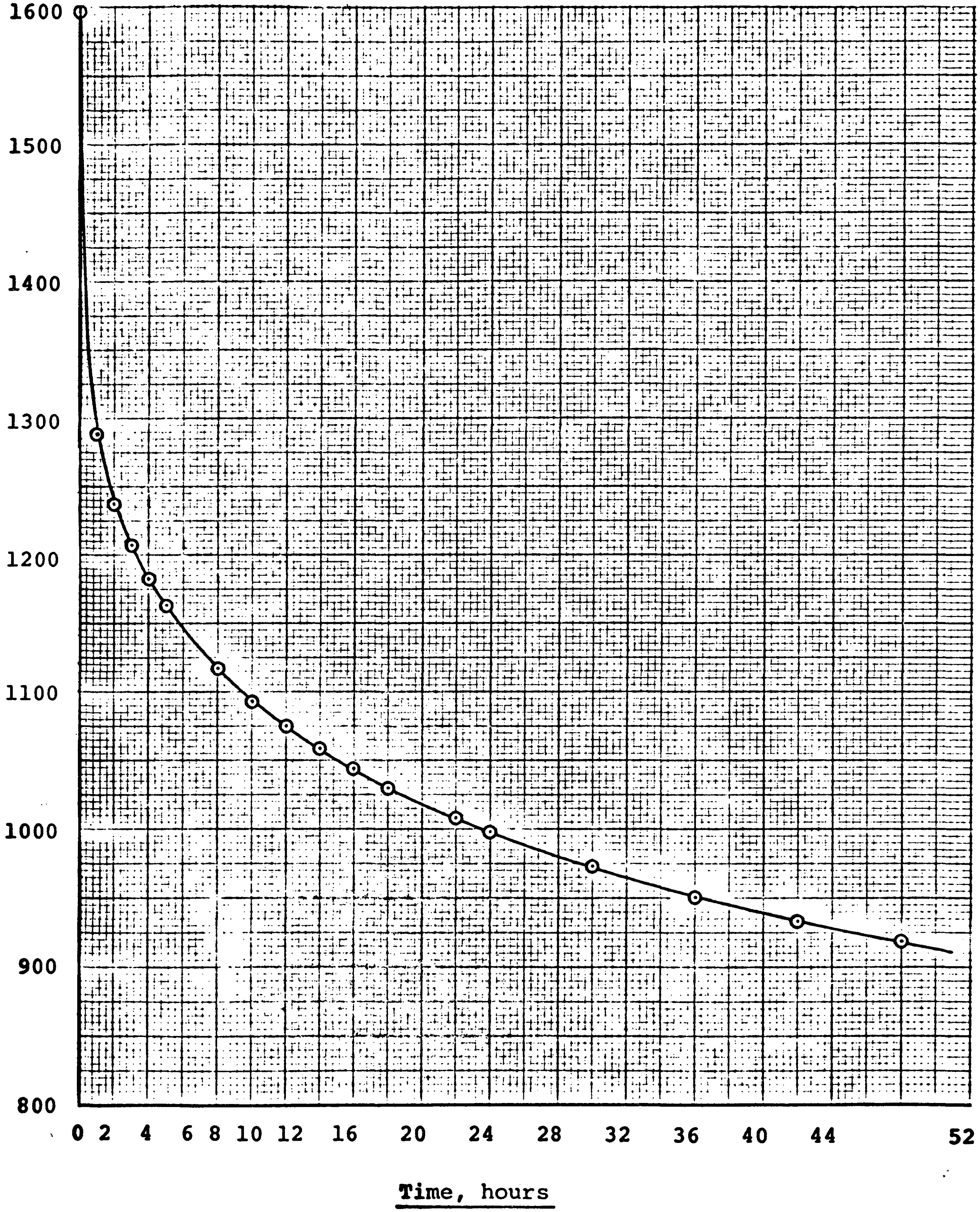
DETERMINATION OF K(P), TRANSMISSIBILITY, STORAGE COEFFICIENT, AND η AS FUNCTIONS OF PRESSURE

A well is opened to flow at a constant rate of 251 BOPD with a formation volume factor of 1.2. The pressure is recorded with a down-hole pressure recorder. The following pressure data are recorded.

t, hours	$p_f \big\|_{r=r_w}$ psig	t, hours	$p_f \big\|_{r=r_w}$ psig
0	1596	14	1059
1	1288	16	1044
2	1237	18	1031
3	1207	22	1008
4	1182	24	999
5	1163	30	973
8	1117	36	951
10	1094	42	933
12	1075	48	919

EXAMPLE

PRESSURE AS A FUNCTION OF TIME



CALCULATION OF TRANSMISSIBILITY AS A FUNCTION OF PRESSURE

(1) TIME, hrs.	(2) dp/dt psi/hr.	(3) PRESSURE psig	(4) T_w=kJ/μ md-ft/cp	(5) ρk/μ	(6) PRESSURE, psia
0		1596			
2	36.6	1237	290.5	36.3	1252
4	21.8	1183	243.9	30.5	1198
6	16.1	1146	220.1	27.5	1161
8	13.0	1117	204.5	25.6	1132
10	10.6	1094	200.6	25.1	1109
12	9.2	1075	192.6	24.1	1090
14	8.1	1057	187.5	23.4	1072
16	7.1	1042	187.2	23.4	1057
18	6.3	1029	187.5	23.4	1044
20	5.6	1017	189.9	23.7	1032
25	4.5	992	189.0	23.6	1007
30	3.8	971	186.5	23.3	986
35	3.2	954	189.7	23.7	969
40	2.7	939	196.9	24.6	954
45	2.6	925	181.7	22.7	940

$$Q = 251 \frac{\text{STB}}{\text{D}} \times 1.2 \frac{\text{R.B.}}{\text{STB}} = 301.2$$

NOTES:

(1) Measured.

(2) Slope of P vs. t plot at time t.

(3) Measured.

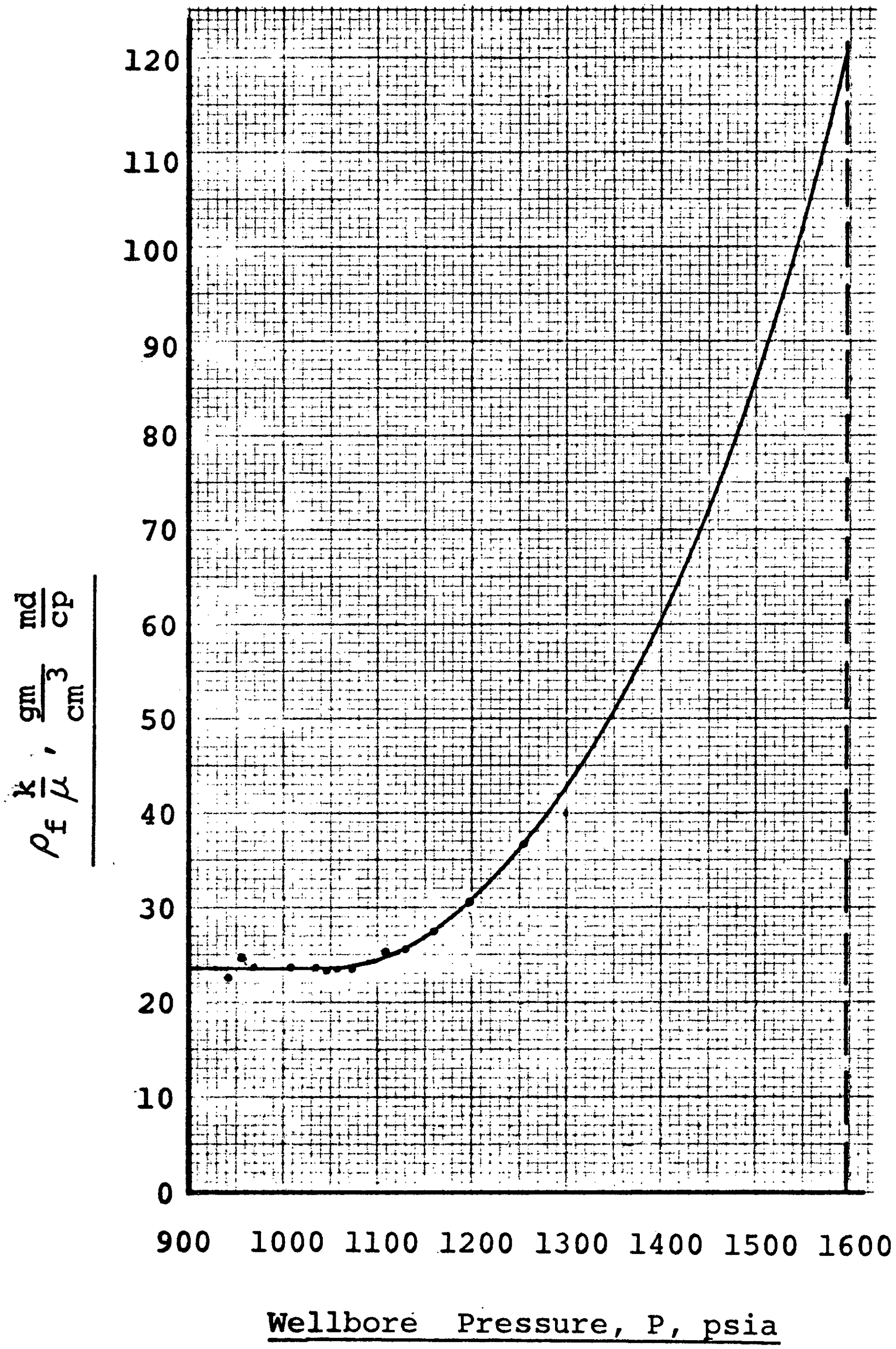
(4) See Equation (61)

(5) $$\rho \frac{k}{\mu} = \frac{\rho_{fw}}{J_w} T = \frac{0.811}{6.5} T$$

$$= 0.125 \; T$$

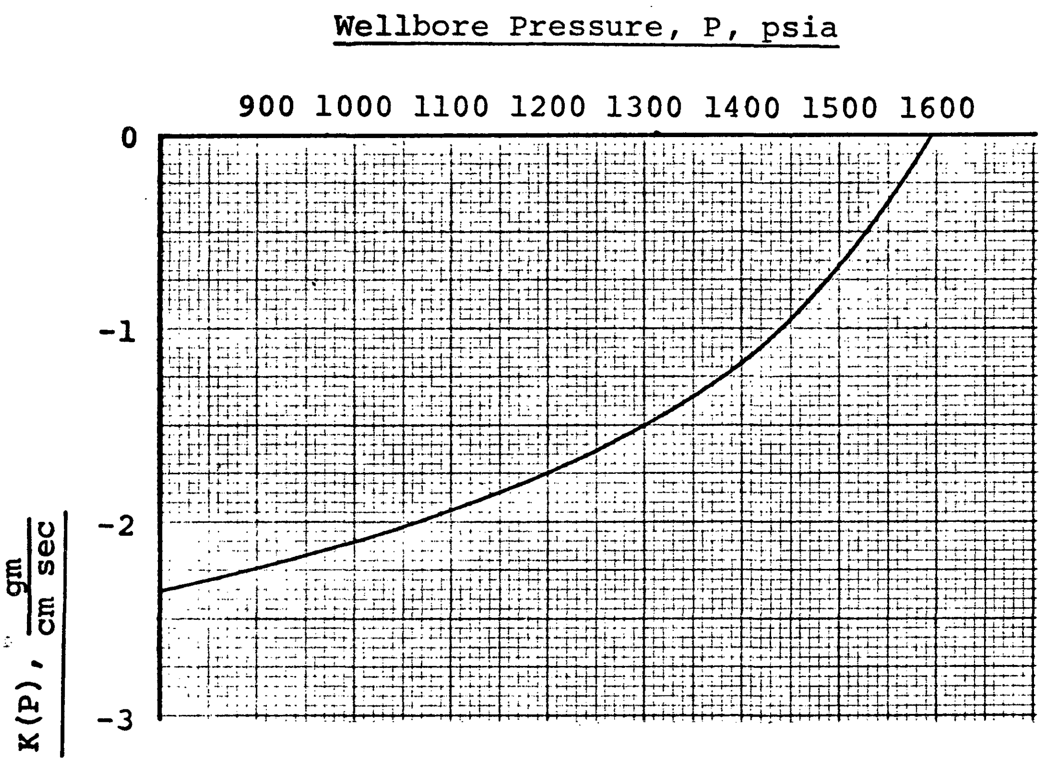
$$= 0.125 \times \text{col } (4)$$

CORRELATION BETWEEN $\rho \frac{k}{\mu}$ AND P FOR DETERMINATION OF K(P) AS A FUNCTION OF PRESSURE



CORRELATION BETWEEN

K(P) AND P



CALCULATION OF η AND STORAGE COEFFICIENT, S

(7) TIME HRS.	(8) PRESSURE PSIA	(9) $K(P_f)$, gm/cm-sec	(10) ln(ηt)	(11) ηt, $\frac{\text{md-hr}}{\text{cp-psi}^{-1}}$	(12) η, $\frac{\text{md}}{\text{cp-psi}^{-1}}$	(13) S, $(\text{psi})^{-1}$-(ft)
2	1252	-1.63	13.673	867,106	433,553	676.85×10^{-6}
4	1198	-1.76	14.392	1,779,726	444,931	568.27×10^{-6}
6	1161	-1.81	14.668	2,345,389	390,898	512.82×10^{-6}
8	1132	-1.88	15.055	3,453,780	431,723	476.47×10^{-6}
10	1109	-1.91	15.221	4,077,035	407,703	467.39×10^{-6}
12	1090	-1.96	15.498	5,378,313	448,193	448.75×10^{-6}
14	1072	-1.99	15.664	6,350,224	453,587	436.87×10^{-6}
16	1057	-2.01	15.774	7,088,414	443,025	436.17×10^{-6}
18	1044	-2.03	15.885	7,920,570	440,032	436.87×10^{-6}
20	1032	-2.05	15.996	8,850,409	442,520	442.46×10^{-6}
25	1007	-2.09	16.217	11,039,232	441,569	440.36×10^{-6}
30	986	-2.12	16.383	13,032,691	434,423	434.54×10^{-6}
35	969	-2.14	16.493	14,548,136	415,661	441.99×10^{-6}
40	954	-2.16	16.604	16,256,025	406,400	458.77×10^{-6}
45	940	-2.18	16.715	18,164,543	403,657	423.35×10^{-6}

$$K(P_f) = \frac{0.00481\ Q\rho fw}{J_w}\left[\ln\frac{1}{t} + \ln\frac{948.24\ \phi\mu c r_w^2}{k} + 0.5772\right]$$

$$K(P_f) = \frac{0.00481 \times 301.2 \times 0.811}{6.5}\left[\ln\frac{1}{t} + \ln\frac{948.24 r_w^2}{\eta} + 0.5772\right]$$

$$K(P_f) = 0.1808\left[\ln\frac{1}{t} - \ln\eta + 4.6572\right] = 0.842 - 0.1808\ \ln(\eta t)$$

NOTES:

(7), (8) Measured.

(9) Conversion Chart, P_f to $K(P_f)$.

(10) $\frac{-K(P_f) - 0.842}{-0.1808} = \ln(\eta t)$

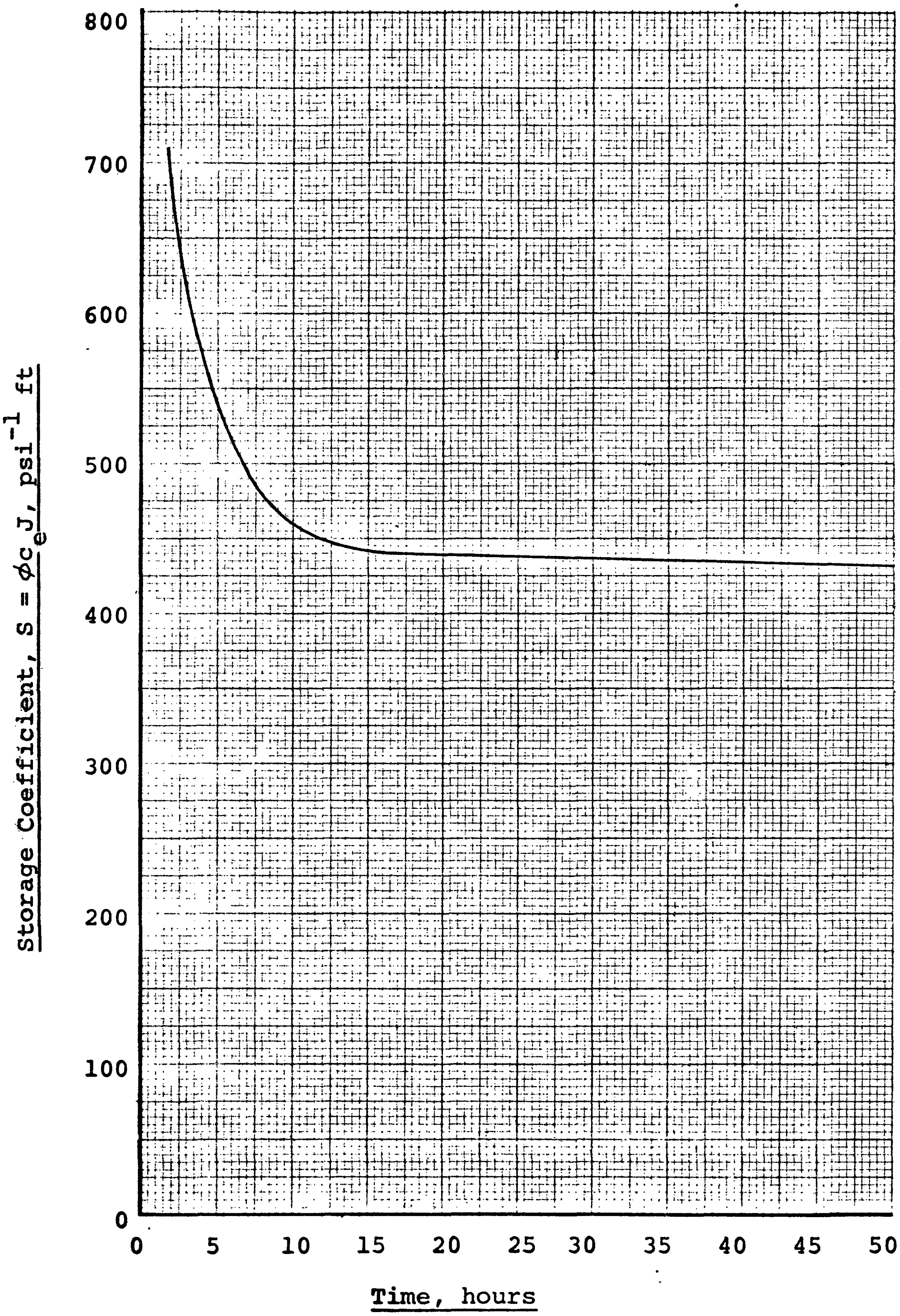
(11) Antilog of (10)

(12) $\frac{\eta t}{\eta} = \eta;\ \frac{\text{col. (11)}}{\text{col. (7)}} = \text{col. (12)}$

(13) $= \frac{\text{col. (4)}}{\text{Avg. col. (12)}}$

STORAGE COEFFICIENT

AS A FUNCTION OF TIME



UNIT-CONVERSION CONSTANT:

$$\frac{kJ}{\mu} = \frac{-70.6\ Q\ (^{B}/D)}{\alpha\left(\frac{psi}{hr}\right)\ t_x\ (hr)}$$

(Slopes are negative for drawdown)

DEVELOPMENT OF UNIT-CONVERSION CONSTANT:

$$T = \frac{kJ}{\mu} = \frac{(md)\ x\ \frac{1d}{1000\ md}\ x\ \frac{0.9869\ x\ 10^{-8} cm^2}{d}\ x(ft)\ x\frac{30.48\ cm}{ft}}{(cp)\ x\ \frac{1p}{100\ cp}\ x1\ \frac{\left(\frac{dyne\text{-}sec}{cm^2}\right)}{1p}}$$

$$= \frac{-Q\ (B/D)\ x\ 5.615\ \frac{ft^3}{B}\ x\ \left(30.48\ \frac{cm}{ft}\right)^3}{86{,}400\left(\frac{sec.}{D}\right)\frac{dp}{dt}\left(\frac{psi}{hr}\right)\ x\ t_x(hr)\ x\ 68{,}948\ \frac{\left(\frac{dynes}{cm^2}\right)}{psi}}$$

$$= \frac{-\ 70.6\ Q\ (B/D)}{\alpha\left(\frac{psi}{hr}\right) t_x\ (hr)}$$

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