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WELL ANALYZER

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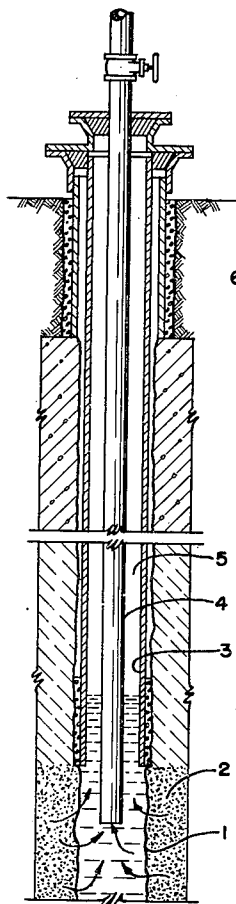


FIG. 1.

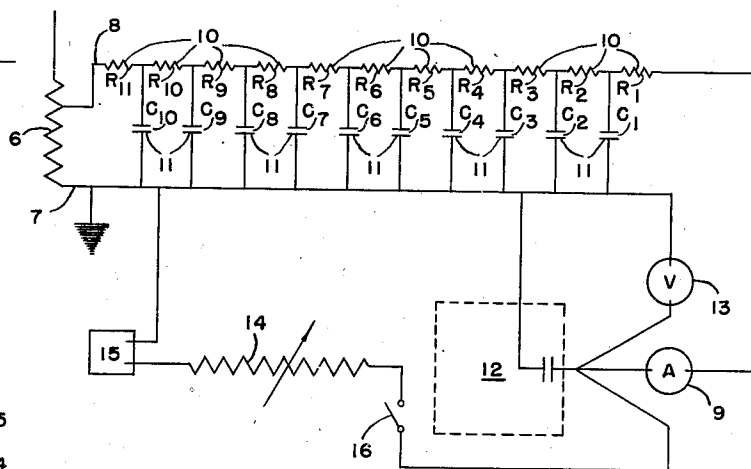


FIG. 2.

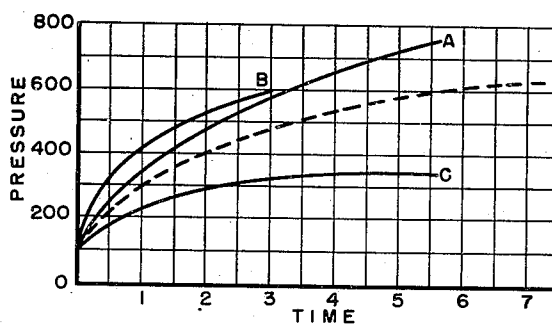


FIG. 3.

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2,472,464

WELL ANALYZER

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4 Claims. (Cl. 235-61)

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The present invention is directed to a method and apparatus for analyzing and predicting the performance of a well producing a fluid from a porous subterranean formation.

In the production of subterranean fluids through a well it is customary to utilize a production string or tubing, which is suspended in the well inside a casing of larger diameter, whereby there is an annular space between the tubing and the casing. As the formation fluid is produced some of it flows up through the tubing and some tends to flow into the annular space. As the fluid is produced there is normally a decrease in formation pressure. For economic production it is desirable to control the rate at which formation pressure decreases; consequently, it is important to study the performance of the producing well with the purpose in view of regulating the rate of production with respect to decrease in formation pressure to realize most efficient recovery of the fluid in place in the formation.

According to the present invention there is provided an electrical counterpart of a producing well in which are embodied electrical elements which are the equivalents of the various parameters which influence well performance and more specifically which determine the rate of decrease of formation pressure at a given rate of production. In a study of a well account must be taken of certain constants, such as, the thickness of the producing formation and its porosity and the capacity of the annular space between the production tubing and the casing, as well as certain parameters, such as formation pressure, formation permeability and the viscosity and compressibility of the fluid, and in addition certain variables such as rate of production and bottom hole pressure. According to the present invention these various factors are accounted for by providing electrical equivalents respectively representing them. For example, the formation pressure is represented by a variable source of power, such as a battery, the output of which is supplied to a potentiometer. The formation permeability and the fluid viscosity, both of which contribute to resistance to flow of fluid through the formation, are represented by variable resistors. The capacity of the annular space between the tubing and the casing is represented by a fixed condenser. The compressibility of the fluid is represented by adjustable condensers. The rate of production is represented by the current flowing in the electrical counterpart, and the bottom hole pressure is represented by a meas-

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urement of voltage in the electrical counterpart at a point corresponding to the point at which fluid flows from the formation into the well bore.

These various factors come into play when a well is converted from the flowing state into the shut-in state. Accordingly, one can fix the values of the electrical counterparts of these various factors by studying the behavior of the well after such a transition, and having fixed these values can proceed to study the behavior of the well, as well as of the formation properties under projected conditions.

The nature of the present invention may be more clearly understood from the following detailed description of the accompanying drawing, in which:

Fig. 1 is a vertical section of a normal well to a study of which the present invention applies;

Fig. 2 is a diagrammatic representation of an electrical counterpart of the well according to the present invention; and,

Fig. 3 is a family of curves illustrating the type of adjustment involved in order to bring the behavior of the electrical counterpart into correspondence with the actual well behavior.

Referring to the drawing in detail numeral 1 designates a bore hole traversing an oil producing formation 2. The bore hole is provided with casing 3 sealed at the top, and with a producing string or tubing 4. It will be understood that various appliances common in such wells, such as blowout preventors, a Christmas tree, a lubricator, and the like, are part of the completed well equipment but are not shown here for the reason that they do not pertain to the present invention. In the following description reference will be made to the annular space 5 between the casing 3 and the tubing 4.

Referring to Fig. 2, the source of power is a potentiometer 6 supplied by a battery not shown. One terminal of this potentiometer is connected to a common ground 7 while the other terminal is connected by conductor 8 to one side of an ammeter 9 through a plurality of resistances 10, which will be referred to as R_1 to R_n , respectively. Between the respective resistances the conductor 8 is connected to the common ground through condensers 11 which will be referred to as C_1 to C_n , inclusive.

In studying any well, it is assumed that for a certain radius around the well, say a few thousand feet, the pressure will remain substantially constant during the limited period of the study and this distance may be called the radius of con-

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stant pressure. From a study of the well's behavior, this radius is estimated by successive adjustment of the apparatus so that during operation the current in R_{11} is no more than leakage current. In preparing for an analysis the first step is to draw a set of concentric circles inside a circle having the radius of constant pressure, by assuming convenient radii ratios such that about 10 successive multiplications of the well bore radius equals the radius of constant pressure. Successive trials may be necessary to get this ratio and the C. P. radius suitably adjusted. The next step is to determine the volumes between successive concentric circles and convert these volumes to fluid capacitance. Fluid capacitance is equal to the product of area, in sq. ft., compressibility, fractional porosity, feet of sand thickness, and the factor for converting cu. ft. to barrels. Each of the condensers 11 represents the fluid capacitance in an annular area between concentric circles. C_1 represents that area immediately around the well, and C_2 — C_{10} representing respectively successively more remote areas. Each of the resistances, R_1 — R_{11} , represents the total resistance to flow of fluid across one of the annular volumes between concentric circles, R_1 being the resistance of the volume immediately adjacent the well, and R_2 — R_{11} representing respectively the resistances of successively more remote annular areas. The total resistance to flow across each annular volume is given by the formula

$$R_T = \frac{v}{2\pi kb} \log_e \frac{r_n}{r_{n-1}}$$

where R_T —the total resistance to fluid flow, v —viscosity of fluid in centipoises, k —permeability (1.127 darcies) barrels/lbs./ft. units, b —thickness in feet, r —distance in feet, and n —the number of concentric circles inside and including the outer circle of the annular area in question. For preliminarily fixing the value of the various resistances, a value of

$$\frac{k}{v}$$

is assumed. Later in adjusting the performance of the electrical counterpart to actual performance, these values may be changed as required.

Thus, it will be seen that the part of the electrical counterpart between ammeter 9 and the source of power represents the various factors involved in the flow of the oil from a point remote from the well to the well bore. Since these various factors determine the rate of flow into the well bore, and since these electrical counterparts determine the magnitude of current indicated by ammeter 9, it follows that this measure of current in the electrical counterpart is a measure of flow of oil into the bore hole from the formation.

The other side of ammeter 9 feeds into a condenser 12 which will be referred to as C_E . This condenser is the electrical counterpart of the annular space between the casing and the tubing. If the casing is open and the well shut in so that liquid flows into the annular space and causes the liquid level to rise, the increase in back pressure exerted on the formation by the fluid in the annular space is proportional to the rate of flow into the well bore. Hence,

$$q = A \frac{dH}{dt}$$

in which q is the rate of flow into the well in

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barrels per day, A is barrels per foot of annular space, and

$$\frac{dH}{dt}$$

is the rate of fluid rise. In case the casing is closed at the top, this equation can be corrected for the back pressure exerted by the gas in the annular space. This equation can be changed into pressure terms and written

$$q = A \frac{dH}{dp} \frac{dp}{dt} - F(b)$$

A condenser of capacity C_E being supplied current undergoes a rate of change in voltage in accordance with the formula

$$i = C_E \frac{dE}{dt}$$

These two latter equations are analogous if "fluid capacitance"

$$A \frac{dH}{dp}$$

is equal to electrical capacitance C_E . Thus, the condenser 12, shown in Fig. 2, having such a capacitance represents the annular space.

The condenser 12 is connected to the common ground. Connected to the conductor 8 between ammeter 9 and the condenser 12 is a voltmeter 13, which is also connected to conductor 7, the voltage recorded by which is a measure of bottom hole pressure in the well.

Just as in a well the oil entering the bore hole goes partly into the annular space and partly into the producing string, so in the electrical counterpart the current in conductor 8 is used partly to charge the condenser 12 and the remainder is delivered to storage, which in this case may be represented by the common ground. How much of the oil is delivered to storage depends on the well control, such as the size of choke employed and the setting of the various valves. Accordingly, between the ammeter 9 and the ground there is a variable resistance 14 which can be manipulated to simulate mechanical well control, to thereby control the current delivered to the unit 15 representing the well head, regardless of the current flowing in conductor 8. Between ammeter 9 and resistance 14 is a switch 16 which is manipulated to reproduce flowing and shut-in conditions.

The unit 15 corresponds to the unit described as unit 32 in copending application Serial No. 504,109 filed September 28, 1943, now Patent No. 2,423,754 in the name of William A. Bruce. The function of this unit is to establish in the circuit a current which will remain constant despite variations in operating voltage, within limits, and can be varied linearly with any function to be studied.

In conducting an electrical analysis of a well in accordance with the present invention, the only laboratory data required are the thickness of the producing formation, penetration of the well, the pressure data on the gas in the annular space and at the bottom of the hole or fluid height data, the producing data prior to the test, and the volume of the annular space. Resistances and condensers representing formation conditions can be assumed in the manner heretofore described. The capacity of the condenser 12 is selected to represent the fluid capacitance of the

annular space between the casing and tubing, and this fluid capacitance is taken to be equal to the vol./ft. of said annular space divided by the pressure in p. s. i. exerted by one foot of fluid. As has been previously indicated, in order to adjust the various parameters to correspond to their actual values in the well being analyzed, the data obtained by measuring bottom pressures at intervals after the well is shut in may be employed.

The purpose of the invention is to supply a method and apparatus for analyzing or predicting the performance of an individual oil well. If, for example, the build-up of bottom hole pressure with time, after a well has been shut in, is known, the electrical system can be set up from known data and adjusted until the build-up curve is reproduced electrically. Then, from the values of resistance, capacitance, and current used to obtain this reproduction, the effective permeability of the formation and the effective compressibility of the reservoir and its fluids can be calculated. Similarly, if values for permeability and compressibility are known, the build-up of a well can be predicted. This build-up curve is used to determine the static or average reservoir pressure, an important value which is sometimes difficult to obtain under field conditions. Also, both of these methods of analysis can be performed under varying well producing conditions.

METHOD

All data concerning the well, the reservoir, and the reservoir fluids are obtained. The area surrounding the well is divided into concentric circular zones, the radius of the outer circle or zone being such that the pressure does not change during the time of the analysis. Normally the radius of circle 1 is arbitrary, being chosen such that usable values of R_1 and C_1 result. Successive radii increase by a fixed factor such that the ratio of the radii of adjacent circles is constant. Then the resistance and capacitance used in the apparatus are made proportional to the fluid resistance and the fluid capacitance of the reservoir enclosed by the successive circles. These calculations are more fully described in the text of the invention (columns 2 and 3).

Data necessary for calculations:

Diameter of well bore=8"

Viscosity of reservoir oil=2 centipoises

Permeability of reservoir rock=25 md=

.025 Darcy=.0281 perm.

Thickness of reservoir formation=80'

Specific gravity of reservoir oil=.8

Potentiometer set to supply 300 volts

Penetration of well=80'

Radius of circle of constant pressure=1500'

METHOD

Radius of circle 1 arbitrarily chosen as 40'. Successive radii calculated so that r_{10} is 1500', the radius of the circle of constant pressure. As a result the ratio of adjacent radii from circle 1 to circle 10 is 1.5.

Before the analogous electrical zone resistance can be found the related zone fluid resistance must be calculated.

$$R_f = \frac{v}{2\pi kb} \log_e \frac{r_n}{r_{n-1}} = \frac{v}{2\pi kb} 2.303 \log_{10} \frac{r_n}{r_{n-1}}$$

Where:

v =viscosity of reservoir oil in centipoise=2cp.

k =permeability in perms

$$=0.25 \text{ Darcies} \times 1.127 \frac{\text{perms}}{\text{Darcy}} = .0281 \text{ perms}$$

b =thickness of reservoir=80'

CALCULATIONS OF FLUID RESISTANCE

Zone 1

$$R_f = \frac{2 \times 2.303 \times \log_{10} 1.333}{2\pi \times .0281 \times 80} = .676 \text{ p. s. i./bbl./day}$$

Zones 2 to 10

$$R_f = \frac{2 \times 2.303 \times \log 1.5}{2\pi \times .0281 \times 80} = .0568 \text{ p. s. i./bbl./day}$$

FLUID CAPACITANCE

$$C_f = \frac{cAbf}{5.614} \text{ bbs./p. s. i.}$$

Where:

c =compressibility of oil= 10^{-5} bbs./bbl./p. s. i.

A =zone area in sq. ft.

b =zone (formation) thickness in ft.=80'

f =fractional porosity=.20

5.614=conversion factor (cu. ft./bbl.)

EXAMPLE OF CALCULATION

Zone 1

$$C_f = \frac{10^{-5} \times 5030 \times 80 \times .20}{5.614} = .1432 \text{ bbl./p. s. i.}$$

Fluid capacitance of other zones calculated in same manner.

CALCULATION OF FLUID CAPACITANCE OF WELL BORE

$$C_f = A \frac{dH}{dP} \text{ bbl./p. s. i.}$$

A =volume of 1 ft. of annular space in bbls.

Circle or Zone	Radius, ft.	(sq. ft.) Total Area	(sq. ft.) Zone Area	Rf Fluid Resistance	Cf Fluid Capacitance	Re Electrical Resistance	Ce Electrical Capacitance
Well	.333	.348			Cw .179		(Cw) 1.43
1	40	5,030	5,030	.676	C1 .1432	R1 .676	(C1) 1.15
2	59.8	11,270	6,240	.0568	C2 .178	R2 .0568	(C2) 1.42
3	89.6	25,350	14,080	.0568	C3 .401	R3 .0568	(C3) 3.2
4	134	56,600	31,250	.0568	C4 .890	R4 .0568	(C4) 7.1
5	200	125,900	69,300	.0568	C5 1.975	R5 .0568	(C5) 15.8
6	300	283,000	157,100	.0568	C6 4.48	R6 .0568	(C6) 35.8
7	448	632,000	349,000	.0568	C7 9.95	R7 .0568	(C7) 79.5
8	670	1,412,000	780,000	.0568	C8 22.22	R8 .0568	(C8) 178
9	1,000	3,142,000	1,730,000	.0568	C9 49.3	R9 .0568	(C9) 394
10	1,500	7,070,000	3,928,000	.0568	C10 112.0	R10 .0568	(C10) 895

NOTE.—Circle 1 is outer radius of zone 1, so C_1 represents the capacitance of zone 1 and R_1 represents the resistance to flow across zone 1.

NOTE.— R_{11} =1 megohm.

dH/dP =change of fluid level with pressure or reciprocal of fluid pressure gradient

$$A = \frac{\pi \times (.333) \times 1'}{5.614} = .062 \text{ bbls./ft.}$$

$$\frac{dH}{dP} = \frac{1}{.8 \times .433} = \frac{1}{.346} \text{ ft./p.s.i.}$$

$$Cf = A \frac{dH}{dP} = \frac{.062}{.346} = .179 \text{ bbls./p.s.i.}$$

Selection of proportionality constants for changing values of fluid capacitance and resistance to electrical capacitance and resistance.

The constant for converting fluid to electrical capacitance is selected so that a fairly large amount of total capacitance is used so errors from leakage are negligible. The constant for converting fluid to electrical resistance is chosen so the resistors of the apparatus will cover all values. The relationship of voltage to pressure is taken such that the pressure range encountered, a maximum of 1000 p. s. i. in this example, in the operation of a well is represented by the 300 volt potentiometer.

The following proportionality constants result:

$$M = \frac{\text{electrical capacitance}}{\text{fluid capacitance}} = 8 \text{ microfarads/bbl./p.s.i.}$$

$$N = \frac{\text{electrical resistance}}{\text{fluid resistance}} = 1 \text{ megohm/p.s.i./bbl./day}$$

$$L = \frac{\text{volts}}{\text{p.s.i.}} = 300/1000 = .3 \text{ volts/p.s.i.}$$

These constants were used to convert the fluid capacitance and resistance values of Table 1 to the corresponding electrical values shown in the table.

It has been shown mathematically in Patent No. 2,423,754 that the following combination of these constants is valid.

$$MN = \text{experimental time/field time} = 8 \times 1 = 8 \text{ sec./day}$$

$$L/N = \text{electrical current/production rate} = \frac{.3}{1} = .3 \text{ microamp./bbl./day}$$

Thus the results of the calculations, in addition to the magnitude of the various resistors and condensers, are as follows:

Current flow such that 400 bbls./day is equivalent to 120 microamperes

Time scale such that a one day well test requires 8 seconds for analysis

Voltage such that 1000 pounds change in well pressure is equivalent to 300 volts.

Thus, complete data are available for setting up the well problem. The values shown are preliminary and after trial runs are made, adjustments lead to the solution as described in columns 5 and 6 of the text. The final values of constants, resistors, and condensers can be used to determine effective values of permeability and compressibility as described before.

When a well is shut in after flowing the bottom hole pressure builds up with time. A typical curve showing this relationship is that represented by a dotted line in Fig. 3. The solid curves A, B, and C represent the variations in voltage indicated by voltmeter 13 with time after switch 16 is opened, this being the electrical counterpart of the build-up of bottom hole pressure when a flowing well is shut in. To coincide with the dotted line, curve A must be lower, and this is accomplished by increasing the ratio of electric

voltage to pressure. If a maximum increase in the voltage pressure factor does not lower curve A enough, the voltage at the radius of constant pressure, that is the voltage supplied by potentiometer 6 is too high and must be decreased. Multiplying the time relationship factor by a constant does not change any of the other factors; therefore, curve B may be fitted to the measured curve by this method. Increasing the relationship factor of electrical capacitance to fluid capacity or increasing the effective well bore will increase the radius of curvature and give curve C the proper adjustment. The foregoing represents simple adjustments. In order to secure coincidence of the voltage time curve with the pressure time curve there will in many cases be required an adjustment of capacitances 11 and/or resistances 10.

Having secured coincidence of the voltage time curve, after opening of switch 16 with the measured pressure time curve on the shut-in well and thereby establishing the various parameters, the behavior of the well under various conditions of production can be studied. For example, it can be determined what will be the effect of increased rate of production on bottom hole pressure, as well as on formation pressure at various distances from the well.

To the extent that this application discloses and claims subject matter common to copending application Serial No. 504,109 filed September 28, 1943 and entitled "Analyzer for subterranean fluid reservoir," it is a continuation-in-part thereof.

The nature and objects of the present invention having been thus described and illustrated, what is claimed as new and useful and is desired to be secured by Letters Patent is:

1. A method for studying the behavior of a well producing a fluid from a subterranean formation, which comprises establishing an electrical circuit having a source of power to represent formation pressure, resistances to represent total resistance to flow of fluid through the formation for a predetermined distance around the well, condensers to represent the fluid capacitance of the formation for said distance around the well, a condenser to represent fluid capacitance of the well itself, and current draw-off means to represent the production of fluid from the well, determining the variations of bottom hole pressure in the well with time when the well is shut in after flowing, adjusting the various elements of the electrical circuit to give a variation in voltage with time at the point in the electrical counterpart corresponding to the bottom of the bore hole corresponding to the variations of bottom hole pressure in the well with time when the well is shut in after flowing, and thereafter introducing into the electrical circuit electrical changes which correspond to projected changes in operation of the well, and measuring in the circuit the effect of such projected changes on the other factors involved in the production of fluid from the well.

2. An apparatus for studying the behavior of a well producing a fluid from a subterranean formation comprising an electrical circuit having a source of power to represent formation pressure and a ground return circuit, resistances arranged in series with said source of power to represent the total resistance to flow of fluid through the formation for a predetermined distance around the well, condensers arranged in parallel between said source of power and the ground to represent the fluid capacitance of the formation for said

distance around the well, a separate condenser arranged between said source of power and the ground to represent the fluid capacitance of the borehole itself, means for drawing current from said source of power through said circuit and means for measuring the voltage at various points in said circuit.

3. A method for studying the behavior of a well producing a fluid from a subterranean formation which comprises predetermining in said formation an area of constant pressure with said well as its center, dividing said area up into a plurality of annular areas concentric with said well, providing a source of electrical power representing the pressure in said area, connecting in series with said source of power a plurality of resistances each representing the total resistance to flow of fluid through the formation embraced by one of said annular areas, connecting between said source of power and the ground a plurality of condensers each representing the fluid capacity of the formation embraced by one of said annular areas, also connecting between said source of power and the ground a condenser to represent the fluid capacitance of the well, determining the variations in bottom hole pressure in the well with time when the well is shut in after flowing, drawing off from said source of power electrical current corresponding to the fluid flowing from said well and adjusting the various elements of the electrical circuit to give a variation in voltage with time in said circuit corresponding to said variations in bottom hole pressure with time, thereafter introducing into the electrical circuit electrical changes which correspond to projected changes in operation of the well and measuring in the circuit the effect of such projected changes on the other factors involved in the production of fluid from the well.

4. A method for studying the behavior of a well producing a fluid from a subterranean formation, which comprises establishing an electrical circuit having a source of power to represent formation pressure, resistances to represent total resistance to flow of fluid through the formation for a predetermined distance around the well, condensers to represent the fluid capacitance of the formation for said distance around the well, a condenser to represent fluid capacitance of the well itself, and current draw-off means to represent the production of fluid from the well, determining the variations in one operating variable of the well with variations in another operating variable, adjusting the various elements of the electrical circuit to give the corresponding variation in the electrical value corresponding to said first operating variable for variations in the electrical value corresponding to said second operating variable, and thereafter introducing into the electrical circuit electrical changes which correspond to projected changes in operation of the well, and measuring in the circuit the effect of such projected changes on the other factors involved in the production of fluid from the well.

WILLIAM A. BRUCE.

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