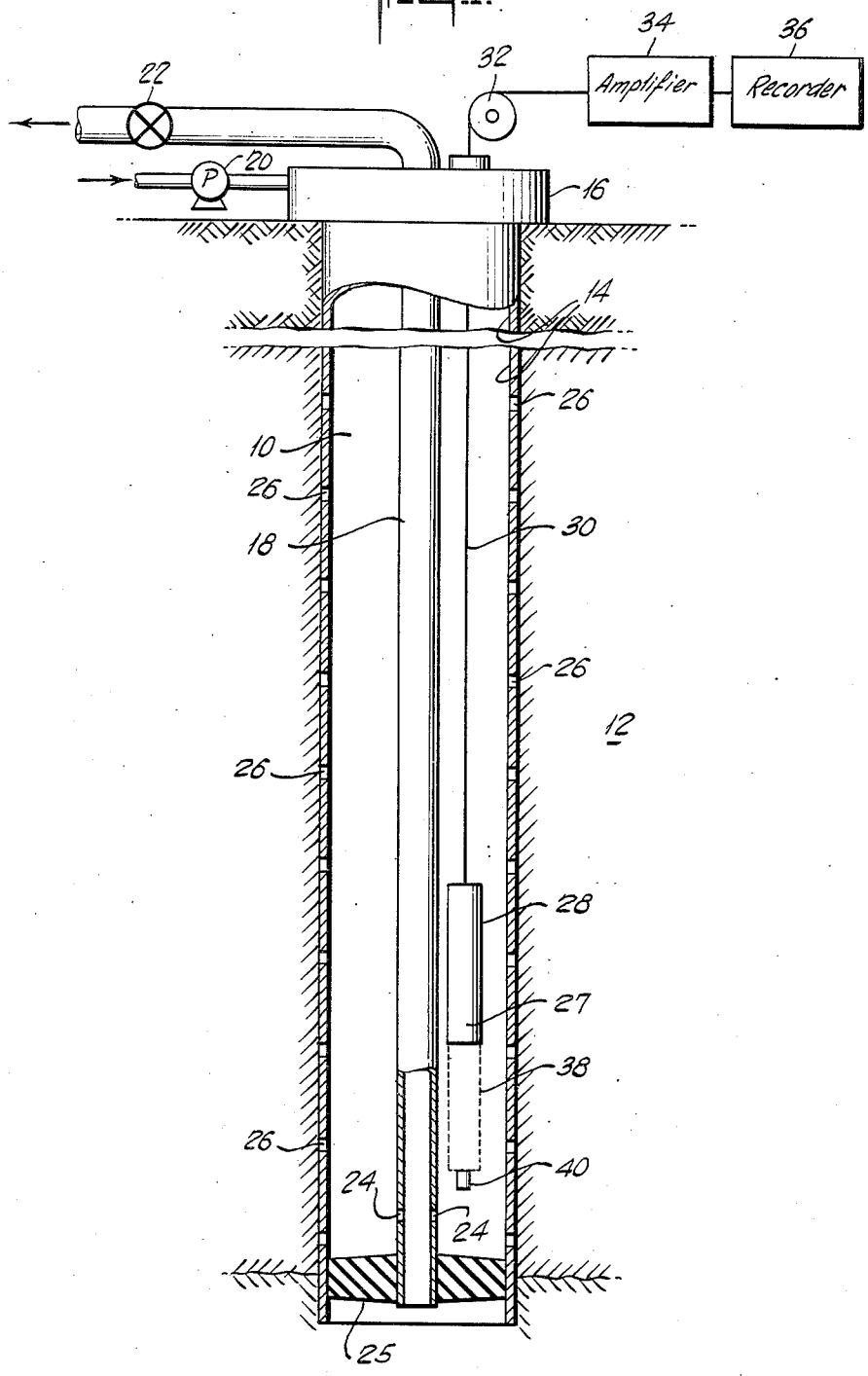
June 12, 1962 J. C. ALLEN ETAL 3,038,333

PRODUCTIVITY WELL LOGGING

Filed July 31, 1958 2 Sheets-Sheet 1

Fig. 1.



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PRODUCTIVITY WELL LOGGING

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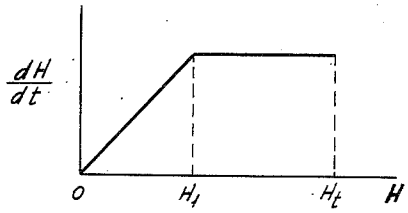


Fig. 2.

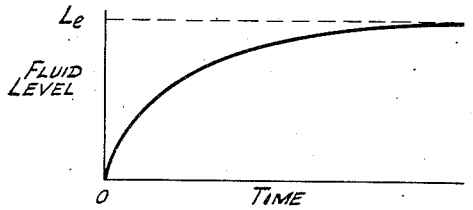


Fig. 3.

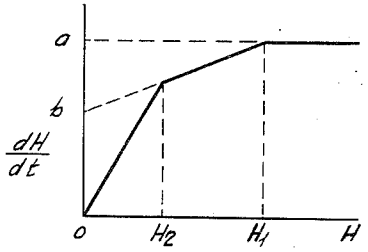


Fig. 4.

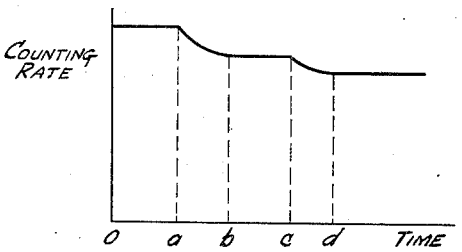


Fig. 5.

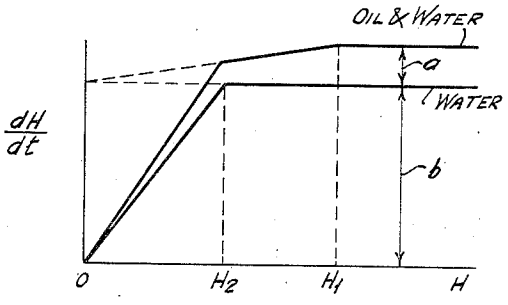


Fig. 6.

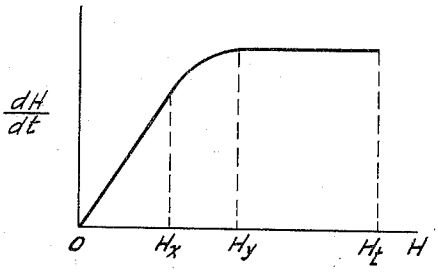


Fig. 7.

United States Patent Office 3,038,333 Patented June 12, 1962

3,038,333

PRODUCTIVITY WELL LOGGING

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Filed July 31, 1958, Ser. No. 752,239
13 Claims. (Cl. 73—155)

This invention relates to oil well production and more particularly to a method and an apparatus by means of which a measurement or determination can be made of the exact location of zones or formations from which a fluid or a plurality of fluids such as gas, oil and water are entering a well borehole.

In oil well production it is, of course, desirable to know the depth and vertical thickness of a formation from which a fluid such as gas, oil or water is entering the hole. In many instances two of these fluids or all three may be flowing into the well at the same time, each from a different zone or formation and it is desirable to ascertain the location of all of these formations. Also it is frequently necessary to know the amount of one or more of the fluids flowing into the well together with the locations of the zones from which they are flowing. A record showing the amount of a fluid and the depth at which it is entering into a well is often called a productivity profile log of the well and the information obtained therefrom may be useful in many ways. For example, it may be desired to seal off a gas or water producing formation from a formation or zone producing oil. This may be done by the proper use of sealing and plugging agents, packers and the like provided the location of the producing zone is known.

The distribution of points of entry of fluids into producing well bores can vary widely. This is true for a single producing horizon that has wide variation in permeabilities and also true of wells that are completed in more than one permeable zone. It is desirable to know exactly the point or points of entry in order to place squeeze cement or plugs for sealing off the undesirable fluids.

In water flooding or gas flooding operations early production of the injected fluid is sometimes experienced and a very low volumetric displacement efficiency is obtained by the injected fluid. Thus it is desirable to plug the previously invaded strata in both injection and producing wells in order to effect a displacement of the unrecovered oil in the uninvaded zones.

In accordance with this invention a productivity profile log is obtained by removing at least a portion of the borehole fluid from the zone of interest of the borehole and observing the rate of change of the liquid level at the zone of interest in the borehole.

In carrying out one embodiment of the practice of this invention, a section of casing opposite the producing zone or zone of interest is perforated. A radiation detector, or other suitable detecting means, is lashed to a section of tubing and the tubing and detector and an accompanying cable arrangement are powered into the well bore simultaneously. The cable arrangement may be connected between the detector and conventional surface equipment which may include suitable amplifying and recording devices. Below the radiation detector a conventional testing tool with an expansion packer is assembled. Affixed to the lower end of the radiation detector is a squirrel cage arrangement containing a source of radiation at the lower end thereof at a fixed distance from the detector. This source is preferably an emitter of soft gamma rays such as cesium 137.

After the tubing and the assembly which includes the detector and the squirrel cage arrangement are lowered to the bottom of the productive zone, compressed gas,

for example, air, is forced into the annular space between the tubing and the casing so as to force all of the liquid from the annular space upwardly through the tubing and to prevent reservoir liquids in the subsurface formations from entering the borehole. With the assembly in place and the well bore filled with gas, the gas pressure in the borehole is released to permit the reservoir liquid in the producing formation to flow into the well bore. Initially a constant counting rate is indicated by the recording device but when the fluid level in the annular space covers the source of radiation a change in the counting rate is indicated at the surface due to the change in density of the medium between the source and the detector. As the liquid level rises in the annular space between the source and the detector the counting rate continually decreases. When the fluid level reaches the detector the counting rate again becomes constant. The recorded log gives the rate of rise of fluid in the well bore at a given location since the time required for the fluid level to travel a given distance has been determined.

When the instrument is at the bottom of the productive zone the first log or observation represents the total rate of flow from the producing formation or formations into the well bore for the entire productive zone or interval. After the first log is obtained the expansion packer is unseated and the entire assembly is raised to a second location. The packer is then reseated and the borehole liquids again forced out of the well bore and another log is obtained. The rate of rise in the annular space at the second location is normally less than the rate of rise at the previous lower level. The difference between these rates of rise or rates of flow into the well bore represents the quantity of liquid flowing into the well bore throughout the interval that the assembly was raised. This operation is then repeated at higher borehole locations so as to provide a complete productivity profile log.

The time interval over which the countng rate is decreasing is the time required for the fluid surface to move from the bottom to the top of the squirrel cage and this indicates the rate of rise of the liquid in the well bore. By making repeated measurements as the fluid level rises in the well bore the rate of rise of the fluid level is a function of time and also as a function of the fluid level can be determined. The position of the fluid level as a function of time can also be determined.

For a better understanding of the invention, reference is made to the accompanying drawing in which:

FIG. 1 illustrates a vertical sectional view of a producing well and apparatus therein for carrying out one embodiment of the practice of this invention;

FIG. 2 is a graph wherein the rate of rise of borehole fluids from the bottom of the borehole to the equilibrium fluid level is plotted against depth for a borehole having only one point of fluid entry;

FIG. 3 is a graph indicating the height of a column of borehole liquid from the point of fluid entry into a borehole to the equilibrium fluid level as a function of time;

FIG. 4 is a graph similar to that shown in FIG. 2 except that it is plotted for a borehole having two points of fluid entry;

FIG. 5 is a graph indicating the counting rate at a given point in the borehole as a function of time wherein the flow rates into the well are so low that an oil-water interface develops;

FIG. 6 is a graph plotted for the rate of rise of the surface of the borehole liquid column and also for the oil-water interface against depth in slowly flowing wells; and,

FIG. 7 is a graph similar to that shown in FIG. 2 except that it is plotted for a borehole wherein the fluid entry is spread over a considerable interval of depth.

Referring in more detail to FIG. 1 of the drawing, a well or borehole **10** is shown as traversing several subsurface formations including a productive zone **12** for which it is desired to make a productivity profile log. The well or borehole **10** is shown as being provided with a casing **14** having a closed casing head **16**. A tubing **18**, having a closed lower end, passes through the casing head **16** and downwardly through the well to a point below the productive zone **12**. At the surface a pump **20** is connected to the casing head **16** and a valve **22** is connected to the upper end of the tubing **18**. The tubing **18** has one or more ports **24** at the lower end thereof. At a point below the ports **24** an expansion packer **25** is attached to the tubing **18** to provide a seal between the tubing **18** and the casing **14**. Casing **14** has perforations **26** throughout the productive zone **12**.

Suspended in the annular space between the tubing **18** and the casing **14** is an assembly **27** including a radioactive logging instrument **28** containing a detector of gamma rays and a squirrel cage arrangement **38** containing a source of radiations **40**. The output from the detector is conducted upwardly through a suspending cable **30**. This cable **30** passes over a suitable cable measuring device **32** which continuously indicates the depth of the instrument **28** in the hole and then to a suitable amplifier **34** and a recorder **36**. The squirrel cage arrangement **38** is affixed to the lower end of the instrument **28** and the source of radiations **40** is located at the lower end thereof at a spaced distance, for example, one foot, from the instrument **28**. This source **40** preferably emits soft gamma rays such as those emanating from cesium 137.

In carrying out the method of this invention the assembly which includes the radioactivity logging instrument and the squirrel cage arrangement is lowered to the bottom of the productive zone **12**. The valve **22** is opened and a gas, for example, compressed air, is forced, as by means of pump **20**, into the annular space between the tubing **18** and the casing **14** to cause all the liquid in the borehole **10** above the expansion packer **25** to be displaced downwardly from the annular space through the ports **24** into the tubing **18** and upwardly through the tubing **18** out of the borehole. After all the borehole liquid above the expansion packer **25** is removed from the borehole the valve **22** is closed and sufficient pressure is maintained in the borehole to prevent formation fluid from entering into the borehole. With the assembly held in a fixed position at a point above and preferably adjacent to the packer **25** the pressure is released in the borehole by opening valve **22**. Since there is now little or no pressure against the wall of the borehole from within the borehole, the reservoir liquid from the productive zone **12** will flow into the well bore. When the liquid level in the annular space covers the source of radiations **40**, a change in counting rate will be noted at the surface recorder **36**. This change is a decrease in the counting rate as the liquid level rises in the annular space in the squirrel cage arrangement between the source **40** and the instrument **28**. As soon as the fluid liquid level reaches the instrument **28**, the counting rate becomes constant. The log obtained at this first position of the assembly provides the rate of rise of the liquid in the well bore between the source **40** and the instrument **28**, since the distance between the source and the detector is fixed and known and the time required from liquid level to rise from the source **40** to the instrument **28** has been measured. This first log represents the total rate of flow into the well bore for the entire productive zone **12**. After this first log is obtained, the expansion packer **25** is unseated and the entire assembly is raised, for example, several feet. The packer **25** is then reseated, the liquids are again forced out of the borehole, if necessary, in the same manner as described above and a repeat log is run. The rate of rise in the annular space at the second position is equal to or less than the rate of rise at the previous level. The difference between these rates of rise or rates of flow of the reservoir liquids into the well bore represents the quantity of liquid flowing into the well bore from the interval between the first and second positions of the expansion packer. To provide a complete productivity profile log of the productive zone **12**, this operation is repeated several times for higher intervals of the productive zone **12**. It should be understood that the logs need not be necessarily made at succeedingly higher points. The logs may be taken in any order as long as they are taken at different depths in the zone of interest.

Although the apparatus illustrated in FIG. 1 includes an expansion packer it should be understood that it is possible to obtain a productivity profile log without the use of an expansion packer. In order to carry out this second embodiment of the practice of this invention, the borehole liquid is forced out of the borehole from the interval or zone of interest in much the same manner as described above. The assembly is lowered to the lowest point of the zone of interest, the borehole pressure is released, and the rate of rise of the liquid at this lowest point is noted. The assembly is then raised above the rising liquid level to a second point and the rate of rise of the liquid at the second point is noted. This operation is repeated at higher levels until readings are taken at several points within the zone of interest. A plot of the rate of rise against depth provides a graph as shown in FIG. 2, the rate of rise

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

being the ordinate and depth in the borehole H being the abscissa, the origin O being the equilibrium position of the liquid level in the well, H_1 being the point of fluid entry and H_t being the bottom of the well. It can be seen that FIG. 2 indicates the rate of rise of the liquid in the borehole due to the entry of the liquid from a single point H_1. The liquid level rises at a constant rate from the bottom of the borehole H_t until it reaches the point of entry H_1. From H_1 to the equilibrium position or O the rate of rise decreases linearly to zero. Accordingly, it can be seen that by determining the rate of rise of the liquid level in the borehole at points below the point of liquid entry a horizontal line indicating the constant rate can be defined and by measuring the rate of rise of the liquid level at points above the point of liquid entry a second line will be defined. The intersection of these two lines locates the point of fluid entry into the borehole and the horizontal line indicates the maximum flow rate from this point.

The second embodiment of the practice of this invention rests on the basic assumption that the rate of fluid flow into a producing well is proportional to the horizontal pressure gradient which acts on the fluids in the subsurface formations in the vicinity of the borehole. This flow rate is maximum when the wall or face of the formation is exposed to atmospheric pressure. The flow rate will decay or slow down when the borehole fluid rises above the point of fluid entry because the borehole fluid pressure at the point of fluid entry opposes the formation pressure to thus nullify at least a portion of the pressure gradient or force which tends to move the formation fluids into the borehole. The fluid level in the borehole will continue to rise at an increasingly slower rate until an equilibrium condition is reached where the fluid flow rate is zero.

In order to more fully describe the principles of the second embodiment, it should be noted that if the borehole diameter is uniform the position of the fluid level can be readily converted to the volume of fluid in the borehole and also the rate of fluid level rise can be converted to the rate of fluid flow into the well. If the fluid enters a borehole within a short interval of depth, the fluid level measured from the point of fluid entry can be plotted against time as shown in FIG. 3. As can be seen in FIG. 3, the liquid level rises rapidly at

first and then slowly approaches the equilibrium position L_e asymptotically. The shape of this curve can be justified by referring to the fundamental assumption. The basic assumption states that

$$\text{rate of flow}=\frac{dV}{dt}=K'(L_e-L)\rho \qquad (1)$$

where L is the length of fluid column above the point of entry, ρ is the density of the fluid, L_e is a constant equal to the length of the fluid column above the point of entry at equilibrium and

$$\frac{dV}{dt}$$

is the rate of flow of fluid into the borehole and K' is a constant of proportionality. From Equation 1, which is a linear function representing the sloping line in FIG. 2, it can be seen that by dividing both sides of the equation by πr^2.

$$\frac{dL}{dt}=K(L_e-L) \qquad (2)$$

where

$$K=K'\frac{\rho}{\pi r^2}$$

and r=the radius of the borehole.

Equation 2 may be simplified by measuring the position of the fluid level relative to the equilibrium level, thus, L_e—L may be referred to as H. Then by differentiating

$$H=L_e-L \qquad (3)$$

$$\frac{dH}{dt}=-\frac{dL}{dt} \qquad (4)$$

and, therefore,

$$\frac{dH}{dt}=-KH \qquad (5)$$

Integrating both sides of equation 5

$$H=Ce^{-Kt} \qquad (6)$$

If

$$H=L_e \text{ at } t=0, \text{ then } L_e=C \text{ and } H=L_e e^{-Kt} \qquad (7)$$

therefore,

$$L_e-L=L_e e^{-Kt} \qquad (8)$$

and

$$L=L_e(1-e^{-Kt}) \qquad (9)$$

which equation represents the curve in FIG. 3.

Heretofore, the method has been described in connection with a single point of fluid entry in a borehole. However, it should be understood that the method of the invention may be used for boreholes having two or more points of fluid entry. If the fluid enters the borehole at two different depths, a curve such as that shown in FIG. 4 is obtained which indicates points of fluid entry at H_1 and H_2. From this curve it can be determined that the initial or maximum flow rate into the borehole at position H_1 is a–b, while the initial or maximum flow rate at H_2 is b.

When relatively low flow rates are encountered in wells which are producing both oil and water, a substantial degree of separation of the oil and water occurs. Under these conditions it is possible to detect the movement of the oil level and the oil-water interface in the borehole. By positioning the assembly **27** including the radioactivity logging instrument 28 and the source of radiations 40 at a given depth in the well a curve such as that shown in FIG. 5 is obtained. As can be seen from a study of FIG. 5, a relatively high constant counting rate is obtained from the time 0 to a during which time the top of the liquid column is approaching the source **40**. During the time interval a to b the counting rate decreases as the oil at the top of the column of the liquids enters into the squirrel cage **38**. At time b the squirrel cage is completely filled with the oil and a lower constant counting rate is measured in the time interval from b to c. As soon as the oil-water interface rises above the level of the source **40**, the counting rate again decreases as indicated during the time interval from c to d, the time required for the oil-water interface to move from the source 40 to the detector 28. Accordingly, it can be seen that the rate of rise of the top of the liquid column including the water and oil, is determined during the time interval a to b and the rate of rise of the water is determined during the time interval c to d. When a record is made at a plurality of points in a zone of interest in a borehole a curve such as that shown in FIG. 6 is obtained wherein the rates of rise of the oil and water level and of the water level alone are plotted against depth. From FIG. 6 it can be seen that oil flows out of H_1 and water flows out of H_2. Once again the initial or maximum flow rates of the water and oil plus water can be determined, and by subtracting the water flow rate from the oil and water flow rate the flow rate of the oil from H_2 can be determined. Thus, as shown in FIG. 6, the oil enters at H_1 with an initial flow rate a while the water enters at H_2 with an initial flow rate b.

It can be seen that the upper curve of FIG. 6 appears to be somewhat similar to the curve shown in FIG. 4 yet the latter figure indicates points of entry of similar fluids from two separate points whereas the upper curve of FIG. 6 indicates points of entry of different fluids from two separate points. However, it should be understood that the curves in FIG. 6 will not be perfectly straight lines as indicated when the density of the two fluids is substantially different. Nevertheless, even when the densities of the two fluids vary appreciably points of discontinuity in the graph will clearly indicate the desired points of entry of the two fluids, i.e., H_1 and H_2.

When fluid entry into a borehole is spread over a considerable interval of depth, the plot of

$$\frac{dH}{dt} \text{ vs. } H$$

has a curvature over this entire interval of H as shown in FIG. 7, the rate of rise of the fluid level from the bottom of the borehole H_t to the lowest point H_y of this interval is constant and the rate of rise of the fluid level decreases linearly from the top of this interval H_x to the equilibrium position or origin O.

It should be understood that reservoir fluid entering the borehole from a point or points above the assembly **27** should not be permitted to enter into the squirrel cage **38** before the fluid has been accumulated in the borehole liquid column. Accordingly, the assembly **27** should be lashed to the tubing **18** in such a manner that an adequate passage be provided between the assembly **27** and the inner wall of the casing **14** to permit all fluid entering the borehole above the assembly **27** to drain into the borehole liquid column without first passing through the squirrel cage arrangement. Alternatively, the assembly **27** may be provided with an umbrella type cover or shield for diverting the falling fluid from the assembly **27**.

It should also be understood that this invention is not limited to a determination of the rate of rise of the borehole liquid level. It is also contemplated within the scope of the invention to determine the point or points of entry of the borehole liquids by measuring the rate of fall or drop of the borehole liquid level. This may be done by pumping the borehole liquid out of the borehole at a known rate which is greater than the rate of entry of the formation liquid into the borehole and determining the rate of drop of the liquid level at predetermined points in a manner similar to that described in connection with the embodiments of the invention wherein measurements of the rate of rise of the borehole liquid level are made. It can be seen that all of the embodiments of the invention provide the same results although in the plotted graphs

the slopes of the line between the equilibrium or O level and the point of entry of the borehole fluid will differ. In the rate of fall embodiment the maximum rate of fluid entry into the borehole will be determined by the rate at which the borehole fluids are being pumped out of the borehole and the rate of drop of the fluid level below the point of fluid entry.

Although a radioactivity logging instrument and a source of radiations has been described as the means for determining the rate of rise or fall of the borehole liquid, it should be understood that other devices which can differentiate between the different fluids in the borehole can be used. Such other devices may include instruments for determining the electrical resistivity of the borehole fluids or means for determining the acoustic velocities in the borehole fluids.

Obviously, many other modifications and variations of the invention as hereinabove set forth may be made without departing from the spirit and scope thereof, and therefore, only such limitations should be imposed as are indicated in the appended claims.

We claim:

1. A method of providing a productivity profile log of a subsurface formation containing a liquid which normally flows into a borehole traversing said formation which comprises removing liquid from the borehole to permit the liquid from a first point in the subsurface formation to enter the borehole, and measuring the rate of change of the liquid level in the borehole at a plurality of vertically spaced locations above and below said first point in the borehole.

2. A method of providing a log of a producing formation traversed by a borehole into which a liquid is flowing from a point in said formation which comprises moving the liquid level of said borehole liquid along the wall of the borehole, and measuring the rate of change of the liquid level in the borehole at a plurality of vertically spaced locations in the borehole above and below said point.

3. A method of obtaining a productivity profile log of a subsurface formation traversed by a borehole containing liquid which comprises applying pressure to the wall of a predetermined portion of the borehole to prevent subsurface formation liquid from entering thereinto, removing the borehole liquid from said predetermined portion of the borehole, releasing said pressure to permit said subsurface formation liquid to flow into said predetermined portion of the borehole, and measuring at a plurality of known vertically spaced points the rate of rise of the liquid level of the liquid flowing in to said predetermined portion of the borehole.

4. A method of obtaining a productivity profile log of a subsurface formation traversed by a borehole which comprises applying pressure to the wall of predetermined portion of the borehole to prevent subsurface formation liquid from entering thereinto, suddenly releasing said pressure to permit the flow of subsurface formation liquid into said predetermined portion of the borehole, and measuring at a plurality of known vertically spaced locations the rate of rise of the liquid level of the liquid flowing into said predetermined portion of the borehole.

5. A method of obtaining a productivity profile log of a subsurface formation traversed by a borehole which comprises applying pressure to the wall of a predetermined portion of the borehole to prevent subsurface formation liquid from entering thereinto, releasing said pressure a known amount so as to permit the flow of subsurface formation liquid into said predetermined portion of the borehole, and measuring at a plurality of known vertically spaced points the rate of rise of the liquid level of the liquid flowing into said predetermined portion of the borehole.

6. A method of obtaining a productivity profile log of a subsurface formation traversed by a borehole which comprises varying the pressure against the wall of a predetermined portion of the borehole which traverses said subsurface formation so as to permit the flow of subsurface formation liquid into said predetermined portion of the borehole and measuring at a plurality of known vertically spaced points above and below said formation the rate of rise of the liquid level of the liquid flowing into said predetermined portion of the borehole.

7. A method of obtaining a productivity profile log of a vertical interval of a subsurface formation traversed by a borehole which comprises varying the pressure against the wall of the borehole so as to permit the flow of subsurface formation fluid into said borehole, and measuring at a plurality of known vertically spaced points above and below said vertical interval the rate of change of the fluid level of the fluid flowing into the borehole.

8. A method of obtaining a productivity profile log of a vertical interval of a producing subsurface formation traversed by a borehole which comprises varying the pressure against the wall of the borehole so as to move the liquid level of liquid flowing from said formation into said borehole along the wall thereof, and measuring at a plurality of known vertically spaced points above and below said vertical interval the rate of change of the liquid level in the borehole.

9. A method of obtaining a log of a producing formation traversed by a borehole which comprises seating a fluid-tight seal at a known depth in the borehole to separate one portion thereof from another, applying pressure to the wall of the one portion of the borehole to prevent formation fluid from entering into the one portion of the borehole, releasing said pressure to permit the flow of the formation fluid into the one portion of the borehole, measuring the rate of rise of the fluid level at the lowest end of the one portion of the borehole, reseating the fluid-tight seal at another known depth in the borehole and repeating these operations, the difference in the rate of rise of the fluid level at two known depths being equal to the rate of flow of the formation fluid into the borehole from the interval between the two known depths.

10. A method of obtaining a log of a producing formation traversed by a borehole containing a fluid which comprises seating a fluid-tight seal at a known depth in the borehole to separate one portion thereof from another, applying pressure to the wall of the one portion of the borehole to prevent formation fluid from entering into the one portion of the borehole, removing the fluid from the one portion of the borehole, releasing said pressure to permit the flow of formation fluid into the one portion of the borehole, measuring the rate of rise of the fluid level at the lowest end of the one portion of the borehole, reseating the fluid-tight seal at another known depth in the borehole and repeating these operations, the difference in the rate of rise of the fluid level at two known depths being equal to the rate of flow of the formation fluid into the borehole from the interval between the two known depths.

11. A method of making a log of a producing formation traversed by a borehole containing a liquid which comprises seating a liquid-tight seal at a known depth in the borehole to separate one portion thereof from another, displacing the liquid in the one portion of the borehole with a gas at a pressure sufficient to prevent liquid from the formation to enter into the one portion of the borehole, suddenly releasing said pressure to permit liquid from the producing formation to flow into the one portion of the borehole, measuring at the lowest end of the one portion of the borehole the rate of rise of the liquid level of the liquid flowing into the one portion of the borehole, reseating said liquid-tight seal at another known depth in the borehole and repeating these operations for said another known depth, the difference in the rates of rise of the liquid levels at two different depths being equal to the rate of flow of liquid into the borehole from the interval between the two depths.

12. Apparatus for providing a productivity profile log

of a subsurface formation traversed by a borehole into which a fluid is flowing from a first point in said formation comprising means for moving the fluid level along the wall of the borehole past said first point, radioactive means positioned at a known location in the borehole for measuring the rate of change of the fluid level at said known location, and means for moving said measuring means to a plurality of other known locations above and below said first point.

13. Apparatus for providing a productivity profile log of a subsurface formation traversed by a borehole containing a liquid comprising an expansion packer, means for seating said packer at a known depth in the borehole to separate one portion thereof from another, means for applying pressure to the wall of the one portion of the borehole to prevent formation liquid from entering into the one portion of the borehole, means for removing the liquid from the one portion of the borehole, means for releasing said pressure to permit the flow of formation liquid into the one portion of the borehole, and means for measuring at the lowest end of the one portion of the borehole the rate of rise of the liquid level of the formation liquid flowing into the one portion of the borehole.

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