

Jan. 25, 1955

E. F. EGAN ET AL
SUBSURFACE EXPLORATION

2,700,734

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2 Sheets-Sheet 1

Fig. 1.

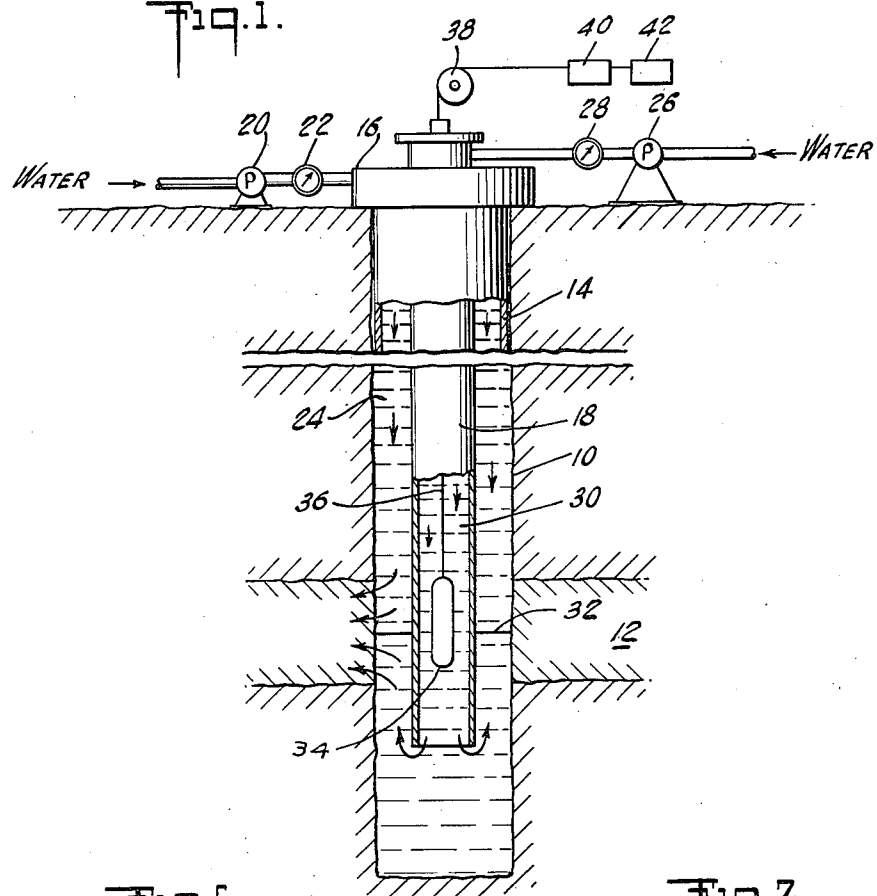


Fig. 6.

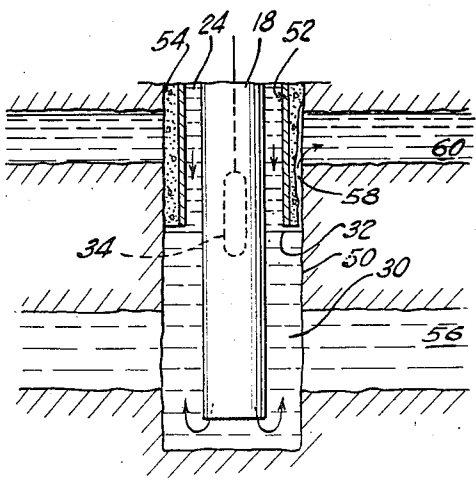
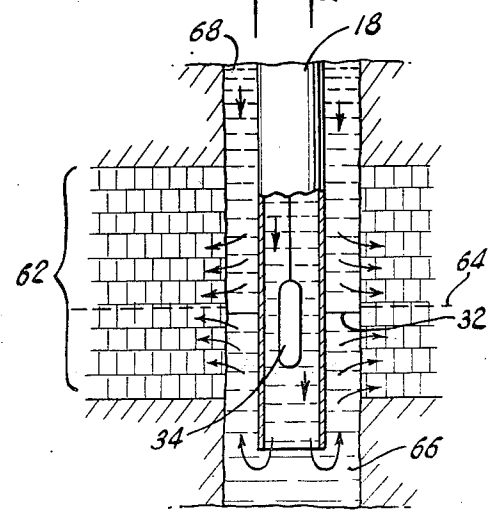


Fig. 7.



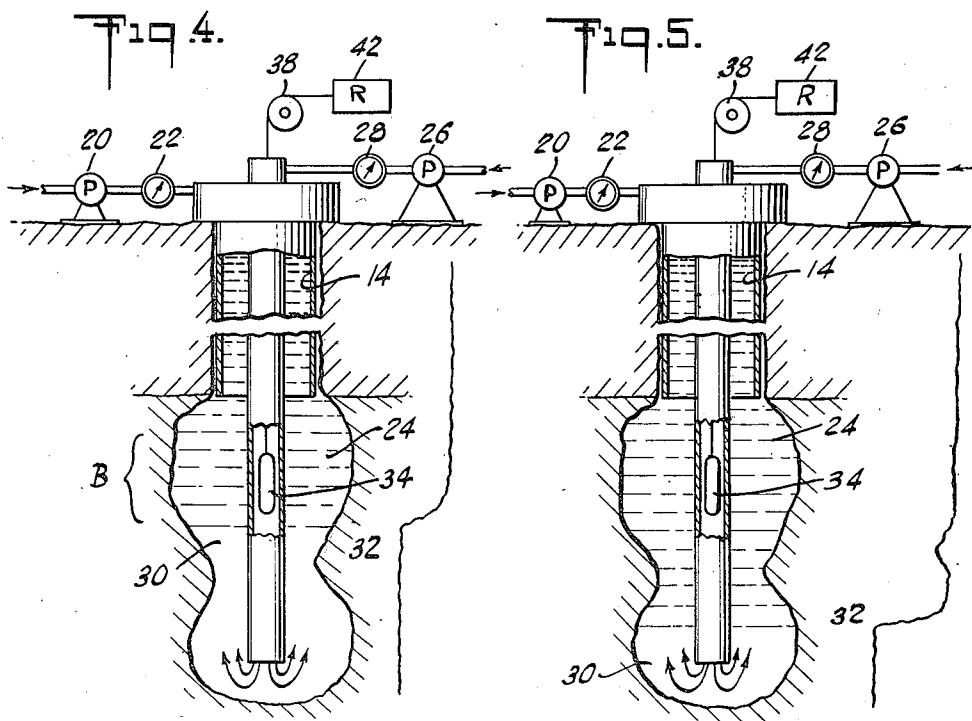
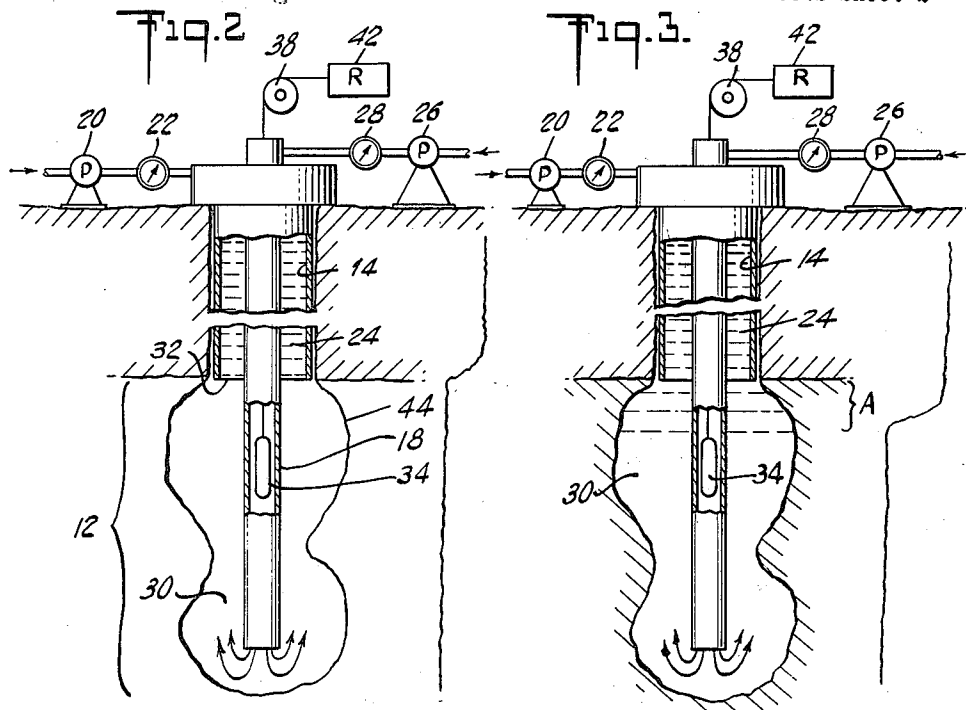
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SUBSURFACE EXPLORATION

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17 Claims. (Cl. 250—43.5)

This invention relates to a method of studying subsurface earth formations and more particularly to a method of measuring the permeability of earth formations traversed by a well or bore hole. The principal purpose of the invention is the provision of a method of this type by means for which accurate measurements can be made and without the use of complicated equipment. This is a continuation-in-part of our application Ser. No. 349,784, filed April 20, 1953, now abandoned for Subsurface Exploration.

One of the objects of the invention is the provision of a method for use in "water injection" wells in which it is desired to know the amount of water passing into various increments of an exposed, more or less permeable formation. This is sometimes referred to as an "injectivity profile" or "permeability log" of a well. It is also contemplated that the method which will be described can be used for locating casing leaks in a well. For instance, it is frequently necessary or at least desirable to determine positively that the injected water is not leaking around the casing shoe and disappearing into a thief zone or formation above the bottom of the casing.

Another object of the invention is to determine the presence of and location of zones of lost circulation in a well.

Still another use of the invention is in connection with selective acidization. Thus, the problem frequently arises of acidizing an oil section located under a gas section in such a way that the acid will be directed substantially entirely into the oil section rather than into the gas section. Again, a similar procedure can be used to acidize an oil section of a formation where the oil section is located directly above a water-containing section.

The importance of secondary recovery or repressuring in oil fields has increased greatly during the last few years, and there is consequently a real need for a better understanding of the engineering aspects of these projects. Detailed studies of reservoir performance under water-flooding conditions can be undertaken only when certain basic data are available, and among the data which is necessary is information concerning the vertical distribution of the injected water in a water injection well. While efforts have been made to obtain data of this kind, no real success has been obtained prior to the development of the method which will be described.

In accordance with this invention as it is applied to the making of an injection profile of a formation into which water is to be injected, two streams of fluid such as water are pumped into the well, one stream through a string of tubing extending downwardly below the formation and the other stream downwardly through the annular spaces between the tubing and the casing or the walls of the hole. The streams are pumped simultaneously but separately, and each stream is carefully metered at the surface. The water pumped down through the tubing will, of course, flow upwardly around the tubing until it meets the water pumped downwardly around the tubing and an interface will exist between the two streams or bodies of water. A small amount of a tracer material such as a radioactive substance is added to the water being pumped down the annular space around the tubing so that all of this water will be radioactive, while the water pumped down through the tubing will be non-radioactive. In order to locate the interface, a radioactivity detector is passed through the tubing, its depth being recorded continuously, and from the record of the output of the detector the depth of the interface can be ascertained, since

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the response of the detector will change more or less suddenly when the detector passes from the radioactive water into the non-radioactive water, or vice versa.

The rates of injection or pumping of the two streams can be varied by means of the pumps at the surface, the rates being adjusted so that at all times the sum of the rates remains constant. By increasing the ratio of the amount to the radioactive water pumped to the amount of non-radioactive water pumped, the interface will be forced downwardly through the well past the exposed walls of the formation or zone to be examined. The rates of injection of the two streams are varied by increments, and the interface will, therefore, move downwardly by steps, the vertical length of these steps depending upon the permeability of the formation. After each adjustment or change in rates of injection, the radiation detector is passed through the well and a record made of the depth of the interface after such adjustment. In this manner an injectivity profile is made of the formation to be examined, and this record will show clearly variations in the permeability of all of the sections or portions of the formation. As will be explained hereinafter, a generally similar procedure can be used for locating leaks behind the casing, zones of lost circulation, the depth at which acidizing of the formations will be most beneficial, etc.

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

Fig. 1 is a vertical, sectional elevation through a well showing the apparatus necessary for making a water injection profile;

Figs. 2, 3, 4, and 5 are vertical sections through a well showing diagrammatically the downward progress of the interface between the radioactive and the non-radioactive liquids and the radioactivity logs obtained for four positions of the interface;

Fig. 6 is a vertical sectional elevation through a portion of the well in which it is desired to determine whether or not water is being injected into a desired formation below the casing or whether it is leaking upwardly around the casing into a thief zone; and

Fig. 7 is another vertical, sectional elevation through a portion of a well in which it is desired to force acid into part but not all of a single formation.

Referring to the drawing, a well or bore hole 10 is shown as traversing several subsurface formations, including the formation 12, for which it is desired to make a water injection profile. The upper portion of the well is shown as being provided with a casing 14 having a closed casing head 16. A string of tubing 18 passes through the casing head 16 and downwardly through the well to a point below the formation 12. At the surface a pump 20 is connected to the casing head through a meter 22 and is adapted to pump a stream of water 24 downwardly into the well through the space between the casing 14 and the tubing 18. A small amount of radioactive material such, for example, as radioactive iodine in the form of sodium iodide is added to the water 24 by means not shown, preferably before the water is taken into the pump 20. Another pump 26 is shown as connected through meter 28 to the upper end of the tubing 18 and is adapted to pump non-radioactive water 30 downwardly through the tubing. The non-radioactive water passes out of the bottom end of the tubing and upwardly around the tubing until it meets the radioactive water 24 at the interface 32. It will be seen that if the pumps 20 and 26 are adjusted to change their rates of pumping while the total amount of water pumped by both pumps remains constant, the interface 32 will be caused to move up or down in the hole, depending upon the two pumping rates.

Shown as suspended within the tubing 18 is a radioactivity logging instrument 34 containing a detector of gamma rays, the output of which is conducted upwardly through the suspending cable 36. This cable passes over a suitable cable-measuring device 38 which continuously indicates the depth of instrument 34 in the hole, and then to a suitable amplifier 40 and a recorder 42. When the instrument 34 is lowered down through the tubing, it will, of course, respond to the radioactivity of the water until it passes the interface 32 when the detector output will suddenly decrease. A record of the output

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of the detector is made continuously by a recorder 42, and this is correlated with the depth of the detector in the hole as measured by the device 38. Thus, by passing the detector 34 through the hole and comparing points in the record at which the detector passes from the radioactive fluid with the depth in the hole at which those points are registered, an accurate measurement is made of the depth of the interface 32.

Referring now to Figs. 2 through 5 of the drawing, it will be seen that as the ratio of the injection rates of the radioactive fluid 24 and the non-radioactive fluid 30 are changed, the interface 32 between the fluids will move along the formation to be examined, as has been explained above. The sum of the rates of injection of radioactive water 24 and non-radioactive water 30 is held constant and for purposes of illustration we will assume that the two streams are being pumped into the well at the total rate of 20 gallons per minute. The rates of the two streams delivered by the pumps 20 and 26 are first adjusted so that non-radioactive water is injected in the tubing at the total injection rate of 20 gallons per minute. After a short period of time, any radioactive water opposite the permeable section 12, indicated in Figs. 2-5 as containing the cavity 44, will be replaced by the non-radioactive water 30 being injected through the tubing. A radioactive log is then run or, in other words, the radiation detector 34 is passed downwardly through the tubing 18. This situation is illustrated in Fig. 2, and it will be observed that the interface 32 is located at substantially the top of the permeable formation. At this time, of course, none of the radioactive fluid 24 is entering the formation since the interface is still at the top of the cavity. As the ratio of radioactive water 24 to non-radioactive water 30 is increased, the interface will move down exposing more of the permeable zone 12 to the injection of radioactive water. The ratio of radioactive water to non-radioactive water is changed by increments, and the location of the interface is found at the end of each increment by passing the radiation detector through the well, as described above.

Fig. 3 illustrates this movement of the interface by changing the injection rates to 5 gallons per minute of radioactive water and 15 gallons per minute of non-radioactive water. The zone located between the interfaces, or rather the two positions of the interface 32 shown in Figs. 2 and 3 and indicated by the bracket A in Fig. 3, is taking water at the rate of 5 gallons per minute, or 25 per cent of the total injected water. Fig. 4 illustrates the additional movement of the interface by changing the injection rates to 9 gallons per minute of radioactive water in the casing and 11 gallons per minute of non-radioactive water in the tubing. This is indicated roughly by the bracket B in Fig. 4. The zone B is, therefore, taking water at the rate of 4 gallons per minute (9 G. P. M.-5 G. P. M.), or 20 per cent of the total injected water. Fig. 5 illustrates the position of the interface with injection rates of 19 gallons per minute of radioactive water in the casing and one gallon per minute of non-radioactive water in the tubing.

Referring again to Fig. 1, it will be understood that the zone, or formation 12 illustrated in that figure, corresponds to the zone indicated by the bracket 12 in Fig. 2.

The method which has been described so far has several advantages over other injectivity profiling systems. For example, the detecting instrument 34 is run in the tubing 18, and this results in an undisturbed interface which, of course, is highly desirable. There is also less danger of the instrument becoming stuck than if it were run through the space between the tubing and the walls of the hole. Again, with the method which has been described, the two injection waters can be, and preferably are, chemically identical since the small amount of radioactive material will not change the chemical behavior of the water 24. This is an important consideration, particularly if the formation contains clay which may swell when contacted by fresh water. The two fluids being injected are completely miscible so there will be no relative permeability effects to take into consideration.

The system which has been described can be used in open hole, as is shown in the drawings, or in a cased hole where the casing has been perforated. Again, with this method, it is not necessary to take into account vari-

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ations in the bore hole diameter, such as is required in some of the other systems. While in the method which has been described the ratios of the injected water have been described as being varied as much as 5 gallons per minute at a time, it is to be understood that very small depth increments can be used, inasmuch as the lower limit of the increments is determined only by the resolving power of the surface pumps and meters. If desired, with one survey of the type which has been described, one may obtain an injectivity profile of the zone being flooded, check the casing for leaks, and evaluate almost any kind of remedial work which has been performed on the well.

Radioactive iodine in the form of sodium iodide has been found to be a very satisfactory tracer material. Due to the extensive use of this compound by the medical profession, its cost has been reduced to a point where it is relatively inexpensive. Again, the half life of 8 days makes it very satisfactory from the health-hazard viewpoint. One of the most desirable features of this material is the fact that the non-metallic iodine, which is the radioactive atom of the compound, has no tendency to replace any metallic ion which might be present in shaley material on the well bore face. This feature enables the operator to make repeat runs since the radioactivity can be removed from the well bore simply by introducing non-radioactive water.

While two streams of water, or at least a liquid, has been described as the material to be injected into the formation, the permeability of which it is desired to ascertain, it is also contemplated that gas can be used. There are, of course, many wells in which it is desired to inject gas into one or more formations for the purposes of repressuring, or the like. Iodine can be dissolved in methane gas and elemental iodine 131 is available, as are several iodine 131 compounds. From economic, half life, chemical, and ease in handling considerations, iodine would be a very satisfactory tracer material to be used in the gas which would be pumped down through the annular space between the tubing and casing, or the walls of the hole.

As was stated hereinbefore, the method substantially as it has been described in connection with injectivity profiling can also be used for other purposes, for example, locating casing leaks. Fig. 6 of the drawing illustrates a section of open hole 50 above which a casing 52 has been set and cemented as indicated at 54. The lower portion of the hole passes through a permeable formation or zone 56 which it is desired to use for injectivity purposes. It is not infrequent that when the casing is cemented, voids such as indicated at 58 may occur in the cement, thus permitting fluid to leak upwardly around the cement and disappear into another permeable formation 60 which is sometimes referred to as a "thief" zone. The presence of such a leak can be ascertained by means of the method which has been described. Thus, it may be found that when the rates of injection are changed so as to increase the rate of injection of the radioactive fluid 24 between the tubing and the casing as compared to the rate of injecting the non-radioactive fluid 30 through the tubing 18, the interface 32 will not move downwardly toward the formation 56, but will remain just below the lower end of the casing as is shown in Fig. 6. The position of the interface will be located, of course, as has been described, by passing a radiation detecting instrument 34 through the string of tubing. The fact that the interface 32 remains just below the bottom of the casing indicates, of course, that the radioactive water 24 is leaking upwardly past the cement into the "thief" zone 60. Remedial steps can be taken to correct this situation, such as by recementing the casing.

If it should be found, as has been described above, that fluid is leaking around the bottom of the casing into a thief zone or zones, it may be desired to locate the position of the thief zone so that steps can be taken to seal it off as by cementing or by the use of some other suitable plugging material. The radioactive liquid in flowing upward through void 58 in the cement and then into one or more thief zones 60 will, of course, produce an artificial radioactivity in these zones. By moving the radiation detecting instrument 34 through the lower portion of the casing, either during or after the time the radioactive liquid is flowing into the zone, the depth and thicknesses of the thief zone, or zone 60, can be readily ascertained since the detecting instrument will provide

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an increased response when horizontally opposite a thief zone. After the zone has been located, steps can be taken as mentioned above, to seal off the zone. Thus, the casing 52 can be perforated either opposite or below the thief zone and cement or other plugging material forced outwardly through the perforations to plug the thief zone. The information as to the thickness of the thief zone, determined as has been described, will also be useful as an indication of the amount of cement or plugging material which will be required.

The method which has been described for injectivity profiling can also be used to locate a zone of "lost circulation" in a well. It frequently happens that a very porous formation exists somewhere along the well, and these formations are often so porous that the drilling mud, which normally recirculates upwardly around the tubing, actually disappears in this zone. It is, of course, necessary then to locate the zone and to treat the exposed face of the formation in some manner, as by cementing, so as to prevent this loss of the drilling fluid. It is believed to be obvious that by using the described method and forcing the interface downwardly while measuring its depth, a point will be found where the interface ceases to fall even with an increased pumping rate of radioactive fluid. This would indicate that, as fast as the radioactive fluid is pumped into the annular space between the tubing and the bore hole wall, it passes outwardly into the zone of "lost circulation."

It is also possible to use the method, which has been described, in selective acidization, i. e., where it is desired to inject acid into a particular section of a formation. Thus, Fig. 7 illustrates a well penetrating a formation 62 which is made up of several sections of varying permeabilities and the lower portion of which, below the dotted line 64, is an oil section, while that portion above the line is a gas section. In such a situation, it is usually desired to force the acid into the oil section rather than into the gas section, and the method described can be used to position an interface 32 at a point opposite the gas-oil contact plane 64. In this case, the acid would be the liquid pumped downwardly through the tubing 18 as shown at 66, and the liquid pumped downwardly around the tubing would preferably be an oil such as is indicated at 68. As in the previous examples, a radiation detector 34 would be passed through the tubing to locate the interface 32 and the pumping rates would be adjusted to maintain the interface at this position so that the acid 66 would enter the oil, or lower portion of the formation.

It is also believed obvious that the same method can be used in a situation where an oil section overlies a water section, and it is desired to force the acid into the oil portion of the formation. In this case, the acid would be pumped down around the tubing and could be made radioactive. The liquid pumped through the tubing would be non-radioactive oil or water.

Although in the description of the method which has been given it has been stated that the interface 32 is moved downwardly in increments along the walls of the formation 12, it is to be understood that the permeability log of the formation can be made upwardly as well as downwardly. Thus, the interface 32 can be positioned first at or just below the lower boundary of the formation 12 and then the pumping rates of the two liquids changed by decreasing the rate of pumping at 20 and increasing the rate at 26 by the same amount, of course, so that the interface 32 will move upwardly to a new position along the wall of the formation. This new position or depth of the interface will then be found, as has been described, by moving the instrument 34 through the tubing and these operations may be repeated until the interface has reached a point above the upper boundary of the formation 12. The resulting log obtained in this manner will be the same as a log obtained by moving the interface downwardly.

Although the radioactive liquid 24 has been described as being pumped down through the annular space between the tubing and the walls of the hole and the non-radioactive liquid 30 through the tubing, it is to be understood that the paths of these liquids can be reversed, i. e., the radioactive liquid can be pumped down through the tubing and the non-radioactive liquid through the annulus without affecting the process.

While one application of this method has been described with reference to the forcing of acid into a for-

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mation, it is to be understood that, if desired, almost any material can be placed in a similar manner. For example, a material such as a plastic or other substance which will affect the permeability of the formation in some manner as by changing the surface tension, plugging pores of the formation, etc., can be pumped into a formation or portion thereof so as to increase or decrease the permeability, if desired. Again, such a substance might be placed in the manner described, which substance would be capable of affecting the producing characteristics of a formation in other ways. For example, the selective placement of a suitable plastic material could be used to consolidate the producing sands in order to prevent the production, i. e., the flowing of sand into the well with the oil.

Although the apparatus illustrated in Fig. 1 shows the use of two pumps, one to pump the radioactive liquid and the other to pump the non-radioactive liquid, it is to be understood that a single pump can be utilized, the output stream from the pump being divided by a suitable arrangement of piping and valves and each divided stream being provided with a suitable meter such as 22 or 28. The radioactive material or tracer can, of course, be injected into the desired one of the streams.

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

We claim:

1. The method of making a permeability log of a subsurface formation traversed by a bore hole which comprises pumping a fluid into said bore hole above said formation, said fluid containing a small amount of a radioactive substance, simultaneously pumping a similar but non-radioactive fluid into said bore hole below said formation, thereby establishing an interface between said fluids, determining the depth in the hole of said interface by measuring the radioactivity of the fluid content throughout that portion of the hole being examined, varying the ratio of the two fluids being pumped into the hole while maintaining constant the sum of the two fluids so as to cause said interface to move along the walls of said formation to another depth, again determining the depth of the interface by making another radiation measurement of the contents of the hole, and repeating these operations while noting the ratios of the two fluids being pumped for each measured depth of the interface in the hole.

2. The method of making a permeability log of a subsurface formation traversed by a bore hole which comprises injecting a liquid into said bore hole above said formation, said liquid containing a small amount of a radioactive substance, simultaneously injecting a similar but non-radioactive liquid into said bore hole below said formation, thereby establishing an interface between said liquids, determining the depth in the hole of said interface by measuring the radioactivity of the liquid content throughout that portion of the hole being examined, varying the ratio of the amounts of the two liquids being injected in the hole so as to position said interface substantially opposite the top of said formation, again changing the ratio of the amounts of the two liquids being injected while maintaining constant the sum of the two liquids so as to cause said interface to move along the walls of said formation to another depth, determining again the depth of the interface by making another radiation measurement of the contents of the hole, and repeating these operations while noting the ratios of the two liquids being injected for each measured depth of the interface in the hole.

3. In the method described in claim 1 in which the subsurface formation to be examined is below the bottom of a string of casing in the hole, the additional steps comprising: increasing the rate of injection of the liquid injected into the bore hole above said formation until the interface moves downwardly out of the bottom of said casing, and locating the depth of the interface below the casing while increasing further the rate of injection of the liquid injected above said formation with respect to the rate of injection of the liquid below the formation, an indication that the interface remains substantially fixed just below the bottom of the casing during said further increase in the rate of injection of the liquid above said formation serving to show that there is a leak into another formation somewhere above the bottom of the casing.

4. The method described in claim 2 in which the interface is lowered by increments through the bore hole to determine the presence and location of zones of "lost circulation," an indication that the interface remains substantially stationary in the hole while the ratio of injected radioactive liquid to injected non-radioactive liquid is increased serving to show that all of the radioactive liquid is passing into a very permeable formation, i. e., a zone of lost circulation.

5. The method described in claim 2, in which acid is to be injected into the oil-containing portion of a gas- and oil-bearing formation and in which the non-radioactive liquid is an acid, the rates of injection of the radioactive liquid and the acid being adjusted so as to maintain the radioactive liquid-acid interface below the boundary between the gas-containing and oil-containing portions of the formation.

6. The method described in claim 5 in which the formation comprises an oil-containing portion above and in contact with a water-containing portion in which the radioactive liquid is an acid and the non-radioactive liquid is water, the interface being maintained below the boundary between the oil-containing and water-containing portions of the formation.

7. The method of making a permeability log of a subsurface formation traversed by a bore hole containing a tubing extending down below said formation which comprises pumping a liquid into the annular space between the tubing and the walls of the hole, said liquid containing a small amount of radioactive substance, simultaneously pumping a similar but non-radioactive fluid into said bore hole below said formation through said tubing, thereby establishing an interface between said liquids, determining the depth in the hole of said interface by measuring the radioactivity of the liquid content throughout that portion of the hole being examined, varying the ratio of the two liquids being pumped into the hole while maintaining constant the sum of the two liquids so as to cause said interface to move along the walls of said formation to another depth, determining again the depth of the interface by making another radiation measurement of the contents of the hole, and repeating these operations while noting the ratios of the two liquids being pumped for each measured depth of the interface in the hole.

8. The method as described in claim 7 in which the pumping rates are adjusted first to position the interface substantially opposite the bottom of the formation, then adjusted by increments to move the interface upwardly along the formation walls, the position of the interface being determined after each increment.

9. The method as described in claim 7 in which the radioactive liquid is pumped down through the tubing while the non-radioactive liquid is pumped into the annular space between the tubing and the walls of the hole.

10. The method as described in claim 8 in which the radioactive liquid is pumped down through the tubing while the non-radioactive liquid is pumped into the annular space between the tubing and the walls of the hole.

11. The method as described in claim 7 in which a radioactive gas rather than a liquid is pumped into the annular space between the tubing and the walls of the hole while a non-radioactive gas rather than a liquid is pumped down through the tubing.

12. The method as described in claim 7 in which a material capable of affecting the permeability of the formation is to be injected into a portion of said formation and in which one of said liquids contains said material, the rates of pumping the liquid containing said material and the other liquid being adjusted so as to maintain the interface at a position opposite the wall of the formation so that the liquid containing said material will enter said portion of the formation.

13. The method as described in claim 7, in which a material capable of affecting the producing characteristics of a formation is to be injected into a desired portion of the formation and in which one of said liquids contains said material, the pumping rates of the two liquids being adjusted so as to maintain the interface at a position opposite the wall of the formation so that the liquid containing said material will enter said desired portion of the formation.

14. The method as described in claim 3 in which, after it has been found that the liquid is leaking into another formation above the bottom of the casing, the position and thickness of that other formation are determined by measuring the radiation entering the hole from the formations above the bottom of the casing, an increase in the intensity of the radiation from any particular zone indicating that that zone corresponds to the formation into which the liquid is leaking.

15. The method of making a log in a bore hole which comprises pumping a fluid into said bore hole in a downward direction, simultaneously pumping another fluid through said bore hole in an upward direction so as to establish an interface between said fluids, determining the depth in the hole of said interface, varying the ratio of the rates of the two fluids being pumped into the hole while maintaining constant the sum of the rates of the two fluids so as to cause said interface to move along the wall of said bore hole to another depth, again determining the depth of the interface, and repeating these operations while noting the distance moved by the interface for each change in the ratio of the rates of the two fluids being pumped into the bore hole.

16. The method of making a permeability log of a predetermined zone of a bore hole which comprises pumping a fluid into said bore hole above said zone, simultaneously pumping another fluid into said bore hole below said zone, thereby establishing an interface between said fluids, determining the depth in the hole of said interface, varying the ratio of the rates of the two fluids being pumped into the hole while maintaining constant the sum of the rates of the two fluids so as to cause said interface to move along the wall of said zone to another depth, again determining the depth of the interface, and repeating these operations while noting the distance moved by the interface for each change in the ratio of the rates of the two fluids being pumped into the bore hole.

17. The method as described in claim 16 in which one of said fluids contains a tracer material.

References Cited in the file of this patent

UNITED STATES PATENTS

2,450,265	Wolf	Sept. 28, 1948
2,648,014	Arthur	Aug. 4, 1953