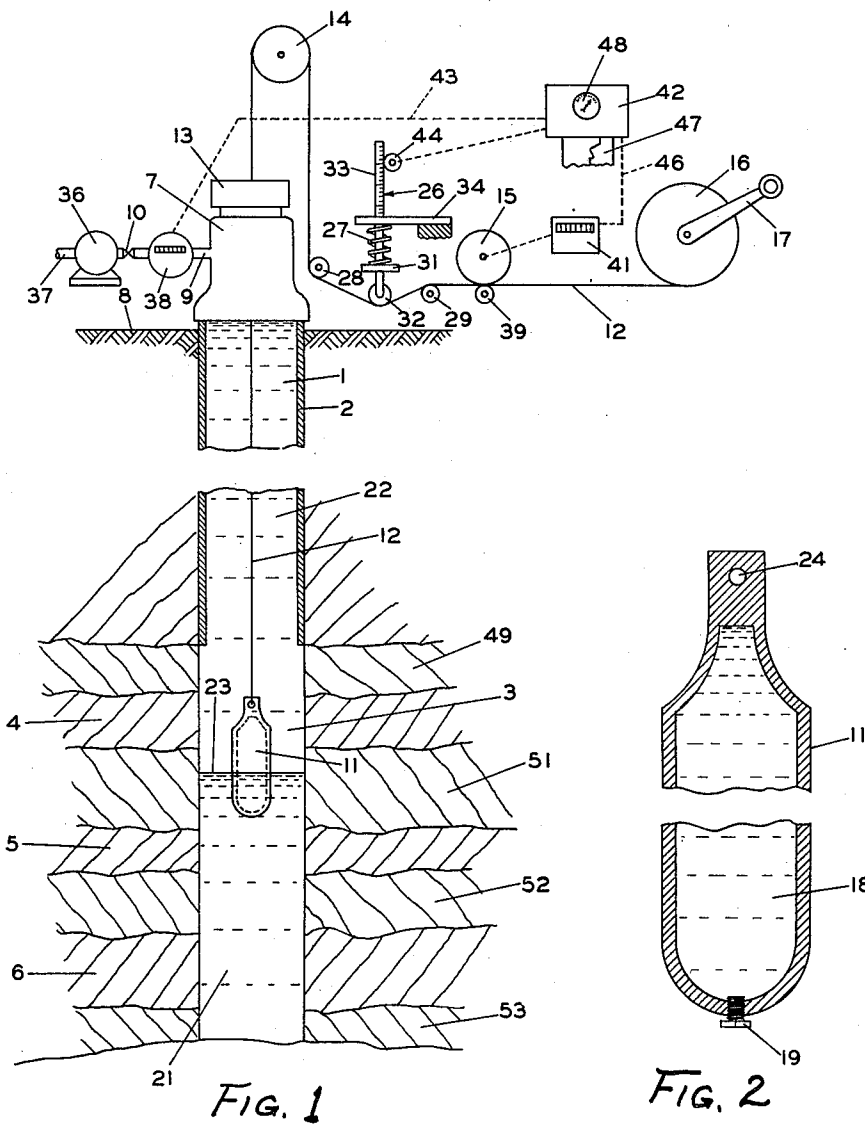


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 APPARATUS FOR AND METHOD OF DETERMINING PERMEABILITY
 OF EARTH FORMATIONS PENETRATED BY WELL BORES
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APPARATUS FOR AND METHOD OF DETERMINING PERMEABILITY OF EARTH FORMATIONS PENETRATED BY WELL BORES

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9 Claims. (Cl. 73-152)

1 The invention relates to a method of determining the permeability of formations penetrated by the bore of a well. It more particularly concerns an improved method of ascertaining the elevation and permeability of formations penetrated by a well by determining the rate at which a given fluid can be made to enter fluid receptive portions of the formations.

One of the principal uses of the invention is in connection with the chemical treatment of oil wells to increase their production, although it may be used for other purposes. In the chemical treatment of wells in which an acid solution is introduced to attack and render soluble calcareous matter in the contiguous productive portion of the formations, it is desirable to know the relative fluid permeability of the portions involved in order that the treating agent may be introduced into that portion the permeability of which is relatively low and, therefore, desirable to chemically treat. In many other instances, such as for example, the use of water flood to drive oil from the formation between an input well and an output well, cementing operations, well completions, and formation testing, it is similarly desirable to obtain knowledge relative to the permeability of the various strata or portions thereof penetrated by the bore of a well.

One of the principal objects of the invention is to provide a method whereby the permeability to fluids of a formation penetrated by the bore of a well may be determined readily.

Another object is to provide a method whereby the relative permeability of a plurality of permeable sections can be ascertained together with their elevations in the well bore so as to provide a complete permeability profile of the well.

Another object is to provide means for accomplishing this method without the use of electrical circuits which are troublesome and often inaccurate or dangerous.

Other objects and advantages will appear as the description proceeds.

In accordance with my invention, I introduce into the well a first liquid in amount sufficient to cover the formations, the permeability of which is to be determined, and then a second liquid of lower density than, and immiscible with, the first liquid so as to form two liquid columns meeting at an interface in the well bore, the interface initially being above the formations the permeability and elevation of which are to be determined. The interface is then caused to move downwardly by introducing more second liquid at a known and preferably constant rate. The

2 elevation of the interface is determined from time to time as it descends in the well and the interval of time elapsing between each such determinations is recorded. The rate of descent at any elevation of the interface is then determined from the distance traversed by the interface and the time elapsed. The rate of descent of the interface is governed by the rate at which the first liquid escapes into the permeable portions of the formation below the interface under the pressure employed (so long as the well bore is of substantially constant cross-section). The rate of descent of the interface decreases as the interface traverses from one formation to the next below receiving first liquid at a rate differing from the rate at which the preceding formation receives first liquid, if any. The difference in these rates of descent is used in accordance with the invention as a measure of the relative permeability of the portion of the formation traversed by the interface as its rate of descent changes.

The invention then consists in the method hereinafter fully described and particularly pointed out in the claims, the accompanying drawing and following description, setting forth a mode of carrying out the invention in a well penetrating three permeable strata, such mode illustrating, however, but one of the various ways in which the invention may be carried out.

In the drawings—

Figure 1 is a diagrammatic view partly in section showing a well penetrating three fluid permeable strata and equipped with apparatus for carrying out permeability determinations according to the method of the invention.

Figure 2 is a detailed view in cross-section of a portion of the apparatus shown in Figure 1.

As shown in Figure 1, the upper portion 1 of the well bore is cased with metal pipe 2 while the lower uncased portion 3 of the well passes through permeable strata 4, 5, and 6, respectively, the relative permeabilities of which are to be determined. Removably attached to the casing is a head 7 above the ground level 8, the head being provided with an inlet 9 and inlet valve 10. Within the well is shown an interfacial float 11 suspended by the wire line or cable 12 which runs through a stuffing box 13 over pulley 14 through a cable length meter 15 onto a reel 16 provided with a crank 17.

There are no conductors in cable 12, although it may be conductive. No electrical apparatus with all its attendant inaccuracy and breakage is needed at all.

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In the more detailed view of the interface locator 11, shown in Figure 2, the hollow body 11 may be filled with a liquid 18 through plug 19 to prevent collapse under hydrostatic pressure in a deep well. Liquid 18 is chosen so that float 11 has an average density (metal body 11 being somewhat high in density and liquid 18 low in density) between the densities of heavy liquid 21 and light liquid 22 so that float 11 will float at the interface 23 between 21 and 22. Body 11 has any suitable attaching means, such as hole 24 for connection to line 12.

It is not obvious that float 11 will continue to float at the interface 23 when a long length of cable 12 is payed out, but I have found that by careful observation of line 12 that even with thousands of feet of cable payed out (when interface 23 is at a corresponding depth), that sufficient buoyancy changes exist when float 11 contacts interface 23 to be noted at the surface. With a skilled operator of reel 16, no instruments are needed, as he can "feel" interface 23 by the reel operation. To make this measurement easy for unskilled operators however, I prefer to use instruments that anyone can read and understand.

Cable 12 passes over pulley 14 and then through a scale generally designated as 26. This scale may be constructed with weights (not shown) or with hydraulic pistons and hydraulic pressure (not shown), but I prefer to use a simple spring 27 urging line 12 out of line between pulleys 28 and 29 by pushing on plate 31 and pulley 32. The movement of 26 could be increased by pantographs (not shown) but can be read by a simple scale 33 on the rod 26 with relation to pointer 34.

Obviously in paying out line as long as 11 is in a single fluid the weight, as measured by tension in cable 12 at 33, will increase steadily, but when buoyancy is added upon contact of float 11 with interface 23 and heavy liquid 21, then the sudden, even if small, decrease in weight will be noted at 33.

Many refinements can be added without departing from the spirit and scope of my invention, all without detracting from the simplicity inherent in not having any electrical cable in the well 1. Electrical cables in wells are subject to breakage, shorting out and attack by salt water, corrosion, oil damage to the insulation, and necessitate slip rings and other apparatus so that the whole system is subject to inaccuracies which cannot be accounted for, nor evaluated, which results in uncertainty and inaccurate surveys. My weight method is positive and foolproof.

A pump 36 can be added to force the liquids 21 and 22 in from line 37 which may lead to separate stock tanks and valves of any type, and the amount of liquid may be metered at 38 by a simple water meter totalizer, or by any recording rate meter desired. The length of line may be measured at 15, a friction wheel 39 aiding, and totalized or recorded as a rate at recorder 41. I prefer to keep the apparatus simple, and would prefer to use a counter at 41, but recognize the value of complete mechanization whenever costs justify the same. In this respect meter 38, scale 33 and depth recorder 41 can all be connected to an automatic recorder and indicator 42 by suitable connections 43, 44 and 46 all old in the art of recorders. Instrument 42 provides an automatic log of the permeability of formations 4, 5, 6 and all other formations 49, 51, 52 and 53 in the form of a record strip 47

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and also an instantaneous indication of the permeability of the formation being passed at the moment on dial 48.

The present expense of 42 is such that all usual operations are conducted at present without parts 42, 43, 44, 46, 47 and 48, but simplification may reduce the price of 42 to make it available, and it is operative in the combination as shown.

In carrying out the method of the invention wherein, for example, it is desired to ascertain the relative permeability of the three strata penetrated by the uncased portion 3 of the well bore, the interface locator 11 is positioned initially at any point above the uppermost permeable stratum 4. Thereafter, a first liquid, as a heavy liquid, such as a saline solution, is introduced into the well through the valve 10 and pipe 9. In order to make certain that a sufficient depth of first liquid has been introduced into the well, it may be filled up or to slightly beyond the casing seat, however, this is usually not necessary as the well drilling log may be relied upon when available to indicate the approximate depth of the shallowest permeable portion of the formation, and it is sufficient for the purpose if this be covered with first liquid before introducing the second liquid.

After the first liquid has been introduced into the well to a suitable depth, a second liquid, such as a light liquid, e. g., oil, which is immiscible with, and of lower specific gravity than, the first liquid is introduced into the well through valve 10 and pipe 9 so as to form two columns which meet at the interface 23 above the formations to be measured. Sufficient pressure of second liquid is built up so as to cause the interface to descend in the bore, such descent being indicated by the increased deflection of scale 26 corresponding to the loss of contact and buoyancy between the heavy liquid and the float 11 as the first liquid descends below the float. The interface locator then is lowered by unwinding cable from the reel 16 at a rate such that it again makes contact with the first liquid. If the interface locator is lowered too rapidly, this will be indicated, or if lowered too slowly, the deflection of the scale will increase and it loses contact with first liquid. Accordingly, the proper rate of lowering of the interface locator can be ascertained and is adjusted so as to maintain the upper part of 11 in the light liquid and the lower part in the heavy liquid. While the rate of lowering of the interface locator is thus regulated to keep pace with the descending interface and liquid is introduced at a substantially constant rate into the well so as to cause the interface to descend under known and controlled conditions, its rate of descent and position are ascertained as by periodic observations of the length of conductor cable 12 payed out and measured by the cable meter 15 while the time elapsing as the interface locator descends to the observed depth is recorded. From the depth of the interface locator thus periodically obtained and the time elapsing in the descending to the observed depth, the relative permeability of the formations traversed by the interface is computed as described in what follows.

In proceeding with the permeability determination, in accordance with the data obtained by the foregoing method, it is convenient to make a plot of the depth of the interface locator, which is taken as the depth of the interface, and correlate this with the time elapsing from

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the beginning of the downward movement of the interface brought about by the introduction into the well of the second, or lighter liquid, at the known rate. From this plot, the rate of descent is computed and plotted against the depth and then the relative permeability is derived, this being plotted to give a complete permeability profile of the well.

In the example chosen, the well bore involved had a uniform diameter of 4.75 inches and, therefore, a liquid volume of 0.924 gallon per foot of depth. After filling with first liquid to a depth of 4890 feet (a point well above the uppermost permeable stratum, e. g., 4, Figure 1) and positioning the interface locator so that it contacted the first liquid, second liquid was introduced into the bore at the rate of 5.54 gallons per minute. The interface was thereby caused to descend in the well hole past the permeable strata 4, 5, and 6 in succession and the time and distance travelled by the interface followed by the interface locator as described. The interface locator descended from 4890 feet to 4980 feet in the first 15 minutes, from 4980 feet to 5010 feet depth in the next 10 minutes, and then from 5010 feet to 5015 feet in the next 20 minutes, these data being plotted. From these data, the rate of descent of the interface in feet per minute was computed and plotted. This graph shows that the interface descended at first at a constant rate of 6 feet per minute which rate corresponded to the computed rate of filling the bore with second liquid, and therefore, no permeable stratum was encountered until the interface reached the depth of 4980 feet at which the rate of descent changed to 3 feet per minute. The rate then remained constant until the depth of 5010 feet was reached at which the rate again changed to the new value of 0.25 foot per minute and thereafter became zero at 5015 feet.

From these rates of descent, the relative permeabilities of the three strata traversed by the interface of its rate of descent changed were computed and plotted. The first change in rate of descent corresponded to decrease of 3 feet per minute indicating that first liquid was entering stratum 4 (4980 feet) at a rate corresponding to $3 \times 0.924 (=2.77)$ gallons per minute, and this is the relative permeability of stratum 4. Similarly, at stratum 5 where the rate of descent changed from 3 to 0.25 feet per minute, $2.75 \times 0.924 (=2.54)$ gallons per minute of first liquid entered stratum 5 and is plotted as the relative permeability of that stratum. Again at stratum 6 where the rate changed from 0.25 to 0, $0.25 \times 0.924 (=0.23)$ gallon per minute entered stratum 6 and represents its relative permeability.

While the method has been illustrated with an example of the usual type of well encountered in practice, it is to be understood that the method may be used with other types of wells penetrating different formations in which other factors besides permeability may affect the rate of descent of the interface, such as variations in bore hole diameter, variations in the pressure applied to the second liquid to cause the first liquid to enter the permeable portions of the well, and differences in the fluidity characteristics of the first and second liquids. In the above example, these disturbing factors were not involved but even when such factors are involved their effects can be predicted and taken into consideration thereby permitting the method wide application under a wide range of well

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conditions. For example, the effect on the rate of descent of the interface of variations in bore hole cross-section can be compensated for and such variations usually reveal themselves in the course of operation of the method by exerting a characteristic slowing or speeding of the descent of the interface, the effect persisting for only so long as the interface traverses from one cross-sectional area to another. Enlargements of the bore hole, for example, reduce the rate of descent in direct proportion to the amount of the enlargement while constrictions operate in directly opposite manner.

The plot of the distance descended by the interface against the elapsed time, when there are such changes in the bore hole cross-section, is merely displaced along the time axis an amount corresponding to the time taken to supply the difference in the amount of liquid involved as the interface traverses that portion of the bore and are easily recognizable as being in general different from changes in the slope of the plot due to the permeability changes being determined. Similarly, pressure effects can be spotted and discounted. For example, the pressure applied, if not maintained constant, can be recorded so that its effect on the rate of descent of the interface can be estimated or distinguished from the effect of permeability. Such distinction can be made on the basis that an increase of pressure gives a proportional increase in the rate of descent of the interface.

Differences in the fluidity characteristics of the two liquids employed do not generally affect the elevations at which the permeable zones are found but may slightly affect the numerical values of the relative permeabilities computed from the rate of descent data when the two liquids have very marked differences in the ease with which they can be forced into strata of equal permeability. By either choosing two immiscible liquids having somewhat similar fluidity characteristics or by compensating for their differences in ease of entering similar formations, their effect on the relative permeability figures is minimized. In any event, any two immiscible liquids which will stratify in the well bore so as to meet at an interface, the depth of which can be measured, may be used to obtain a useful measure of relative permeability of the liquid receptive quality of adjacent formations.

Other modes of applying the principle of my invention may be employed instead of the one explained, change being made as regards the method herein disclosed, provided the steps stated by any of the following claims or equivalent of such steps be employed.

Having described my invention, I claim:

1. In a method of determining the fluid permeability and elevation of earth formations penetrated by a well bore, the steps which comprise introducing into the well a first liquid in amount sufficient to fill the well to a point above the formations to be measured; introducing into the well a second liquid having a lower density than the first and immiscible therewith so as to form two liquid columns meeting at an interface in the well above the formations to be measured; continuing the introduction of the second liquid at a known rate so as to force the first liquid out of the well into the adjacent formations while ascertaining the rate of descent of the interface thereby causing the interface to descend, its rate of descent changing on traversing a fluid permeable portion of the well; and ascertaining the

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elevation of the interface by lowering a float of lower average density than said first liquid and greater average density than said second liquid to the interface between said liquids by a measuring line, and weighing said float and line to determine when said float is at said interface as its rate of descent changes, the change in the rate of descent being a measure of the permeability of the formations at the elevation at which the rate of descent changes.

2. In the method of determining the fluid permeability and elevation of earth formations penetrated by a bore of a well, the steps which consist in filling the bore with a saline liquid to a point above the formations to be measured; introducing into the well at a constant rate an oil so as to form two liquid columns meeting at an interface in the well above the formations to be measured while ascertaining the rate of descent of the interface, the interface falling in the well bore as the first liquid is forced by the second liquid into the adjacent formations to below a fluid permeable portion thereby changing its rate of descent; and ascertaining the elevation of the interface by lowering a float of lower average density than said first liquid and greater average density than said second liquid to the interface between said liquids by a measuring line, and weighing said float and line to determine when said float is at said interface as its rate of descent changes, the change in the rate of descent being a measure of the permeability of the formations at the elevation at which the rate of descent changes.

3. In a method of measuring the elevation and relative permeability of fluid receptive portions of the earth formations penetrated by the bore of a well having a known cross-section, the steps which consist in introducing into the well bore a first liquid in amount sufficient to fill the bore to a point above the fluid receptive portions of the formations to be measured; introducing a second liquid immiscible with the first and having a lower density so as to form two liquid columns meeting at an interface in the well bore above the formations to be measured, the second liquid being introduced at a known rate so as to force the first liquid into fluid receptive portions of adjacent formations below the interface and thereby cause the interface to descend; periodically ascertaining the elevation of the interface by lowering a float of lower average density than said first liquid and greater average density than said second liquid to the interface between said liquids by a measuring line, and weighing said float and line to determine when said float is at said interface and the corresponding time elapsing during the descent thereof at the ascertained elevation, whereby to obtain a descent rate corresponding to each formation traversed by the interface, the difference between any preceding descent rate and the next following being a measure of the fluid permeability of the fluid receptive portion of the formations traversed by the interface as its rate of descent changes.

4. In a method of measuring the elevation and relative permeability of fluid receptive portions of earth formations penetrated by the bore of a well having a substantially uniform cross-section, the steps which consist in introducing into the well bore a first liquid in amount sufficient to fill the bore to a point above the fluid receptive portions of the earth formations to be measured; introducing a second liquid immiscible with

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the first and having a lower density so as to form two liquid columns meeting at an interface in the well bore above the formations to be measured; suspending in the well bore at the interface an interface locating float, introducing said second liquid at a constant rate so as to force said first liquid into fluid receptive portions of the adjacent earth formation below the interface and thereby cause the interface to descend; lowering the interface locating float at a rate such that it remains at the interface, periodically ascertaining the elevation of the interface locating float and the corresponding time elapsing during the descent to said elevation by lowering said locating float, which is a float of lower average density than said first liquid and greater average density than said second liquid to the interface between said liquids by a measuring line, and weighing said float and line to determine when said float is at said interface, whereby to obtain a descent rate corresponding to each formation traversed by the interface, the difference between any preceding descent rate and the next following being a measure of the fluid permeability of the fluid receptive portions of the formations traversed by the interface as its rate of descent changes.

5. In a method of determining the permeability profile of a well bore penetrating a plurality of fluid permeable strata, the steps which consist in filling the bore with a liquid to a point substantially above the shallowest stratum; introducing a second liquid immiscible with the first and of lower specific gravity so as to form a column of the second liquid upon the first liquid meeting at an interface above the shallowest stratum; applying pressure upon the first liquid with the second liquid sufficient to cause the first liquid to flow into the fluid receptive strata below the interface thereby lowering the interface past each such strata in succession at a rate which changes as it traverses a fluid receptive stratum; and ascertaining the difference in the rate of lowering of the interface before and after it traverses each fluid receptive stratum due to escape of first liquid thereinto by lowering a float of lower average density than said first liquid and greater average density than said second liquid to the interface between said liquids by a measuring line, and weighing said float and line to determine when said float is at said interface, said differences being a measure of the relative permeability of each stratum.

6. Apparatus for determining an interface between two immiscible liquids of different densities comprising in combination a float of a density intermediate the density of the two liquids and adapted to assume a position generally corresponding to the interface, a reel, a measuring line wound on said reel and secured to said float, and a scale for weighing the unreeled portion of said float and attached measuring line.

7. In the method of determining the fluid permeability and elevation of earth formations penetrated by a bore or a well, the steps which consist in filling the bore with a saline liquid to a point above the formations to be measured; introducing into the well at a constant rate an oil so as to form two liquid columns meeting at an interface in the well above the formations to be measured while ascertaining the rate of descent of the interface, the interface falling in the well bore as the first liquid is forced by the second liquid into the adjacent formations to below a fluid permeable portion thereby changing its rate of descent;

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and ascertaining the elevation of the interface by lowering a float of lower average density than said first liquid and greater average density than said second liquid to the interface between said liquids by a measuring line, measuring the tension in said line as it is lowered into the well to determine when said float is at said interface, a decrease in tension indicating that the float is positioned in the heavier liquid below the interface, an increase in tension indicating that the float is positioned within the lighter liquid above the interface, and controlling the rate of descent of the float into the bore hole in accordance with such changes in tension of the measuring line to maintain said float continuously at the interface.

8. In a method of measuring the elevation and relative permeability of fluid receptive portions of the earth formations penetrated by the bore of a well having a known cross-section, the steps which consists in introducing into the well bore a first liquid in amount sufficient to fill the bore to a point above the fluid receptive portions of the formations to be measured; introducing a second liquid immiscible with the first and having a lower density so as to form two liquid columns meeting at an interface in the well bore above the formations to be measured, the second liquid being introduced at a known rate so as to force the first liquid into fluid receptive portions of adjacent formations below the interface and thereby cause the interface to descend; periodically ascertaining the elevation of the interface by lowering a float of lower average density than said first liquid and greater average density than said second liquid into the liquid in the bore, determining the tension in said line as the float

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is lowered to determine when said float is at the interface, an increase in tension indicating that the float is positioned in the light liquid above the interface, and a decrease in tension indicating that the float is positioned within the heavy liquid below the interface, and paying out the line upon which the float is suspended in accordance with such changes in tension so as to maintain the float continuously at the interface.

9. Apparatus for continuously determining the location of an interface between two liquids of different densities in a well bore which comprises, in combination, a float having a density intermediate that of said two liquids, a measuring line secured to said float, means for lowering said line and said float into a well bore, and means for determining the tension in said line as it is lowered into the well bore, an increase in tension indicating that the float is positioned in the light liquid above the interface, and a decrease in tension indicating that the float is positioned in the heavy liquid below said interface.

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