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Tracing Fluid Movements with a New Temperature Technique

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ABSTRACT

A new, "a priori" differential temperature survey has been developed, which overcomes the flaws that made earlier systems of little use. Although every portion of the system employs new techniques, the key to its new and surprising capabilities is the memorizing and comparing of two absolute measurements, made by the same sensor, on the same run into a well.

This new tool has successfully performed tasks not previously assigned to temperature equipment, including; behind-pipe oil finding and oil-water contact location, injection profiles, fracture treatment evaluation, lost circulation location and production profiles.

A priori profiles have not only shown the relationship between fluid input and shut-in temperature slope, but have led us to theorize that, in profile situations, a true temperature distribution probably exists in the macro-annulus, but that it must be moved into the near annulus, or the borehole, in order to be measured.

Further study has caused us to doubt the common idea that all of an intake zone takes fluid of similar temperature, and to theorize that each increment of intake zone takes fluid of a different temperature. To provide this temperature spectrum, fluid column thermodynamics are envisioned that create a radial temperature gradient, whereby the topmost intake increment takes its fluid from the warmest, outer annulus of the column, while the coolest, central fluid continues to the deepest intake increment. Laboratory experiments indicate that such a distribtuion is entirely possible.

References and illustrations at end of paper.

INTRODUCTION

A few years ago the first attempts wer made to employ a differential temperature tool; that is a tool that seeks to measure the difference in temperature between two proximate points in the bore hole. (Usually two to eight feet apart). Unfortunately, the first approach, to obtaining the differential temperature, was the obvious one of employing two separate sensing elements, physically separated by a chosen fixed spacing.

Although this type tool obtained a differential value of sorts, it had several irreparable shortcomings. Since the body of the tool is necessarily a source or sink of heat, (depending on conditions) the only true temperature log is one obtained by a leading element, on a first run into the well. Although the erroneous reading of a trailing element might, if absolutely unavoidable, be tolerated in the large value of an absolute reading, it can be disasterous to the often tiny, differential value. Even if there were some way to overcome this difficulty, the limit to which two discrete elements can be matched in characteristic would severely limit the mimimum credible level of measurement.

To complicate matters, these early differential tools employed a system which required power-handling thermistors which were bulky and rather sluggish. As might be expected, the acceptance of such a system was rather limited, even though the potential value of a differential measurement was recognized.

The differential temperature log is intrinsically capable of providing several advantages over the traditional absolute log. To begin with, the difference temperature can be known with a much great accuracy than the absolute temperature, since a change of .005° F, that might represent all of the differential temperature, might represent as little as .00002% of the absolute temperature. Secondly, if an absolute temperature survey were to be presented at anywhere near the differential sensitivity, it would be a meaningless jumble of scale changes.

Finally, where it has been long known that the absolute temperature log sometimes requires extending slopes, etc., to pinpoint changes, the differential log, in a sense, does this for you by presenting different slopes as distinctly different lateral displacements. This presentation has become extremely valuable with recent revolutionary developments in the application of temperature techniques to well logging, to be discussed herein.

THE A PRIORI DIFFERENTIAL TEMPERATURE SYSTEM

In 1965, came a technological breakthrough that finally made the measurement of a valid differential temperature value possible. This is the Johns-Lowrie, "A Priori" differential measurement system. Although it is applicable to any well log, it has been applied chiefly to the measurement of differential temperatures.

This system is based on the realization that it is completely unnecessary to measure the temperature at a point whose temperature has just been measured. Restated more technically, the temperature at any point above the present position of a single element (be it 2', 3', 6' or whatever distance) is a priori information, and as such, need only to be stored in memory to be compared to the present temperature to obtain a valid differential reading. In this method, both of the absolute values used in obtaining the differential are virgin, undisturbed values. Further, this system is not married to an inflexible physical spacing, and it is only a matter of mathematics to provide any desired effective spacing without changing the downhole tool in any way.

To take further advantage of this new method of obtaining the differential temperature, a completely new absolute temperature tool has been developed. One of the novel features of this new tool, borrowed from other modern technology, provides a much higher order of range and resolution, by operating a temperature oscillator of an entirely different type, at a frequency many times higher than those previously used. This high frequency is heterodyned with a highly stable, tunable, local oscillator at the surface. The relatively low difference frequency can be counted by ordinary techniques, even though it retains the quality improvements of the high frequency operation. In addition, a simple resetting of the local oscillator gives range after range of temperature resets without the former requirement of extremely great zero suppression in the recording device.

The final step in utilizing, to best advantage, the features of the a priori differential and the high-frequency, heterodyne tool, is the introduction of a completely new measuring element.

This new type element is an outgrowth of transistor technology and is called a, "Sensistor". The sensistor, like the thermistor, is a semi-conductor with high temperature sensitivity. However, unlike the thermistor, which had a highly non-linear, negative temperature coefficient of resistance, the sensistor has a linear, positive temperature coefficient of resistance. (See Figure 1) Sensistors are quite small and are now being especially prepared for the new tool without any encapsulation whatever, so that they may be encapsulated in an optimum fashion for this new well logging application.

APPLICATIONS OF THE A PRIORI DIFFERENTIAL TEMPERATURE SURVEY

All of the possible applications of the survey cannot, at this time, be reported, since new ones seem to be reported regularly. However, the most common present applications can be described as follows:

Behind-pipe Oil-finding and Oil-water Contact Location

Geophysicists have long known that, due to constant heat flow from the core of the earth to the surface, each bed should exhibit a separate and distinct thermal gradient, inversely related to its thermal conductivity, rather than the single isotonic "geothermal gradient" so commonly assumed in the well logging industry.(1) Where the geophysicist has been able to obtain meaningful information only by employing static measurements across a large interval, we are now able, with the a priori differential tool, to make a repeatable, continuous, high resolution log of these subtle slope changes. The credibility of the a priori feature permits sensitivities suffcently greater than the best absolute logs to easily recognize the minute slope changes while the differential feature provides readout directly in terms of slope. This survey is directly analagous to the lateral resistivity survey, where we provide constant current through the bed and measure the voltage gradient.

If we can discern the difference in gradient between a limestone (.01 watt/cm°K) and a shale, which may have a thermal conductivity as little as 1 1/2 times (.015 watt/cm°K) that of the limestone, it follows that within a homogenous, porous bed we can recognize change from water-to-oil or oil-to-gas saturation since water exhibits a thermal conductivity (.006 watt/cm°K) four times that of oil (.0015 watt/cm°K), and oil five times that of natural gas. (.0003 watt/cm°K) (2)

For reasons that will become apparent in subsequent discussion, the thermal conductivity type survey is not possible soon after production or injection of fluid in, or near, the zone of interest. Although these surveys are best made in wells that have been static for a long period, under some conditions, they are practical after complete circulation, where thermal admittance will modify, but not destroy the log.

Figure 2 is an a priori differential temperature log run under static conditions in a Lea County, New Mexico well which had been abandoned by a major oil company. Completed in 1938, the well initially produced 500 BOPD. Two years ago the 2nd (lower) Yates zone went to 100% water production and recently the 1st (upper) Yates began producing sufficient water as to create a production problem.

The new owner wished to test the Tansel zone, known to fall between a salt bed and the 1st Yates, but found it very difficult to locate with the usual lithologic logs. In figure 2 the solid trace is the a priori differential temperature, the dashed trace is a 1°/in. absolute temperature and the two vertical lines define the slope excursion limits in each direction, beyond which a dominant saturation is indicated, as judged by the remainder of the well.

The 2nd Yates, known to be now 100% water-saturated, exhibits lower slope values than anything other than the base of the salt, which actually exhibits a negative slope. The reason for this cooling trend in the base of the salt is not known. Since this zone is known to wash out, one possibility would be the latent heat of solution.

The upper portion of the 1st Yates exhibits one of the two extraordinarily high positive slopes on the log indicating the remaining oil saturation in this zone. The other high positive gradient area immediately below 2800' was assumed to be an oil saturated Tansell section. On this basis the casing was perforated from 2836' to 2837.5' and the well initially flowed 100% oil. At last report the well was pumping 100% oil.

The Injection Profile

For a great many years researchers have sought to obtain injectivity information from absolute temperature surveys without much notable success. Although prior temperature theory was inadequate to predict it, the a priori differential temperature log has proven to be an excellent injection profiling tool and many such logs are run each day as a routine procedure.

Experience with these surveys has taught that definitive injection information is available, only by cessation of injection and observance of a shut-in period. It has also been learned, empirically, that injection quantity is not related to the absolute temperature, but to the slope (dt/dh) of the shut-in log. Since the a priori differential temperature system displays slope directly as lateral displacement on the chart, it provides a direct presentation of the injection profile. Since empirical proof of the profile came first, it will here be treated first, with a theory being offered later to account for results.

Figure 3 shows an a priori differential temperature injection profile and the results of a dual detector fluid velocity tracer on the same injection well. The stations of the fluid velocity survey are indicated by the black dots connected by a dotted line. The solid trace is the a priori differential while the dashed trace is the absolute temperature. The fluid velocity survey, like all previous surveys, is really only capable of detecting where the fluid is leaving the casing, and therefore, indicates all of the fluid loss from the bottom perforation. The a priori differential temperature log shows that the fluid, in fact, is channelling downward with input between the bottom perforation and total depth as indicated by the cross-hatched area, and with some fluid moving beyond total depth. Most such channels are of such small cross-section and well enough shielded from the inside of the pipe as to be seldom seen, even on the solution type, of radioactive tracer survey. On the other hand, the a priori differential temperature survey seems to be pretty much oblivious to the presence, or absence, of pipe.

Several major oil companies, before adopting the a priori differential temperature as their primary injection profiling tool, compared it to the surveys that they had been using, in the same wells. To obtain substantial agreement it was necessary to locate injection wells with, essentially, nothing wrong with them, or at least, no major channeling involved since the previously available surveys should be accurate in this case.

Figure 4 shows the results of one such comparison log. The solid trace of the lefthand log is the a priori differential temperature injection profile, while the dashed trace of the lefthand log is the shut-in absolute temperature. The righthand log is a density-matched bead type radioactive tracer injection profile. The numbers on each log, at each zone are the percentage of input into that zone, as interpreted from each survey, and a general agreement can be seen. Much of the variance within each zone can probably be attributed to the strong effect of hole size and shielding on the radioactive profile. In addition, the strong peak in the tracer at the top of the 3400' zone is quite likely due to some mismatched beads floating to the top of the minor channel there. Where the a priori differential temperature shows that the entire top zone is taking fluid, it is interesting to note that the tracer is only able to show that the fluid is leaving the two sets of perforations. This situation has been found to be quite typical, and points out the near impossiblity of finding a well with absolutely no channeling.

Figure 5 shows a special case of the a priori differential temperature injection profile, the Fracture Treatment Evaluation Log. In this case, there has been short-term injection on a grand scale, and the small magnitude of the lithogic-dependent portion of the log above the fractured interval indicates the very low sensitivity employed. On the other hand, since the input is short-term the disturbed annulus of formation is finite, and it is common practice in these surveys to limit shut-in time to an hour or so.

By contrast, in injection wells that have experienced huge cumulative injection, a priori differential temperature logs have been run periodically from four hours to over one hundred hours after shut-in without significant changes in profile. In some such wells profiles have been seen after several years of shut-in, and it seems likely that they may never return to so-called, "geo-thermal" a condition that could probably only exist in a bore that traversed no permeable beds.

It is interesting to note that, during the repeated, like differential profiles mentioned above, the conventional absolute temperature was changing, rapidly at first, with an ever diminishing closure toward its undisturbed value. This is just one more indication that, as far as fluid movement into, or out of a zone is concerned, the slope value is all-important while the much used absolute temperature can prove to be anything from slightly useful to downright misleading.

Figure 6 is another special case of the a priori differential temperature injection profile, Lost Circulation Location. This survey was made in a major company drilling well in Oklahoma. Here, the injection, (lost circulation) zones exhibit positive slopes since the mud has been to bottom and circulated back up the annulus to these zones, where it is entering them with a temperature higher than that of the earth at this depth. For confirmation, circulation was reversed, a waiting period observed and another a priori differential temperature survey was run. This log was essentially a mirror image of the first log since the mud had now travelled down the annulus and arrived at the lost circulation zones cooler than the earth's temperature at that depth.

The Production Profile

Recalling the oil-finding application, each bed, in a static well was said to have a gradient related to its thermal conductivity. These gradient changes were seen in spite of the fact that the casing, and its contained fluid, constitute a thermal, "short circuit" and they are, necessarily, less than their respective true, in situ, gradients beyond the influence of the borehole.

The production profile is possible because, when we move fluid from the undisturbed zone into the borehole, we also, in a sense, move a true, undisturbed temperature distribution into the borehole, where we can measure it. After a period of shut-in, this undisturbed type slope is distinguishable from the remainder of the well, whose slopes are dulled by the presence of the pipe and its contained fluid column. Although, admittedly, production profiles are sometimes very difficult to obtain and often based on extremely minute anomalies, no previous survey has even pretended to be able to profile production.

In figure 7 a new log is used, (maybe presumptuously) to prove a new log. The two a priori differential temperature logs of figure 7 are injection and production profiles in the same major oil company well in Sterling County, Texas. Each has its shut-in absolute temperature log shown next to it, with the dashed straight line between them indicating a theoretical, "static," gradient. Although a good general agreement can be seen, it is noteworthy that the detail does not directly correspond. Of course, this could be due to a shortcoming in one, or both, profiles but, in view of the survey's other accomplishments, it seems entirely possible that both are correct and that these zones do, indeed, take fluid somewhat differently than they make fluid.

The logs of figure 7 exhibit one area of outstanding difference, immediately below 8550' where they indicate that one zone that produces fluid, (after previous fracture treatment) does not take fluid at these nominal injection conditions. If both logs are true, they point to the fallacy of running a radioactive tracer survey in a producing well, by injecting and assuming that the contaminated fluid is taken where the well fluid is produced.

Miscellaneous Applications

Although usually not necessary, the a priori differential temperature log may be used in any case where the traditional absolute temperature survey gives usable information. For instance, the exothermic heat from new cement can usually be seen days later than with the best of absolute surveys. Microvolume gas production at very small pressure differentials, although not economically interesting in a producing zone, might be of more interest in the form of a tubing or casing leak, and one major gas company found, in a controlled test, that the a priori differential temperature tool could easily see gas leakage through an .062" hole with a 2 psi pressure differential across it.

A NEW INTERPRETATION THEORY

The a *priori differential temperature* survey has a rather unorthodox history in that the system was devised, placed in the field and its profiling capability empirically proved without any theory being available to satisfactorily account for these results. Reviewing figure 4, a close look at the absolute temperature log, (dashed trace) reveals that, after the shut-in period, each zone of intake exhibits a negative slope, that is, warmest at the top of the zone and coolest at the bottom of the zone with the slope reversal, (from negative to positive) at the lowest point of intake into that zone. This fact, since being brought to attention by the a priori differential tool, has proved very disturbing to many analysts who, for years have equated the major input with the coolest temperature, even on shut-in logs. We now know that the coolest temperature, in fact, marks the end of input in that zone.

Another view that has been held for years by many, including this writer, (3) is that all of an intake zone tends to take fluid of essentially the same temperature, as suggested by the temperature log made during injection. (see trace T_0 in figure 8) If this view were correct, it would leave us hard pressed to explain what happens to the temperature log after successive periods of shut in. (T_4,T_{16},T_{48} in figure 8) It can be seen that, as could be expected, the entire temperature log progressively warms back toward geothermal since, during injection, the entire well bore, including some small annulus of formation, has been subjected to a gross cooling.

The most important feature, by far, to be seen *in figure* 8 though, is that, from after several hours of shut-in on until the features are lost, if ever, is that the top of the intake zone becomes much warmer than the bottom (often as much as 20°). This is not the first time that this phenomenon has been noted, but earlier researchers tended to base their explanations on currently available theory. Some even suggested that maybe the heat was conducted into the top of the intake zone from the zone above. This hypothesis had to be rejected in the present study for several reasons. Firstly, if this idea were valid, it would seem that the bottom of the intake zone would have to be warmer, not cooler, than the top since it is adjacent to an even warmer bed below. Secondly, although we have described the differences in thermal conductivity of various rocks with various contained fluids, all of them are quite poor conductors of heat. Thirdly, if by some unimaginable means, there existed the extremely high thermal conductivity that would be required to account for the rapid warming of the top of the intake zone immediately after shut-in, the entire input-caused anomaly would surely be expected to disappear quickly and not last for days, weeks or sometimes years as we really experience. Finally, the fact that the slope of the shut-in temperature log is related to the pre-shut-in intake rate has been substantiated so many times by seating nipple plugs, selective packer techniques and comparison to other profiles such as the examples presented earlier. Such a relationship could hardly be attributed to a mere conduction of heat from an adjacent bed.

The failure of known theory to properly account for this observed phenomenon has forced us to seek some new theory, and this we have done. Keep in mind that what we are treating here is only a theory and, as such, is subject to possible error. The first assumption arrived at was that, if the warming in portions of the intake zone does not arise from an adjacent zone, it must, then arise from within the intake zone, itself.

This first assumption then dictated that some mechanics be sought to support it.

The search could only be resolved by overcoming the inhibition of a long accepted theory, and deciding that the intake zone probably does not all take fluid of essentially the same temperature, but rather, that each increment of it takes fluid of a different temperature, depending on the cumulative intake of all of the increments above it.

The second assumption can only have merit if fluid-column mechanics can be offered that would provide fluid of various temperatures to different intake increments, and, for once, we are confronted with a concept that is neither surprising, nor difficult to accept. It is only logical that a column of fluid moving through an infinite medium of higher temperature than that of the fluid, will have heat transferred to it from the medium. Naturally, this transfer is, first, to the outer annuli of the column. If the fluid column were not moving, the transfer would continue into the center of the column until, after a sufficient time, a cross section of the column would exhibit a practially uniform temperature. However, the fluid column is moving, and during the time required for transfer to the center, that portion of the column has moved to a new environment, where the temperature of the surrounding medium is higher. This process proceeds continuously, with the result that the temperature of the center of the column lags well behind that of the outer annuli, with a radial temperature distribution between. This thermodynamic system should lend itself to computerized mathematical modeling, which has not been attempted at this writing. Laminar flow, which prevails in most normal injection situations, is of course, necessary in order to preserve this radial distribution. A second, but probably less important, force is also acting to create such a radial distribution since, in laminar flow, the center of the fluid column is moving faster than the outer annuli. If this radial distribution exists, the top increment of intake zone can be expected to take its fluid from the outside, warmest annulus, etc. until the coldest, central fluid goes into the bottom increment. A review of figure 5 lends some support to this notion since this log followed a high-rate fracture treatment, where flow was quite possibly turbulent and no overall negative slope is evident. With turbulence, an intake zone could be expected to conform to our older ideas, and actually take fluid of near uniform temperature throughout. It is of great significance that, with turbulent flow, the injecting and shut-in logs are quite similar. It can be seen in figure 5 that this condition does not prevent our obtaining a profile since zero slope still represents a more negative slope than geothermal, but it may be that the profile in this case is not as quantitatively accurate, or it may be. Only further investigation will determine this.

If all of the above were to be true, it would lead to a somewhat startling corollary; that is that a temperature distribution very mu like that of the shut-in log must exist, even while injecting at some distance back from the well bore, and that what the shut-in period accomplishes is to allow this true temperature distribution, by heat transfer, to move into the well bore where we can measure it. Armed with the knowledge of this possibility, we have looked back at logs made during injection, and found some (usually low rate wells) that actually exhibit some negative slope, even during injection. That this indication is usually small, or abse is apparently because the injection log tends to be merely a log of the injection fluid's temperature.

It seems likely that both types of fluid profiles are made possible by moving a true, macro-annulus temperature distribution in to where we can measure them. In the case of injection this movement is accomplis by heat transfer during shut-in, while, in the case of production it is accomplished by physically moving fluid from the macro-annul through the near annulus until it also has a true distribution. Here the shut-in period serves to permit the uninvolved portion of the well bore to recover from the gross warming, caused by produced fluid passing, and return to a near normal temperature.

As a result of all of the above conjecture, a rather simple injection well model was constructed, not to necessarily prove the theory but merely to show its plausibility. In this model, pictured in figure 9, a porous pap filter serves as the intake formation. Three probe type thermometers are imbedded on a chord through the filter, one at the vertical center, and one each, three inches above and below the center. The total height of the filter is eight inches.

In a continuous situation of circulating 140° water through the jacket and adding 60° water to the tubing, sufficient to keep it full, we were only able to obtain a 3° differential across the six inch interval, warmest at the top, coolest at the bottom. This caused us to suspect that our constant addition of water, only a few feet above the filter, might be introducing a turbulence that was not being eliminated in this short travel, so another experiment was performed.

The second experiment was begun with the jacket empty. The tubing was filled with 60° water and kept full until we could assume a stable condition existed. While still keeping the tubing full of 60° water, the jacket was filled (not circulated) with 140° water. As soon as the jacket was filled, the addition of 60° water to the tubing was stopped and the level in the tubing was allowed to fall. Whether due to the elimination of turbulence, or to some overlooked circumstance, we experienced a 43° temperature difference across six inches of porous zone, as shown in figure 9. Our field experience with the accuracy of the slope-input relationship would predict that, with this filter of homogenous permeability, a linear temperature gradient could be expected, and it is interesting to note that the center temperature (98°) differs by only 1.5° from the mean temperature (99.5°) of upper (121°) and lower (78°) measurements.

CONCLUSIONS

The new a priori differential temperature system has shown itself capable of sensing meaningful anomalies many times smaller than previously possible. This capability has made it possible to apply temperature techniques to situations not previously associated with the temperature logging art, as well as to learn much more of the behavior of well temperatures. A slope-input relationship has been established, making the direct slope reading feature of the system of particular benefit.

Field results with this new tool have prompted a search for new theory, including some laboratory experiments. The result of this effort, in itself, is not our prime concern but, rather, the hope that other researchers be persuaded that well temperature techniques are far from being simple and of limited value, and that even these recent advances are only beginning to touch on the ultimate possibilities for the art. If the industry can be convinced to prosecute the indicated work, it seems likely that absolute quantitative, rather than relative, profiles may be achieved, the a priori differential temperature may take a place as a primary, open-hole log and, for the first time, an approach to continuous, in situ permeability measurements may be possible.

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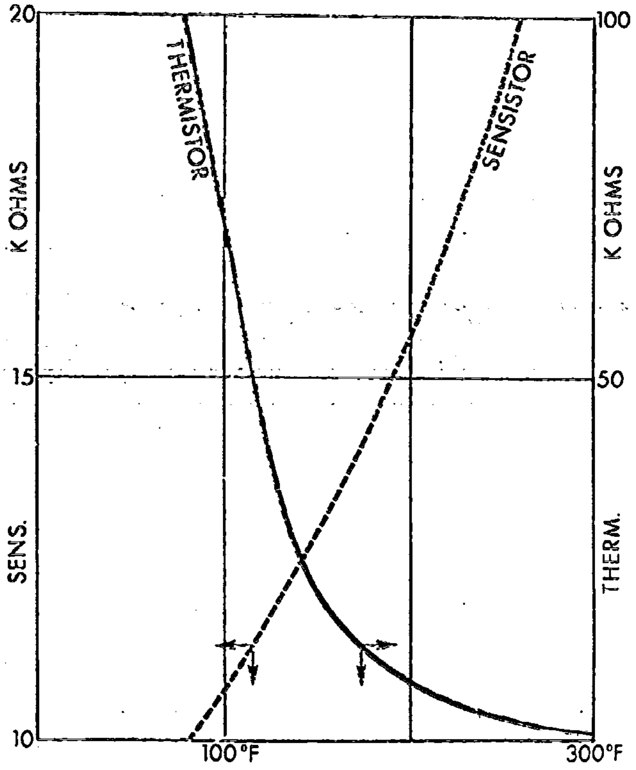

Fig. 1

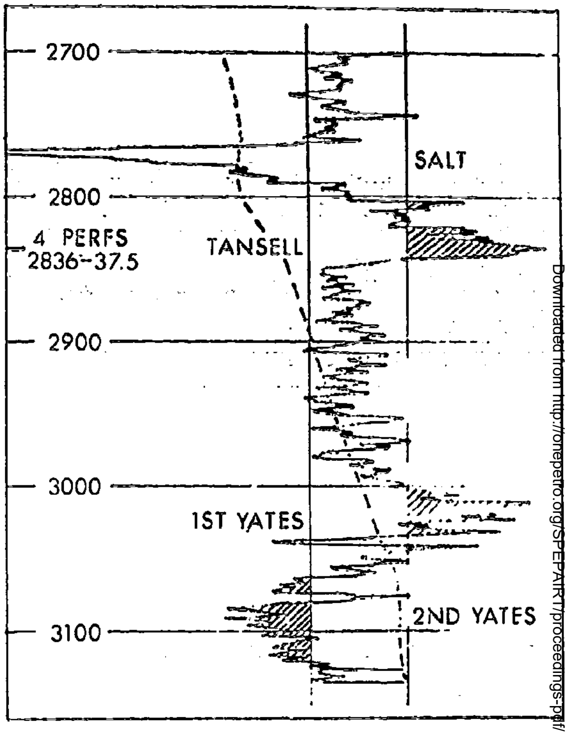

Fig. 2

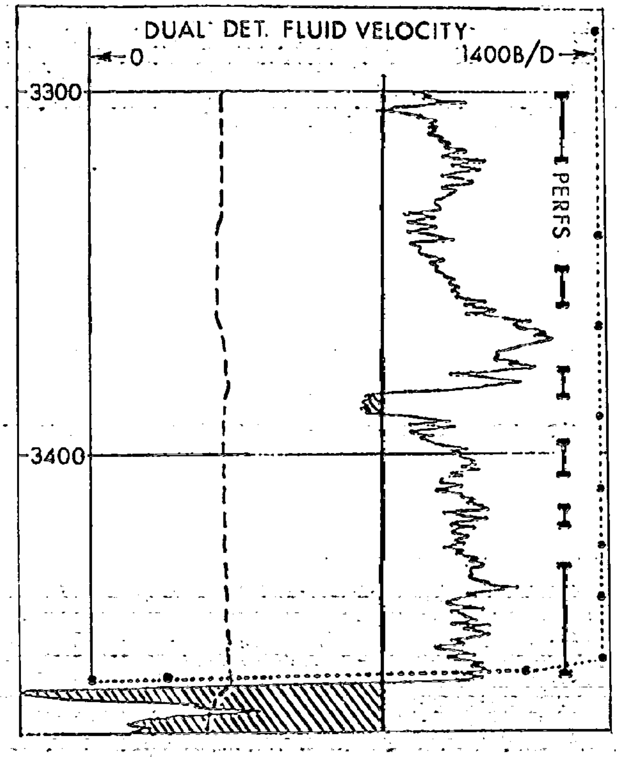

Fig. 3

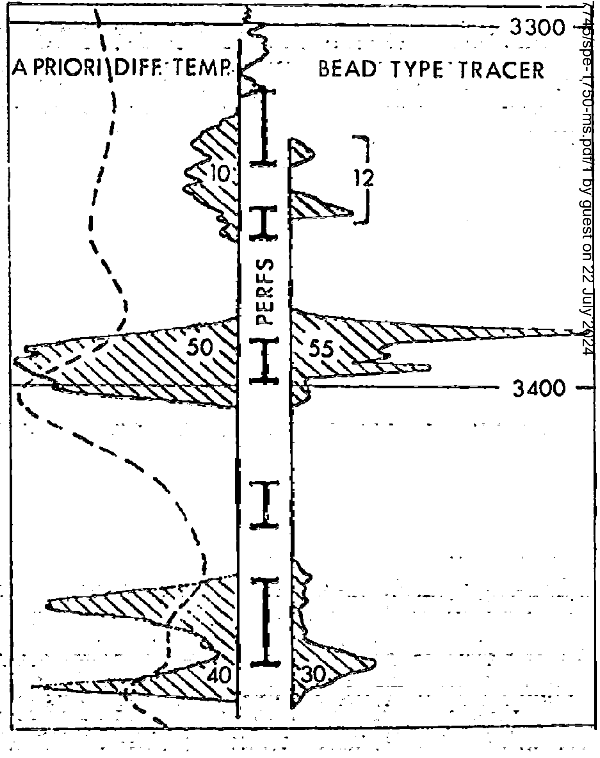

Fig. 4

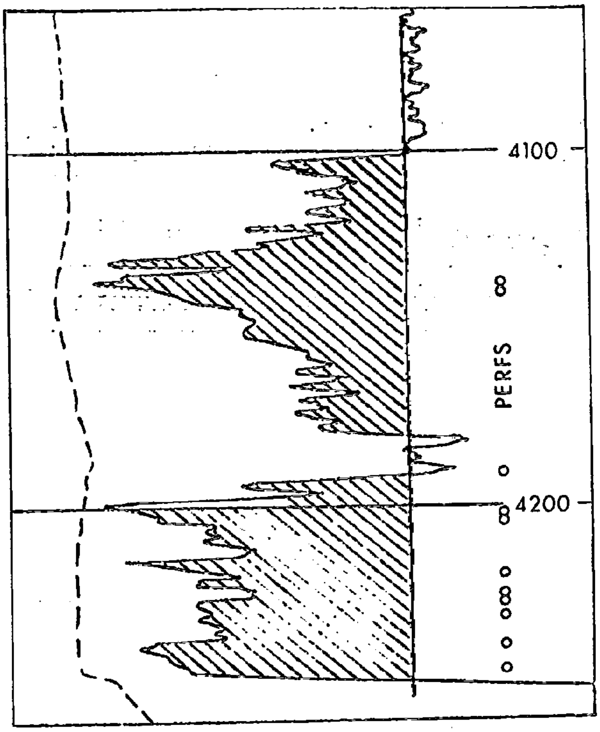

Fig. 5

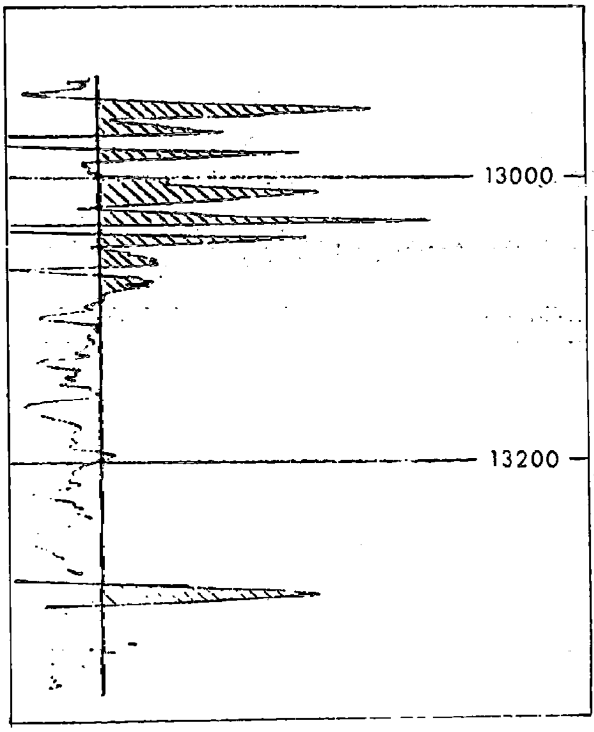

Fig. 6

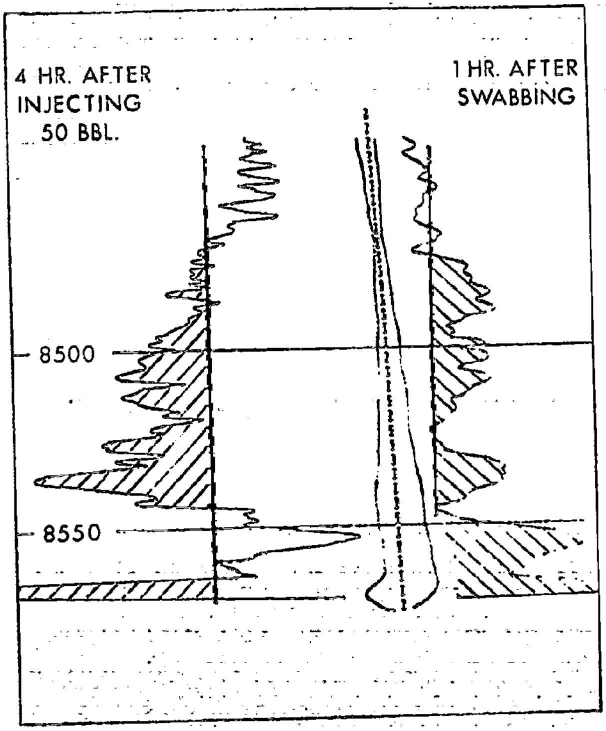

Fig. 7

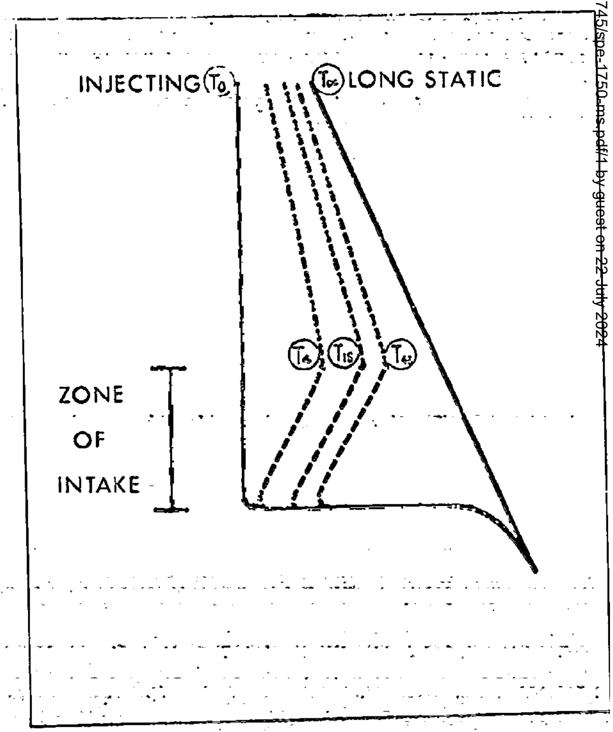

Fig. 8

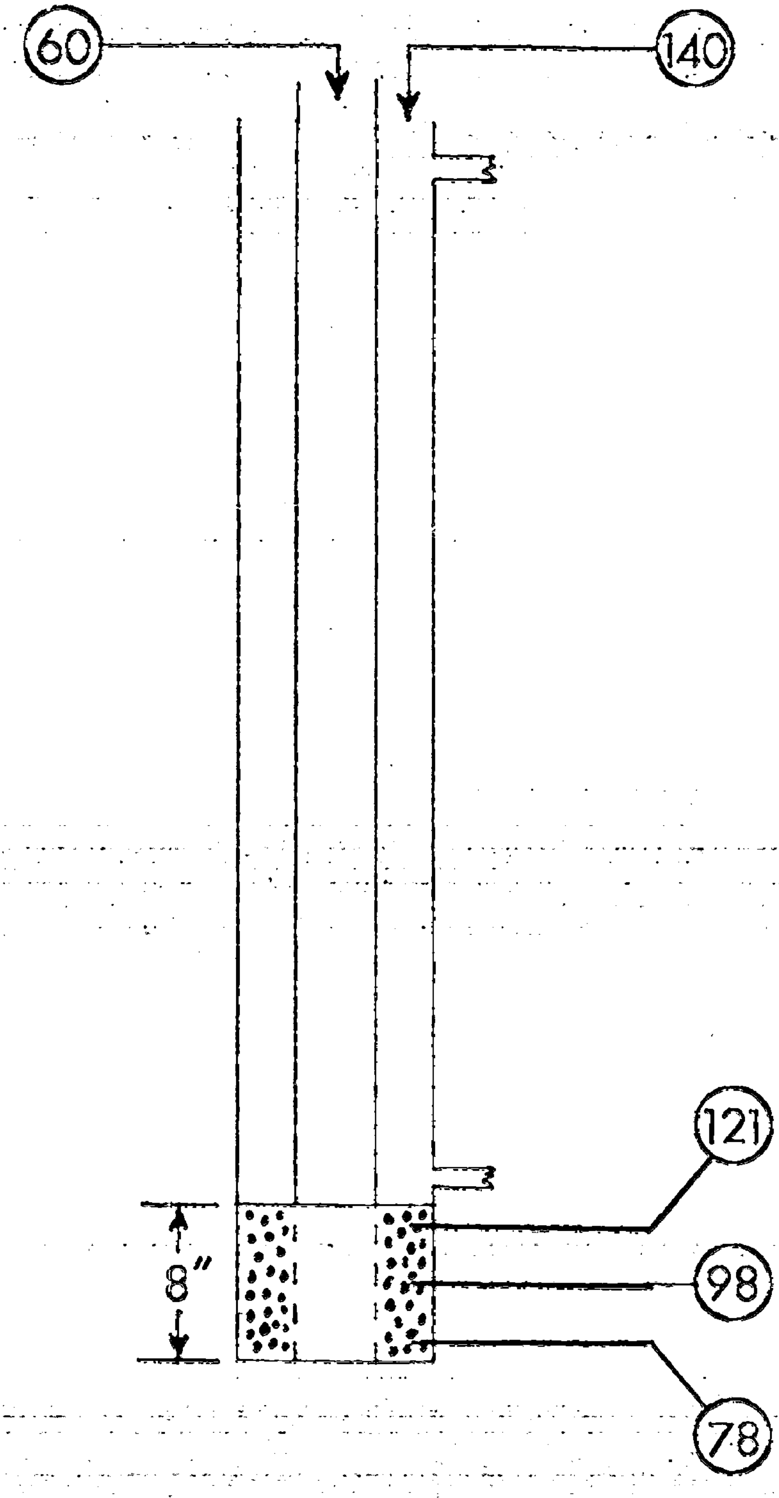

Fig. 9