Proper Tool Selection for Refined Production and Injection Well Profiling

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Making an alalysis of downhole fluid movement is always complicated by many variables; laminar flow, turbulent flow, hole size, differential flooding, and tool configuration are some of the more common variables which we must overcome. Many others exist. The ultimate wireline survey would be one which would eliminate all of them. Unfortunately, all of these variables have not been eliminated, although efforts have been made to minimize several of them.

Analysis of downhole fluid movement in both producing and fluid injection wells has been attempted for several years. Tracing of radioactive isotopes has been used since the early 1940's,[1] but until the late 1950's, tracer surveys, as such, left much to be desired. The spinner survey was some improvement, but even with the present day spinners or Flowmeters, which provide the most accurate method of measuring fluid movement in the pipe or bore hole, several conditions exist which prevent optimum results. With the advent of soluble radioactvie isotopes and "ejector" tools, tracer surveys began to make a name for themselves in the early 1960's. With improved tools and techniques analysis of downhole fluid movement has now become a refined art.

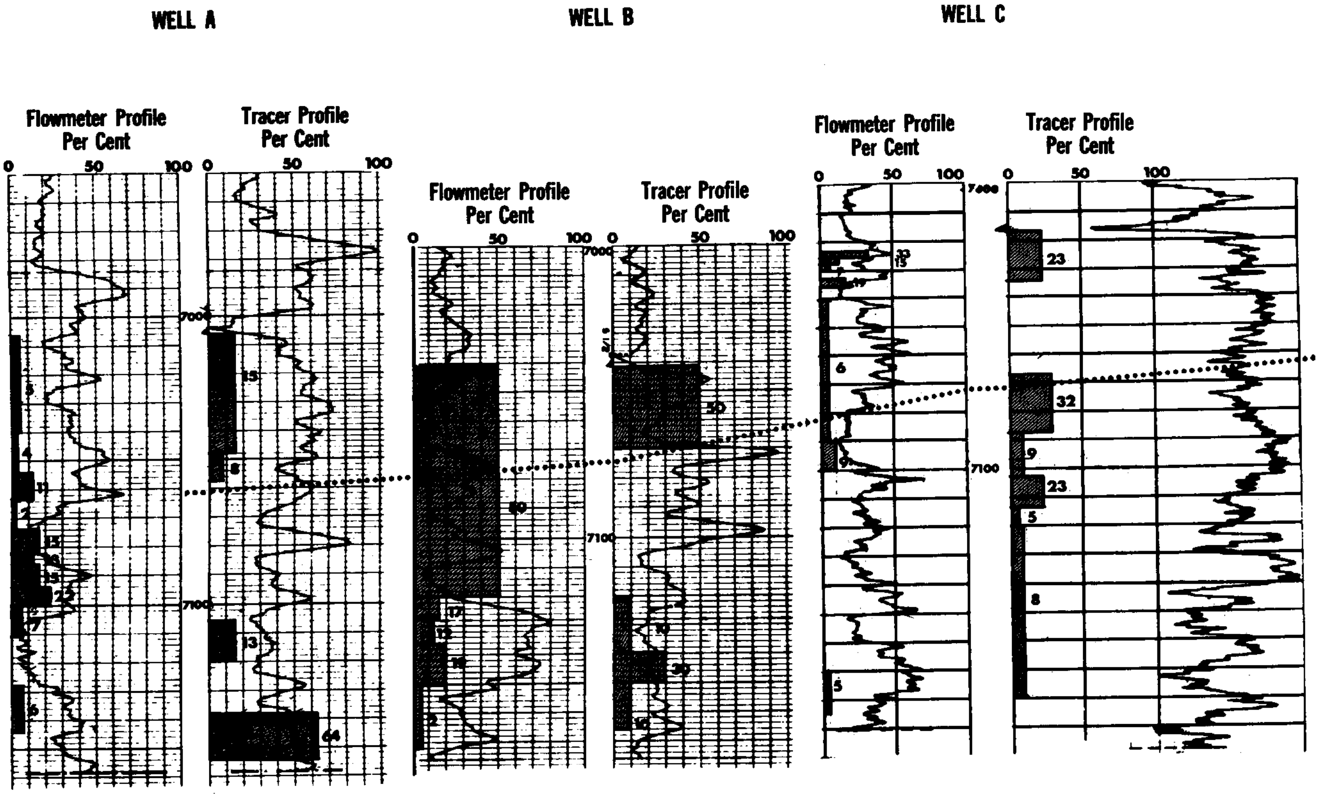
FLOWMETER vs. TRACERS

The Flowmeter, being differentiated from the spinner by the use of a packer element to divert all of the fluid flow through the spinner section, is a very accurate tool for measuring fluid movement in the pipe or bore hole. This tool has an accuracy range of 95-97 per cent. However, it has its limitations. It is not possible to check for communications or channeling behind casing. This is a readily acknowledgable defect. A more serious problem, however, occurs in open hole completions where natural vertical fractures exist in the formation.

Diversion of the entire flow through the spinner section of the Flowmeter is usually accomplished by pumping up the inflatable packer element with either wellbore or self contained fluids until a seal is effected with the pipe or bore hole. Since it is a through tubing tool, the packer element is very thin and can only stand a small amount of differential pressure when it is inflated, generally less than 15 psi. Although it appears insignificant, differential pressures of less than the above limit can cause erroneous results under certain conditions.

The condition under which erroneous results are most often seen is that of natural vertical fractures in open hole completions. Many times, excellent Flowmeter packer seals do not result in successful measurement because the differential pressure created by friction loss through the Flowmeter mandrel is sufficient to cause the fluid to by-pass the tool through natural fractures in the formation. This is especially true of several dolomitic reservoirs in the Permian Basin. Figure 1 is a cross section of a dolomitic reservoir in West Texas. All five wells are injection wells. Both Flowmeter and Tracer surveys were run on these wells, one immediately after the other, to determine the more suitable tool to utilize for optimum profiles in this area. The Flometer injectivity profile is shown on the left side of each log and the injectivity profile as determined by the tracer tool is shown on the right side. The Flowmeter profiles indicate large losses of water above the pay in Wells C, D, and E; whereas, the tracer profiles show a little better distribution of the injected fluid over the pay secton. The question arises, therefore, as to which is the more accurate profile.

To arrive at a more positive conclusion, additional formation data was required. A review of core analyses and visual inspection of the cores from wells in this area indicated that natural vertical fractures existed. Immediately, the Flowmeter is suspect. Also, core analysis indicated that the porous zone near the top of the pay in Well D had stringers of relatively high permeability, in excess of 200 md, as com-



pared to an average permeability of approximately 10 md. Although this is a condition which results in poor waterflood performance, it is one, which in this case, provided a means for positively determining which survey proved to be more accurate.

A map of this area is shown on Fig. 2. Producing Well "F" located between injection wells "C" and "D" started producing large volumes of water a few months after injection began. Tracing the problem injection well was relatively simple, since the water being injected into Well "C" was produced water from the formation being flooded and the water being injected into Well "D" was water of a much lower salinity (approximately 40 per cent of that of the formation water).

Chloride tests on the produced water from the producing Well "F" compared almost identically to the chloride content of the water being injected into Well "D." Remedial work to Well "D" improved both the profile on the injection well and the WOR in the problem producing well. The results of the remedial work indicated that the profiles by the tracer surveys were more representative than those by the Flowmeter.

Further proof that the tracer profiles were more representative was evidenced by the fact that both the well due west (Well "G") and the well due south (Well "H") of injection Well "C" experienced substantial responses, which could not have happened if the Flowmeter profiles were accurate. This is a good example where produciton data, core analyses, and primary log data were used in conjunction with the fluid movement logs to provide the proper tool for optimum results for profiling open hole completions in a formation containing natural vertical fractures. Under these conditions, the tracer tool was selected.

Under different conditions, such as slow velocities, the Flowmeter would give the best results. Velocity measurements by the tracer tool, where fluid is moving slower than 0.075 ft./sec., introduced more possibilities of interpretive error in the volumetric calculations and the resultant profiles. These interpretive errors can be more easily understood after a review of Figs. 3 and 4. Figure 3 presents a graphical solution of the equation:

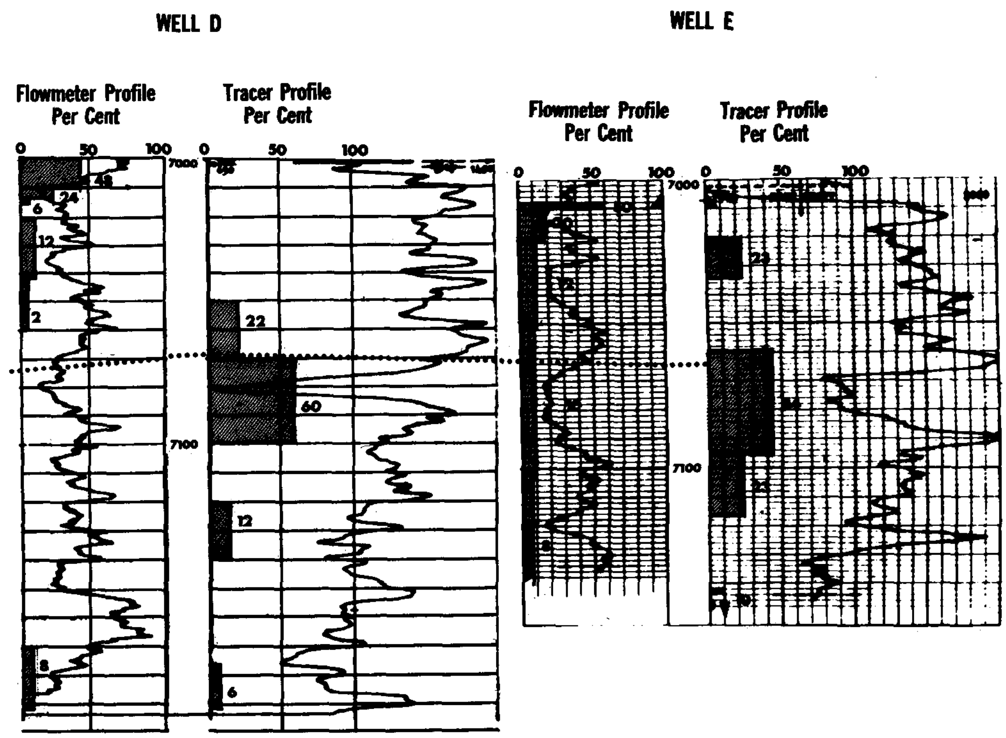


FIG. 1
FLOWMETER PROFILES VS. TRACER PROFILES
Open Hole — Natural Vertical Fractures

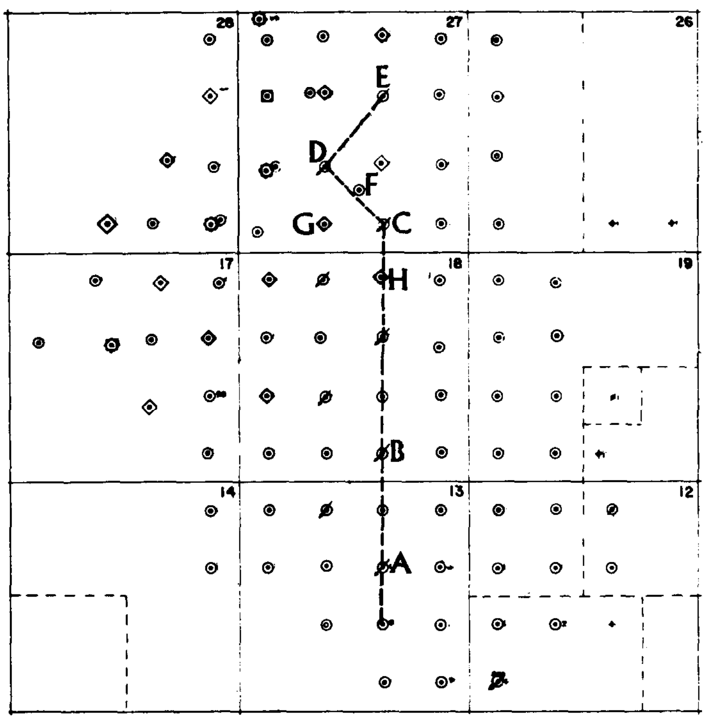


FIG. 2
TRACE OF CROSS-SECTION
Flowmeter vs. Tracer

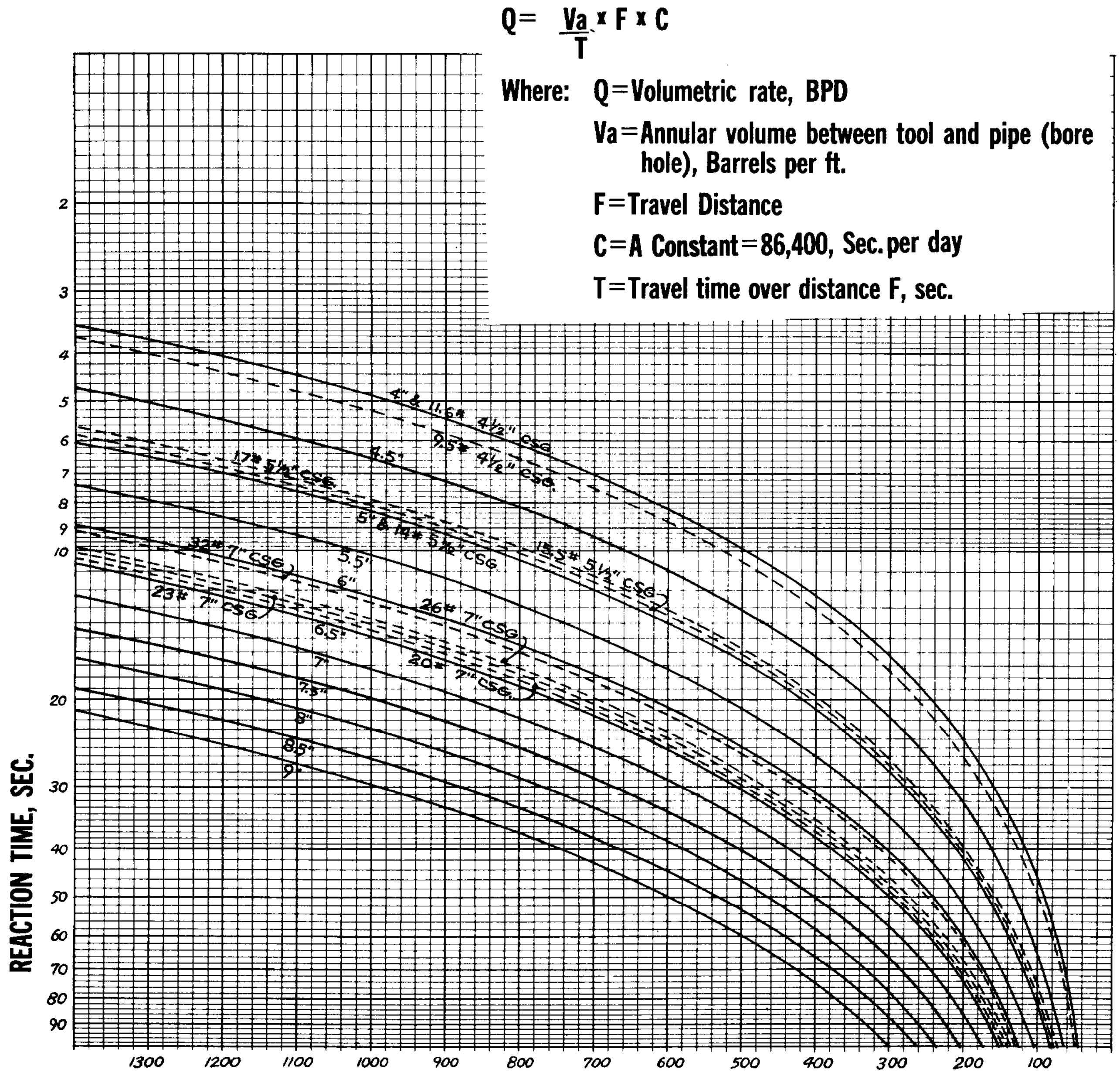


FIG. 3
GRAPHICAL SOLUTION VOLUMETRIC CALCULATIONS FROM VELOCITIES

$$Q = \frac{Va \times F \times C}{T}$$

Where: Q = Volumetric Rate, BPD.
Va = Annular Volume Between The Tool and The Pipe (or bore-hole) in Barrels Per Foot.
F = Travel Distance, Ft.
C = A Constant = 86,400, sec. per day.
T = Time to Travel Distance F, sec.

For any tool configuration with a fixed value of F, the only two variables would be reaction time, T, and the annular volume, Va. Since the tool diameter is fixed, the only variable in Va would be the pipe or borehole diameter. In cased holes the pipe diameter is constant leaving only a variable of time; whereas, in open hole completions, the hole size can, and usually does, vary.

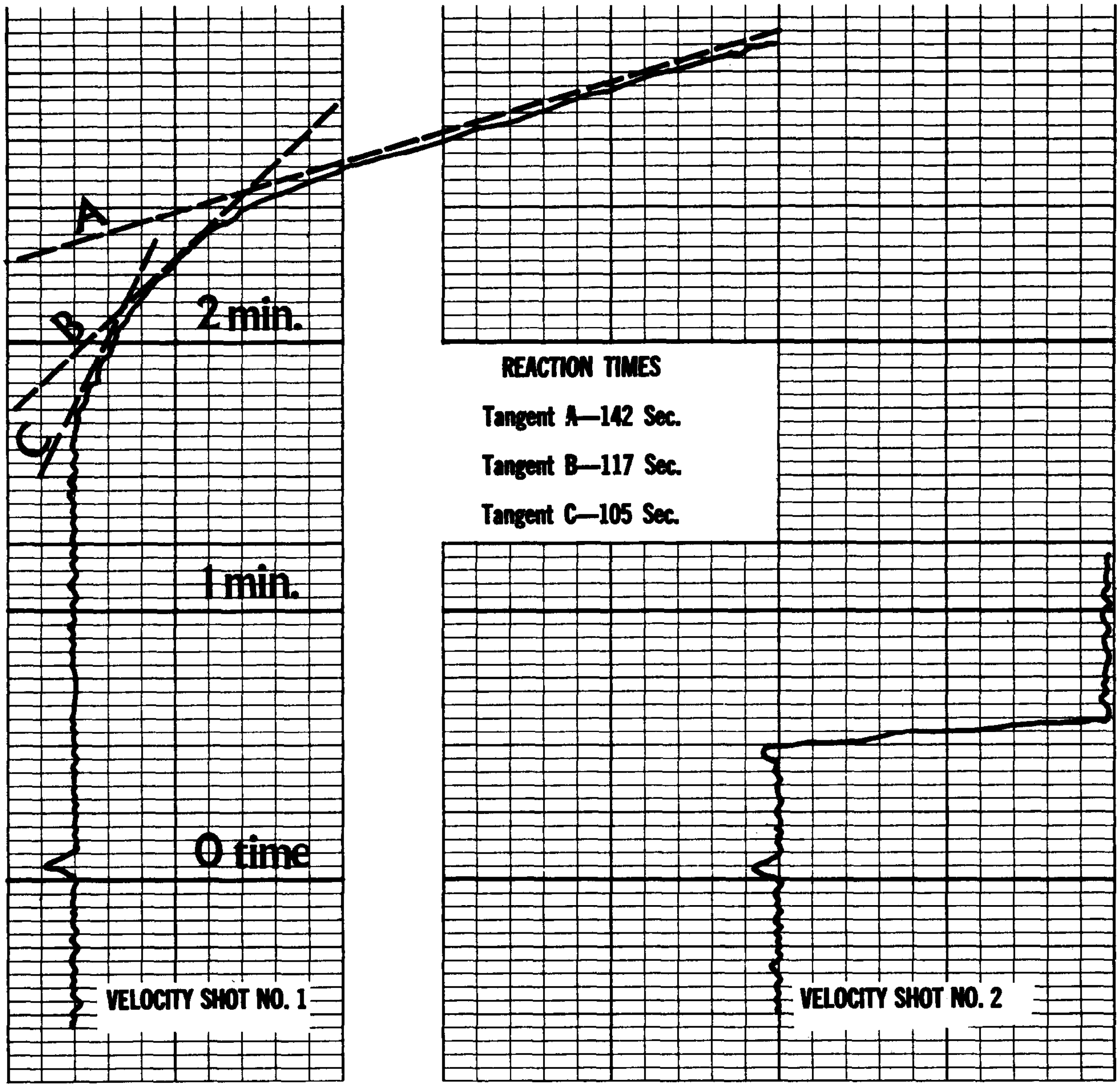


FIG. 4
VELOCITY MEASUREMENT
AT DIFFERENT RATES

Inaccurate values of both reaction time and hole size can substantially affect open hole profiles by the tracer velocity measuring method. Volumetric calculations are more affected by the hole size at the faster rates than at the slower rates. A comparison of the volumetric rates for 4-in. and 9-in. holes at a reaction time of 30 sec on Fig. 3 indicates a difference of approximately 820 BPD. A reaction time of 100 sec would result in a difference of only 245 BPD between the 4-in. and 9-in. holes. This difference, with a decrease in rates, a correct reaction or travel time becomes more and more important since its effect does not change.

Ironically, as the reaction time becomes more important in the volumetric calculations, the probability of error in determining an accurate reaction time becomes increasingly larger. Consider Fig. 4 for a minute. At the slower rates, the radioactive slugs ejected for the velocity measurements have a tendency to spread slightly. As a result of this spreading, a sharp reaction does not result as the radioactive slug approaches the detector. (Velocity Shot No. 2, Fig. 4.) Instead, a gradual increase in radiation counting rate is experienced until the maximum counting rate is reached (Velocity Shot No. 1, Fig. 4). A sharp reaction occurs at higher velocities and the reaction time is easily and accurately determined by scaling off the time-calibrated logging paper. The problem with slower velocities is determining when the slug reaches the detector. Since a gradual increase in radiation occurs, the reaction time is read at the point where the tangents to the base radiation and to the induced radiation intersect. The tangent to the base radiation is very easily and accurately interpreted, but the tangent to the induced radiation is subject to considerable interpretive error.

An example of the interpretative error which can result is shown by Velocity Shot No. 2 in Fig. 4. Note that three possible tangents to the induced radiation are shown. Although this example represents extreme and slightly exaggerated conditions, it does emphasize the fact that interpretative errors are inherent in velocity measurements in slow moving fluids. Consequently, the Flowmeter, which can accurately measure flowrates as low as seven BPD, gives much better results at the slower rates. At the slower rates, the pressure drop through the Flowmeter is negligible and almost completely eliminates the problem of causing fluid to channel through fracture systems in all but the most extreme cases.

CENTRALIZED TRACER TOOL

One of the variables in velocity measurements with tracer tools is that of measuring different velocity vectors in laminar flow. Refer to Fig. 6. In laminar flow, a measurement can be made in the peak velocity vector, the average velocity vector, or in any of the infinite number of vectors between no flow at the pipe face and the peak vector. Without centralization, this condition exists in the straightest of holes and is a certainty if any vertical deviation exists. With a non-centralized tool, there is no way of knowing when a velocity measurement is not representative unless an excessive number of measurements are made. These erratic velocity measurements not only create doubt in the reliability of tracer surveys but also result in excessive logging time which means increased cost to the customer.

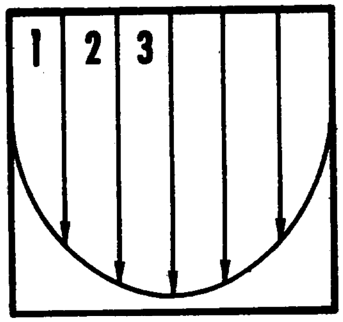


FIG. 5 VELOCITY PROFILE IN FLOW CHANNEL— LAMINAR FLOW

The solution to this is a tool which can be centralized while making velocity "shots" and still offer the convenience of through tubing application. Figure 5 presents such a tool. The centralizer arms are spring loaded, interlocking, and operated with surface power very similar to the arms of a microcaliper. When not expanded, the arms fold flat into recessed grooves and do not protrude past the O. D. of the tool. The arms are expanded just prior to a series of velocity measurements and left expanded until the measurements are completed, or until it is necessary to lower the tool for tracing runs or other operations.

Centralization of the tracer tool minimizes erratic velocity measurements by measuring in a comparable velocity vector throughout the entire section to be surveyed. Thus centralization not only minimizes the erratic measurements, but also reduces logging time which results in less cost to the customer. In cased holes or gauge open holes, the centralized tool almost completely eliminates erratic measurements. In open holes where the borehole diameter changes only moderately, erratic measurements are held to a minimum. Shot holes still remain a problem.

A discussion of Fig. 7 will explain what is meant by erratic velocity measurements. This figure compares velocity shots in an open hole completion with both the centralized and non-

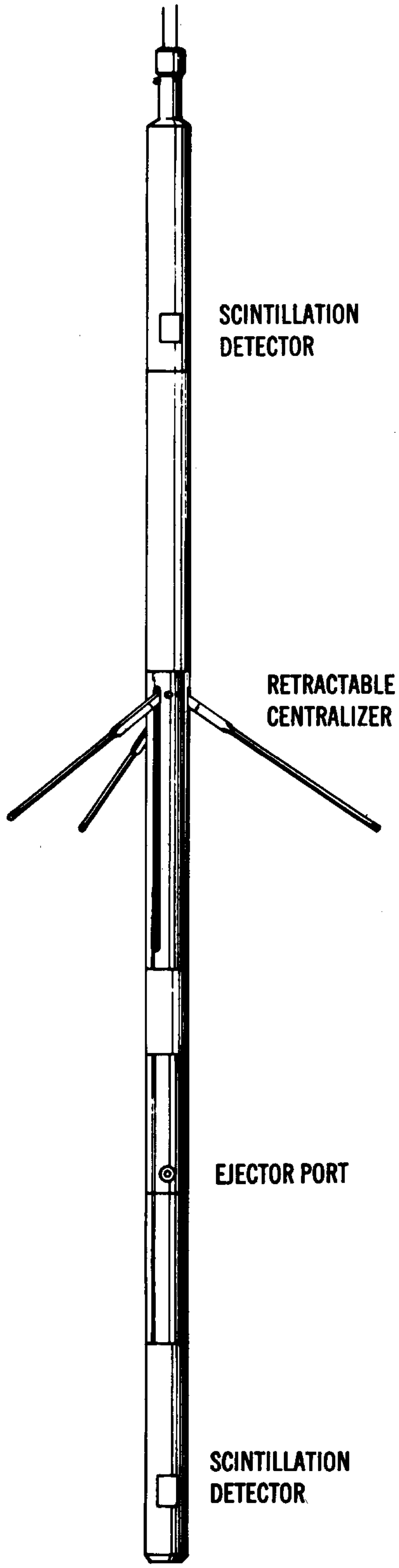


FIG. 6
CENTRALIZED TRACER EJECTOR TOOL

centralized tools. These surveys were run on the same well, one right after the other. Velocity shots were made at the same point with each tool. Note that some of the measurements with the non-centralized tool result in larger volumes of fluid moving below points of lower volumes. These occur at depths of 5090 ft, 5110 ft, 5130 ft, 5150 ft, 5170 ft, 5180 ft, 5190 ft. and 5210 ft. This is quite common with non-centralized tools. In comparison, volumetric rates as determined by velocity shots with the centralized tool exhibit a definite trend of continuity. Only one erratic measurement is indicated at 5130 ft, a definite improvement over the non-centralized tool.

The tool with a single centralizer located near the ejector port provides excellent results in non-directionally drilled wells where the deviation is only slight. The tool can be adapted with an additional centralizer section enabling centralization in directionally drilled holes of any deviation. Thus, analysis of downhole fluid movement can now be done accurately with tracer tools in directionally drilled holes.

SCINTILLATION DETECTORS vs. GEIGER COUNTERS

Scintillation detectors have replaced Geiger counters (Geiger-Mueller Tubes) as gamma-ray tools for primary logging because they are considerably more sensitive to natural formation radiation and provide a better description of lithology. This, the industry has recognized and accepted. With tracer tools, however, the Geiger counter is still the most commonly used gamma-ray detector. There are arguments that since the induced radiation from the radioactive isotopes introduced into the wellbore is many times greater than the natural formation radiation, the Geiger counter is an adequate gamma-ray tool for tracer surveys. For velocity measurements, when the isotope is in the fluid stream immediately adjacent to the tool, there is no doubt that the Geiger is adequate. When tracing channeling and communications, however, the scintillation detector is far superior. Figure 8 is a plot of tests conducted comparing the detection efficiency or depth of investigation of scintillation detectors and Geiger counters.

These tests were conducted in a test chamber as shown in the upper right of this figure. A 2⅞-in. casing was cemented in the chamber and one-half-inch holes were spotted at distances ranging from 2 to 16 in. at 2-in. increments. The chamber was immersed in water and tests were

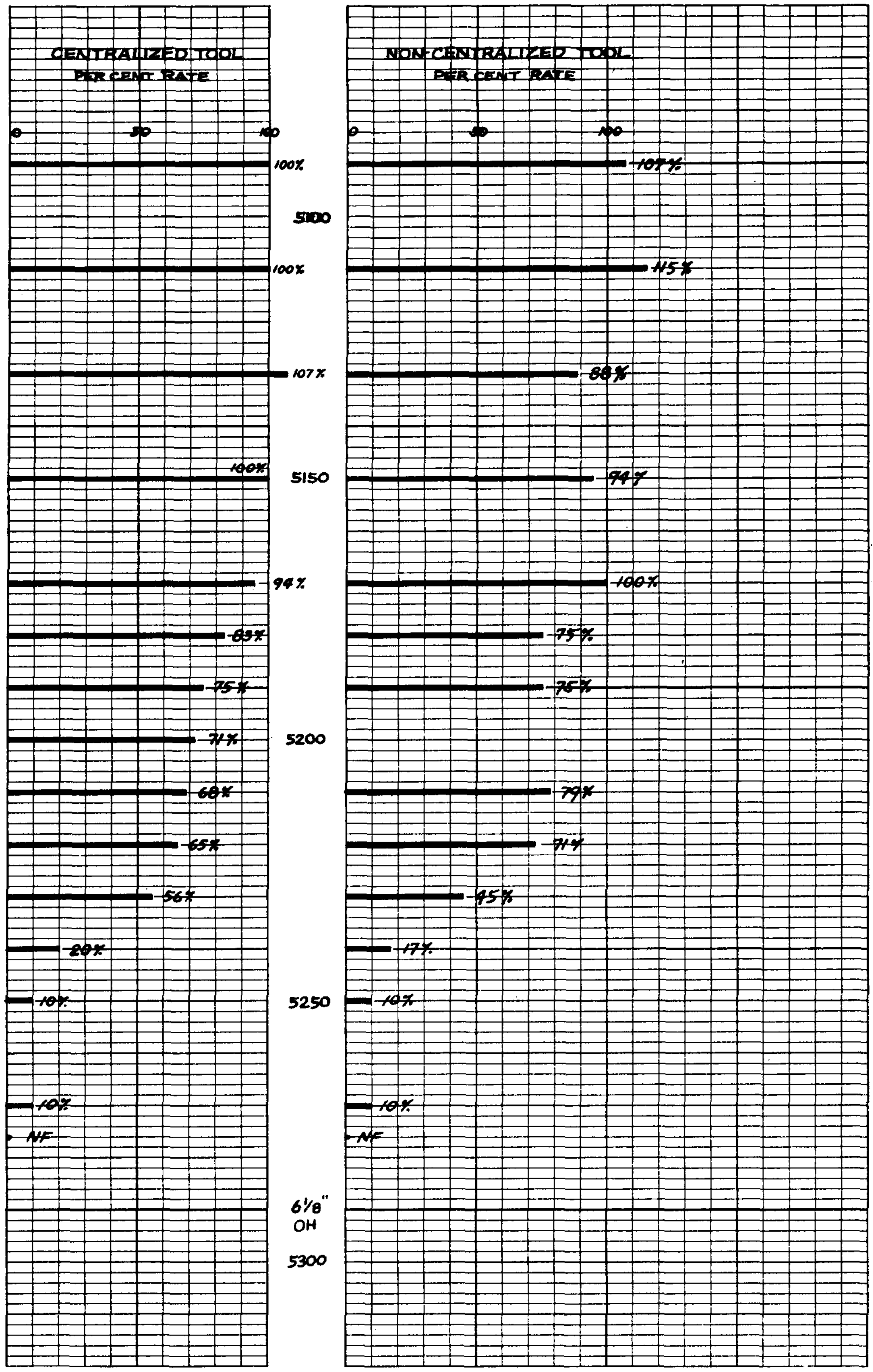


FIG. 7
COMPARISON OF VELOCITY MEASUREMENTS
BY A CENTRALIZED TRACER TOOL
WITH A NON-CENTRALIZED TOOL

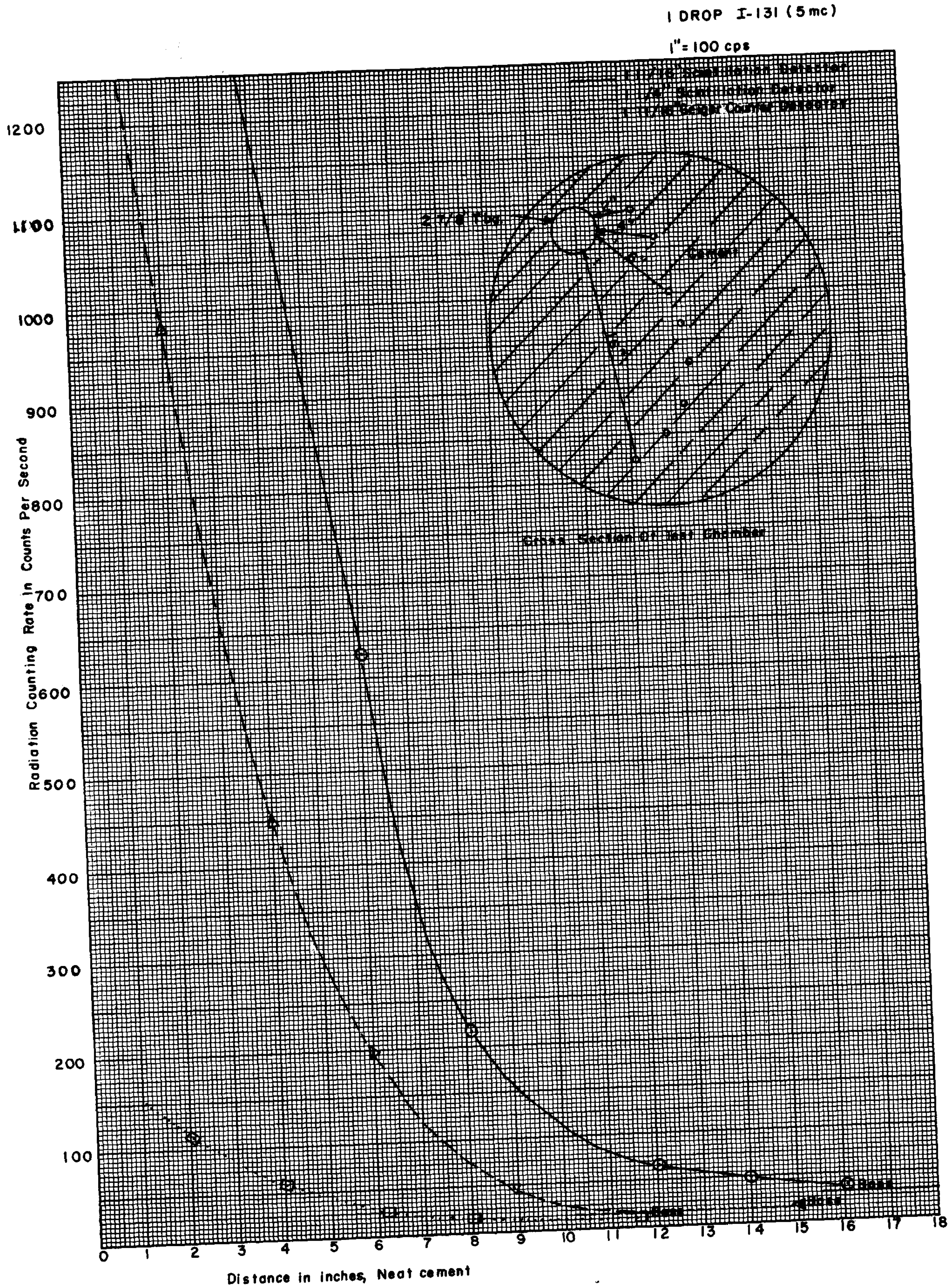


FIG. 8
COMPARISON OF SCINTILLATION DETECTOR WITH GEIGER COUNTER

run on three tools, a 1-11/16-in. O.D. scintillation tool, a 1¼-in. O.D. scintillation tool and a 1-11/16-in. O.D. Geiger tool.

The tools were centered in the 2⅞-in. casing and one drop (equivalent to a 1½-sec ejection) of I-131 of 5 mc strength, was put in a small glass vial 1½-in. long. I-131 has a Mev rating of 0.364 and a half life of 8.1 days. After a base log was run without any induced radiation, the vial was then lowered into each of the holes and the radiation counting rate was recorded. The calibration or amplification of the recording equipment was set at 1-in. equals 100 counts per second, which is fairly standard tracer logging amplification. The radiation counting rate in counts per second was plotted against thickness of cement for each tool. The 1-11/16-in. O.D. scintillation detector, as shown by the solid line, recorded off scale, i.e., above the maximum recording rate of the surface equipment, at the 2 and 4-in. distances. A small amount of deflection above base was still being recorded at 16-in. This deflection above base was so small it was necessary to scale it off on the recording chart to actually determine its existence.

The results of the 1¼-in. O.D. scintillation tool are presented as the dashed or broken line. The 1-11/16-in. O.D. Geiger tool recorded a counting rate as shown by the dotted curve. These tests were run to show the difference between the ability of the two types of detectors and should not be construed to represent downhole conditions. It is highly unlikely that the amount of radioactive material used in these tests would ever be concentrated in a 1½-in. section in a channel. The point is that the probability of detecting a channel with a scintillation detector is much greater than it is with a Geiger counter.

TOOL CONFIGURATION

One of the most important aspects of profiling by velocity measurements with tracer tools is the tool configuration. The length of the measuring sections of different tools varies slightly but all are generally five ft. or greater. Since velocity calculations are subject to more error when profiling on shorter increments than the tool spacing, profiles should not be detailed over less than the tool spacing except under cetrain conditions. Walker, Sherwood, Sumner and Marshall[2] have presented a method of calculating velocities for increments shorter than the measuring section of a tracer tool. This method applies to velocity shots across intervals taking fluid and is valid only under the assumption that the fluid loss is uniform over that interval. Suppose, for example, that distribution of fluid is wanted over 2-foot intervals. With tool configuration of 5 ft. or more, it would be necessary to overlap the tool setting as shown in Fig. 9. When the tools are overlapped, the accuracy of each velocity at succeedingly lower points is dependent on the accuracy of the velocity immediately above it. Consequently, one erroneous velocity measurement magnifies the error in all of the succeeding velocity determinations. Velocity 1 (V_1) at station 3, Fig. 9, is equal to V_2 at station 2; V_1 at station 4 is equal to V_2 at station 2, and so on. Consequently, an inaccurate V_2 at station 2 would automatically affect the accuracy of the velocity determination at station 4.

In cased holes it is not necessary to calculate volumetric rates. The fluid distribution can be detailed over 2-ft intervals by velocities alone provided all velocity measurements are accurate. Open holes present more of a problem since borehole size changes can affect both velocity measurements and the resultant volumetric calculations.

Another approach to profiling over smaller increments is to change the tool configuration. As shown on Fig. 10, the velocity measuring section of a tracer tool can be shortened for simplification of shorter increment profiling. Considering a tool where velocities are measured from a positive ejector to a gamma detector, the actual physical spacing is 5.5 ft. With scintillation detectors, a response from the radioactive slug is recorded one foot above the detector. Therefore, the effective spacing is 4.5 ft. By turning the detector section upside down and inserting a 2-ft spacer, a physical spacing of 3-ft results with an effective spacing of 2-ft. With this spacing, the accuracy of velocity measurements are not dependent on the accuracy of any other velocity measurement above it. Also, this smaller spacing allows accurate measurement of velocities between closely spaced perforated intervals. Readings can be made in the blank intervals between perforations as short as 3-ft.

The one limitation to the shorter spacing is that fluid velocities must be less than 2-ft/sec. Accurate velocity shots are impossible at rates higher than 2-ft/sec.

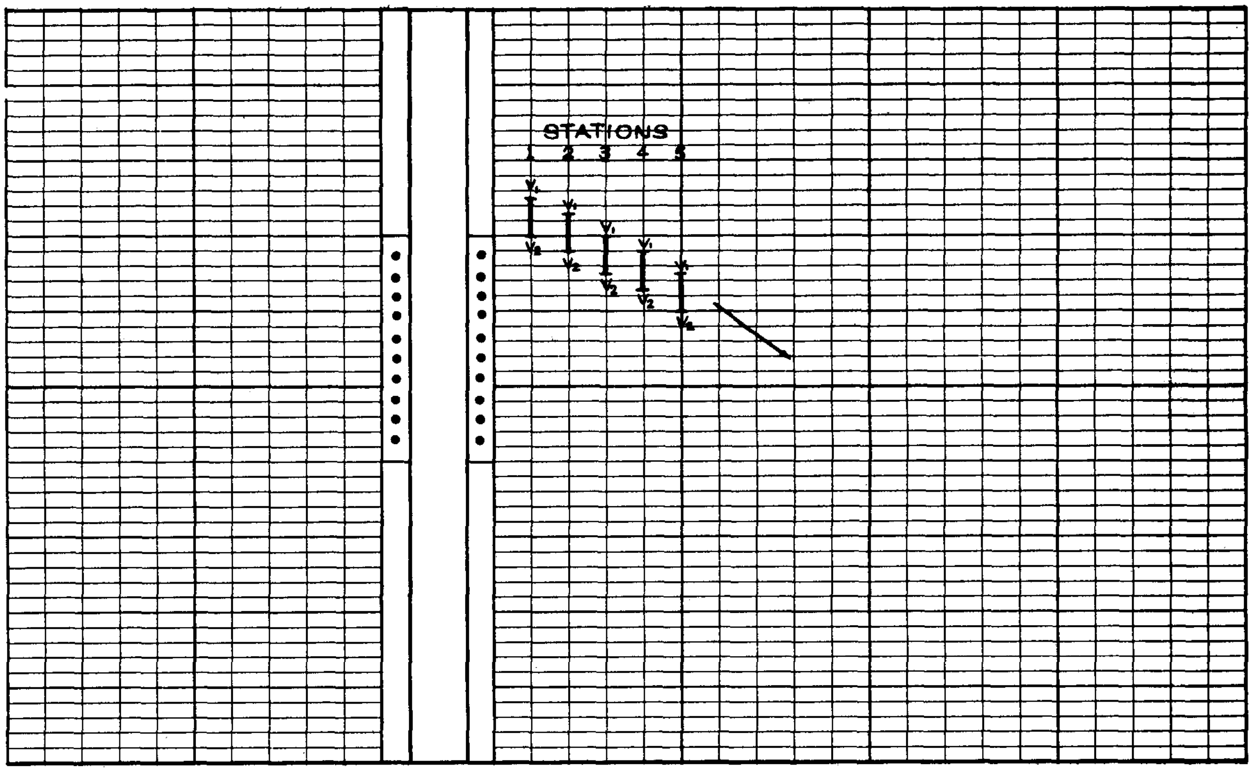


FIG. 9
TOOL OVERLAP FOR SHORT INCREMENT PROFILING

SOLUBLE vs. INSOLUBLE RADIOACTIVE ISOTOPES

The first radioactive tracers run for tracing downhole fluid movement utilized an insoluble radioactive isotope. The problems with the earlier radioactive tracers were not only with tools and techniques, but also the fact that at best, only qualitative results were obtained. Although tools and techniques have improved considerably, the use of insoluble or "plate-out" isotopes still does not provide sufficient data for a thorough and complete analysis of downhole fluid movement. Some improvement results from the use of soluble radioactive material. The following presents a comparison of soluble and insoluble isotopes.

The soluble materials is readily adaptable for velocity shots where most of the insoluble material is not. Some of the insoluble material can be used for velocity measurements but when it is used with tools that are capable of measurements, the amount of material introduced into the flow stream is a small fixed amount. This limits the actual tracing of the material. In most cases, where insoluble material is used, a large slug is dumped or ejected and logging runs are made to watch dispersal of the radioactive slug. As the insoluble isotope "plates out" on the formation over the intervals taking fluid, a radioactive increase or "hot-spot" is recorded. A study of the gamma-ray trace showing these "hot-spots" results in a qualitative analysis of where the fluid is going. In comparison, when tracing with soluble radioactive isotopes, "hot spots" do not result unless there is no fluid movement. Dissipation of radioactive intensity indicates the zone's taking fluid when soluble isotopes are used. Here again, tracing of soluble material gives only qualitative results; however, with tracing (logging) runs and velocity measurements, a complete survey is obtained with the soluble material. The operator should know which type of radioactive material is being used to analyze the fluid movement in the well, because interpretation of the two types are different.

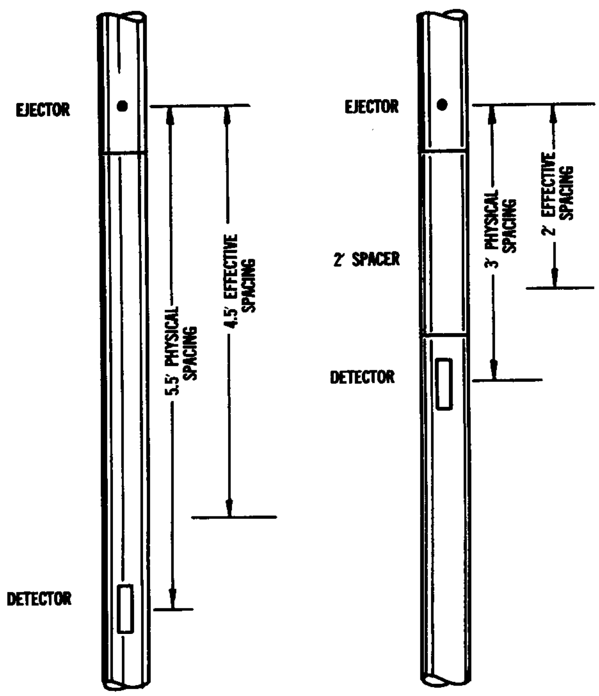


FIG. 10
TRACER TOOL CONFIGURATION

Efforts have been made to come up with a satisfactory method of profiling wells by measuring the radioactive intensity of the "hot-spots" resulting from the insoluble material. One of the methods used is to planimeter all of the increases in intensity above base intensity on the gamma-ray trace and allocate, percentage-wise, the fluid to these intervals on the basis of the area under the increased intensity. Theoretically, this method has merit. In application, however, too many variables exist to make it practical. All substance has some amount of gamma-ray absorbing power, whether the material is air, water, cement, steel, sandstone or limestone. The effect of each will vary, and is generally expressed as the half-value thickness (HVT). The denser the substance, the greater the gamma-ray absorbing power or the smaller the HVT.

Profiling by planimetering the radioactive "hot-spots" is satisfactory if the insoluble isotope "plates out" on the formation face and the gamma-ray detector tracing the isotope remains equi-distant from the formation face throughout the logging run. In fractured reservoirs, some of the insoluble isotope can often be carried into the fracture several HVT's from the tool. In this case, what would appear to be an insignificant amount of radiation, and consequently, would indicate an insignificant amount of fluid entering the formaiton at that point, could actually be a major portion of the total fluid being injected. Since it is almost impossible to know just when this condition exists, it is likewise impossible to know when the profile, as determined by planimetering radiation "hot-spots", is accurate.

Another problem with insoluble isotopes is their relatively long half-life. I-131, the most commonly used soluble isotope has a half-life of 8.1 days. After approximately 40 days, I-131 will have dissipated to the point that it will no longer affect gamma-ray logging. On the other hand, the insoluble isotopes have half-lives of 64 days and longer; thus the time that it will affect gamma-ray logging is considerably longer.

CONCLUSION

Too many times in the past, operators, either through lack of knowledge of tools or lack of proper investigation of the problems and conditions of wells, have not received optimum information for the dollar spent. The selection of the proper tool for the particular situation can result in a more refined survey substantiating, to some extent, the old cliche, "The end justifies the means."

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