New Developments in Radioactivity Logging for Well Completion and Secondary Recovery

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ABSTRACT

Along with the development of new tools there are continuous improvements of existing tools and techniques. It is the purpose of this paper to review some of the new radioactivity tools that have been developed and also review some of the existing tools that have undergone significant improvements. The following major subjects are discussed:

The casing potential profile, the densilog, small diameter radioactivity instruments, radioactivity tracer injector, and the perforating-formation collar chart. The interpretation of radioactive tracer surveys and porosity determinations from the neutron curve will also be discussed.

Because of the number of subjects covered, the explanations are brief and confined to the theory of operation, the significant improvements, results obtained and the advantages to be derived from their use.

INTRODUCTION

The successful completion of an oil well presents many problems. Fortunately, there is usually a tool or a technique that will solve these problems. Quite often, however, it is not realized that such a tool or technique exists and the problem is left unsolved or it is solved in a manner that is far more costly than it should be. This is caused, in part, by insufficient information regarding various tools readily available.

Usually a tool or technique in interpretation is publicized when it is first developed. Later, improvements may greatly extend the usefulness of the tool or technique, but in many cases these improvements are not publicized. Consequently, many are not aware of the full potentialities of the available tools and techniques. This paper will try to highlight some of the recently developed tools and techniques and improvements so that the solution to some of the problems that beset the petroleum industry can be more easily and economically solved.

THE CASING POTENTIAL PROFILE

Casing failure has long been a thorn in the side of the production man. A very large percentage of casing failure is caused by external casing corrosion. At the present time there is a sharp upward trend of interest shown in the detection of external casing corrosion and its control. One of the more effective methods of detecting corrosion is the casing potential profile. The more common method used to correct the corrosive condition is to apply current to the casing from an external source.

The casing potential profile is merely a profile or a plot of the differences of potential that exist between various points in the string of casing. This difference of potential or voltage drop that exists between two points in the casing is caused by the current flowing in the casing between these two points. Since the resistance of the casing is known, it is possible to calculate the magnitude of the current flowing between two points by using the casing resistance and the voltage drop between these two points. Therefore, a polot of the potentials that exist between various points in the casing will reveal the points at which current is entering or leaving the casing.

Current Flow

The current flow in the casing is caused by electrolytic or "battery" action between different formations. The point at which the current leaves is the point of corrosion. The speed at which the corrosion is progressing can be determined by the magnitude of the current leaving the casing and by the length of casing in which this corrosion action is taking place.

It is possible to prevent current from leaving the pipe at these points of corrosion and thereby prevent any further corrosion. This can be done by applying current from an external source to the casing. A casing potential profile survey made after the application of external current will confirm whether or not the corrosion areas have been nullified. Because of the number of subjects to be covered in this paper, space does not permit any detailed discussion of corrosion or the protective techniques. However, the references shown at the conclusion of the paper give a rather complete coverage of all phases of the corrosion problem.

Casing Potential Profile

The equipment used to obtain a casing potential profile is fairly simple. Both the surface and the subsurface equipment is shown in Fig. 1. The original equipment has been redesigned to simplify and stabilize its operation.

The subsurface equipment consists of two electrodes that may be separated any desired distance by selecting the proper length spacer which is merely a section of

2" pipe. These electrodes are insulated electrically from each other and from the spacer. Contact is made with the casing by three spring loaded knives in each electrode. The knives have a tip that is extremely hard which allows them to dig into the casing slightly to establish a good electrical connection.

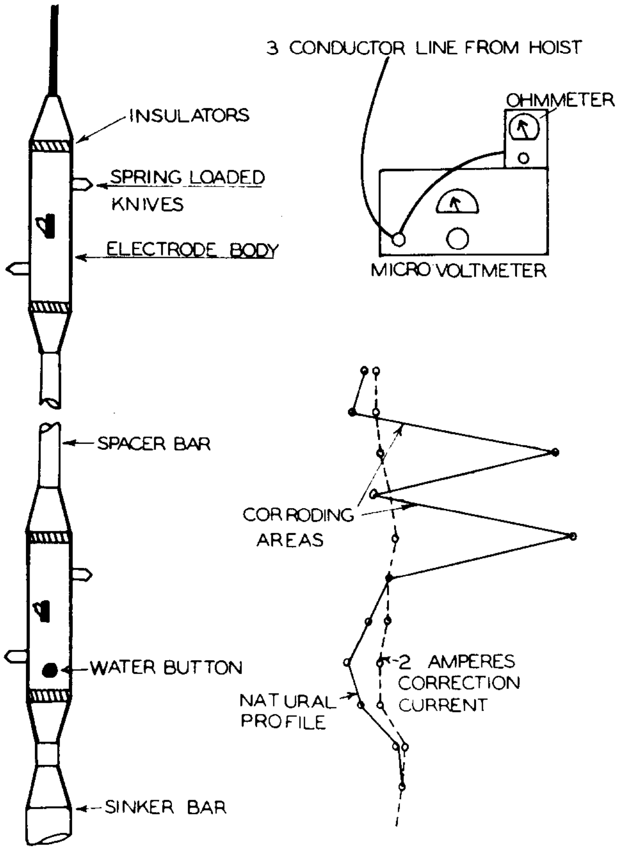


FIG I CASING POTENTIAL PROFILE (EQUIPMENT & RESULTS)

The electrodes are run on a three-conductor wire line. One conductor goes to each electrode and the third conductor goes to a "water button" on one electrode. This makes it possible to obtain a comparative resistance reading of the borehole fluid at any time during the survey. It is desirable to run the survey with no fluid or with oil in the hole. A borehole fluid with a low resistance usually causes electrolytic action and results in a false reading.

Micro-Volt Meter

A stable, direct reading, micro-volt meter is connected to the electrodes through the three-conductor wireline. This voltmeter has a very high input impedance and therefore draws an extremely small amount of current. This minimizes any error that might exist because of poor electrical contact between the electrodes and the casing.

Usually the electrodes are spaced 25 feet apart and readings are taken at 25 foot intervals. When a reading is taken, the knives are set by slacking off on the wireline. The micro-volt meter on the surface will then indicate the potential difference between the two points in the casing at which the knives are set. Although it is not a continuous logging process, reading at 25 foot intervals can be taken at the rate of about one per minute, thereby approaching an average logging speed of 25 feet per minute.

Results of Survey

Fig. 1 shows a typical casing potential profile plot before and after protective current has been applied to the casing. Note that the corroding zones shown on the first run do not exist on the run made after the protective current has been applied. The slope of the casing potential profile indicates the points where the current is entering or leaving the pipe.

Starting at the bottom of the profile and working up, all areas where the profile slopes upward to the left are corroding areas where current is leaving the pipe. If the slope is to the right, current is entering the pipe and no corrosion is taking place. When the profile has a zero slope, current is neither entering nor leaving the pipe and, of course, no danger areas exist.

Conclusion

In a field where corrosion is a problem, the casing potential profile is a very valuable survey. It indicates the zones in which corrosion is taking place and will also indicate whether or not corrective measures have been successful. A few wells surveyed in an area before and after corrective current has been applied will indicate the minimum amount of current that is necessary (in that area) to prevent corrosion. This results in an economical corrosion prevention program.

THE DENSILOG

The densilog is becoming well established as a log that will consistently give reliable density and porosity readings regardless of the type or salinity of the borehole fluid. It is an open hole log and operates on the principle of the absorption of gamma rays being proportional to the density of the material through which they pass. There are a number of control devices in industry that work on this same principle. They are used primarily to measure the thickness of materials that have a constant density.

Obtaining the density of the formations in an oil well is more difficult than most density measurements by the gamma ray method because the gamma ray detector is in the same vertical plane as the gamma ray source. Therefore, the formation to be measured cannot be directly between the detector and the gamma ray source.

Theory of Operation

The densilog instrument is shown in Fig. 2. The gamma ray source and the detector are well shielded on all sides except the side that is being pressed against the formation by the bow spring. Because of this heavy shielding, nearly all the gamma rays that reach the detector must come through the formation. Gamma rays travel in a straight line unless they are "scattered" by colliding with the electrons in the material through which they are passing. This "scattering" is known as the compton effect.

Each time a gamma ray strikes an electron it changes direction and loses some of its energy. The gamma ray may undergo a number of collisions and direction changes before it reaches the detector. The electrons in the formation increase in number as the density increases, thereby increasing the chance of multiple collisions by a gamma ray before it reaches the detector. The more energy the gamma ray loses, the more readily it is absorbed by the photoelectric effect, which is another method by which gamma rays are absorbed in their travel through matter. The net result is that fewer gamma rays are detected as the density of the formation increases.

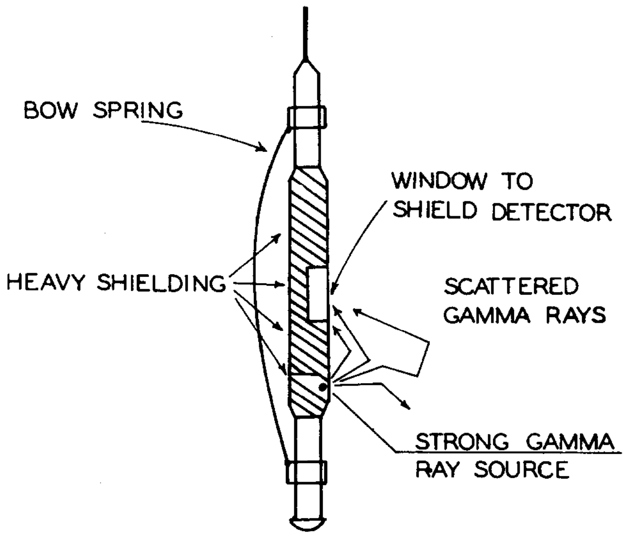


Fig. 2 DENSILOG INSTRUMENT

The gamma ray source commonly used with the densilog equipment is cobalt 60. This source constantly decreases in strength and has a half-life of 5.3 years. A curve for each source makes it possible to determine the source strength at any time. As the source strength decreases, the sensitivity on which the log is run is increased, so that the log will always be about the same size regardless of the source strength.

Density Determinations

To accurately determine densities, the response of the instrument to materials of known density in various hole sizes and mud weights is measured and calibration curves or charts are prepared that will permit the determination of density in different hole sizes and fluid weights. A chart of this type is shown in Fig. 2A. To determine density with this chart it is necessary to multiply the sensitivity on which the log was run by the source strength. This factor is then located on the vertical scale on the left of Fig. 2A. From this point move horizontally to the right until the line denoting the proper hole size is intersected, then place this point on the zero reference line shown on the log.

The density of any point may then be determined by noting where the point of interest lies on the density scale. If the scale is on opaque paper, it can be folded at the point representing the sensitivity multiplied by the source strength. This will allow the density to be

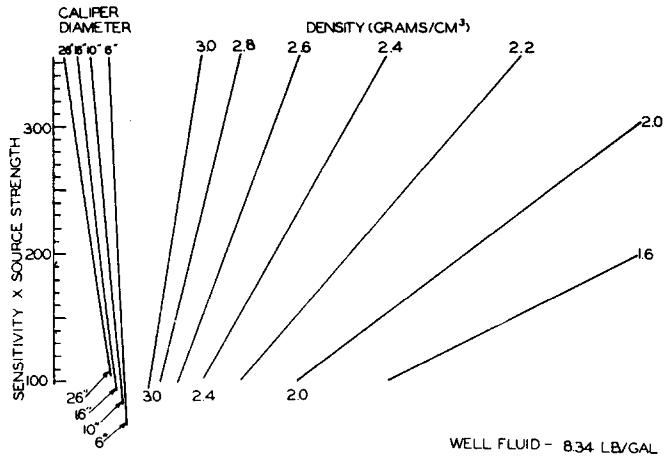


Fig. 2 A DENSILOG SCALE

determined in the same manner that one would use a ruler to determine inches from a zero reference point.

Caliper Log

It is very important to use a caliper log in conjunction with the densilog. This gives the correct hole size to be used with the densilog scale or chart. It will also indicate the points at which the hole is so badly washed that the logging tool cannot make proper contact with with sides of the borehole. If the tool does not make good contact with the formation, much of the response can be attributed to the borehole fluid.

In an extremely large washed out section the density measured will be that of the borehole fluid only. Fortunately, most of the zones of interest do not wash enough to prevent accurate density readings. The effect of the borehole enlargements on the densilog is illustrated in Fig. 2B. The section from 7750 to 7800 is so badly washed that the densilog is of little value in this section.

Porosity Determinations

Accurate determinations of porosity can be obtained from the densilog if the grain density of the formation

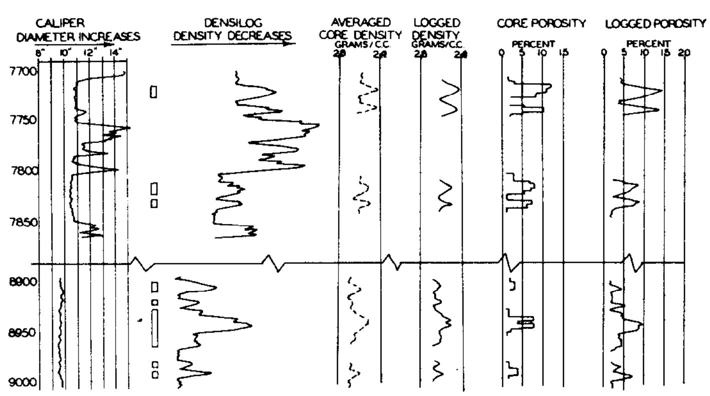


Fig. 2 B COMPARISON OF DENSILOG & CORE DATA

in question is known. Usually, this value is known. Some commonly accepted values are 2.65 grams/CM^3 for sand, 2.71 G/CM^3 for limestone and 2.85 G/CM^3 for dolomite.

The formula shown below is one method of obtaining the porosity from the densilog data and the grain densities.

$$\phi = \frac{D_G - D_B}{D_G - D_F}$$

D_G = Grain Density or density of matrix material
D_F = Density of fluid filling pores
D_B = Bulk Density (taken from densilog)
ϕ = Decimal Porosity

This formula gives accurate porosity readings. However, in order to avoid the numerous computations necessary to evaluate a log, it is much simpler to prepare a scale showing the densilog response for values of porosity such as 5, 10, 15, 20 percent. Of course, it will be necessary to prepare a different scale for each grain density that is to be used. The formula shown below is used to construct this scale.

$$D_B = D_G - \phi (D_G - D_F)$$

Example:

Sand (D_G = 2.65)
D_B = 2.65 - .05 (2.65 - 1.00)
D_B = 2.567 G/CM^3 for sand with 5% porosity.

Porosity Chart

A completed porosity chart is shown below for the grain densities of 2.65 G/CM^3, 2.71 G/CM^3 and 2.85 G/CM^3. These values are considered by many to be the best values to use for sand, limestone and dolomite respectively.

POROSITY	DENSITY		
	D_G = 2.65	D_G = 2.71	D_G = 2.85
0	2.650	2.710	2.850
5	2.567	2.625	2.757
10	2.485	2.539	2.665
15	2.402	2.454	2.573
20	2.320	2.368	2.480
25	2.237	2.282	2.387
30	2.155	2.197	2.295

The porosity values obtained by use of the densilog compare favorably with those obtained by core analysis. However, it must be realized that the porosity obtained by the densilog is an average of a one to two foot section. On the other hand, the porosity obtained by core analysis is usually a very small section. Two cores taken six inches apart may vary widely in porosity. It is felt that in many cases the densilog, because of its ability to average large sections, will give porosities more representative of the formation than those obtained by coring.

Applications and Results

Fig. 2B shows the comparison of the density and porosity values obtained by core analysis and those obtained from the densilog. The upper section of this illustration is sand and shale formations. The lower section is limestone.

In addition to obtaining the density and porosity under all borehole fluid conditions, there are a number of instances in which the densilog has considerable value when making difficult interpretations. Among these is the picking of dolomite sections in limestone, distinguishing between lignite streaks and producing formations and evaluating other type formations which have a characteristic density but appear to be producing zones of sand, lime, etc. on other logs.

Conclusion

The Densilog gives reliable density and porosity values regardless of the type fluid in the borehole. It is much more economical than coring and usually will give all the necessary information that is obtained from the core analysis. The log is very helpful in making difficult evaluations. It is quite possible that the Densilog will become a major log in most well completions.

Radioactive Tracer Applications

The use of radioactive isotopes to study well problems is a standard practice today. The radioactive isotope is prepared in a suitable form and strength for a particular well and is injected into the well. A gamma ray instrument is used in locating the radioactive material or in tracing the movement of fluid in the well. Typical isotope preparations include radioactive fluid (oil or water), sand, resin, and gas.

Typical applications include location of top of cement, of squeeze cement and plastic, of fracturing material, acid, holes in casing and tubing, circulation zones, channel in cement, injection profile (permeability study), and oil or liquified petroleum gas - salt water interface and possibly more.

RADIOACTIVITY LOGS IN WATER FLOOD

Fig. 3 is an example of the use of the radioactivity log to study the injection profile in a water injection well. This is a reef limestone reservoir, and water is being injected to the entire open hole section below 7" casing. The base gamma ray curve (dotted curve) is recorded on a low sensitivity prior to any injection of radioactive tracer material.

In this well 5.9 millicuries of iodine 131 in particle form, 50 to 100 mesh, was forced into the flow line with 1500 lbs. of air. The logging was performed with a 1 3/4 inch diameter gamma ray instrument lowered through the tubing on a 3/16 inch diameter line and a special flow-by tube. The wireline control head actually reduces pressure on the cross sectional area of the cable so that the instrument may be raised or lowered with a minimum of weight. Logging may then continue while injecting. The tracer in water was injected at the rate of 2650 barrels per day at 500 lbs. pressure.

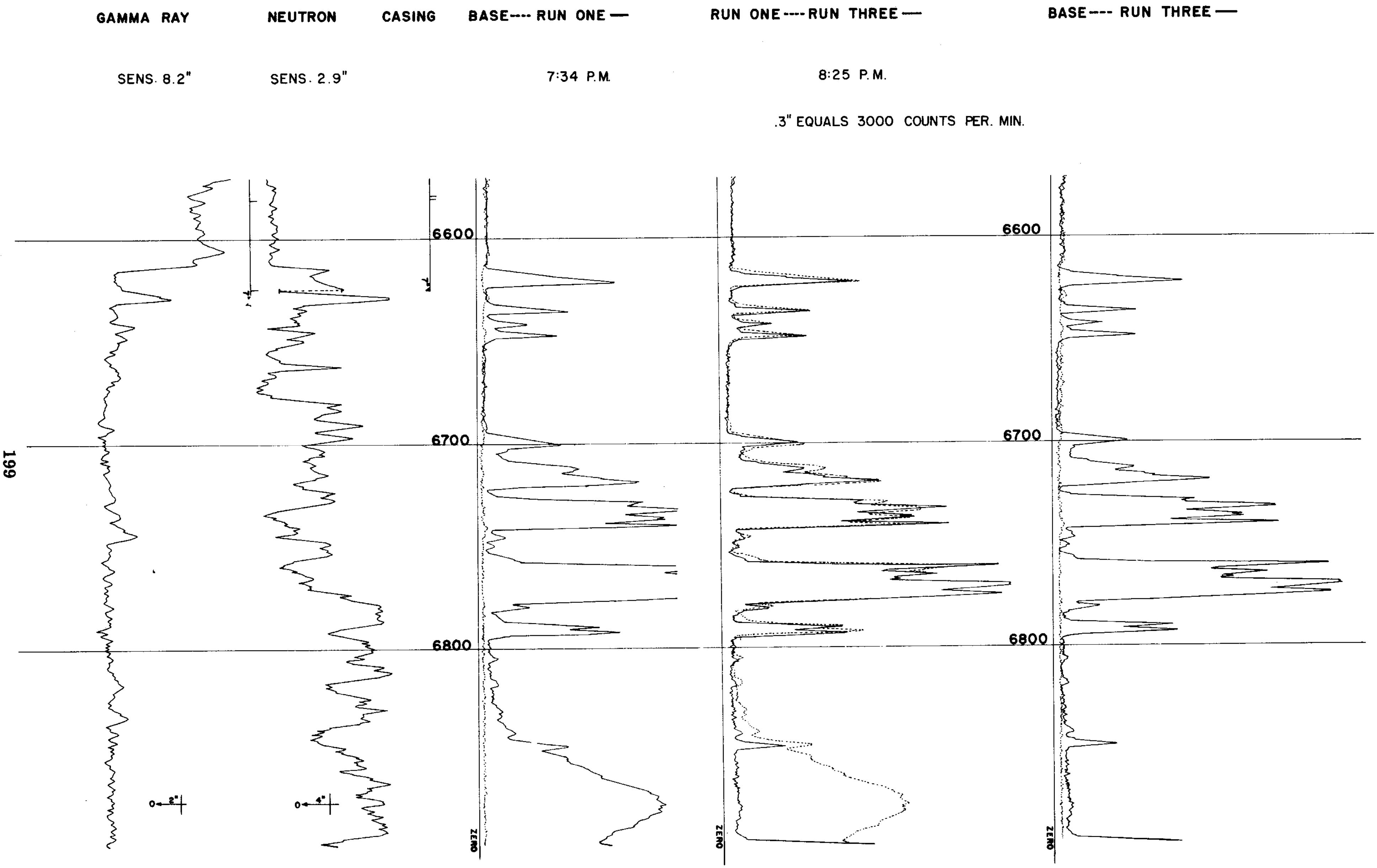


Fig. 3

INJECTION PROFILE – INPUT WELL

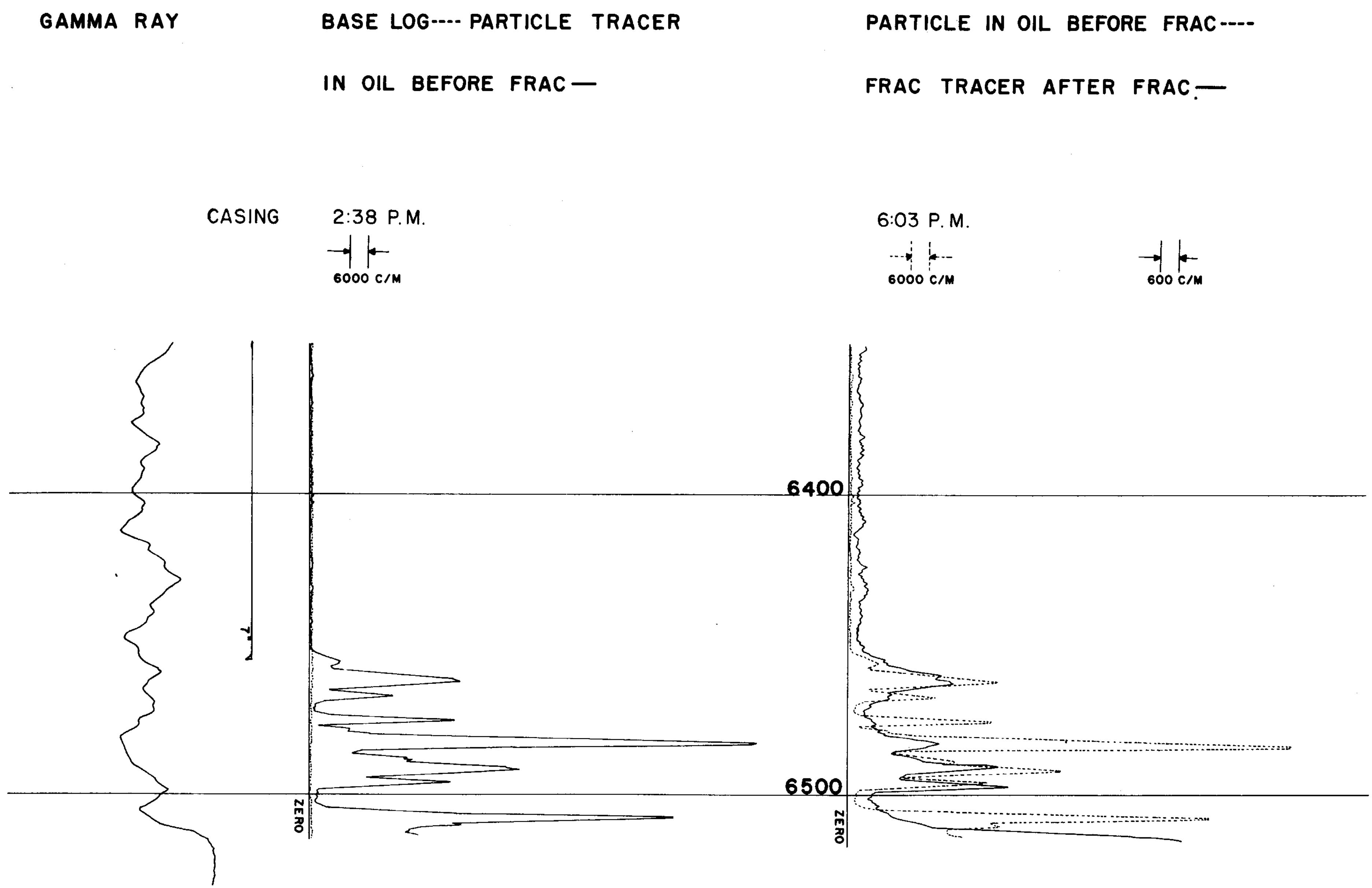


Fig. 4 LOCATION OF RADIOACTIVE SAND

Leak Is Shown

Run No. 1, recorded 2 hours and 34 minutes after forcing the material in the flow line, shows several major zones from 6696 to 6794 feet taking the water as evidenced by the high gamma ray departure from the base log. The remainder of the tracer slug is seen from 6846 feet to the bottom of the hole. This departure at the bottom disappears as injection continues, and on the final run it appears that some of the water is going out the bottom of the hole. The kick from 6616 to 6624 feet indicates a leak around the casing shoe. From the high intensities, it would appear that the greater portion of the water is being injected at 6726 to 6742 feet, and 6758 to 6778 feet.

Fracture Treatments

The gamma ray curve in conjunction with radioactive tracers has been successful in the study of formation fracturing. There are several approaches to the study of fracturing, some making use of an injection profile before fracturing, and some after. The comparison of the two profiles should show the sections fractured. Another approach is to activate the particles of sand in the fracture treatment.

Fig. 4 shows a gamma ray curve obtained before casing was set. To the right of the gamma ray (the dotted line) is the base log run prior to injection of any tracer material. The gamma ray instrument was brought out of the hole, and the oil was pumped in at 17 barrels per minute at 3100 lbs. psi to establish the frac rate. After stopping the pumps, the well went on a vacuum in ten minutes. 3.3 millicuries of particle iodine 131 was injected with oil and displaced to the bottom of the tubing at the rate of one barrel per minute. Then 60 barrels of oil was pumped at the rate of 16 barrels per minute at 3200 lbs. psi. Well pressure bled off in approximately 20 minutes, and the solid line gamma ray was recorded indicating multiple zones of fracture. Later the well was fractured using 10,000 lbs. of visco frac with radioactive material, and was pumped in at the rate of 16.5 barrels per minute at 4000 lbs. psi.

After the pressure bled off and the well was cleaned to bottom the after-frac profile was recorded. This profile is presented as the solid line and the before-frac curve is superimposed as the dotted line. Good agreement is seen when the different methods are compared. The differences might be explained by the radioactive sand in the fracture treatment having moved into the formation fractures beyond the range of detection. It is possible, however, that the other zones were more permeable and the majority of the frac went as shown.

In most tracer surveys it is necessary to run the base log, pull out of the hole, run a dump bailer and dump the radioactive material above the zone of interest, pull the dump bailer out of the hole, and run the logging instrument back in. A second method consists of leaving the instrument in the hole after the base log and pumping down the radioactive material from the surface. Each of these methods has obvious drawbacks.

Down Hole Injector

A tracer material injector has been developed to expedite tracer logging. It consists of a sub that is inserted between the top of the logging instrument and the cablehead of the conductor line. The radioactive material is in a container in this sub. It is a sufficient distance from the gamma ray detector to have no appreciable effect on the log. See Fig. 5.

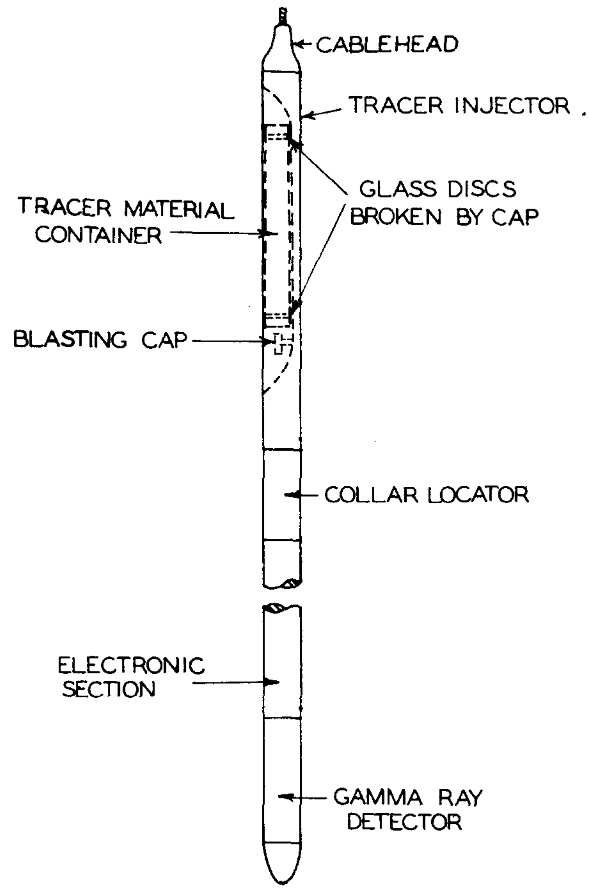


Fig. 5 1 3/8" TRACER INJECTOR

The logging tool, with injector and radioactive material in place, is run in the hole. After completion of the base log, the tool is positioned a desirable distance above the zone to be investigated. The radioactive material is released into the well bore. The tracing job is then performed in a normal manner.

Advantages

The advantages of using a downhole tracer injector are immediately apparent. It eliminates the need to run tools in and out of the hole or to pump tracer material down from the surface. Much less injection fluid will be required than would be needed if the tracer material were pumped down. In addition to these benefits, the tracer material injected a short distance above the zone of investigation will not disperse to any degree; it will if pumped a considerable distance. An injection profile can be relied upon only if it is made under normal injection conditions. This requires a "settling down" period for the well and will be more easily achieved if only one run into the well is required rather than a number of runs.

The need for a downhole tracer injector has been evident for some time. This one, although still on field test, appears to meet most of the requirements of such an injector. It should make its worth felt in certain types of radioactive tracer studies.

THE PERFORATING-FORMATION-COLLAR CHART (P-F-C CHART)

It is now possible to obtain a correlation chart, casing collar log, and to perforate all on one run in the well. This device, which is now on field test, will effect a considerable saving in rig time on wells that require a log for correlation purposes prior to perforating. The perforating-formation-collar chart is not intended to give the same information as a standard gamma ray and neutron radioactivity survey. However, it is adequate if only a correlation gamma ray chart and a collar log are required. Although the device does not have the efficiency of a scintillation instrument, its gamma ray detector is only seven inches long which makes it possible to define fairly thin beds. As a matter of fact, the detector is shorter than nearly all other standard gamma ray radioactivity instruments with the exception of the scintillation equipment. The perforating-formation-collar chart equipment is accurate, dependable and safe.

Instrumentation

The P-F-C subsurface instrumentation is shown in Fig. 6. The instrument can be utilized with either bullet or koneshot perforating equipment. Safety and dependability were prime considerations in the design of the P-F-C equipment. There has been no change in the casing collar locator (CCL) and gun assembly. The P-F-C instrument is simply coupled to a standard CCL and gun assembly.

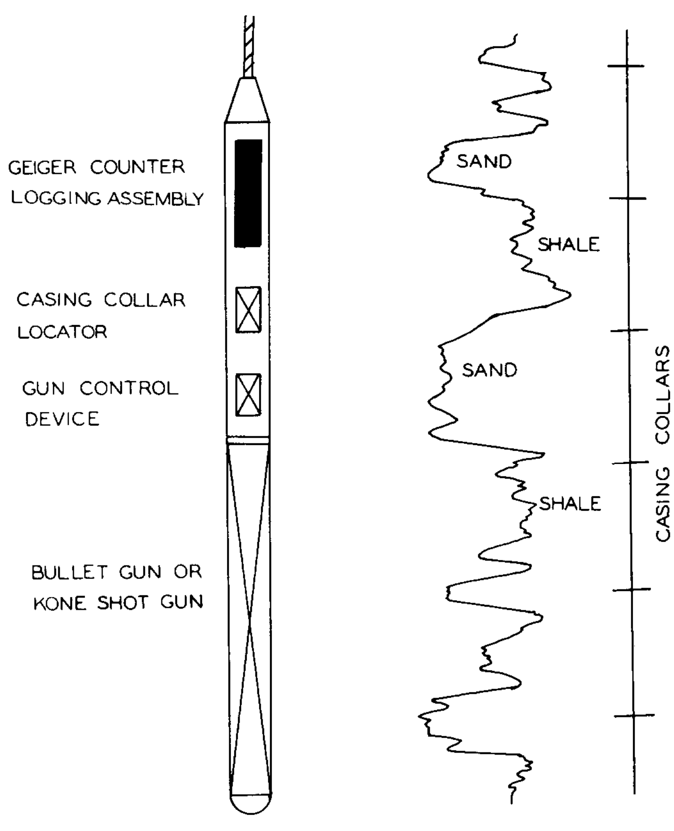


Fig. 6 PERFORATING FORMATION-COLLAR DEVICE

There are several safety features that are of interest. To begin with, the subsurface equipment is operated from a surface power supply that is incapable of producing enough electrical power to fire a gun even if its total output were applied directly to the gun. The power supply's maximum output is only one-tenth the minimum current required to fire the gun. This feature alone would prevent any possibility of the gun firing due to a malfunction of the tool.

Safety Angle

However, to carry the safety angle even further, the gun has a control device, commonly called a controller, which has to be activated more than once for the firing mechanism of the gun to be connected to the line. It would require the combined maximum output of twenty power supplies of the type used with the P-F-C in order to obtain enough electrical energy to activate the gun controller and fire the gun. Both the bullet gun and the koneshot gun utilize the controller as an added safety feature.

The surface equipment consists of a recorder and one panel which contains all the necessary equipment to power the subsurface instrument and to record the gamma ray chart and CCL log. The complete set of equipment is mounted in the hoist truck. The P-F-C chart and the collar log have the same general appearance as a conventional gamma ray and collar log. The surface electronic equipment is very similar to the conventional equipment that is used to record Geiger counter logs.

Advantages

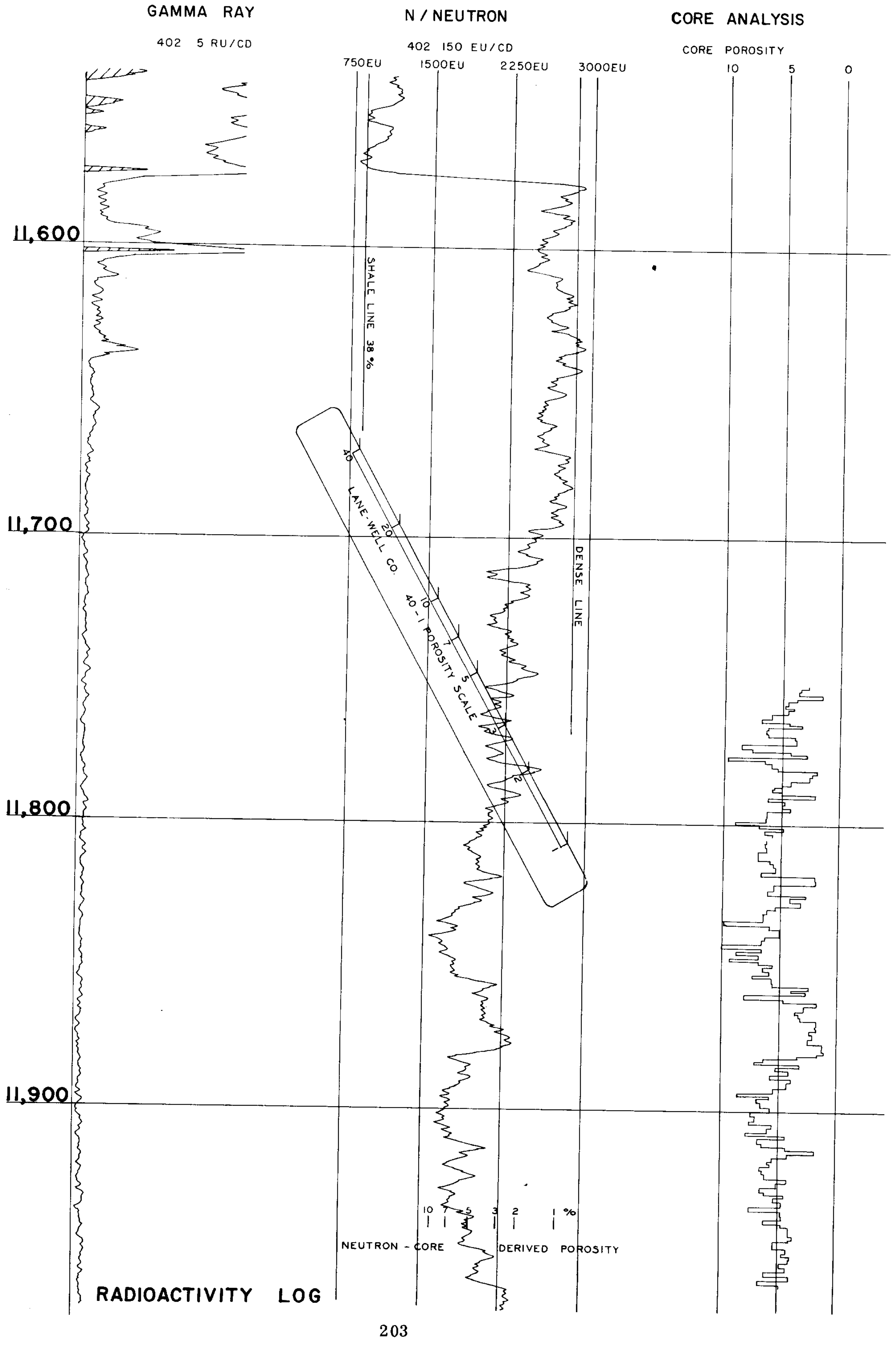
After the P-F-C chart is run, it can be used as a correlation log and the well can be shot in the normal manner without coming out of the hole, since the gun is already attached. In many instances, after the well is perforated, the zone of interest can be relogged and the perforations can be detected with the CCL. This will give a permanent record of the formation and the perforated zone which have been recorded simultaneously. This advantage, along with the advantages of accurately shooting thin zones and a large saving in rig time, make the P-F-C equipment very valuable in dependable and economical well completions.

Conclusion

The perforating-formation-collar chart is a practical method to obtain necessary correlative information, prior to perforating, at a minimum cost. It also assures accuracy in perforating thin zones and offers a possibility of obtaining a permanent record of the perforations.

POROSITY DETERMINATIONS

Several constructive and informative articles have been written on the determination of porosity from the radioactivity log, (1, 2) and this paper will not go into


GAMMA RAY
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N / NEUTRON
402 150 EU/CD
750EU
1500EU
2250EU
3000EU
CORE ANALYSIS
CORE POROSITY
10
5
0
11,600
11,700
11,800
11,900
SHALE LINE 38 %
DENSE LINE
LANE-WELL CO. 40-1 POROSITY SCALE
40
20
10
7
5
3
2
1
10 7 5 3 2 1 %
NEUTRON - CORE DERIVED POROSITY
RADIOACTIVITY LOG

Fig. 7

the same detail. To initially derive curves for specific areas, it is necessary to core a well and plot the resulting core porosity versus the correlated neutron deflection in environmental units. A line is then drawn through the average of the scattering of points. Fig. 7 is a radioactivity log, recorded with scintillation equipment, of the Devonian formation in West Texas. The Devonian in this area is a fractured limestone having a low matrix porosity. To the right, the whole core analysis is plotted and correlated for depth. Fig. 8 is the neutron derived porosity curve resulting from plotting the percent porosity versus the neutron deflection. This curve will now apply to logs run in uncored wells of the Devonian formation in this area.

Another technique that has met with success in determining porosity in uncored wells, where there is no neutron derived porosity curve, is the use of the 40-1 scale. This method requires the selection or choice of numerical values on a dense zone and a good consistent shale. Most shales of the Pre-Permian have an indicated 38% to 42% porosity. This, of course, is not porosity in the true sense of removable fluids.

It can be seen from Fig. 3 that the average shale line above the Devonian formation is recording at approximately 875 environmental units. From Fig. 8 it can be seen that 875 environmental units intersects the average line drawn through the scattering of points at approximately 39%. The dense reference line is selected as the average of the maximum neutron intensities, and, depending on the area, will range from 1% to 2%.

On Fig. 7, at 11,940 feet the neutron derived porosity scale, using the data from the core analysis, has been placed on the log and can be compared with core analysis. At 11,700 - 11,800 feet the scale, using the 40-1 method, has been placed on the log for comparison. Experience in this area has resulted in the selection of 38% for the shale line value and 1% for the dense line.

Method Recommended

This method is recommended in areas where neutron derived porosity (core analysis) curves are not available and reliable shale and dense lines can be drawn. New reference lines should be selected when the following conditions are encountered -- sensitivity changes, fluid to dry annulus, open hole to cased hole, and changes in the type of formation.

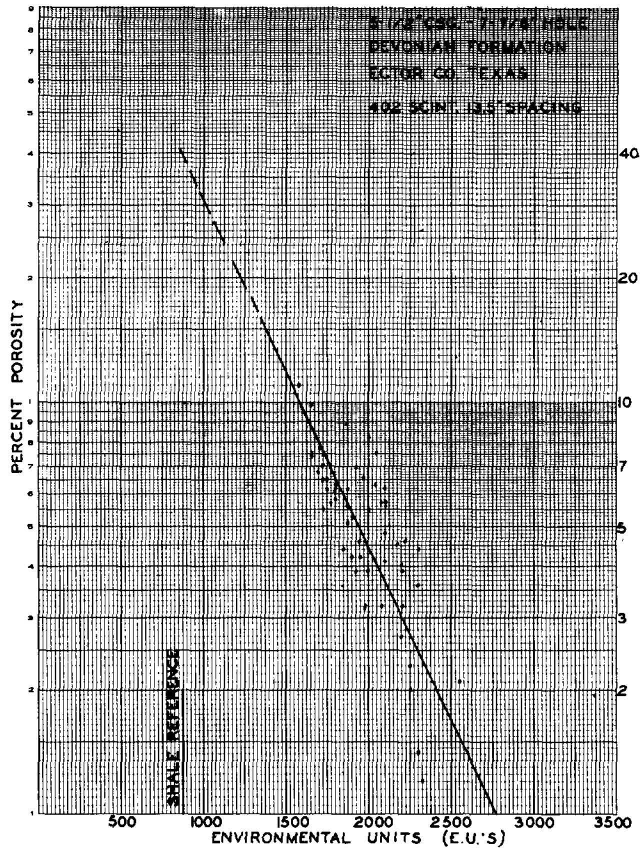

Fig. 8 NEUTRON DERIVED POROSITY CURVE

Last year saw the introduction of neutron conversion charts (4) that provide a means for comparing neutron curve responses obtained under empty or liquid filled open hole conditions in bore holes ranging from 4 to 9 inches in diameter with the neutron instruments operated at various source-to-detector spacings. Given the neutron curve response under one set of borehole conditions, the charts may be used to determine the response which would be obtained in similar rock under a different set of conditions.