Production Logging
or
"I Wonder Where The Oil Bank Went"

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Production logging may be defined as the use of any analytical technique which attempts to determine the subsurface flow path of a fluid. This definition of production logging could therefore include such analytical methods as stratification analysis, step rate tests, pressure analysis and through formation subsurface tracers. Production logging in this presentation will be limited to the tools and techniques used in determining the flow path of produced and injected fluids within and in the vicinity of the well bore.

The institution of secondary recovery projects has increased the demand for production logging, as knowledge of fluid movement within the reservoir becomes essential in evaluating the success of these projects. The development of several types of tools and techniques has resulted in establishing definite advantages and disadvantages for each type of tool or technique. The well conditions and the time at which any survey is run in many cases determines the best type survey or combination of surveys to be used. An understanding of the tools, techniques and their limitations can assist in determining the best survey for your problems.

TEMPERATURE DETECTION TOOLS

One of the earliest tools adapted to production logging was the temperature tool, Fig. 1, commonly used to determine the top of cement in new wells.[8] The temperature sensing element in this type of tool is a resistance wire or a semiconductor which forms one leg of Wheatstone Bridge Circuit. Resistance changes resulting from temperature variations unbalance the bridge and the variations are recorded at the surface.

All logging systems exhibit a characteristic known as time delay. The time delay in a given logging system is a function of the delays in all components. One source of time delay is the response time of the sensing element; another is the response of the recorder. In temperature logging, the response time of the sensing element, the resistance wire, is the time required

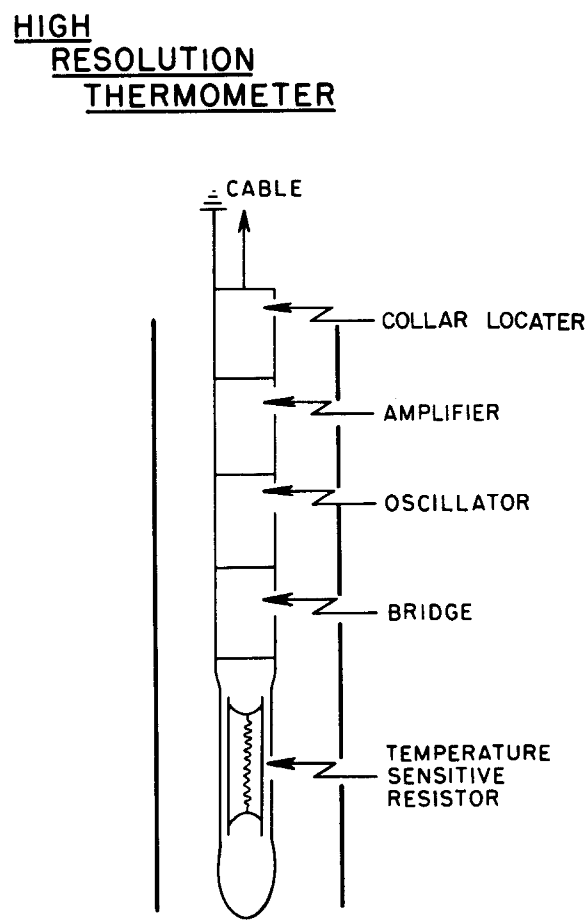


FIGURE 1

for the element to come to the environment temperature. The response time of the recorder is the time required for the recorder pen or the light beam to travel the limits of the recording paper or film. Time delay factors impose limits on logging speed.

Temperature log interpretation is based on controlling one or more variables at a constant rate. One variable is heat transfer. A well in thermal equilibrium implies a constant production or injection rate. Injection rate controls heat transfer into the formation. Temperature logs are also useful in observing changes in heat transfer rates with changes in injection rates. A well in thermal equilibrium and no fluid movement will log the geothermal gradient, (Fig. 2). Figures 3 and 4 depict typical temperature logs on wells in thermal equilibrium, constant injection rate.[3]

Temperature surveys, when applied to production logging, pointed to a need for increased logging sensitivity to delineate small temperature changes. Increasing the sensitivity resulted in the temperature log crossing the logging paper several times while traversing the well bore, thereby confusing interpretation. Wide paper and diagonal paper logs were developed to improve the presentation. The ΔT or differential temperature tool, shown in Fig. 5-A, was developed to log a straight line under normal gradient conditions while traversing the well bore, Fig. 5-B. The logging sensitivity could therefore be increased to improve the presentation of the temperature anomalies. The ΔT tool consists of two resistance elements spaced a known distance vertically on the tool, and both elements included in the bridge circuit so that only changes in the difference temperature of the elements caused significant changes in the bridge circuit and de-

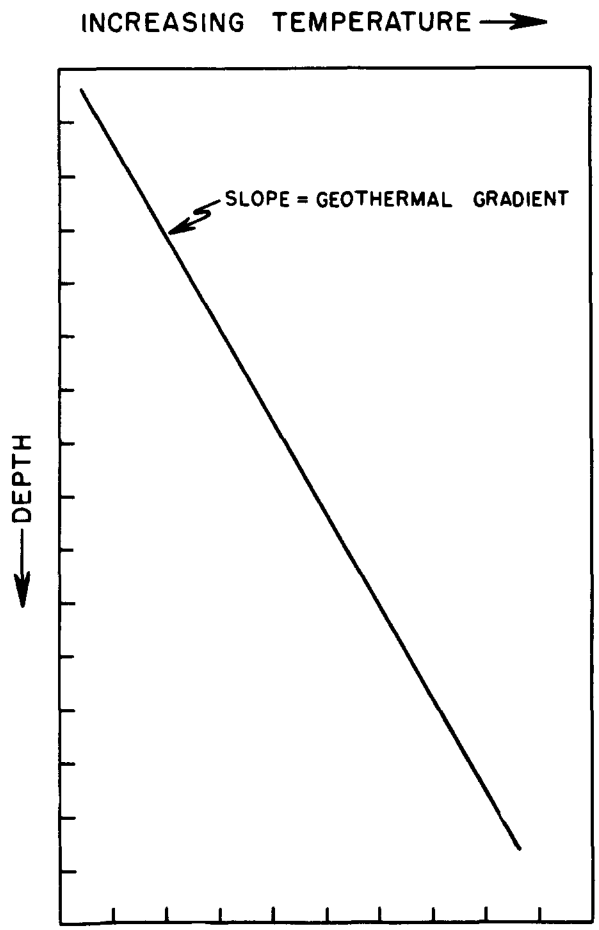


FIGURE 2

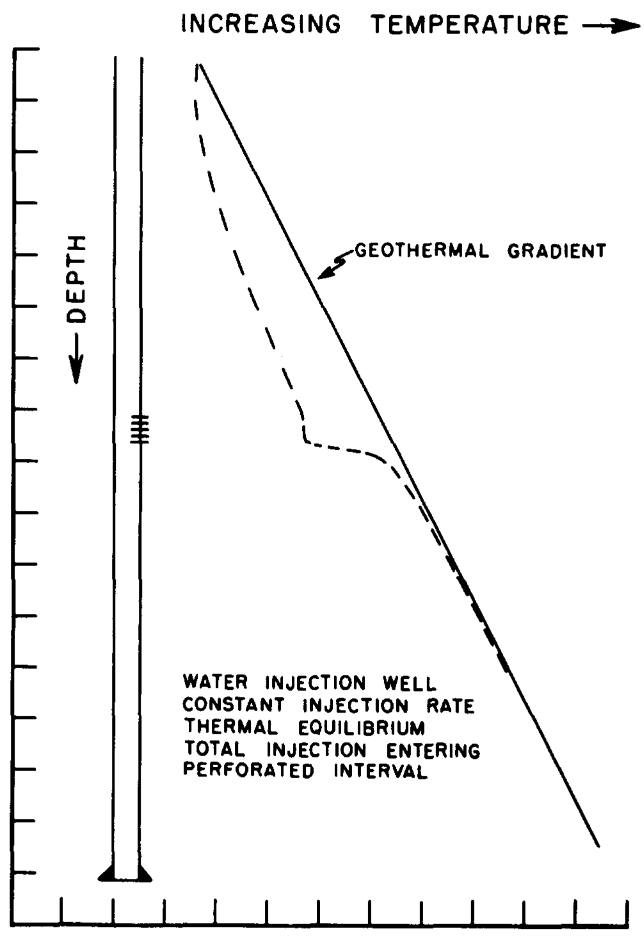


FIGURE 3

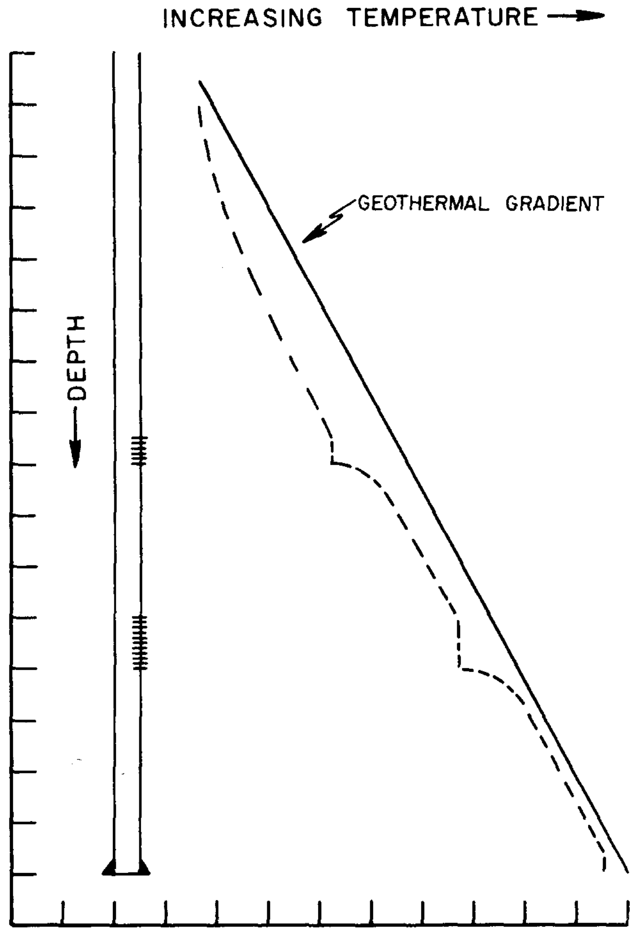


FIGURE 4

flection of the recorder. An inherent problem of the $\triangle$T type tool is unequal influence of the tool and wire line temperature on the sensing elements during the traverse of the well bore. The realization of this problem spawned several variations of the $\triangle$T type tool. These variations (a priori) use a single sensing element and memory circuits to compare a "memorized" value of a previous temperature with a current value and record a function of the difference. There should be no attempt to interpret any "$\triangle$T" or "a priori" log without a temperature log for verification.

Temperature tools and $\triangle$T or "a priori" type tools can only log the temperature or change in temperature of the contacted fluids within the well bore. Temperature logging with static well conditions is useful in evaluating limits of injection, and in some cases may provide a basis for calculating approximate injection volumes into multiple zones.[1]

Temperature logging under dynamic producing conditions requires a gas to expand into the well bore, causing a temperature reduction at the point of gas entry or liquid entry into the well bore, causing temperatures greater than the geothermal gradient to occur in the fluid column above the point of entry. A survey or a series of surveys in a field can be used to determine gas-oil contacts, gas-bearing strata, channeling behind casing, casing leaks or any temperature anomaly associated problems.

A commonly used technique of temperature logging injection wells is to run the log at an arbitrarily selected period of time after stopping

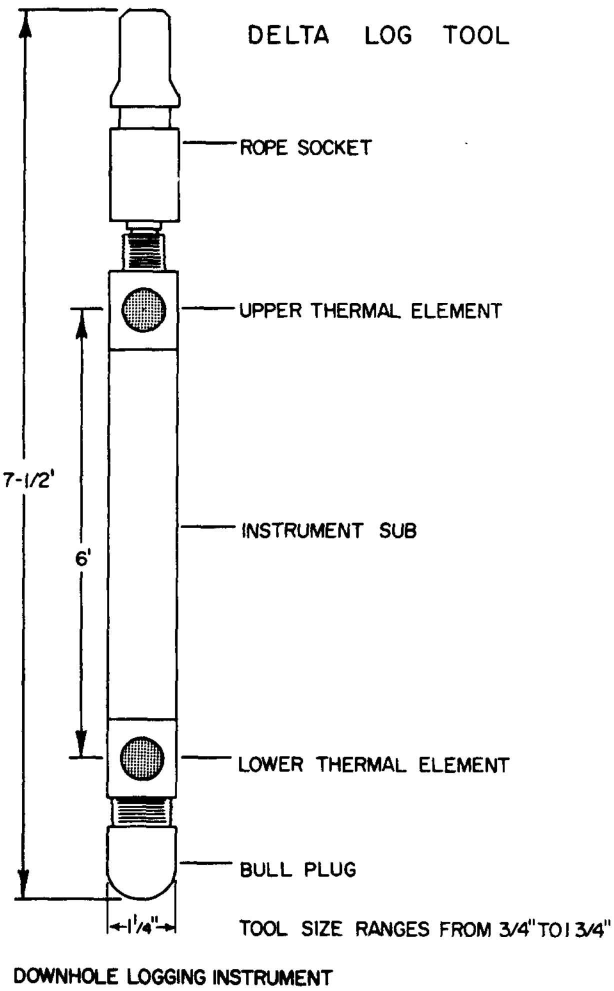


FIGURE 5-A

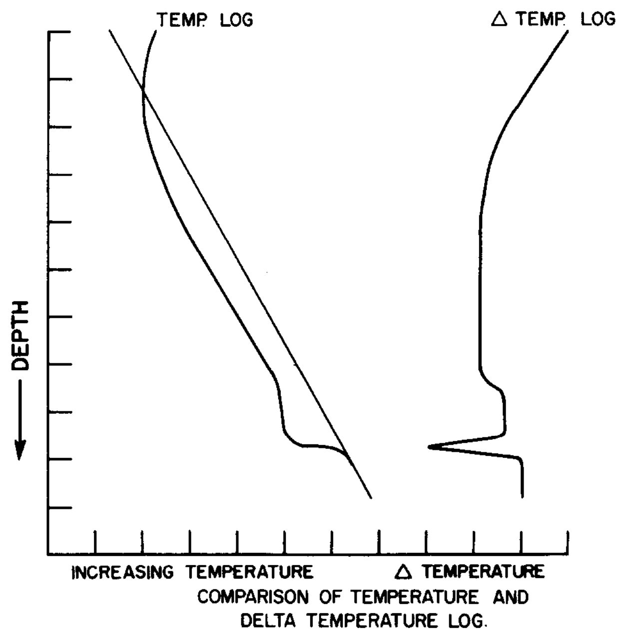


FIGURE 5-B

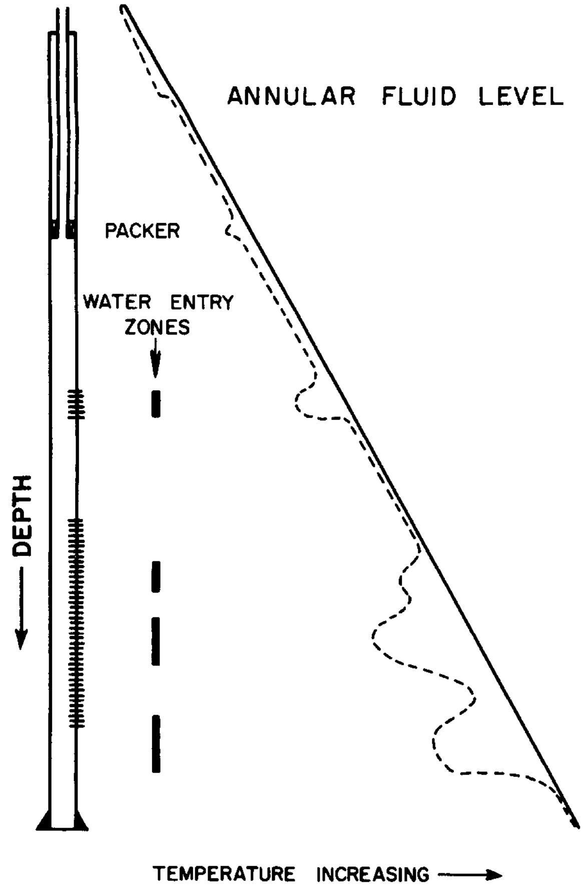


FIGURE 6

injection. The interpretation of the log is based on the premise that the degree of formation cooling is dependent upon the amount of cooling fluid that passes through the formation. Stopping the injection allows heat to be transferred to the well bore fluid column at a rate dependent on the temperature of the surrounding formation. Strata which have been cooled more than the surrounding formation are interpreted as the injection strata (Fig. 6).

Multiple runs at increasing times are useful in determining the optimum waiting time for the conditions involved. Situations can occur where additional information may be detected from multiple runs, as shown in Fig. 7.

There are several mechanical problems which must be recognized and minimized in temperature logging. Changes in hole size, cement sheath, casing seats, liner overlap, tubing and packers all tend to influence the rate of heat flow to the well bore; therefore an accurate diagram of the well mechanics is necessary for adequate evaluation of any temperature survey. There should be no change in fluid level, or any loss of fluid through a lubricator while running a static survey, otherwise the fluid temperatures may shift and mask the log over the desired interpretive interval. Another factor which influences temperature logging interpretation is the effect of stimulation treatments, particularly fracturing. Fractures usually extend in some horizontal direction beyond the limits of investigation of any production logging technique, limiting the accuracy of quantative interpretation in thick multizone formations. Temperature logging techniques are among the best methods available to evaluate the effective vertical extent of a fracture near the well bore.[2]

Temperature logging has been applied to evaluation of stimulation treatments immediately after the treatment is performed. More recently, these techniques have been applied to the control of stimulation treatments while treating equipment is on location. The cooling effect of fracture treatments and heating effect of acid reaction with formations indicate the zones

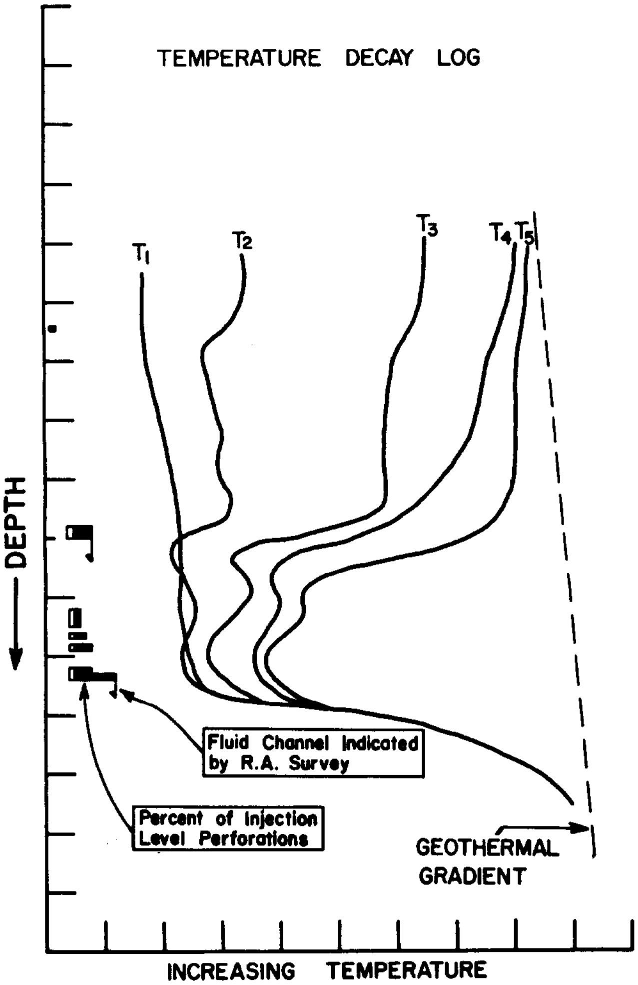


FIGURE 7

treated. This can be done within a sufficiently short period of time to make the process economically feasible in applicable cases. Corrective action can then be immediately applied to obtain the desired end result.

The expense of temperature surveys is usually lower than other production logging surveys, particularly when run in group projects. This fact gives temperature logging an economic advantage in making field studies and in periodic maintenance of injection projects.

MECHANICAL FLOWMETERS

The first attempts to directly measure the movement of fluids within a well bore were based on mechanical movement of a propeller or spinner driving an impulse generator. The continuous flowmeter (Fig. 8) is useful in measuring relative fluid flow at high flow rates; at lower flow rates, inertia of the spinner and fluid bypassing reduce the accuracy of this tool. A tool was subsequently developed to reduce the effect of bypassing by adding an expandable steel-fingered conical fan-type device to force more of the fluid through the spinner section. Later developments resulted in packer type flowmeters (Fig. 9). The balloon packers in these tools are capable of packing the tool to casing annulus and forcing all fluid through the spinner section. These tools are capable of measuring fluid flow in the well bore with accuracies of approximately two per cent, as long as there is only a liquid phase flowing and no channeling occurs outside the casing. Free gas in the flow stream spin the measuring turbine faster than liquid flow rate; therefore in multiphase flow an additional log is often needed to evaluate the fluid density in the flowing column.

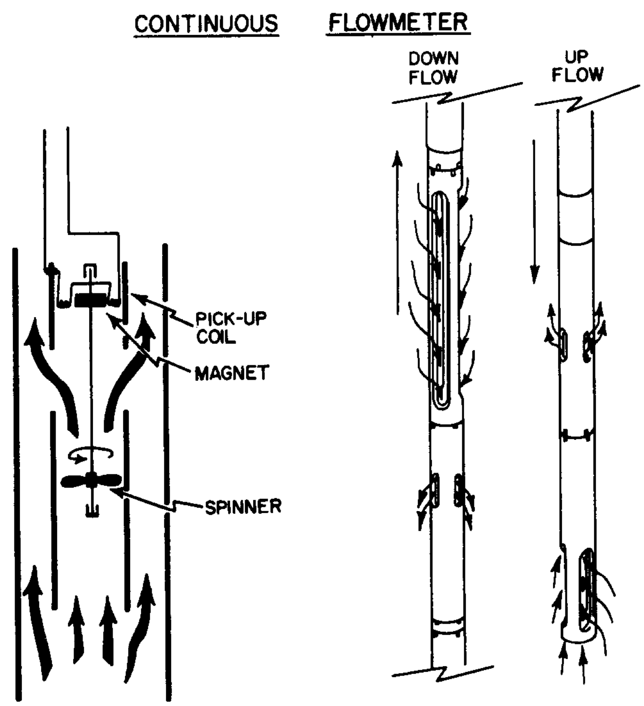


FIGURE 8

Figure 10 is an example of a flowmeter survey on a producing well with additional data supplied by densimeter and water cut meter.[5]

The principle advantages of the packer flowmeter are its accuracy of measurement of liquid flowing in the well bore and its ability to meas-

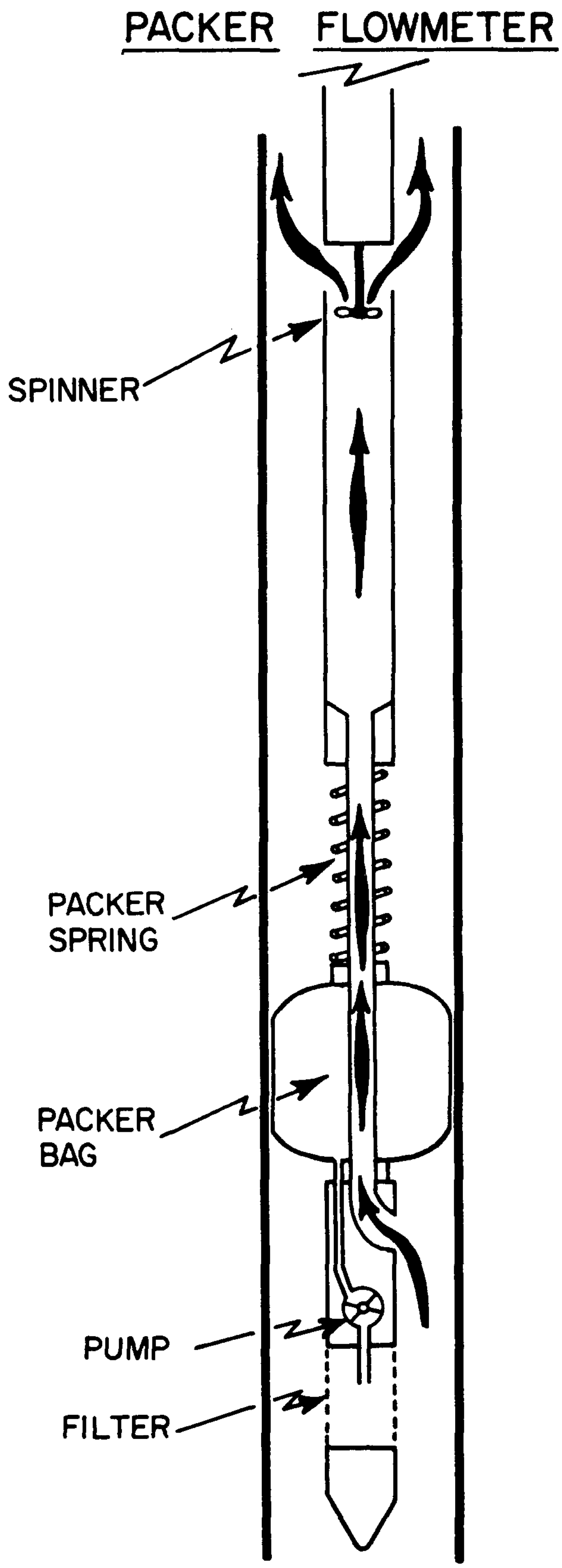


FIGURE 9

ure low flow rates.[4] The packer flowmeter has been used in open-hole completions; however, this application requires that the open hole be packed off with the flowmeter packer in a sufficient number of places to obtain a useable log. A method of evaluating this requirement is to run a caliper survey to determine hole conditions prior to running a production log.

The cost of a packer flowmeter survey is usually 150 to 250 per cent of the cost of a temperature survey.

RADIOACTIVE SURVEYS AND TECHNIQUES

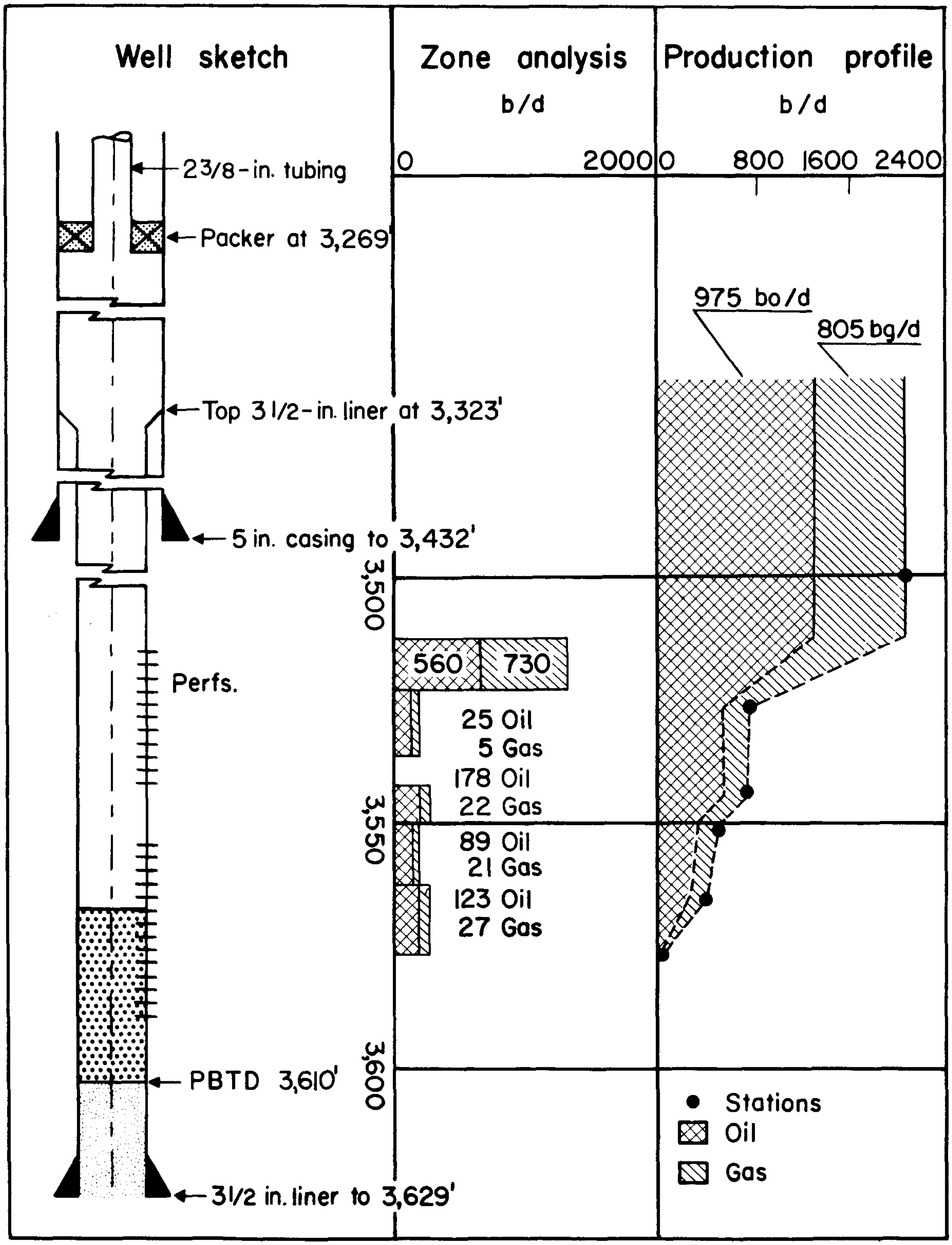
Radioactivity is the process whereby certain elements or isotopes spontaneously emit particles and/or rays by disintegration of the nuclei of their atoms. Radioactive materials used in production logging are isotopes, and can be prepared in many forms, such as plastic particles, liquids, or a varnish baked on sand.

Plastic particles are used in one technique to plate out on the formation face of injection wells. The amount of logged radiation is interpreted as indicating the location of permeable zones and relative rate of injection into these zones. The method is useful in locating lost circulation zones in drilling wells. Wells with reservoir conditions of vugular porosity, fractures, fracture treated wells, and open shot hole completions are not applicable to quantitative interpretation of this survey.

Radioactive sand is used to determine the limits of sand placement near the well bore in a fracture treatment.

Radioactive isotopes in liquid form have the largest application to production logging. They may be prepared for water or oil solubility as the application requires. Radioactive iodine (I-131) with its half-life of eight days, comparatively low cost and ready availability, is most often used. Table I is a listing of a few isotopes and their application parameters.[6]

The presence of radioactivity is detectable with photographic film, electroscope, ion chambers, geiger tubes, scintillation crystal with photo multipliers, and bismuth dectectors, (Fig. 11). Three detectors are used in production logging, Geiger, scintillation and bismuth. The scintillation detector has the largest capture range in the energy spectrum and high efficiency (Fig. 12). The bismuth detector has a slightly lower capture range and efficiency, but has the advantage of working at higher temperatures than scintil-



Well sketch
Zone analysis
b/d
Production profile
b/d
0
2000
0
800
1600
2400
2 3/8-in. tubing
Packer at 3,269'
975 bo/d
805 bg/d
Top 3 1/2-in. liner at 3,323'
5 in. casing to 3,432'
3,500
560
730
Perfs.
25 Oil
5 Gas
178 Oil
22 Gas
3,550
89 Oil
21 Gas
123 Oil
27 Gas
3,600
PBTD 3,610'
Stations
Oil
Gas
3 1/2 in. liner to 3,629'

FIGURE 10

OIL SOLUBLES

ISOTOPE	FORM	PROPERTIES	REMARKS
Cobalt Co-60	Cobalt Naphtenate in Benzene or Xylene carrier	5.3 years half life. High energy emitter. Completely oil soluble. Insoluble in water. Stable to 300° F.	Surface placement down-hole, dump bailer or ejector. "Pump-in" tracers on production wells. Erratic results if water is present in well fluids.
Antimony Sb-124	Radioantimony in benzene carrier	60 day half life. Medium energy gamma emitter. Completely oil soluble. Insoluble in water. Stable to 475° F.	Surface placement down-hole dump bailer or ejector. Pump in oil tracer for high tempera-ture wells or where ex-treme chemical stability is needed, erratic results if water present in well fluids
Iridium I-192	Radioactive iridium in benzene or xylene carrier	74 day half life. Medium energy gamma emitter. Oil soluble. Insoluble in water. Stabilized for organic solutions.	Surface placement or downhole dump bailer or ejector pump in oil tracer. Erratic results if water present in well fluids.
Iodine I-131	Solution of Elemental Iodine in Benzene	8.1 day half life. Medium energy gamma emitter. Moderately stable in oil to 250° F. Oxidizes at temperatures above 250° F. Insoluble in water.	Surface placement or downhole dump or ejector. Oil tracers where short half life is desired. Erratic results of oxi-dized or if water present in well fluids.
Iodine I-131	Liquid - pure Iodo-Benzene C_6H_5I	8.1 day half life. Medium energy gamma emitter. Specific gravity is 1.8. Boiling point is 400° F. Oil soluble. Insoluble in water.	Surface placement, down-hole dump or ejector. Oil tracer. Very stable at high temperatures or in organic solutions. Erratic results if water present in well fluids.
		WATER SOLUBLES	
Iridium Ir-192	Iridium in water solution	74 day half life. Medium energy gamma emitter. Stabilized and miscible in water and acid. insoluble in oil. No inter-ference with logging operations after one year.	Surface placement, down-hole dump or ejector. Water flood injection profiles, channel location, etc.
Iodine I-131	Radioiodine in water solution	8.1 day half life. Medium energy emitter. Miscible in water. In-soluble in oil. Available in three forms. Stabilized to prevent oxication in air, water or acid.	Surface placement, down-hole dump or ejector for water flood profiles and tracers. Cement top and squeeze locator tag. Indicate when ordering to obtain correct colution.
		INSOLUBLES	
Cobalt CO-60	Solid-spherical particles 25 - 1000 microns in diameter	5.3 years half life. Temperature tolerance 900° F. Gamma emitter oxidizes to radioactive sulphide residue. Half life long enough to interfere with radioactivity logging operations for 21 to 26 years	Can be mixed with cement or propping agents - not recommended for oil well tracers.
Cobalt Co-60	Particle in nearly neutral Aqueous Coliodial sus-pension		For placement in injection streams by surface place-ment or dump bailer for "plate out" tracer, lost circulation, filter cake evaluation, etc.
Cobalt Co-60	Solid, Nodule or button		Attached to downhold tool-tracer material produced by ionization downhole. Used in velocity deter-mination.
Silver Ag-110	Particles in nearly neutral Aqueous Collodial suspension	270 day half life. Temperature tolerance 950° F. High intensity gamma emitter. Oxidizes to radioactive sulphides. Interferes with radioactivity logging operations for 3 to 4 years.	For placement in injection stream by surface place-ment or dump bailer for plate out operations. Fine particle size 5 - 20 microns allows some intrusion into more per-meable zones.
Iridium Ir-192	Varnish baked onto Ottawa Sand of selected mesh size	74 day half life. Temperature tolerance of 2454° F. Medium gamma emitter. Use in oil or water. No interference with logging after one year.	For placement in sand or propping agents for frac evaluation. Can be handled with reasonable safety.
Iridium I-192	Impregnated resin. Density 1.1. Mesh sizes 16-400	74 day half life. Temperature tolerance of 212° F. in brine carrier. Unstable in oil at 212° F.	Surface placement or downhole dump bailer for "plate out" operations, lost circulation, filter cake evaluations, etc.
Iodine I-131	Impregnated resin. Density 1.1. Mesh sizes 16-400.	8.1 day half life. Temperature tolerance of 212°F. in brine. Carrier is unstable in oil at 212° F. After 45 days no logging interference.	Surface placement or down-hole dump bailer for "plate-out" operations, lost cir-culation, filter cake evaluations, etc.
		GAS TRACERS	
Bromine Br-82	Gas tracer containing Methyl Bromide (CH_3Br) in pressurized cylinder	35.9 hours half life. High energy gamma emitter. Boiling point is 40° F. at 150 psi. No interference with future logging operations.	For surface placement or special downhold carrier. Dangerous to handle on surface without proper equipment.
Iodine I-131	Liquid Ethyl Iodide (C_2H_5I) in sealed glass ampules	8.1 day half life. Medium energy gamma emitter. Specific gravity of carrier 1.93. Boiling point is 163° F.	For surface placement or special downhole carrier.
Iodine I-131	Liquid Methyl Iodide (CH_2I) in sealed glass ampules	Specific gravity of carrier 2.279, boiling point 108.5° F.	Low boiling point gas tracer for use as above.

TABLE I

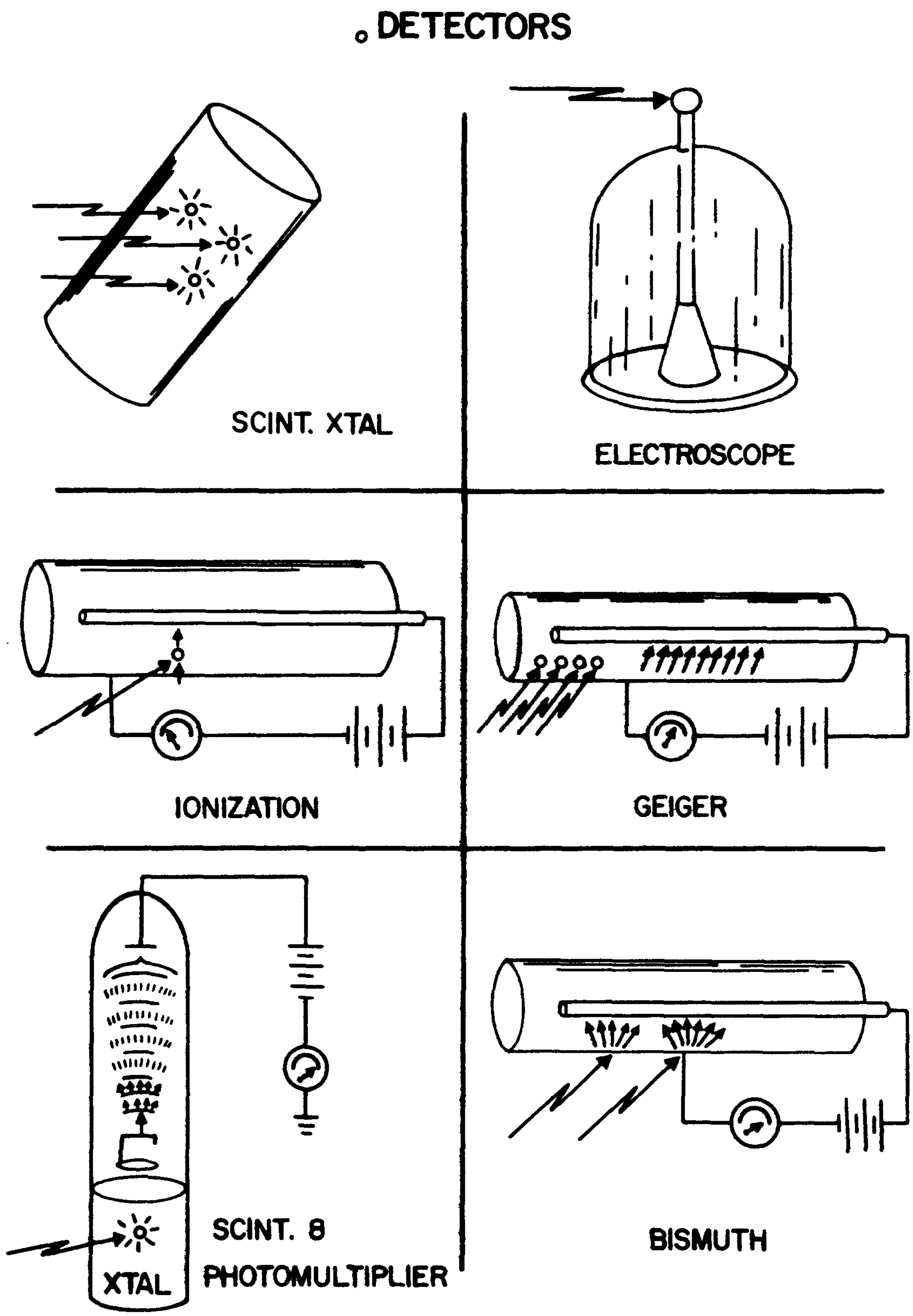

DETECTORS
SCINT. XTAL
ELECTROSCOPE
IONIZATION
GEIGER
XTAL
SCINT. 8
PHOTOMULTIPLIER
BISMUTH

FIGURE 11

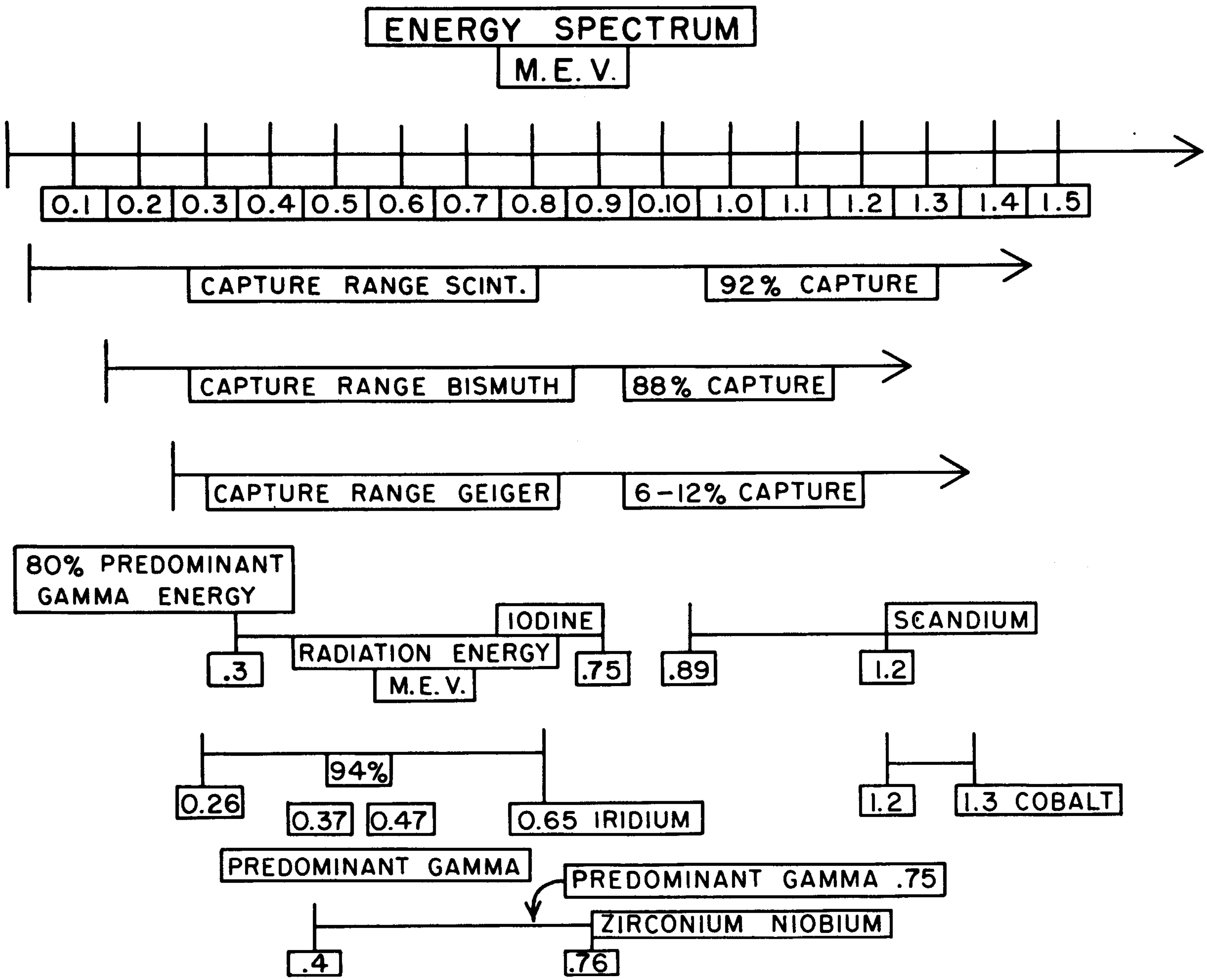
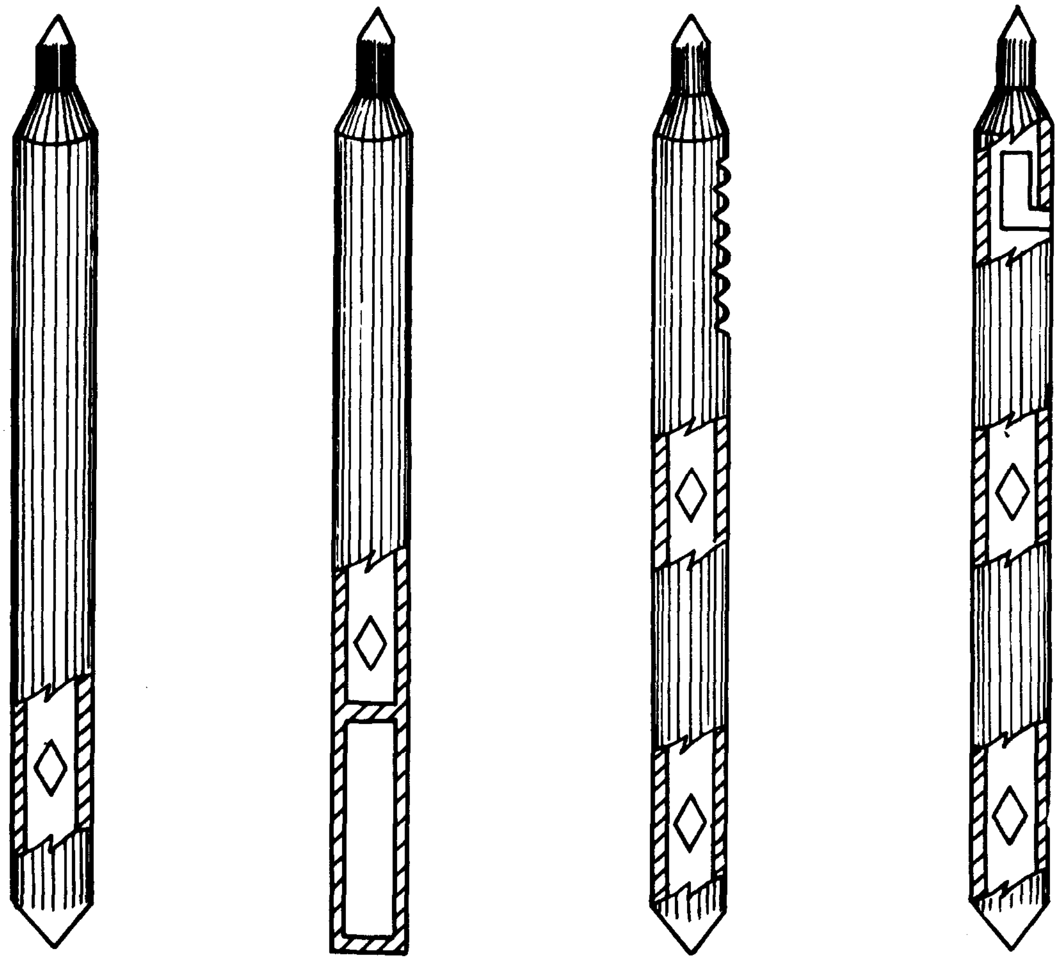

ENERGY SPECTRUM
M.E.V.
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.10
1.0
1.1
1.2
1.3
1.4
1.5
CAPTURE RANGE SCINT.
92% CAPTURE
CAPTURE RANGE BISMUTH
88% CAPTURE
CAPTURE RANGE GEIGER
6-12% CAPTURE
80% PREDOMINANT GAMMA ENERGY
IODINE
RADIATION ENERGY
M.E.V.
.3
.75
.89
SCANDIUM
1.2
94%
0.26
0.37
0.47
0.65 IRIDIUM
1.2
1.3 COBALT
PREDOMINANT GAMMA
PREDOMINANT GAMMA .75
ZIRCONIUM NIOBIUM
.4
.76

FIGURE 12

lation photomultiplier equipment. The time constant of the bismuth detector is slower than scintillation equipment, requiring a slower logging speed.

The original technique of radioactive tracer logging consisted of injecting a dose of radioactive material into the injection well at the surface, waiting until the material reached the top of the completion interval, making a series of logging runs over the completion interval with

TRACER & PROFILE TOOL TYPES



GAMMA RAY DETECTOR	GAMMA RAY DETECTOR WITH DUMP BAILER	AMPULE RUPTURE IONIZING BUTTON	SOLENOID EJECTOR WELL PRESSURE DISPLACEMENT POSITIVE PISTON DISPLACEMENT

FIGURE 13

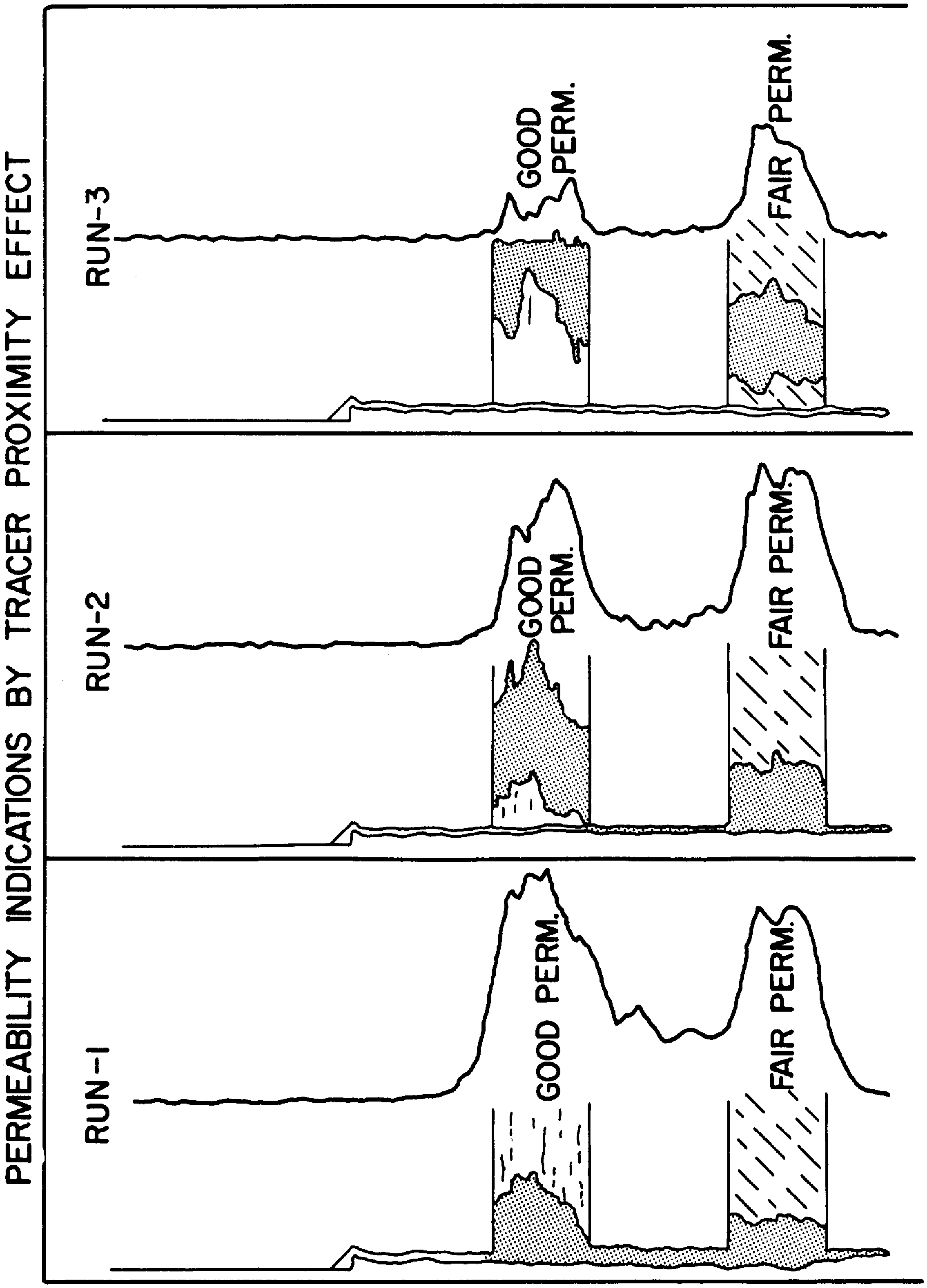

PERMEABILITY INDICATIONS BY TRACER PROXIMITY EFFECT
RUN-3
GOOD PERM.
FAIR PERM.
RUN-2
GOOD PERM.
FAIR PERM.
RUN-I
GOOD PERM.
FAIR PERM.

FIGURE 14

GAMMA ABSORPTION DENSITY TOOL

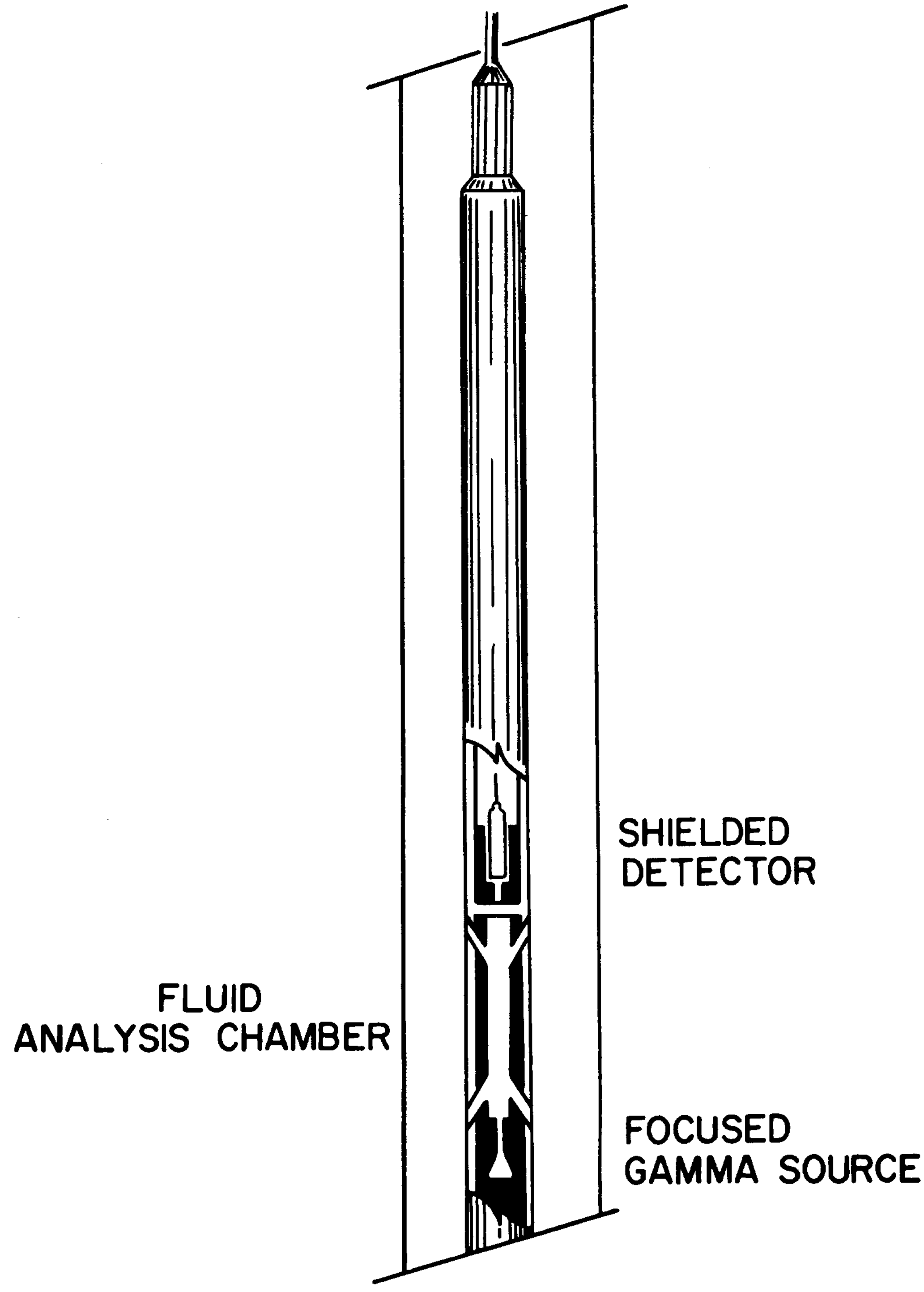


FIGURE 15-A

a gamma-ray detector and observing the changing radiation patterns. Dispersion and mixing of the radioactive material during its downhole traverse limited the succesful interpretation of the survey and prompted the development of methods to inject material downhole near the detector tools. These methods include breaking glass vials, direct injection with a plunger pump, striking an electric arc across a cobalt button, and use of a dump bailer (Fig. 13).

Improved logging techniques and analysis methods resulted from the ability to inject radioactive materials into the flowing stream near the radiation detectors. These techniques are based on timed logging runs, on timing the velocity of a radioactive slug, and calculating volumes traveling in the well bore based on decreasing size of the leading slug. The last method is known as the Self method.[7] Radioactive tracing tools have been improved by adding dual detectors and mechanically arranging the tool components so that any combination of detectors and injector may be made in the down-hole tool. Dual detector equipment improved the accuracy of fluid measurement with radioactive tracers by fixing the distance between two detectors. Accurate timing of a radioactive slug between two identical detectors and knowledge of the hole size permits calculating flow rate.

The ability of radioactive tracers to present indications of fluid movement beyond the pipe and into the formation is a definite advantage over mechanical flow meters. Indications of permeability can be detected with radioactive surveys (Fig. 14).

One of the oldest radioactive methods of determining injection profiles is a patented process called Isoflow. This process required tubing to be set at the bottom of the hole and an open casing annulus. The injection stream was split at the surface with a proportioning valve, and fluid injected into the annulus was tagged with a radioactive tracer. By varying the injection percentage in the tubing and the casing annulus, the down hole interface could be determined between the injection water entering from the annulus, and the injection water entering through the tubing. A gamma-ray detector in the tubing would detect this interface, and an injection profile could be constructed by knowing the proportional fluid rates into the annulus and tubing.

FLUID IDENTIFICATION TEST

Four different tools are available to determine the type of fluid flowing in a multiphase system. These are the gamma absorption tool, the capacitance tool, oscillation frequency tool, and pressure gradient tool. The gamma absorption tool consists of a gamma-ray source and a gamma-ray detector constructed in such a manner that the fluid flowing in the well bore passes through an isolated chamber between these components. The difference in gamma absorption of the flowing fluids may be correlated to the density of the fluids (Fig. 15-A).

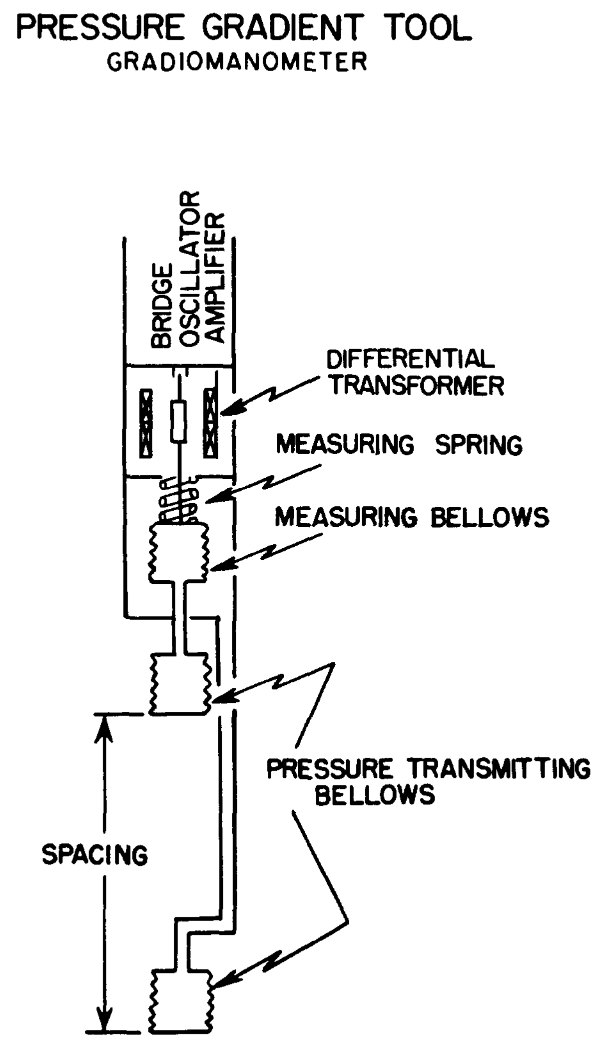


FIGURE 15-B

The capacitance tool consists of two electrodes which form a capacitive component in an electronic oscillator. The dielectric constant of the fluids flowing between the electrodes varies the capacitance and oscillator frequency. The frequency variation is measured and recorded as water cut percentage, when free gas is not flowing, three-phase fluid flow complicates interpretation since three unknowns are introduced.

The oscillation frequency tool consists of a cylindrical vane which is placed in a flowing fluid stream. The density of the flowing fluids controls the natural oscillation frequency of the cylinder. This oscillating frequency can therefore be used to determine the density of the flowing fluids.

The pressure gradient tool is also used to determine the density of fluids flowing between two points (Fig. 15-B). The tool consists of two sensing bellows vertically spaced and operating against a measuring bellows. Variations in pressure gradient between the sensing bellows are mechanically coupled to a differential transformer and recorded at the surface as a change in density.

Combination tools are often used in evaluating producing wells. It is essential to know the type of fluids flowing as well as the volumetric rates. The most generally used tools for this application are packer flow meter and one of the fluid identification tools. Figure 10 is an example of a combination packer flow meter densimeter and capacitance water-cut meter survey.

PRODUCTION LOGGING APPLICATIONS

The tools applicable to evaluation points of fluid entry or exit in a well such as packer leaks, holes in the casing or tubing, are in the temperature, flow meter, fluid density, gradient and tracer ejector tools. Tools capable of indicating channeling are the tracer ejector tool and temperature tool. Tools used to evaluate fracture treating and perforating are temperature and radioactive tools. Injection profiles can be determined with the tracer ejector, flow meter, and temperature tools. Production profiles, including fluid identification, are determinable with temperature surveys, packer flow meter, fluid identification tools, and tracer ejector. Each production logging tool has been developed to meet a specific need.

REFERENCES

1. "Shut In Temperature Profiles, Tops-Bottoms-Volumes" SPE 1782, by Horace Kading, Worth Well Surveys, Inc., Midland, Texas
2. "Evaluation of Fracture Treatments with Temperature Surveys" SPE 1287, by B. C. Agnew, Humble Oil and Refining Company, Monahans, Texas
3. "Production Logging as Applied to Past Primary Production" by H. M. Bullard, R. D. Clark, D. H. Rush, Birdwell Division of Seismograph Service Corporation, presented at Fifth Annual Logging Symposium, Midland Texas, May 13-15, 1964, Midland, Texas
4. "A New Approach to Permeability Profiles" by Wallace B. Johnson, Wright Surveys, Odessa, Texas—Ninth Annual West Texas Oil Lifting Short Course, Texas Technological College, April 12-13, 1962.
5. "Producing Logging—Profit Builder for Producers" by J. D. Matlock, Schlumberger Well Service, Tulsa, Oklahoma Oil & Gas Journal, December 18, 1967
6. "Review of Tracer Surveys" by Wallace B. Johnson, Cardinal Chemical Inc., and Billy P. Morris, Cardinal Surveys Company, Midland, Texas, Spring Meeting, Division of Production, American Petroleum Institute, March 18-20, 1964
7. "A New Fluid Flow Analysis Technique for Determining Bore Hole Conditions" by Charles Self and Mat Dillingham, The Western Company, SPE 1752
8. "Production Logging: The Key to Optimum Well Performance" SPE 944, by R. T. Wade, R. C. Cantrell, A. Poupon and J. Moulin, Schlumberger Well Surveying Corporation, Houston, Texas and Paris, France