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New nuclear logging methods

with 11 figures and 3 tables

by L. RYBACH* and A. H. YOUMANS**

Abstract – During the past few years several new logging methods have been applied in petroleum exploration. The construction of miniaturized accelerators as neutron sources – which fit into casing and can operate even at extreme borehole conditions – initiated the development of a number of new types of log: the neutron lifetime log is used to determine water saturations and to locate water/oil and oil/gas boundaries behind casing and to monitor reservoir parameter changes, the oxygen log can distinguish oil from water in the rock pores, the silicon log is of valuable assistance for lithologic studies. Presence and quantity of chlorine in porous zones can be determined by the chlorine log. The flowing neutron log indicates zones of gas entry, while the epithermal neutron log gives an improved estimate of the hydrogen content of formations. The dual spaced density log measures formation bulk density corrected for the effect of mud cake and borehole roughness. Operating principles and field examples are described.

1. Introduction

Nearly thirty years have passed since the introduction of nuclear methods into well logging (HOWELL and FROSCH, 1939). Until very recently the natural gamma, neutron and gamma-gamma logs (the «conventional» nuclear methods) were merely considered as supplements to the «classical» electric logs. In the latter group, development is now largely concentrated on rapid interpretation techniques of the data recorded by

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standard equipment (e. g. automatic interpretation at the well site with small digital or analog computers; TIXIER et al., 1965).

However, in the field of nuclear logging several new methods have been developed in the past few years. As their introduction into commercial logging service in different parts of the world has been very successful, operating principles and practical examples will be summarized in this paper.

2. Neutron logs

2.1. Neutron Generators

In conventional neutron logging the neutron source is a capsule containing a radioactive alpha particle emitter mixed with beryllium. Gamma radiation incidentally emitted from the neutron source, especially in the case of Ra-Be mixture which has been most often used, created unwanted safety hazard problems and placed a practical limit on the intensity of sources which could be used in field operations. More recently, neutron sources have become available which use, instead of radium, some element which emits less gamma rays – such as actinium, polonium, plutonium or americium. Even so, the capsuled type source is hazardous to use and store, even when limited in size to something below about 10^7 neutrons per second[1]). To solve this problem and to attain a number of other technical advantages, a neutron source was required which could be «switched off». Such a source, a *neutron generator with an output of 10^8 n/sec*, has been proven feasible, (YOUMANS and ZIMMERMANN, 1959). One such device has a diameter of only 2-1/8" (WICHMANN, HOPKINSON and YOUMANS, 1967). These neutron sources employ the nuclear reaction[2]) T (d, n) He^4 to produce 14 Mev neutrons. Neutrons of this high energy can *penetrate more deeply into the formation* than neutrons from the Ra-Be source. The device (Fig. 1a) consists mainly of an ion acceleration tube to produce a flow of high energy deuterium ions which bombard the tritium target, and a Van de Graaff generator to supply high voltage of about 125 kV for the ion acceleration tube. Design of an instrument capable of operating at extreme borehole conditions has been the most difficult aspect of this development. In the U.S., neutron lifetime logs made with this type of neutron source have been run in wells with *temperatures above 300° F.* Neutron generators of this type are in use in various parts of the world and are now considered suitable for routine commercial logging.

2.2. Neutron Properties of Rocks

Neutrons emitted from a downhole source into the formation are rapidly, but not instantly, captured by the rock material. At first, they are slowed down from their high initial energy of 14 Mev to the «thermal» level of 0.025 ev by scattering. During this slowing down process, collision with hydrogen atoms is by far the most influential reaction. Once thermalized, the neutrons are readily captured by various nuclei. For example, a silicon nucleus Si^{30}, can capture a neutron, whereupon immediately one or more high energy capture gamma rays are emitted: Si^{30} (n, γ) Si^{31}. The number of the emitted gamma quanta (i. e. the intensity of the gamma radiation) is a measure of the number of captures and of the capture gamma ray multiplicity. The probability for

[1]) To obtain a neutron output of 10^7 n/sec, 1 curie radium is necessary. The mean neutron energy is 5 Mev.

[2]) Nuclear reactions are usually written in an abbreviated form. Instead of

Target Nucleus + Irradiating Particle = New Nucleus + Emitted Particle,
e. g. tritium + deuterium ion = helium + neutron

one can write simply T (d, n) He^4.

such a capture reaction is given by the *thermal neutron absorption cross section* per atom, σ (barns). Table 1 shows some possible capture reactions with the corresponding σ values. Note the high σ for chlorine.

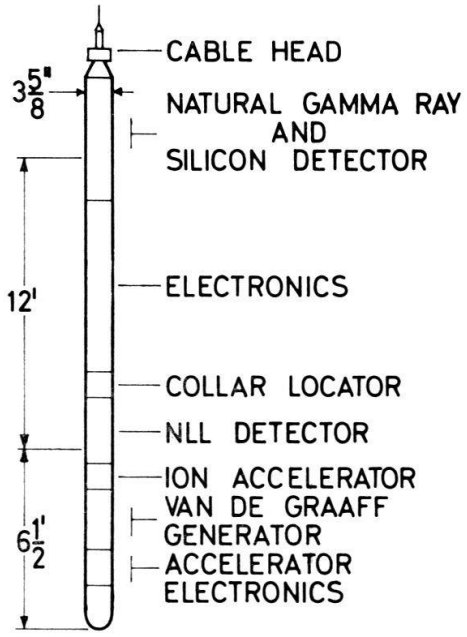


Fig. 1a

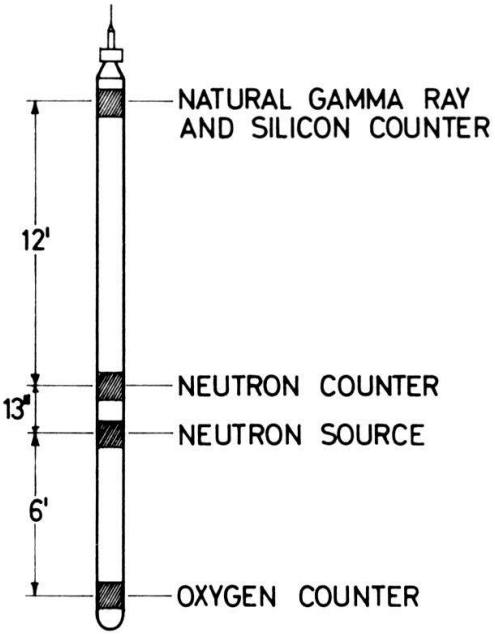


Fig. 1b

Fig. 1a: Neutron lifetime log instrument (after WICHMANN et al., 1966).

Fig. 1b: Logging tool for silicon and oxygen activation curves.

Table 1. Thermal neutron capture reactions, atomic absorption cross sections (1 barn $= 10^{-24}$ cm^2). Figures from «Chart of Nuclides», General Electric Co., 9th ed. (1966).

Reaction	σ (barns)
O^{16} (n, γ) O^{15}	0.0002
Al^{27} (n, γ) Al^{29}	0.23
Si^{28} (n, γ) Si^{29}	0.08
Cl^{35} (n, γ) Cl^{36}	44.0
K^{41} (n, γ) K^{42}	1.1
Mn^{55} (n, γ) Mn^{56}	13.3

Capture cross section values are more convenient to use in well log interpretation if given in terms of cross section per unit volume of rock material. This may be derived if the composition of the medium is known: σ (barn/atom) $\times$ N (atoms/cm^3) must be calculated for each element and all added together; the sum gives the macroscopic cross

section per cubic centimeter Sigma (Σ), with the dimension cm^2/cm^3. Sigma is usually given in units of 10^{21} implied, but not written for convenience. Sigma values for various materials to be found in a borehole are given in Table 2.

Table 2. Macroscopic neutron capture cross section for various reservoir rocks, fluids and hydrocarbons.

Material	$\Sigma(10^{21}$ barns/$cm^3)$
Sandstone	5 – 15*
pure SiO_2	4.3
Limestone	8 – 12*
pure $CaCo_3$	7.1
Shale	20 – 40
Fresh Water	22.2
Salt Water (100 000 ppm NaCl equivalent)	55.6
Salt Water (200 000 ppm NaCl equivalent)	93.9
Oil (dead crude)	22.2
Methane (at 150° F and 5.5 kpsi)	10.0

*) depends on the content of boron, lithium and other rare elements with very high capture cross sections ($\sigma_B = 750$ barns, $\sigma_{Li} = 70$ barns).

2.3. Neutron Lifetime Log[3])

The thermal neutron capture cross section Σ, as explained above, is a basic physical parameter of the formation which depends on the chemical constituency of the rocks and on the amount and type of fluid in the pore volume. Σ can be determined by observing thermal neutron «die-away» in the rock following a burst of neutrons from a pulsed neutron generator. In neutron lifetime logging the tool is designed to measure gamma radiation – produced by thermal neutron capture reactions – during selected intervals when no neutrons are being emitted by the source. The neutron generator is switched on and off electronically, emitting neutrons in brief intense uniformly repetitive pulses. During the quiescent interval between the pulses, neutron induced radiation is detected. The «decay» of the neutrons in the formation is manifested by a like decay of the neutron capture gamma ray intensity measured by the detector during discrete time intervals or «gates».

The pulsed neutron source in the logging tool operates at a repetition rate of 1000 cps (1000 μsec period). The source emits 14 Mev neutrons in the time interval between 0 and 30 microseconds. A gated scintillation counter measures the gamma radiation intensity from 400 to 600 microseconds ($T_1 = 500$ μsec) and independently in an adjustable second gate, usually from 700 to 900 microseconds ($T_2 = 800$ μsec). At 1000 microseconds the source is turned on and the cycle repeated.

[3]) Neutron Lifetime Log and NLL are trademarks of Lane Wells Co., a Division of DRESSER INDUSTRIES, Inc.

Following thermalization of the neutrons, the exponential decay of the thermal neutrons is expressed by the equation

$$N_2 = N_1 e^{-\Sigma v \Delta t} \qquad (1)$$

N_1: Number of thermal neutrons at the time T_1 after the pulse
N_2: Number of thermal neutrons at the time T_2 after the pulse
Δt: $T_2 - T_1$ (μsec)
v: velocity of thermal neutrons (2.2×10^5 cm/sec)

The ratio of the measured gamma radiation intensities (which must be corrected for background, if any) is proportional to the neutron lifetime (L). L is defined as the time during which the number of neutrons in the formation decays to half its value. From (1) follows

$$L\ (\mu\text{sec}) = \frac{3.15}{\Sigma} \qquad (2)$$

and

$$\Sigma \left(\frac{10^{21}\ \text{barns}}{\text{cm}^3}\right) = \frac{10500}{\Delta t} \log \frac{N_1}{N_2} \qquad (3)$$

Since the intensity of the capture gamma radiation is proportional to the number of neutrons in a given medium, gamma ray intensities measured by the gated scintillation detector (the log readings) can be inserted in (3) to calculate Σ.

During logging operations the tool (Fig. 1a) is moved along the borehole at normal logging speeds (20–30 feet/minute). Four curves are recorded simultaneously (Fig. 2, Fig. 8), i. e. the gamma ray counting rate at each of the two gates, a computed Σ curve and a source monitor curve. The monitor curve is used to verify the stability of the neutron output.

The maximum depth of penetration is about 3 feet. It can be shown (YOUMANS et al. 1966, CALDWELL et al., 1966) that after a 400 μsec delay between the neutron pulse and the early gate measurement none of the borehole parameters (casing, fluid type, hole size, sonde excentricity, etc.) influence the neutron lifetime log. Thus Σ can be determined *through casing*.

The data can be interpreted qualitively by looking for a considerable «separation» of the gate counting rate curves which occurs at low values of Σ as an example when hydrocarbons are present in the formation[4]). The Σ curve (electronically calculated) is usually recorded on a linear scale from 10 to 50 units ($\times 10^{-3}$) (Fig. 8).

Since Σ is the summation of capture cross sections of the individual atoms in one cm³ of material in a reservoir rock which contains both hydrocarbons and formation water, Σ_{rock}, Σ_{water} and $\Sigma_{hydrocarbon}$ all contribute to Σ according to the volume occupied:

$$\Sigma = \Sigma_r\ (1 - \Phi) + \Sigma_w\ \Phi\ S_w + \Sigma_{hc}\ \Phi\ (1 - S_w) \qquad (4)$$

where Φ is the porosity and Sw the water saturation. If reliable values can be assigned to the parameters Φ, Σr, Σw and Σhc, Sw can be determined from the Σ value measured by the log:

$$S_w = \frac{\Sigma - \Sigma_r}{\Phi\ (\Sigma_w - \Sigma_{hc})} + \frac{\Sigma_r - \Sigma_{hc}}{\Sigma_w - \Sigma_{hc}} \qquad (5)$$

[4]) The greater the value of the term $\Phi\ (\Sigma_w - \Sigma_{hc})$ the easier it is to distinguish between oil and water. In general, for fresh water Σ_w is about equal to Σ_{hc}.

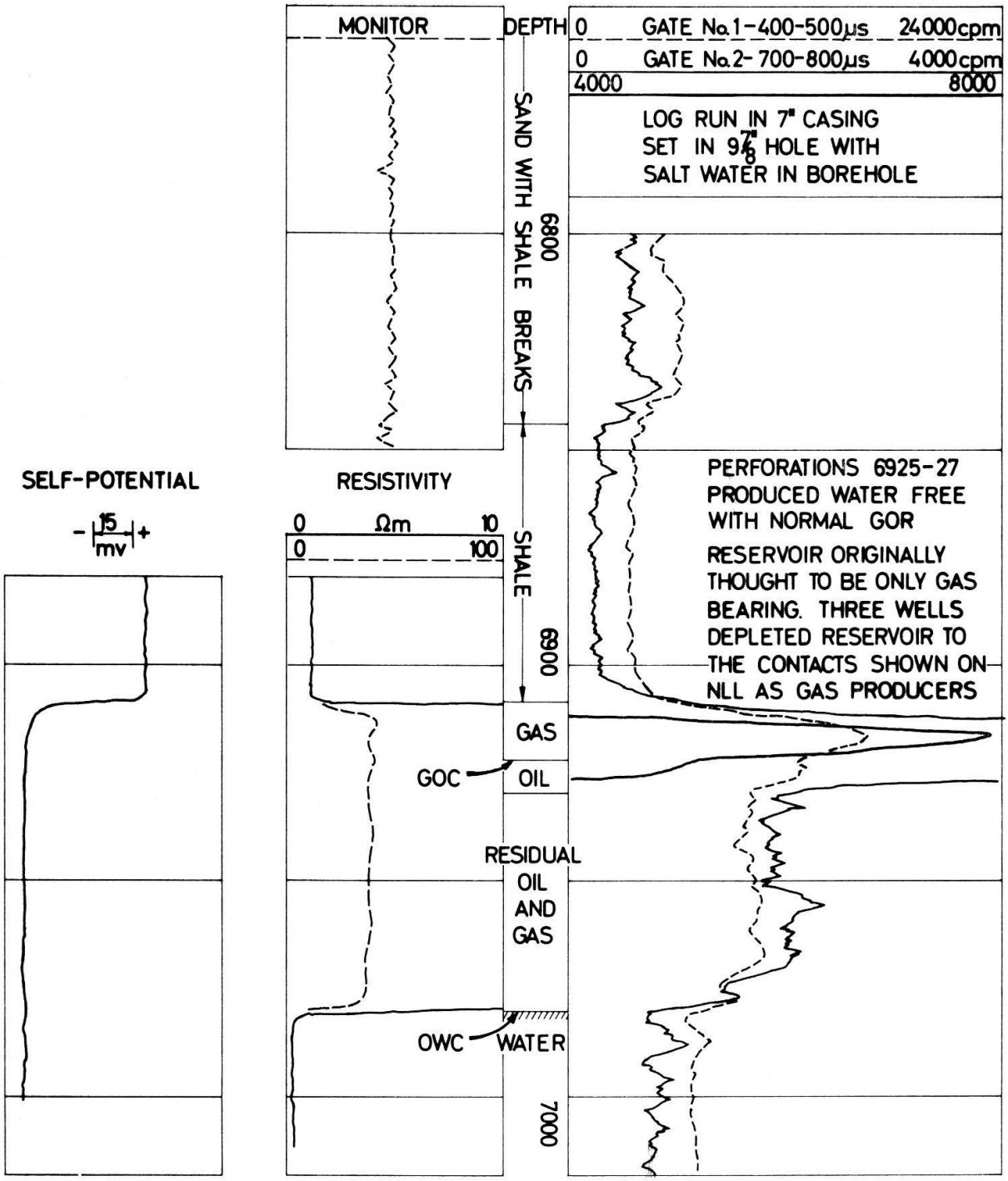


Fig. 2: Field log (Louisiana Gulf Coast well) showing results of qualitative lifetime log interpretation. (For simplicity, only the 50-foot intervals are shown, omitting the 2- and 10-foot lines.)

Fig. 3 shows the graphic representation of equation (5) for $\Sigma_r = 5.0$, $\Sigma_w = 100$, $\Sigma_{hc} = 22.2$. A special advantage of the neutron lifetime log is its ability to distinguish between fresh water and gas since gas normally has a lower value of Σ than does water. Open hole resistivity logs do not ordinarily show a contrast between gas and fresh water, both being nonconductive; so there is frequent need to locate shallow cased off gas sands. The neutron lifetime log has been found superior to conventional neutron

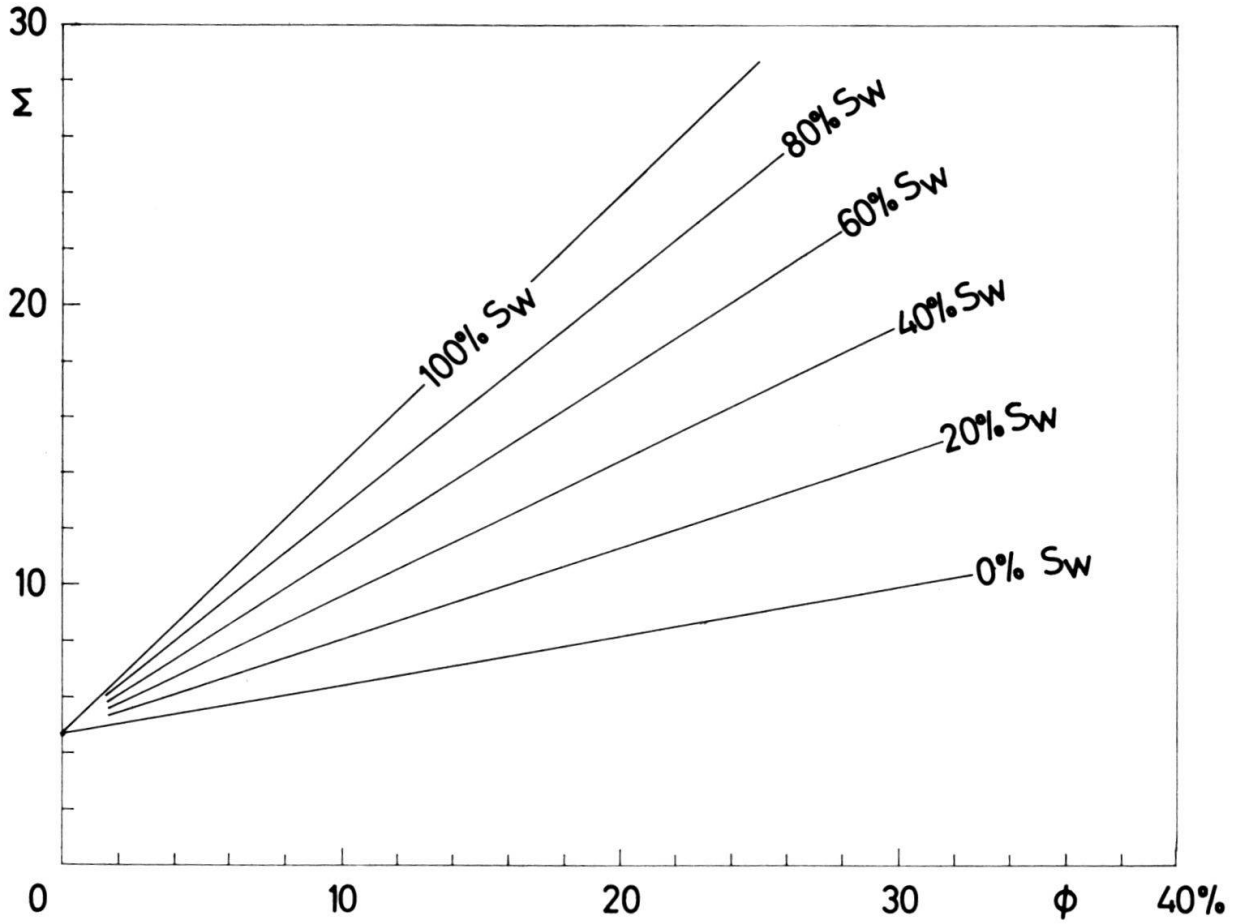


Fig. 3: Neutron lifetime log interpretation chart (from MARQUIS, 1964). To evaluate the water saturation Sw the diagram is entered with Σ determined from the log. The porosity Φ must be known from open hole logs or from a cased hole neutron log.

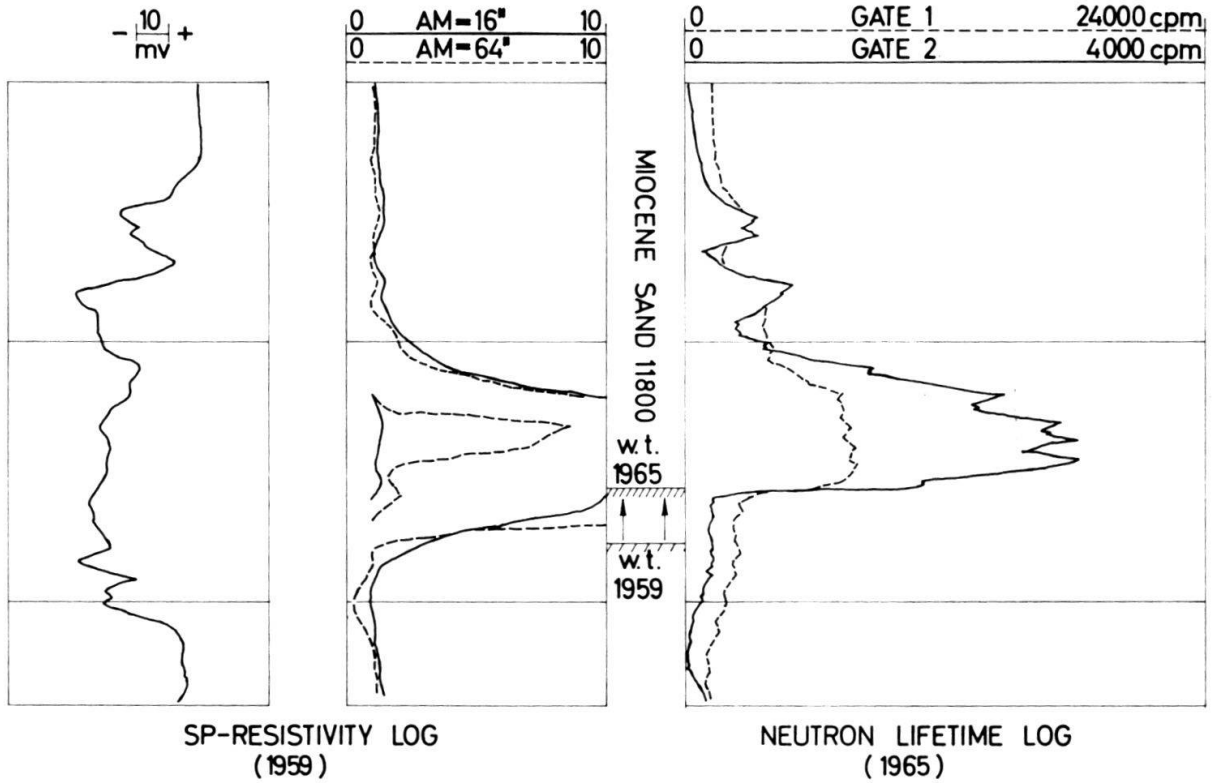


Fig. 4: Field log (Southern Louisiana well). Correlation of early electric log and recent lifetime log shows extent of water table (w. t.) movement (from MARQUIS et al., 1965).

logs for this purpose because (a) it is quantitative, (b) it samples a greater volume of the formation, and (c) it is unaffected by the presence or absence of gas in the annular space outside the casing.

The Σ values or qualitative inspection of the two «gate» curves can lead to the *determination of water/oil and oil/gas contacts* (Figs. 4 and 5). Since these contacts can be located through casing, it is possible to follow up progressive changes by repeated measurements. In fact, one of the major applications of the neutron lifetime log is *reservoir monitoring*. The determination of changes in S_W, water table movements, and changes of hydrocarbon properties in productive wells are all feasible since the measurement is independent of borehole conditions (MARQUIS et al., 1965).

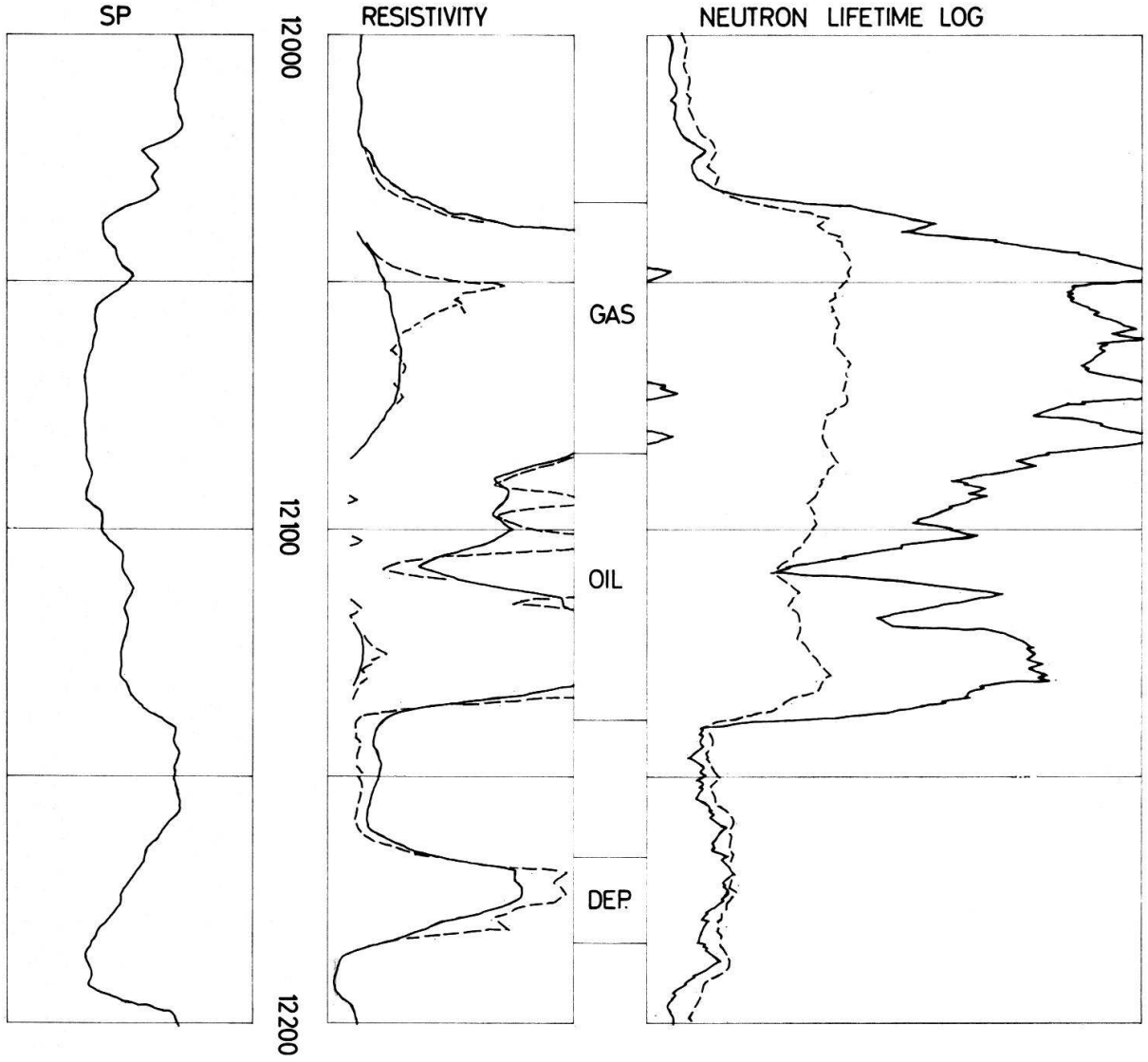


Fig. 5: Comparison of electric log and lifetime log identifies gas-oil contact (Σ gas $>$ Σoil) and delepted interval. Same well as in Fig. 4.

2.4. Flowing Neutron Log

In conventional «static» neutron logging the response[5]) of the tool is mainly determined by the hydrogen content of the medium surrounding the neutron source. Since

[5]) Readings from standard neutron logs as well as those from natural gamma logs are now expressed in «API-Units». The American Petroleum Institute has established calibration facilities (BELKNAP et al., 1960) at the University of Houston, Texas.

methane and ethane gases are relatively poor in hydrogen as compared with heavier hydrocarbons and water, a neutron log run in a flowing well may detect intervals of gas entry. The flowing neutron log device has a diameter of 1–¾" to fit into tubing. *Zones of gas entry cause large shifts in the neutron curve* (Fig. 6). The amplitude of such shifts depends upon gas/oil ratio in the formation and on pressure, temperature, casing size, etc. in the hole. Changes in the position of the gas/oil contact during production can be monitored by consecutive runs.

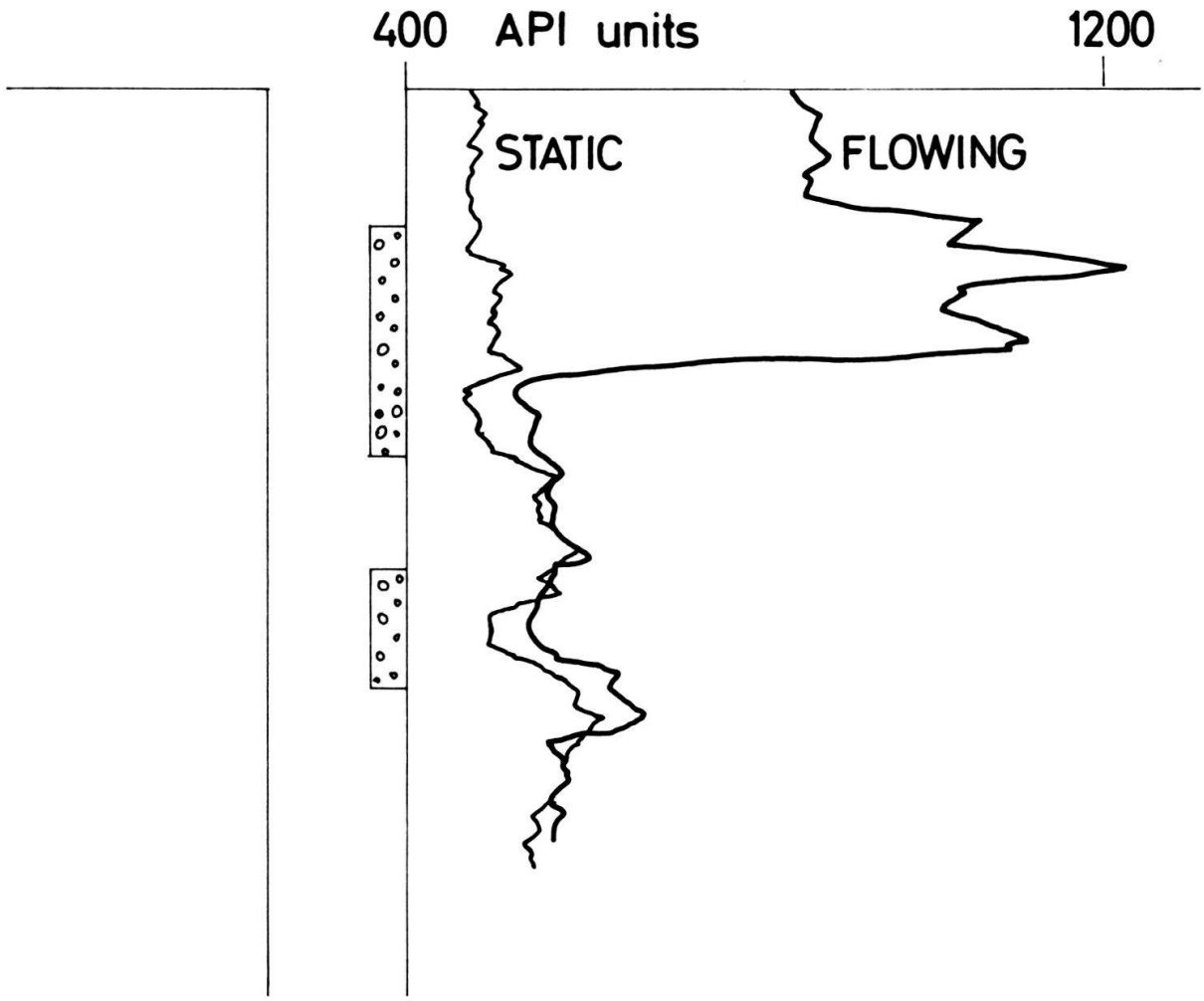


Fig. 6: Static vs. flowing neutron log shows points of gas entry in producing well. Symbols indicate perforated interval (Venezuela well).

2.5. Epithermal Neutron Log

In conventional neutron logging a neutron source is positioned from 10 to 30 inches from a radiation detector, with shielding disposed between. In the past, instruments have been built in which the radiation detectors were geiger counters, ionization chambers, proportional counters and various types of scintillation counters. In recent years it has been generally recognized that these do not produce identical logs and that an epithermal neutron detector produces superior results. An instrument which detects gamma rays makes a neutron-gamma log; one that detects thermal neutrons, a neutron-thermal neutron log; one that detects epithermal neutrons, a neutron-epithermal neutron log – or simply an epithermal neutron log. Many neutron logs are a combination

of these types. Each neutron instrument, depending on the details of its construction, responds in a characteristic way not exactly like any other instrument of different design. In general, the neutron log is run as a porosity measuring device and it is preferred that the instrument respond primarily to variations in formation hydrogen content. It should be influenced as little as possible by borehole parameters, rock chemistry, tool position in the hole, etc. It has been found that the neutron-gamma type of log as well as the neutron-thermal neutron log are prone to respond excessively to these factors whereas a neutron-epithermal neutron log is superior in this regard. Because the epithermal neutron log is not affected by water salinity or by thermal neutron capture characteristics of the formation, it can be more accurately and more reliably related to porosity. An epithermal neutron curve is given in Fig. 9.

One type of epithermal neutron instrument has been developed which has the source and detector assembly mounted in a short section of housing adapted to be held against the borehole wall by an opposing spring-loaded arm which serves to measure the borehole diameter. Since borehole diameter variations cause variations in the log, the simultaneous caliper makes it possible to electronically correct the log before recording it.

3. Activation logs

3.1. Principle of Activation

Many of the common elements which occur in sedimentary rocks can be made radioactive by bombardment with 14 Mev neutrons. The new isotopes (products of neutron induced reactions, see chapter 2.2.) usually emit gamma rays. In a given formation (with a given chemical composition) the artificially produced radioisotopes can be distinguished on the basis of their half life and gamma energy. Table 3 lists some important activation reactions with fast neutrons. The neutron generator of the type used for neutron lifetime logging can be used for activation. For this purpose it may operate continuously rather than pulsed.

Table 3. Fast neutron activation cross sections, half lifes and characteristic gamma lines of the products (after WOOD et al., 1965)

Reaction	σ(barn)	Half life	Gamma energy (Mev)
Si^{28} (n, p) Al^{28}	0.25	2.3 min	1.78
O^{16} (n, p) N^{16}	0.09	7.1 sec	5.7
Al^{27} (n, p) Mg^{27}	0.07	9.5 min	0.83; 1.01
Cl^{37} (n, α) P^{34}	0.04	12.4 sec	2.1; 4.0

Gamma radiation in boreholes can be measured by scintillation detectors which consist of a NaI crystal and a photomultiplier tube. Rugged «high temperature» photomultipliers developed in the past few years operate successfully at temperatures up to 300° F without thermal isolation (CAUSSE, 1960). The difficulties in obtaining electronic stability have been solved to a great extent (YOUMANS and MONAGHAN, 1957). With scintillation detectors the spectrum of the gamma radiation can be analyzed. This makes possible the identification of radioisotopes produced by neutron activation in the borehole. The measured intensity of a given gamma line is proportional to the concentration of the corresponding element in the formation.

The optimum speed for activation logging depends on the half life of the isotope of interest. As a result of 14 Mev neutron activation, oxygen is converted into N^{16},

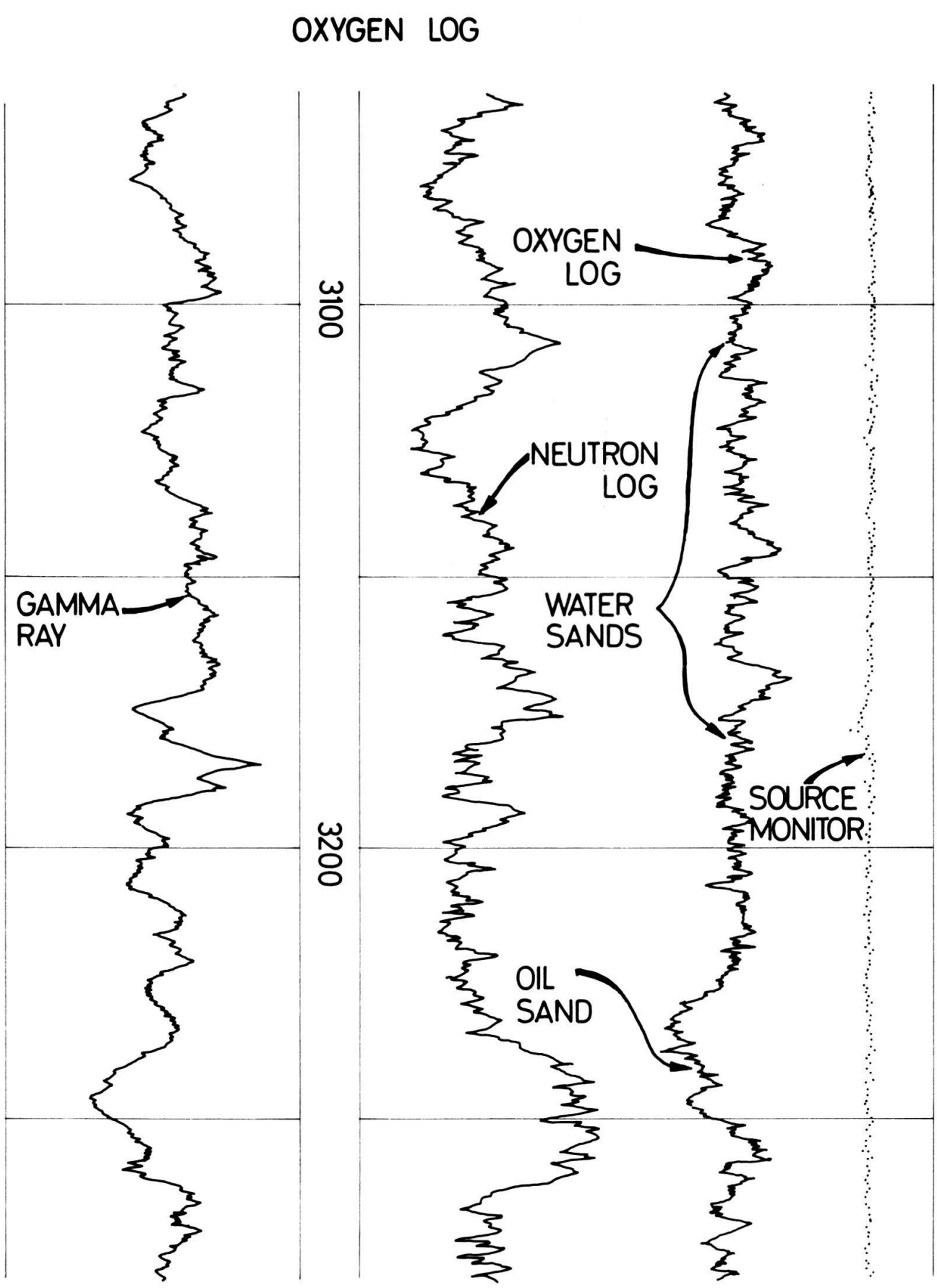


Fig. 7: Example of oxygen activation log (Oklahoma well). Note the lower oxygen response in the oil sand section.

a nitrogen isotope which decays with a 7.3 sec half life period (see Table 3). Similary, silicon is transmuted to Al^{28}, which has a half life of 2.3 min. These isotopes can be measured by continuous logging with the radiation detector following behind the neutron source an appropriate distance. Activated aluminium produces Mg^{27} (9.5 min half life). This isotope must be measured by stopping the tool at the zone of interest.

3.2. Oxygen Log

Hydrocarbons contain no oxygen; it is therefore the purpose of oxygen logging to differentiate between water-bearing and hydrocarbon-bearing horizons. The induced N^{16} activity is measured by a scintillation counter trailing some six feet behind a neutron generator; the relatively high gamma energy ($\sim$ 6 Mev) makes it easy to discriminate against other induced radiation. Owing to the short half life period of N^{16} (7.3 sec) logging speeds[6]) up to 40 feet/minute can be used. The neutron source must be a source of 14 Mev neutrons as the reaction does not occur with neutrons from a Ra-Be source. One type of instrument designed to measure oxygen is shown in Fig. 1b. With this tool, oxygen and a «common» neutron curve can be made simultaneously during uphole logging; a silicon log (see next chapter) can be obtained while going in the hole. An example of the oxygen log with the natural gamma ray and neutron logs is shown in Fig. 7. Note the lower oxygen response in the oil sand.

Although oxygen logging has been shown to be a sensitive way to distinguish between oil and water, very little commercial application for this log has developed. This is primarily because the measurement is very sensitive to variations in the cement and fluids in the annular space around the casing of the logged well. Its greatest utility is expected to be in areas where reservoir water is very fresh, making it difficult by conventional logging means to identify oil zones.

3.3. Silicon Log

The silicon activation log is most effective as a lithology indicator to differentiate between interbedded sands and limes. In carbonaceous sandstones the extent of calcareous cementation can be determined.

During silicon activation an aluminium isotope, Al^{28} is produced (see Table 3). Its activity can be measured with the normal neutron lifetime logging tool when it is equipped to make a simultaneous natural gamma ray log (Fig. 1a, 13 feet source-to-detector spacing). The log is made while going in the hole at a logging speed of 10 feet/minute. This curve is valuable as an aid in interpreting the neutron lifetime log. Fig. 8 shows different logs recorded by the same neutron lifetime device. The silicon curve was obtained while going in the hole. The lifetime log (early and late gate, Σ curve, source output monitor) was recorded during uphole operation, together with the natural gamma log and the casing collar locator. The same detector (the upper one in Fig. 1a) is used for the natural gamma ray curve and for the silicon curve. Both logs are recorded with the same sensitivity (API units).

The two cross hatched zones in Fig. 8 indicate the most promising intervals for possible production as can be judged from the lifetime and natural gamma logs. The area was known to contain occasional lime streaks and calcareously cemented sands. With this local knowledge on hand, it was deduced from the relatively small silicon activation deflection between 4375 and 4380 feet, that the interval would probably be tight

[6]) Optimum logging speed v for any isotope can be calculated from the source-to-detector distance l and half life $T_{1/2}$ according to $v = 0.693\ l/T_{1/2}$.

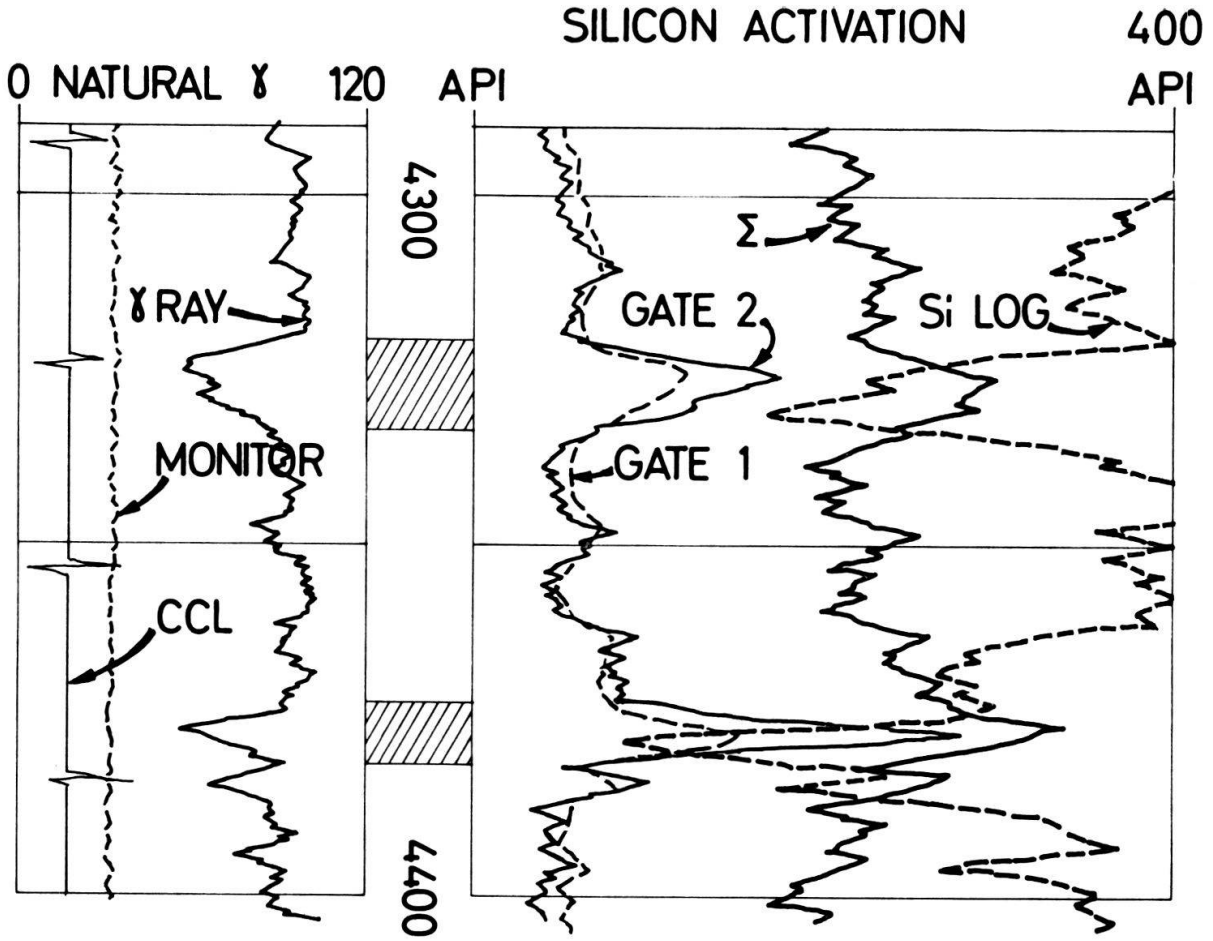


Fig. 8: Lifetime log, automatically computed Σ curve and silicon activation curve (Harris County, Texas well). Hatched intervals indicate zones which may be productive. Decreased silicon response in lower zone suggests that this interval is tight and nonproductive due to carbonate cementation. Test confirmed this. Upper interval produced 40 bbl oil/day with no water.

due to its low silicon content, i. e. high carbonate content. The zone was dry tested with perforations at 4378 feet. With the favorable lifetime response, in addition to a high silicon activation deflection (indicating low calcium carbonate), the upper zone was interpreted as porous and hydrocarbon-bearing. The interval was perforated from 4322 to 4326 feet and initially produced 40 barrels of oil per day with no water.

Besides silicon and oxygen, many other elements can be activated to a smaller extent. The induced activity A measured at any time t_2 is given by

$$A = N\sigma f\,(1 - e^{-\lambda t_1}) e^{-\lambda t_2} \qquad (6)$$

where f is the neutron flux (n/cm², sec); N the number of atoms which may be activated per cm³ of rock material; σ the activation cross section (barns); λ the decay constant of the activated isotope, and t_1 the duration of activation; t_2 is the elapsed time between irradiation and measurement. For example, the *aluminium activation* product Mg^{27} has a longer half life than silicon or oxygen. Therefore a given amount of aluminium irradiated for a short time will only produce approximately one tenth of the induced gamma radiation compared with a similar amount of equally irradiated silicon, other parameters being equal. In reservoir rocks aluminium is mostly incorporated in the clay minerals. Shaliness of sand formations could be detected in this way, probably better than by natural gamma ray logging. Though aluminium activation logging has not yet achieved much importance in petroleum exploration, it may

be worth mentioning that in prospecting for bauxite this method has an important application. *Manganese activation* (Mn^{55} (n, γ)Mn^{56}) is also used in the mining industry.

The application of *sodium activation* has been repeatedly reported by Russian authors (e. g. BARSUKOV et al. 1965, p. 79). The activation reaction Na^{23} (n, γ)Na^{24} produces a sodium isotope with 15 hour half life, a fact which excludes continous operation. Sodium, which can be determined «point by point», is only one of the possible cations in formation brines. To evaluate formation waters, salinity logging for chlorine is more convenient.

4. Chlorine log

Most of the formations of interest for oil production contain rather saline connate water. When this water is displaced by oil, the chlorine content of the formation is significantly decreased. The presence and quantity of chlorine in the formation can be determined by chlorine logging.

Chlorine possesses a uniquely high thermal neutron capture cross section (see Table 1). The energy of many of the gamma rays emitted at the instant of capture is sufficiently high ($>$ 6 Mev) to be discriminated from the majority of capture gamma rays from other elements present. Several chlorine logging systems have been used to evaluate the chlorine content by selectively detecting specific high energy capture radiation using energy-sensitive scintillation detectors (STROUD and SHALLER 1958, DEWAN et al., 1960). These methods have achieved some success, but have not in general been accurate and sensitive enough to permit a reliable estimate of water saturation. Other types of chlorine log comprise various combinations of two neutron logs differently responsive to chlorine. For example, a neutron-thermal neutron curve matched to a neutron epithermal neutron curve will exhibit varying degrees of departure as a function of chlorine content of the formation (see Fig. 9). Similarly a neutron-gamma curve matched to a neutron-thermal neutron curve comprises a combination which will show maximum departure in zones of high salinity. The calibration of such tools can be based on sections with known porosities and salinities in the borehole profile, or by inserting the tool into a neoprene sleeve (neoprene contains 40 weight % chlorine).

Chlorine logs have had little success in open hole logging since fresh mud filtrate invasion reduces the chlorine concentration in the invaded zone (the depth of investigation of the chlorine log depends on the penetration of fast neutrons, which varies from 6" at high porosities to 1 to 2 feet at low porosities). Some efforts have been made to use chlorine logs in open holes drilled with low water-loss mud. Best results are, however, obtained in cased wells which have been cemented for a time sufficient to re-establish the original fluid saturation conditions in the flushed and invaded zone behind the casing and cement.

Although chlorine logging has been extensively discussed in the literature and is the subject of many U. S. patents, it has in fact never attained general acceptance as a reliable means for evaluating cased off formations. Although based on valid theoretical principles, the measurements are in practice seriously influenced by variations in borehole conditions behind the casing to such an extent that the log is usually regarded as no better than qualitative for distinguishing between oil and water zones.

With the advent of the neutron lifetime log, which determines chlorine content in a more quantitative way, chlorine logging with capsuled sources has received less attention. It is anticipated that improved methods will be developed which employ the neutron generator and adapt chlorine logging principles to provide additional information to enhance the utility of the neutron lifetime log.

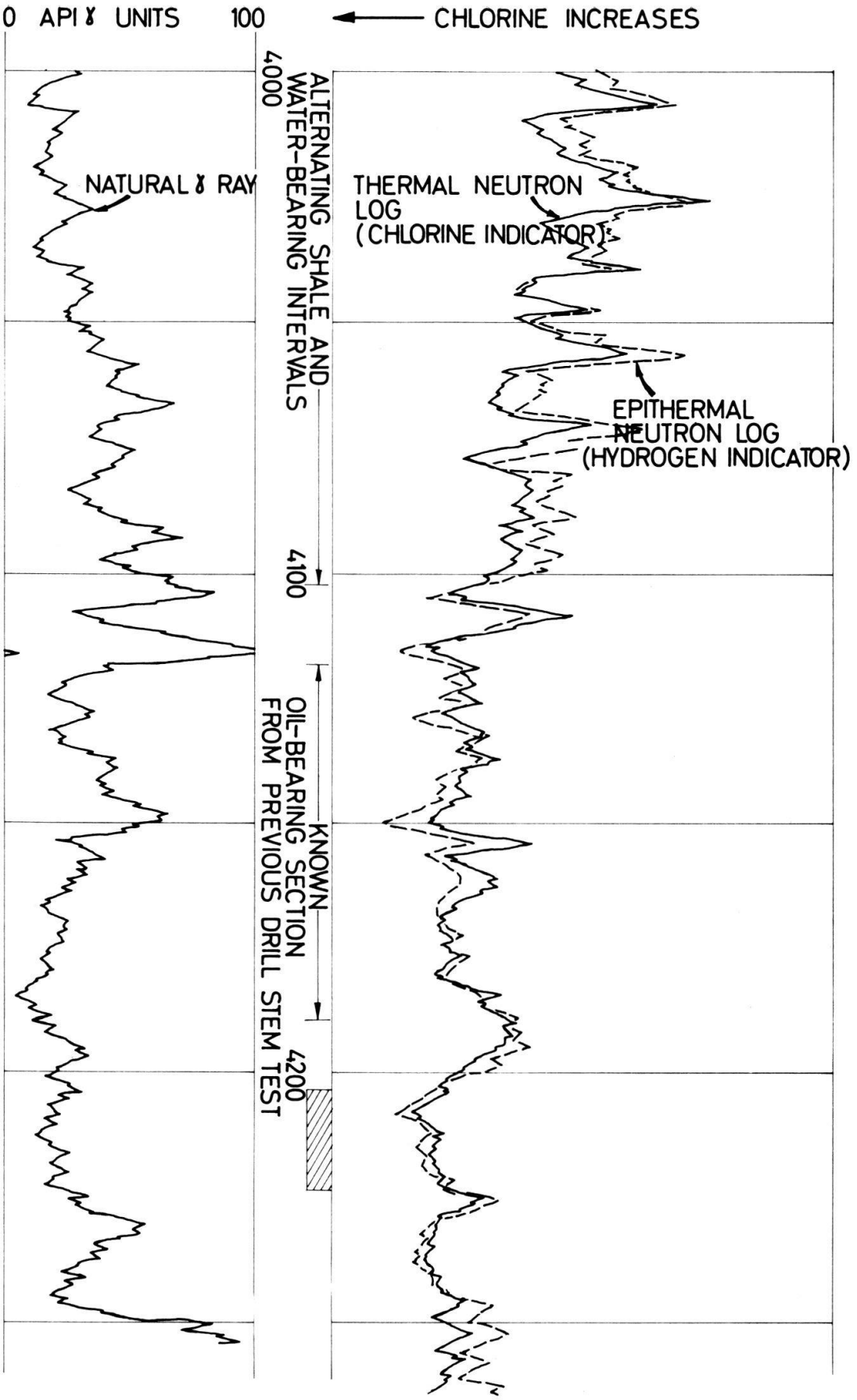
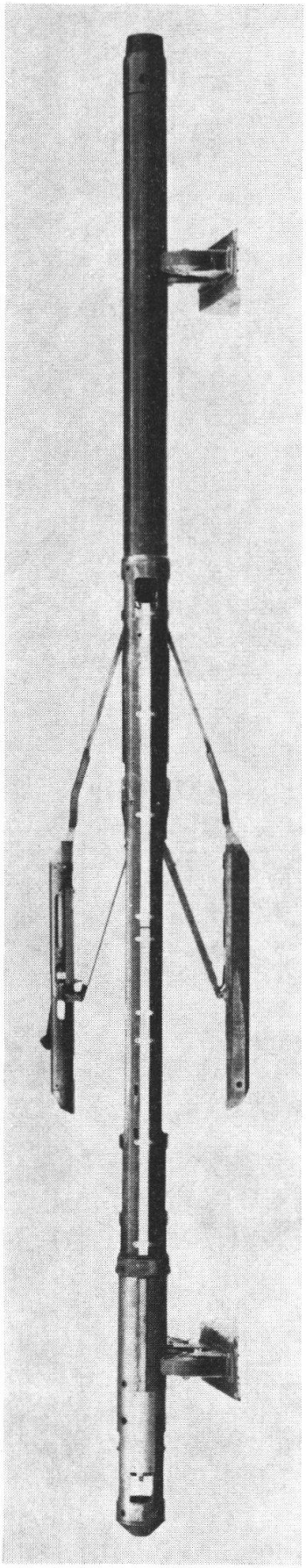


Fig. 9: Example of chlorine log (West Texas well). Both neutron curves have the same zero line and are scaled in counts per minute. For any given porosity the ratio «thermal neutron response/epithermal neutron response» decreases with increasing chlorine content. The interval of lowest response (4204–4224 feet) produced 40 bbl oil/day with no water after perforation.



5. Dual spaced density log

Logs employing a gamma ray source and a gamma ray detector in a system designed to measure formation density have been called gamma gamma density logs, or simply density logs. A new development in density logging has attained considerable success in improving formation density determinations in cases where a mud cake is present or where rugosity or roughness of the borehole wall prevents the logging instrument from touching the rock face uniformly along its length. The method employs a «pad» containing the gamma ray source and two detectors at different spacings. The pad is held against the borehole wall by an opposing spring which also serves as a caliper arm (Fig. 10).

The two detectors produce separate gamma gamma logs with differing depths of investigation due to their differing spacing from the source. On this account, they are differently affected by mud cake and stand-off from the borehole wall. By exhaustively evaluating the response of both curves in the presence of mud cake of all types, it is possible to derive a corrected formation density measurement (WAHL et al., 1964). This is done electronically and the recorded log is displayed along with the uncorrected curves together with a natural gamma ray log and a caliper as shown in Fig. 11. The density log is used in open hole as a porosity sensing device, especially in shaly sands.

Fig. 10: Dual spaced density log instrument containing a gamma-ray source and two detectors at different distances from the source. Density sensing pad is the one on the right. Total length: 9' 10".

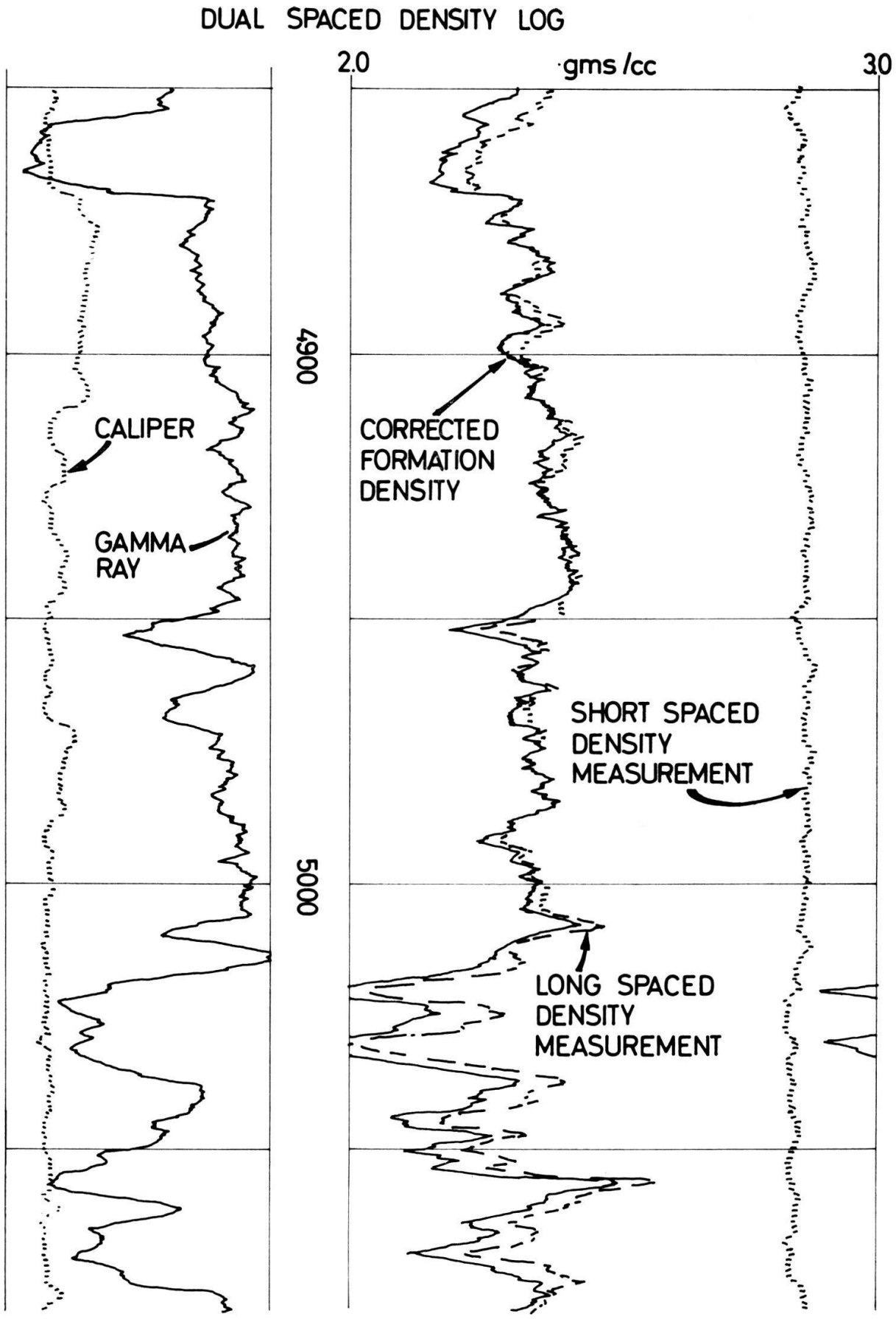


Fig. 11: Example of dual spaced density log (US Gulf Coast well).

6. Trends in nuclear logging development

As petroleum becomes scarcer on a world wide basis, there will eventually develop a compelling need to locate and recover as much oil as possible from old wells. Nuclear logs offer the best prospect for finding cased off oil. To this end, the future will see increased emphasis on tools and techniques which can reliably assay oil content in spite of the presence of casing and cement. The greatest prospect for significant improvements in nuclear logs appears to lie in the use of the neutron generator along with more refined techniques for spectral analysis of gamma ray and neutron energies. The neutron lifetime log has proven the electromechanical neutron generator to be practical for field use. More refined adaptations of the generator appear only to await an indication by the oil industry that such exotic devices would in fact be used commercially on a large enough scale to justify the great cost of their development.

Literature

Barsukov, O. A., Blinova, N. M., Vybornykh, S. F., Gulin, Y. A., Dakhnov, V. N., Larionov, V. V. and Kholin, A. I. (1965): Radioactive Investigations of Oil and Gas Wells. Pergamon Press.

Belknap, W. B., Dewan, C. V., Kirkpatrick, C. V., Mott, W. E., Pearson, A. J. and Rabson, W. R. (1960): API Calibration Facility for Nuclear Logs. American Petroleum Institute, Dallas.

Caldwell, R. L., Allen, L. S. and Mills, W. R. (1966): Theoretical and experimental model results in neutron lifetime logging. *In:* «Radioisotope Instruments in Industry and Geophysics». Proc. Symp. Warsaw 1965, Vol. II, pp. 65–84. IAEA, Vienna.

Causse, J. P. (1960): New rugged high-temperature photomultipliers. IRE Trans. Nuc. Sci., NS *7*, 66–71.

Dewan, J. T., Stone, O. L. and Morris, R. L. (1961): Chlorine logging in cased holes. Journal of Petroleum Technology, June 1961, 531–537.

Howell, L. G. and Frosch, A. (1939): Gamma-ray well-logging. Geophysics *4*, 106–114.

Marquis, G. L. (1964): The neutron lifetime log. Lane Wells Technical Bulletin, Houston.

Marquis, G. L., Wichmann, P. A. and Millis, C. W. (1965): Studies of producing reservoirs with the neutron lifetime log. Journal of Petroleum Technology, April 1966, 412–418.

Stroud, S. G. and Shaller, H. E. (1958): New radiation log for the determination of reservoir salinity. SPE of AIME, Preprint No. 1118G.

Tixier, M. P., Eaton, F. M., Tanguy, D. R. and Biggs, W. P. (1964): Automatic log computation at well site: formation analysis logs. Journal of Petroleum Technology, January 1965, 11–18.

Wahl, J. S., Tittman, J., Johnstone, C. W. and Alger, R. P. (1964): The dual spacing formation density log. SPE Trans. *231*, 1411–1416.

Wichmann, P. A., Youmans, A. H. and Hopkinson, E. C. (1966): Advances in neutron lifetime logging. Journal of Petroleum Technology, April 1967, 479–486.

Wood, J. D., Downton, D. W. and Bakes, J. M. (1966): A fast-neutron activation analysis system with industriel applications. *In:* «Modern Trends in Activation Analysis». Proc. of Int. Conf. 1965, College Station Texas, pp. 175–181.

Youmans, A. H. and Monaghan, R. (1957): Stability requirements for scintillation counters used in radioactivity logging. SPE Trans. *210*, 231–240.

Youmans, A. H. and Zimmermann, C. W. (1959): Recent advances in the use of nuclear physics in oil well surveys. Proc. Fifth World Petroleum Congress, New York.

Youmans, A. H., Hopkinson, E. C. and Wichmann, P. A. (1966): Neutron lifetime logging in theory and practice. SPWLA Transactions 1966, Q 1–17.