

July 18, 1950

J. M. THAYER ET AL
METHOD AND APPARATUS FOR PRODUCING
NEUTRON LOGS OF DRILL HOLES

2,515,534

Filed June 23, 1948

6 Sheets-Sheet 1

Fig. 1.

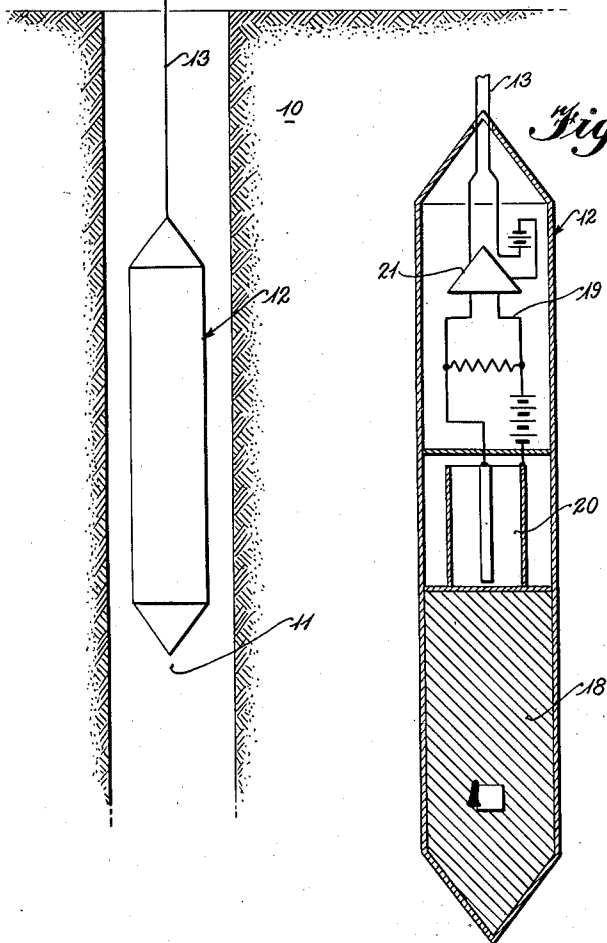
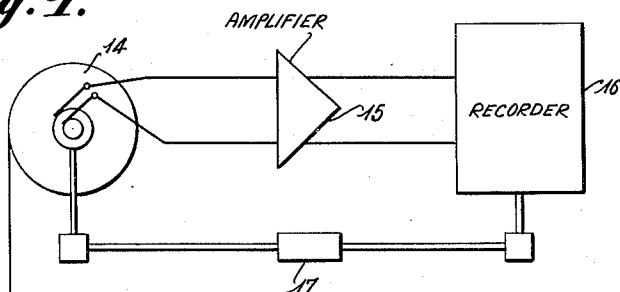
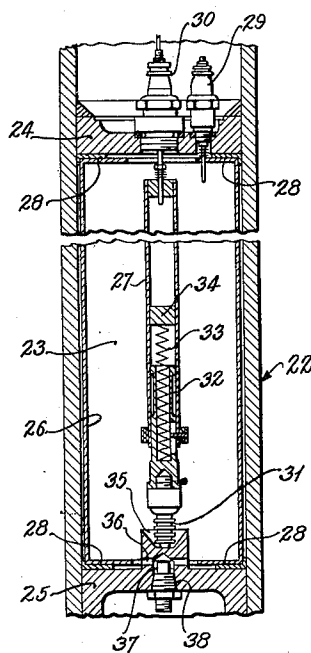


Fig. 2.

Fig. 5.



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Fig. 3c

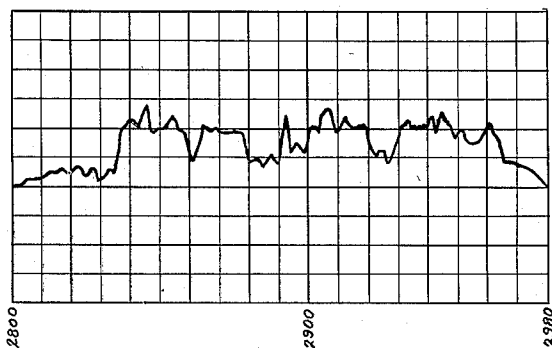


Fig. 3b

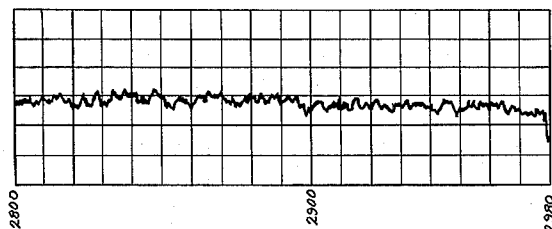
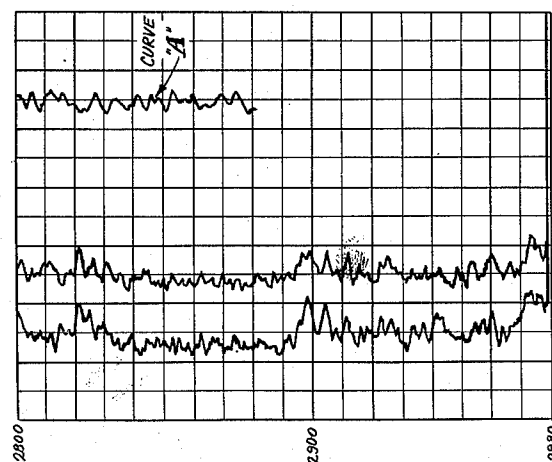


Fig. 3a



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Fig. 3.e

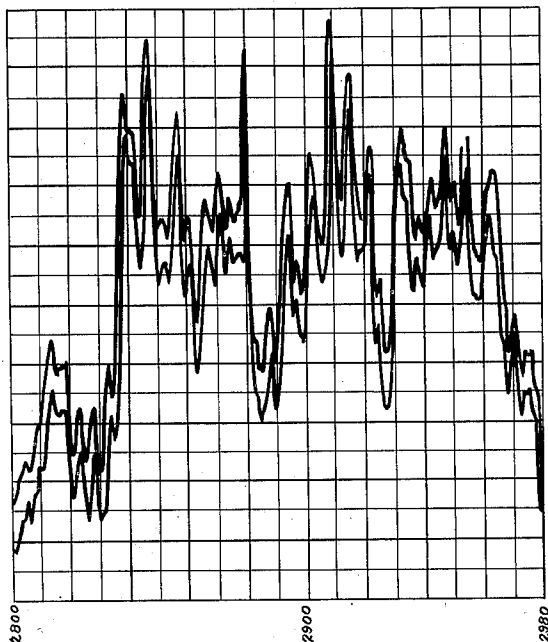
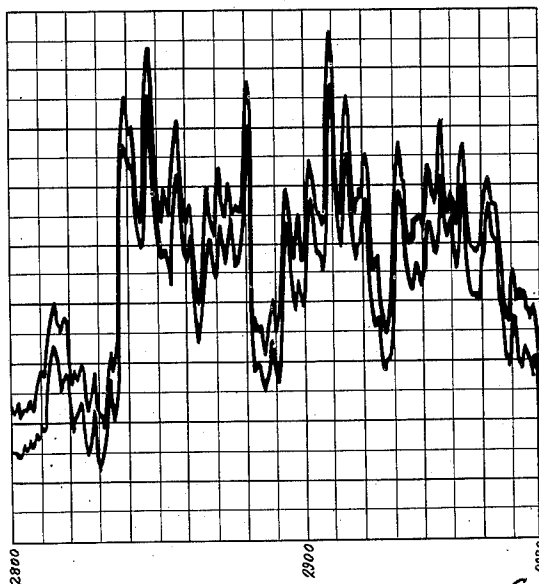


Fig. 3.d



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Fig. 3^h

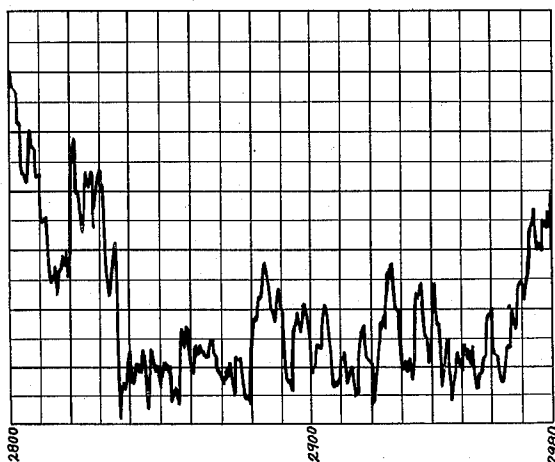


Fig. 3^g

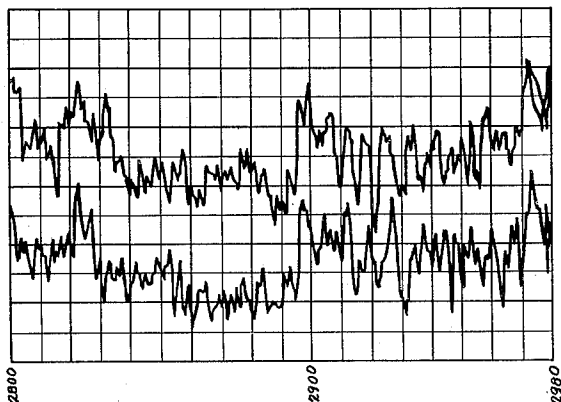
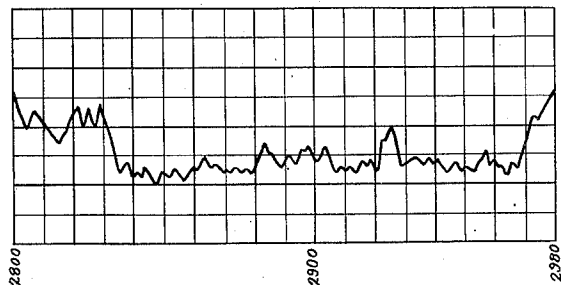


Fig. 3^f



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Fig. 4c

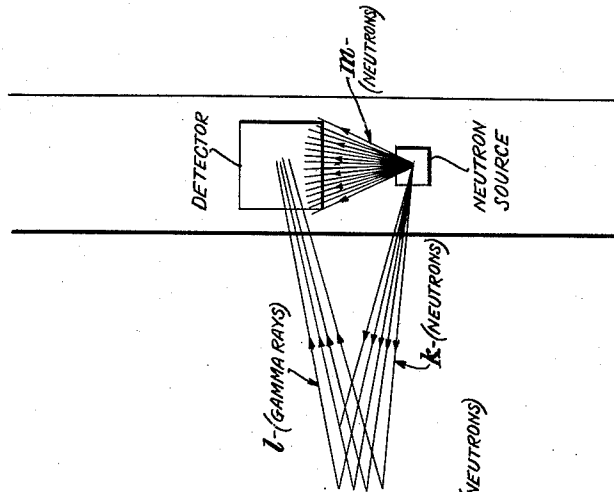


Fig. 4b

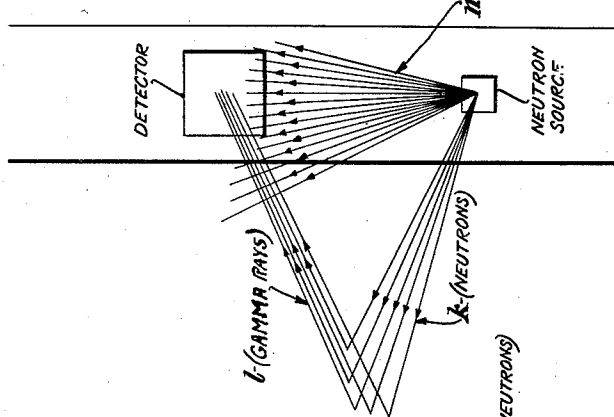
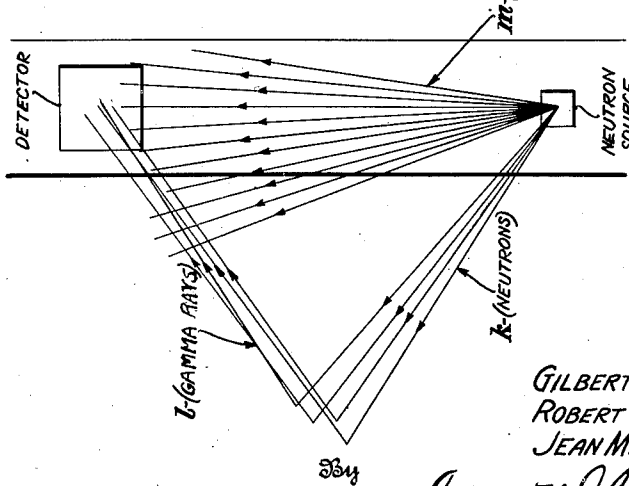


Fig. 4a



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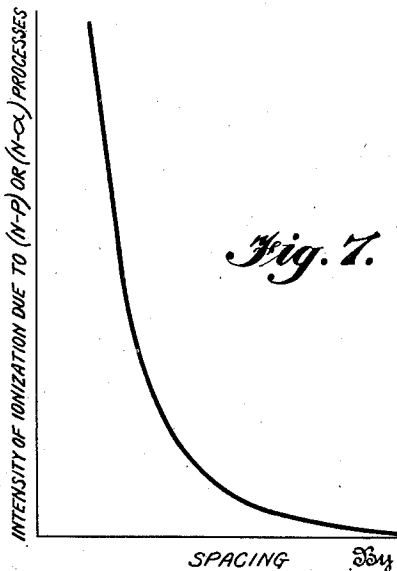
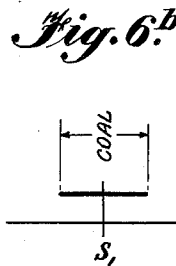
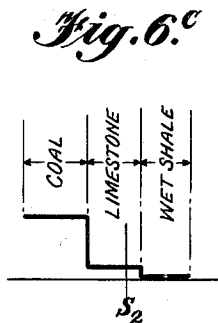
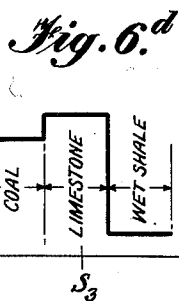
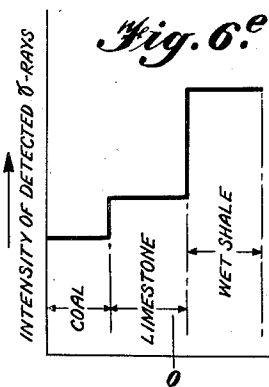
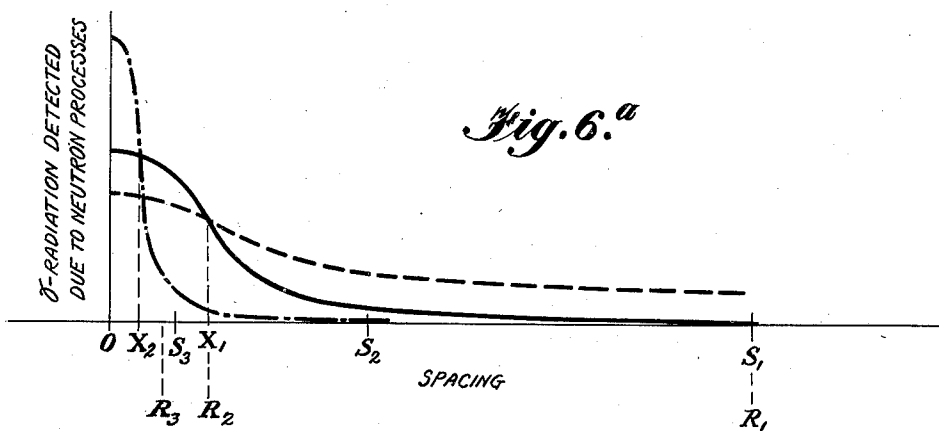
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6 Sheets-Sheet 6



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UNITED STATES PATENT OFFICE

2,515,534

METHOD AND APPARATUS FOR PRODUCING
NEUTRON LOGS OF DRILL HOLES

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Delaware

Application June 23, 1948, Serial No. 34,788

2 Claims. (Cl. 250-83.6)

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This invention relates to the art of sub-surface exploration, principally oil well logging, and more particularly to a radioactivity type of exploration in which a source of fast neutrons is used in conjunction with a gamma-ray detector. Commercially such a radioactivity log made by the use of a source of fast neutrons and a gamma-ray detector is known as a neutron log. This is true despite the fact that no neutrons are directly detected.

In recent years neutron oil well logs have achieved a degree of popularity not shared by the logs made by other methods. This is believed to be attributable to the fact that, in a substantial proportion of surveys made, they correlate more accurately with the lithology of the strata penetrated by the well. These logs have been made by traversing the well with a source of neutrons, usually 300 to 500 millicuries of radium intimately mixed with a predominant proportion by weight of powdered beryllium, to irradiate with fast neutrons the strata lining the well and simultaneously traverse the well with an associated gamma-ray detector to detect and record gamma rays in correlation with the depth at which they are detected. The detector, for example an ionization chamber, and the source are assembled to make a single unit, with the detector vertically spaced from the source.

By extensive experimentation we have discovered that the neutron log does not in many important instances adequately depict the lithologic properties of the strata surveyed. We have carefully investigated and correlated numerous instances of this kind and, as a result of exhaustive study and experimentation, we believe that we have now found the solution to this problem and have discovered how to make adequate neutron logs of oil wells, and analogous sub-surface passages, in virtually all instances.

One of the facts which we have discovered is that prior workers have not, in making and interpreting their logs, taken into consideration the variation in scattering from point to point in the well of the primary gamma radiation emitted by the neutron source and detected by the ionization chamber along with the gamma radiation resulting from the neutron processes occurring in the strata. We have found that this is a very important factor.

The radium-beryllium source, which has been accepted as a standard neutron source by those working in the art, is composed of an alpha rayer in the form of radium, atomic number 88 and mass number 226, in secular equilibrium with its daughter products, intimately mixed with a target material, beryllium. The mixture is enclosed in a metallic capsule which in turn is surrounded

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by a lead shield made as thick as practical, the diameter of the wells to be logged being the limiting factor. The lead shield is used as an attenuator of gamma radiation which is emitted by the source mixture along with the neutrons. We have found, however, that such a source emits gamma radiation far in excess of that which we have found permissible in making uniformly good logs under various well conditions.

We have also investigated the effect of gamma rays naturally emitted by the strata penetrated by a well, and we have found that the ionizing processes which they cause to occur in the detector are ordinarily small in comparison with those occurring due to the primary radiation when a conventional source of neutrons sufficiently strong for satisfactory logging is used. Therefore, no further reference will be made to them in this application.

In addition to our above mentioned discovery that primary gamma radiation from the radium-beryllium source is responsible in an important way for serious inadequacies in the logs, we have further discovered that a good neutron log can be made in virtually any bore hole by employing neutrons largely free from accompanying gamma radiation, and by otherwise following the disclosure of this application.

Pure radium, atomic number 88 and mass number 226, would be ideally suited for use in such a neutron source, because it can be used to produce neutrons and it does not emit gamma radiation. Radium, however, does not remain in a pure state for the reason that it is continually decaying to form daughter products, some of which are strong gamma rayers. Radium, therefore, goes into secular equilibrium with its daughter products. The nuclear processes which are continually taking place in radium are as follows:

Radium, atomic number 88 and mass number 226, is an alpha rayer which emits alpha rays of from 4 to 5 m. e. v. energy and in so doing decays to form radon, a gas. Radon also emits alpha radiation. The capsule in which the source material is contained retains this radon gas as it is formed and it goes to equilibrium. Radon is a powerful alpha rayer, giving off alpha rays of 6 m. e. v. energy. In emitting alpha rays of this energy it decays to radium A, which is also an alpha rayer. Radium A, by the emission of alpha radiation, decays to radium B. Radium B is a beta and a gamma rayer. The energy of the gamma radiation given off by radium B is approximately 0.5 m. e. v. Radium B decays into radium C which is, for the greater part, also a beta rayer. The gamma radiation given off by radium C has an energy of about 2.1 m. e. v. 99.65% of radium C decays by the emission of

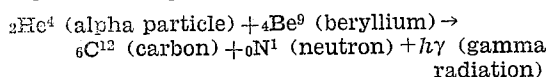
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beta radiation to form radium C', and the remaining 0.35% decays by the emission of both alpha and gamma rays to form radium C''. Radium C', by the emission of alpha radiation, decays to form radium D, and radium C'', by the emission of beta radiation, also decays to form radium D. Radium D decays by the emission of beta and gamma radiation to form radium E. This gamma radiation is very soft, having an energy of only 0.047 m. e. v. Radium E, by the emission of beta radiation, decays to form radium F, and radium F in turn, by the emission of alpha radiation, decays to form lead, atomic number 82 and mass number 206, which is stable.

Since all of the elements in the above series are in secular equilibrium, it can be seen that there are present some daughter products which emit hard gamma radiation which cannot be greatly attenuated by a lead shield of practical dimensions which would fit into a well. Those hard gamma rays which are not absorbed by the shield reach the walls of the well and are scattered thereby and some of them reach the detector where they are detected.

The beta radiation emitted by certain of the above daughter products when stopped by a target material produces gamma rays of about 600,000 electron volts energy. This action is comparable to that of an X-ray tube, the stopping material being the target. The chances of stopping a beta ray to produce gamma rays are, however, small, about one in 1000, and we have found that this phenomenon is not of significant importance in the neutron logging process.

The nuclear reaction which occurs in the source capsule which produces fast neutrons is



The neutrons produced by the above reaction have an energy of approximately 5 m. e. v. For every neutron produced by the above reaction a photon of gamma radiation having an energy of approximately 3 m. e. v. is produced. Gamma radiation of this energy cannot be filtered with a practical amount of lead shield, commensurate with drill hole dimensions, to less than one gamma ray to four neutrons.

We have discovered that these last mentioned two sources of gamma radiation, viz., gamma rays produced by beta ray and alpha ray impingement on target material are tolerable in good neutron logging. The gamma radiation which we have discovered not to be tolerable is that originating with the equilibrium mixture of the radium and its daughter products. To summarize, the significant gamma radiation emitted by the radium-beryllium source is, first, gamma radiation originating with the radium and its daughter products of approximately 2 m. e. v. energy, and, second, gamma radiation resulting from the nuclear reaction of the alpha rays and beryllium of approximately 3 m. e. v. The gamma rays given off by the radium and its daughter products are about 5000 times more numerous than the neutrons produced by the nuclear reaction of alpha rays and beryllium.

With a practical thickness of lead shield surrounding a radium-beryllium source, about 1000 of the gamma rays per neutron are emitted from the exterior of the shield. This gamma radiation is scattered by the formations in the vicinity of the source and some of the scattered radiation reaches the detector in varying amounts and is

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recorded, along with the desired gamma radiation produced by neutron reactions in the strata. In many cases, the scattered gamma radiation reaching the detector is substantially constant for all portions of the well. In these cases neutron logs can be made with the radium-beryllium source which are reliable and which truly correlate with the geology of the strata penetrated by the wells. This is due to the fact that the ionizing processes occurring in the detector which are produced by the scattered gamma rays are at a substantially constant rate resulting in a correspondingly constant flow of output current in the electrode circuit of the detector. Under these circumstances the ionizing processes in the detector produced by the desired gamma radiation resulting from neutron reactions in the strata, and which vary in rate in accordance with lithological characteristics of the strata, will be superimposed on those due to the scattered gamma radiation which originates in the neutron source. The output current from the detector then is composed of two components: one of substantially constant magnitude, that due to detected scattered gamma radiation, and one varying in magnitude in accordance with the lithological characteristics of the strata, that due to gamma radiation produced by neutron reactions occurring in the strata. Only in such cases can a neutron log be made with such a source that accurately represents the lithological characteristics of the formations. There is no way of determining from the log itself before, during, or after the making of the log if the well is one of this type. This is a very important consideration, because frequently there is no way of knowing whether the log is or is not an accurate log.

Usually while logging with a radium-beryllium source the gamma radiation emitted by the source is scattered by the walls of the wells and reaches the detector in an amount which depends upon the size of the boring, the character of the rocks (largely density), the thickness of the casing, the density of fluid in the well, and possibly to a small extent upon other factors. Since these factors vary with depth in a manner which does not necessarily agree with, but is often opposite to, the properties of the formations which cause the neutron reactions, the result is to obscure, nullify, and often reverse the deflections of the log that are due to detected gamma radiation which is produced by neutron reactions in the formations. In particular, all moderately small deflections are subject to suspicion since ordinarily it cannot be determined whether they are due to changes in the porosity or other factors affecting the neutron reactions in the formations, or are due to such factors as slight changes in diameter of the well or density of the formations which change the amount of scattered gamma radiation.

We have discovered and demonstrated that we can make a good log using a neutron source which does in fact emit some gamma radiation provided, however, that the variations of the detected gamma radiation recorded on the log and resulting from neutron reactions occurring in the formations are sufficiently greater than the variations of detected scattered gamma radiation which originates with the neutron source that the true lithological characteristics of the formations as depicted by the gamma radiation resulting from the neutron reactions in the formation will not be obscured.

Following our above described discoveries concerning the effect and tolerability of gamma ra-

diation emanating from the neutron source, we have discovered a method of making good neutron logs in virtually any well or bore hole. The method which we have discovered depends upon the provision of particular types of neutron sources. The term "source" is used here to include the neutron producing reactants, and their container and all shields, in other words, everything that is inside the outer surface of the source enclosure. This method also, as will hereinafter appear, deals with such matters as strength of source, neutron producing reactants, gamma-radiation attenuating shields, materials used in the detector, spacing of the source from the detector, and density of the fluid in the well.

We have discovered that radium F as an alpha rayer and beryllium as a target material constitute an excellent source of neutrons for the purpose of this application. Radium F is ideally suited for the reason that it gives off no gamma radiation and has no daughter products which emit gamma radiation. Radium F, however, has a short half-life, 140 days, and for this reason must be replaced too often to make it alone an entirely satisfactory source of alpha radiation.

We have, however, found a solution to this problem. We have discovered and demonstrated how to provide a source, having all the advantages of radium F and avoiding the serious disadvantage noted above, and at the same time being free from any new disadvantage. In accordance with our invention an adequate source of neutrons is provided which is substantially constant over a long period and is free from non-tolerable undesired phenomena.

One embodiment of this aspect of our invention involves the use of radium D. Radium D, as pointed out above, decays by the emission of beta radiation to radium E. The half-life of radium D is approximately 22 years. It is, however, not an alpha rayer. Radium E, a daughter product of radium D, by the emission of beta radiation decays to radium F, polonium, the desired alpha rayer. Since radium D, E and F, as well as radium G, stable lead, are in secular equilibrium, the supply of radium F is continually being replenished. The result is that, by using radium D in the source, we provide an alpha rayer, radium F, which in effect has a half-life of 22 years. Radium D and E emit substantially no gamma radiation. Any gamma radiation given off by radium D and E is soft and can be attenuated with a minimum of shielding and presents no problem whatever in the design of a practical source. Such a source would still emit gamma radiation which results from the alpha ray-beryllium reaction that produces the fast neutrons. This gamma radiation when emitted by the reactant materials has an energy of approximately 3 m. e. v. Gamma radiation of such energy cannot be greatly attenuated with a lead shield of practical thickness. It can, however, be reduced to approximately one photon of gamma radiation for every four neutrons emitted. We have determined that this proportion of gamma radiation is well within tolerable limits. Compared to the standard source, that which utilizes as reactant materials radium (atomic number 88 and mass number 226), in secular equilibrium with its daughter products, and beryllium, the source above discussed embodying our invention is approximately 5000 times better from the point of view of quanta of gamma radiation per neutron emitted from the exterior surface thereof.

It will be noted that in discussion of neutron sources the prior art has heretofore regarded a great variety of alpha rayers with a variety of target materials as equivalents when used as reactant materials for producing fast neutrons. A consideration of the above facts will show that such assumption of equivalence between such materials as radium (atomic number 88 and mass number 226), in secular equilibrium with its daughter products, and radium F, both working upon beryllium targets, is completely fallacious.

A practical source, which approaches what we have found to be the upper tolerable limit of the proportion of photons of gamma radiation emitted to neutrons emitted, may be defined as one which emits 500 times less gamma radiation than the standard neutron source, namely, the source which utilizes radium (atomic number 88 and mass number 226), in secular equilibrium with its daughter products, and beryllium as reactant materials. There is radiated from the outside of the shield of the standard neutron source about 1000 photons of gamma radiation for each neutron that is emitted. We have found that, in a satisfactory source, two photons of gamma radiation for each neutron emitted can be tolerated. Such a source, although approximately 8 times worse than our radium D-beryllium source described above, is believed still to be within tolerable limits, but not necessarily the equivalent of our preferred sources for all purposes. A source meeting the above standard is sometimes referred to hereinafter as "substantially gamma-ray free."

Another embodiment of this aspect of our invention utilizes actinium (atomic number 89 and mass number 227), in secular equilibrium with its daughter products, as an alpha rayer, and beryllium as a target material. Actinium has five alpha rayers among its daughter products in secular equilibrium with it. The energy of the alpha radiation given off by each of these five members is about 1 m. e. v. higher than the alpha radiation emitted by radium (atomic number 88 and mass number 226) and each of its daughter products. Additionally, since the alpha radiation from actinium is more energetic than that from the members of the radium series, the mixture of actinium and beryllium does not need to be as intimate as the mixture of radium and beryllium. The number of gamma rayers in that part of the actinium series that is of interest is comparable to that of the radium series. However, the highest energy of the gamma rays emitted by the actinium series is quite low by comparison, lying between 0.3 and 0.4 m. e. v. We can without difficulty provide a lead shield of practical dimensions for well logging which will attenuate this gamma radiation. One inch of lead will adequately attenuate this gamma radiation.

Another aspect of our invention is that an extremely small source can be used, or actinium in very impure state can be used. Actinium in secular equilibrium with its daughter products is approximately two times better than radium (atomic number 88 and mass number 226), in secular equilibrium with its daughter products, per millicurie of activity for producing neutrons and approximately 20 times better than radium D, in secular equilibrium with its daughter products, per millicurie of activity. The weight ratio

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for equal radioactivity units of actinium to radium D is

$$\frac{13.5}{22}$$

The weight ratio, for equal radioactivity units, of actinium to radium (atomic number 88 and mass number 226), is

$$\frac{13.5}{1590}$$

Therefore, weight for weight, actinium bears a neutron producing ratio to radium of

$$\frac{3180}{13.5}$$

or approximately 235. This means that, in accordance with our invention, it is possible to use actinium which is approximately 235 times less pure than radium in the same space and with equal results from the point of view of quantity of neutrons produced. Due to the need for less thickness of shield by a factor of 10, 100 times as much space becomes available for the source material. Therefore, actinium can have a degree of impurity which is one part actinium in 23,500, so long as the impurities are not gamma rayers. Such an alpha rayer, when used with beryllium, and the mixture provided with a practical amount of lead shielding, compares favorably with radium D, in secular equilibrium with its daughter products, as to the gamma radiation and neutrons emitted from the outer surface of the source.

A well-logging neutron source which employs any of the above neutron producing reactants, which are described as illustrative embodiments of our invention, and a practical gamma-radiation attenuating shield, would thus fall within the limits of toleration defined above for a practical source for the purposes of this invention.

Regardless of the type of neutron source used there is still another effect which we have found must be minimized or largely eliminated from the neutron log. This effect occurs at random intervals of time and is evidenced by sudden transitions, or fluctuations, of appreciable magnitude in the trace of the log. When these transitions occur on the trace, along with transitions of comparable magnitude which are occasioned by changes in the lithological characteristics of the formations, the log is incapable of being properly interpreted. Furthermore, these random transitions, depending on the time of occurrence and the direction of the transition on the log that is due to a change in the lithological characteristics of the formations, can overemphasize, obscure, or even reverse the wanted transition. In fact, the degree of reproducibility of a log is measured by the relative magnitudes of the unwanted random transitions and the wanted transitions that are occasioned by variations in lithological characteristics of the formations. These fluctuations are inherent in the desired processes and are caused by the statistical variation in alpha radiation given off by the alpha rayer in the source, the statistical variation in the number of neutrons produced in the source per second, and the resultant statistical variations in the gamma radiation produced by neutron processes in the formations. These fluctuations are minimized by employing a sufficiently strong neutron source and an efficient detector.

We have found that there are additional fluctuations, or transitions, which are attributable to neutrons that have passed directly from the

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source to the interior of the detector and there reacted with some material inside the detector (in an ionization chamber, the aluminum of which the central electrode is formed, or the iron or steel of which the outer electrode is formed) to produce a proton or an alpha particle. A proton or alpha particle, in its path of travel through the ionizable medium in the detector, produces enough ions to cause such a variation in the current output from the detector. For a detector having a given cross-sectional area, the opportunities for producing this effect vary with the distance between the source and the detector in accordance with the inverse-square law. The randomness of the effect, however, is attributable to the fact that only an occasional neutron is captured and gives up all its energy in the production of a proton or alpha particle in the detector. We have found that the average rate of occurrence of these processes can be reduced by increasing the distance between the detector and the neutron source and by reducing the cross-sectional area of the detector to present a smaller target for the direct neutrons. The increase in distance, however, as will be explained later, has a limit, and to go beyond this limit would not be practical.

We have found that this effect can also be minimized by using a stronger source, that is, one which emits more fast neutrons per unit of time. By using a stronger source more neutrons per unit of time will be emitted in all directions and the detected gamma radiation arising from neutron processes in the formations will increase, resulting in a more intense component of useful current flowing in the detector circuit. While the increase in the number of neutrons emitted per unit of time by the source will proportionally increase the opportunities for neutron-proton or neutron-alpha particle reactions to occur, we have nevertheless found that the resultant effect is only an increase in the average rate of occurrence of these reactions and not an increase in the magnitude of the ionizing process produced by each particle released in the ionizable medium. Therefore, the use of a stronger source increases the intensity of the wanted component of current flowing in the detector circuit without correspondingly increasing the magnitude of the fluctuations due to the random processes. The sensitivity of the detecting system can then be reduced to minimize its response to the random processes without seriously impairing the useful intelligence depicted by the log.

Although ways have been described above for minimizing the effect produced by these random processes, we have also discovered that this effect can be largely eliminated. This can be accomplished by using as a detector an ionization chamber which employs as an ionizable medium a substance which does not emit heavy ionizing particles when bombarded with neutrons and forming all metallic surfaces that are exposed to the ionizable medium inside the ionization chamber of a metal that will not emit heavy ionizing particles, such as protons and alpha particles, when bombarded with neutrons. We have discovered that argon and tin or tellurium, respectively, are ideally suited for these purposes. The metallic elements of the ionization chamber which have surfaces exposed to the ionizable medium inside the chamber need not be formed wholly of tin but may be plated with tin to a thickness, for example, at least 0.002 inch, which will absorb heavy particles, such as protons and

alpha particles, that are emitted by the plated metals when bombarded with neutrons thereby preventing the heavy particles from reaching the ionizable medium in the chamber. Tellurium may be similarly employed.

In addition to providing the type of neutron source above described, and minimizing or largely eliminating the unwanted effect produced inside the detector by the random processes described above, provision is made to augment the effect produced by the detection of gamma radiation which has originated with the neutron processes occurring in the formations when they are irradiated with fast neutrons. This is accomplished by using a source of adequate strength, i. e., one which emits enough neutrons per unit of time, e. g., 0.5×10^7 neutrons per second, to produce an intensity of gamma radiation in the formation, by neutron processes therein, to give a readable log when detected and recorded in correlation with the depth at which such radiation is detected.

We have found that the desired effect originating in different sub-surface formations can be selectively augmented, and that this can be accomplished by regulating the distance between the neutron source and the detector. That is, if we are seeking to locate a certain type of underground strata, we have discovered how to emphasize on the neutron log the presence of that particular type of strata. This distance above mentioned is critical, and from the point of view of useful gamma radiation produced by neutron reactions in the strata, we have found that it varies with the number of neutrons emitted by the source per unit of time and the average range of the neutrons in the formations adjacent the well. The range of neutrons in formations depends on the lithological properties of the formations. For example, in a dry formation, such as dry coal, the range of neutrons therein would be greater than the range of neutrons in a wet formation, such as a wet shale. The range of neutrons in a limestone would lie between the ranges for neutrons in dry coal and in wet shale. We have discovered that the intensity of detected gamma radiation from a particular formation is optimum when the spacing of the neutron source from the detector is of the order of, but not greater than, the neutron range in that formation. If we wish to emphasize the transitions in the log due to variations in a particular type of formation, we use a spacing between the source and the detector that is of the order of, but not greater than, the range of neutrons in that particular formation. From the geological history of the sub-surface strata in a particular area we can anticipate what formations are likely to be encountered in the well and can select a spacing between neutron source and detector which will be most favorable to the differentiation between the particular strata in which we are interested. Generally speaking, if we desire to differentiate between wet and very wet formations a relatively small spacing would be used between the neutron source and detector. On the other hand, if we desire to differentiate between a dry formation, such as coal, and a limestone, a greater spacing would be used. Taking these facts into consideration, we have found that in order to make a single log of a well which portrays the maximum information, a satisfactory spacing between the neutron source and detector can usually be selected which is a

compromise for all formations of interest that it is expected to encounter in the drill hole.

In many parts of the country oil wells are completed by "shooting" them with nitroglycerine. If a neutron log is made of such a well, without previous knowledge of the fact that it had been "shot," we have found that the interpretation of the log may be subject to serious error. In such wells large cavities are formed in the region where they are "shot." These large increases in diameter of the drill hole in the "shot" region introduce a substantial thickness of fluid between the neutron logging instrument and the walls of the well. We have discovered that, since well fluids contain a substantial proportion of water or oil which are high in hydrogen content, great adsorption of neutrons emitted by the source is experienced, resulting in a low intensity of gamma radiation produced in the formations adjacent the enlarged portion of the hole. Under such conditions the transitions in the log which depict changes in lithological formations are small in magnitude. However, with previous knowledge of the fact that the well has been "shot," we have discovered that the desired effect on the neutron log can be augmented in any one of the following three ways: (1) removing the fluid from the well as by pumping or bailing; (2) displacing the drill hole fluid wholly or in part by a fluid, such as carbon disulphide, which is relatively transparent to neutrons; or (3) using displacement shields formed of materials such as aluminum, having a thickness which will permit the free passage of the instrument through other portions of the drill hole, to displace the fluid lying between the neutron logging instrument and the walls of the drill hole.

The primary object of this invention is the provision of method and apparatus for producing neutron logs which accurately and consistently depict the lithological characteristics of the formations penetrated by bore holes. It is an object of this invention to provide method and apparatus, comprising a source of neutrons, for obtaining a log of subsurface formations which corresponds under virtually all conditions to neutron reactions occurring in the formations which are occasioned by neutrons emanating from the source. It is a further object to provide a neutron logging method and apparatus which embodies all features essential to making logs that depict lithological characteristics accurately, and at the same time to recognize and eliminate, or minimize within tolerable limits, all significant phenomena which interfere with making such logs.

It is further an object of the invention to delineate the effect on neutron logs of gamma radiation other than that produced by desired neutron reactions in the formations, and to identify and eliminate the most damaging source of this undesired radiation. It is also a purpose of this invention to apprehend and evaluate all undesired gamma radiation, to determine tolerable limits, and to provide method and apparatus for restricting same within such limits, including the provision of shielding where such means is effective in attaining said tolerable limits.

An important object of this invention is to define and provide a class of neutron sources by means of which accurate neutron logs can reliably be produced. It is an object of the invention to provide economically and scientifically practicable neutron sources of adequate permanence and strength which are essentially or tolerably free of gamma-ray emission. Specifically,

it is an object of the invention to provide a neutron source which employs radium D, in secular equilibrium with its daughter products, and a material such as beryllium, as neutron-producing reactant materials; a neutron source which employs actinium (atomic number 89 and mass number 227), in secular equilibrium with its daughter products, and a material such as beryllium, as neutron-producing reactant materials; and a neutron source which employs, as an alpha rayer, radium F and a material such as beryllium, as neutron-producing reactant materials. It is a further object to provide said actinium source in notably small physical dimensions, if desired. It is also an object to provide the said actinium source in proper strength and quality, but nevertheless in highly impure state as regards the actinium alpha rayer, provided the impurities are not gamma rayers. It is also an object to provide a neutron source, having a practicably constant strength and a practicably long half-life, which contains, as an active constituent, an alpha-particle emitter of short half-life which is continually replenished.

It is a further object of this invention to determine the causes of certain sudden random fluctuations which have characterized and impaired neutron logs heretofore made, and to provide a solution for this difficulty. It is an object of the invention to minimize the effect of these random fluctuations on the log to tolerable proportions by increasing the desired radiation reaching the detector without increasing the magnitude of said fluctuations. It is also an object to reduce the frequency of occurrence of these random fluctuations on the log by enlarging the spacing between the detector and the neutron source without, however, seriously deviating from the optimum spacing requirements based upon other considerations. It is a further object to minimize, or wholly or largely eliminate, these random fluctuations by ascertaining and suppressing the phenomena from which they result. It is a specific object of the invention to accomplish this by using an ionizing chamber as a detector, and forming surfaces that are exposed to the ionizable medium inside the chamber of a substance that will not emit heavy ionizing particles when bombarded by neutrons.

It is a further object of the invention to augment selectively on the neutron log transitions indicative of different subsurface formations. It is an object to emphasize on the log the presence of a particular formation deemed to be of special interest. It is a particular object of the invention to accomplish this by regulating the spacing between source and detector. It is a specific object to detect a particular formation by spacing the source and detector a distance of the order of, but less than, the range of neutrons in that formation. It is a further object of this invention to differentiate between very small percentages of fluid content of formations that are otherwise the same. It is a specific object of this invention to teach the manner in which a reliable neutron log can be made with weak neutron sources. It is also an object to provide a compromise spacing, based on the foregoing considerations, which will enable satisfactory differentiation between and location of various formations of interest.

It is a further object of the invention to minimize or eliminate error in neutron logs occasioned by enlargements in the well bore, and to accomplish this by suitably altering the composition of the well fluid to reduce its capacity for

absorbing neutrons, or to displace the well fluid wholly or partially by means carried by the subsurface instrument.

It is also an object of the invention to provide any one or any combination of the features described herein in neutron logging methods or apparatus, depending upon the requirements of the particular problem at hand.

Other objects and advantages of the present invention will become apparent from the following detailed description when considered with the drawings, in which:

Figure 1 is a diagrammatic illustration of a neutron logging operation;

Figure 2 is an enlarged vertical sectional view of the subsurface instrument;

Figures 3a to 3h are reproductions of sections of well logs made of a particular well from a depth of 2800 feet to 2930 feet under various conditions;

Figures 4a to 4c illustrate the manner in which the number of neutrons entering a detector varies with the spacing between the neutron source and the detector and also the paths followed by the useful radiation in the formations;

Figure 5 is a fragmentary view of the subsurface instrument showing in vertical section details of an ionization chamber;

Figures 6a to 6e illustrate the effect of varying the spacing of the neutron source from the detector on the useful detected gamma radiation which has been produced in different kinds of formations; and

Figure 7 is a curve which has been plotted with the spacing of the neutron source from the detector as abscissae and the intensity of ionization due to neutron-proton or neutron-alpha particle processes that is caused to occur in the detector as ordinates.

Referring to the drawings in detail, particularly Figure 1, there is illustrated a well surveying operation in which a fragment of the surface 10 of the earth is shown in vertical section. A well 11 penetrates the earth's surface and may or may not be cased. Disposed within the well is the subsurface instrument 12 of the well logging system which additionally comprises a cable 13 for suspending the instrument in the well, a drum 14 from which cable is payed out or on which cable is wound when causing the capsule 12 to traverse the well, electrical connections from slip-rings on the axle of the drum 14 to an amplifier 15, which in turn is electrically connected to a recorder 16 in a conventional manner. Recorder 16 is driven through a transmission 17 by the drum 14 as the cable is payed out from or wound thereon. The record thus made by the recorder as the capsule 12 traverses the drill hole will be in correlation with depth.

As shown in Figure 2, the capsule 12 comprises a neutron source 18 forming the bottom portion thereof and a gamma-radiation detecting system indicated generally as 19 which makes up the upper portion of the capsule. The gamma-radiation detecting equipment 19 can be such as that disclosed in Patent No. 2,349,225 or such as that shown in Patent No. 2,390,965. For purposes of describing this invention an ionization chamber 20 is shown as the radiation sensitive element. As disclosed in Patent No. 2,308,361, the operation of a system of this character when producing a neutron log is that the capsule 12, made up of a source of neutrons 18 and a gamma-radiation detection system 19, is caused to traverse a well. Neutrons emitted from the source enter

the walls of the well and, by nuclear reaction with matter contained in the walls, produce gamma radiation in amounts proportional to the lithological characteristics of the materials of which the walls are formed. This gamma radiation produced by nuclear reactions in the strata is detected by the gamma-radiation detector 23 by reason of the fact that it produces electrical signals that are related in magnitude to the intensity of the gamma radiation detected, and these signals are amplified by an amplifier 21 and transmitted over conductors contained in the cable 13 to the surface of the earth where, if necessary, they are further amplified by the amplifier 15 and recorded by the recorder 16 in correlation with the depth at which they were detected.

It is to be understood that any conventional well-logging gamma-radiation detecting and recording system can be employed in conjunction with a proper neutron source while practising that form of the present invention in which a neutron log is made directly.

Commercially a log made by the above described operations is known as a neutron log. This is true although no neutrons are directly detected and recorded. In every instance to date the record has been one of gamma radiation intensity versus depth. Those working in the art have heretofore assumed that such a log truly represents an effect produced in the strata by irradiating the strata with neutrons. That is, the log was purported to be a measurement of the gamma radiation produced by the nuclear reaction of neutrons and elements contained in the strata versus depth. Our research, however, has shown that this is not the case. The log made by the commercial neutron logging method is a composite log that is produced while recording at least three, and possibly four, effects. These effects are:

1. Gamma radiation arising from the interaction of neutrons with substances in the strata.
2. Gamma radiation which has been emitted by the neutron source and which, by direct or indirect paths, arrives at the detector.
3. An effect believed to be a neutron-proton or neutron-alpha reaction occurring in the detector as a result of neutrons travelling directly from the neutron-emitting source into the detector and there reacting with some substance in the detector.
4. The effect that is caused by natural gamma radiation emitted by the strata. This fourth effect is normally so small in comparison to the other three effects that it can be considered in most instances negligible.

The first of the four above enumerated effects is the desired effect which correlates with the lithological properties of the formations penetrated by a well and serves admirably as an index by means of which the formations can be identified. The last three effects are those which we have found to be undesirable since they lead to erroneous interpretation of the log. Effects Nos. 2 and 3 also render the log incapable of being reproduced under the same operating circumstances. Therefore, we have found that, in order for a neutron log to truly depict the lithological characteristics of the formation penetrated by a well, these last three effects must be minimized or largely eliminated and that the first effect must be augmented.

This is illustrated in Figures 3a-3h. In these figures there are reproduced sections of logs made

of a particular well from a depth of 2800 feet to a depth of 2980 feet. Figure 3a is a standard neutron log; that is, it is a log which has been made while using the "so-called" standard radium-beryllium neutron source above described. The log has been duplicated so that random variations which are statistical in nature may be observed. The insert curve A is a record of the random variation which has been made with the detecting instrument stationary. The sharp transitions occurring in this insert fragment of a trace are attributable to ionizing processes occurring in the detecting instrument as a result of neutron-proton and/or neutron-alpha particle reactions therein and to statistical variations in the neutron flux. This random effect is clearly discernible in the two logs of Figure 3a if a close comparison is made of the logs. The well in which the two logs of Figure 3a were made was of substantially uniform diameter over the distance logged. Therefore the variation in gamma radiation which was emitted by the neutron source and which had been scattered by the strata was substantially negligible. As a result, the two standard neutron logs depict with acceptable accuracy the lithological characteristics of the strata in the well.

In order to determine the effect of gamma radiation which was emitted by the neutron source and scattered by the strata lining the well, a log was made of the same portion of the well while using a neutron-free gamma-radiation source which emitted gamma radiation of the same intensity as that emitted by the standard neutron source. This log is shown in Figure 3b. It will be noted that the variation of detected scattered gamma radiation is quite small in comparison to the variation of detected gamma radiation in Figure 3a. Therefore, from this log it is safe to assume that the two logs shown in Figure 3a are essentially of gamma radiation produced by neutron reactions in the strata versus depth.

In order to show the variation in the effect produced by gamma radiation which has been scattered by the formations and has reached the detecting instrument, the same well, logs of which are shown in Figures 3a and 3b, was shot with nitro-glycerine. A caliper log was then made of that portion of the well between the depths of 2800 feet and 2980 feet. This caliper log is shown in Figure 3c. This log shows that enormous cavities were created in the well and the inner walls thereof are anything but smooth. The diameter of the hole varies over a wide range.

After the well had been shot a standard neutron log was again made. By separate operations this log was duplicated. These two logs are shown in Figure 3d. By comparing these two logs of Figure 3d with those shown in Figure 3a, it will be seen that they in no way resemble each other. All parameters other than the diameter of the drill hole remained constant when the logs of Figures 3a and 3d were made. This clearly illustrates the effect of the variation in well diameter on the standard neutron log. We have found that variations of $\frac{1}{2}$ " or more in well diameter will produce variations in the standard neutron log which would lead to erroneous interpretation.

Now compare the logs shown in Figure 3e to those shown in Figure 3d. The two logs shown in Figure 3e are logs which have been made while using a neutron-free gamma-ray source, the gamma rays emitted from which were of the

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same intensity as those emitted by the standard neutron source. The logs of Figure 3c can be said to truly represent the variation in detected scattered gamma radiation which was emitted by the gamma-ray source. At a glance the logs of Figures 3e and 3d appear to be duplicates. This is because the effect of scattered gamma radiation which has been emitted by the source has varied widely with the hole diameter. In fact, the logs made with the neutron-free gamma-ray source (Figure 3e) correlate with the caliper log (Figure 3d).

Since the variation of detected scattered gamma radiation is for the greater part attributable to the variation in well diameter, if one subtracts the logs made while using a neutron-free gamma-ray source from those made while using the standard neutron source, a log will be obtained which truly represents a measure of the gamma radiation produced by neutron reactions in the strata versus depth. This has been done. The result is illustrated in Figure 3f. A comparison of the log of Figure 3f with the log shown in Figure 3a will show that they closely correlate. Therefore, it becomes apparent from our discoveries that if one desires to make a neutron log which truly depicts the lithological characteristics of the strata penetrated by a well, the effect of gamma radiation given off by the neutron source, scattered by the strata and thereafter reaching the detector, must be taken into consideration and largely eliminated. For, as clearly illustrated above in Figures 3a to 3f, in wells where the diameter varies from point to point in depth, the effect of the detected scattered gamma radiation is to obscure, nullify and even reverse the deflections of the log that are due to detected gamma rays which are produced by neutron reactions in the formations.

We have found that the solution to this problem is to use a neutron source which does not emit more than a tolerable number of photons of gamma radiation per neutron produced. As pointed out above, radium D in secular equilibrium with its daughter products and beryllium make a neutron source which is ideally suited for neutron logging when a shield of practical density and thickness is used about the reactant materials. The neutron producing reaction of such a source will produce one photon of gamma radiation for each neutron produced. The use of a shield of practical density and thickness will attenuate the number of photons of gamma radiation to approximately one photon of gamma radiation for every four neutrons emitted from the external surface of the source. This ratio of gamma radiation to neutrons is well within the tolerable limits of a practical neutron source in accordance with our invention. Primary gamma radiation of such intensity, after having been scattered by the formation adjacent the drill hole, produces only a negligible effect in the detecting instrument. The intensity of the gamma radiation which arises from neutron reactions with elements contained in the formations is sufficiently greater by comparison that variations due to lithological characteristics of the strata are outstanding on the log over any effect that is produced by the scattered gamma radiation.

The same section of the particular well, whose logs have been discussed above in connection with Figures 3a to 3f, has been logged while using a radium D, in equilibrium with its daughter products, and beryllium neutron source, it being

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understood that the shield of practical density and thickness is an essential element of the source. Such a log made before the well was shot is illustrated in Figure 3g. Except for a difference in overall amplitude due to a difference in sensitivity of the recorder, the log shown in 3g compares favorably with the subtraction log shown in Figure 3f. A log made with the same source after that section of the well had been shot is shown in Figure 3h. Except for general overall increase in amplitude this log also correlates quite closely with the subtraction log of Figure 3f. Comparing the log of Figure 3h with that of Figure 3g it will be seen that the major transitions are outstanding in both logs. In fact, the overall general characteristics of the records are the same. A few of the major transitions that are outstanding in both 3h and 3g are at 2820 feet, just above 2900 feet and just above 2980 feet.

Although the correlation of the radium D logs with the subtraction log of Figure 3f is quite good, the reproducibility of details of the logs is nevertheless not as good as it might be. This is due to the fact that only a small amount of radium D was used in the neutron source, because no more was available. This amount of radium D represents approximately the lower limit of alpha rayer that can be used to constitute a practical neutron source, whereas approximately five times this amount would be desirable. As the curie activity of the radium D in the source is increased, more neutrons are produced in the source and emitted thereby. The reproducibility of the radium D-neutron source logs increases substantially as the square root of the number of neutrons emitted by the source. The more neutrons there are entering the strata the more gamma radiation will be produced by their reactions with elements in the strata, resulting in a substantially corresponding increase in the number of photons of gamma radiation which produce ionizing processes in the detector. In fact, if the intensity of the useful gamma radiation is sufficiently great, the sensitivity of the recording system can be reduced to a point where its response to the statistical or random processes will be negligible. Relatively speaking the use of a radium D-beryllium source of optimum strength will minimize or largely eliminate the undesired effects and augment the desired effect.

In addition to the use of radium D and its daughter products as an alpha rayer in a neutron source for well logging actinium, atomic number 89 and mass number 227, in secular equilibrium with its daughter products can be used. As pointed out above, actinium and its daughter products have five alpha rayers, each of which emits alpha radiation having energies approximately 1 m. e. v. higher than the alpha radiation emitted by radium, atomic number 88 and mass number 226, and its daughter products.

Although actinium, atomic number 89 and mass number 227, in equilibrium with its daughter products, when used as an alpha rayer in a neutron source, may be used in the same manner as radium and radium D, it is not the equivalent of either. The neutron source produced by the use of actinium has properties which are entirely different from those produced by the use of radium or radium D as alpha rayers. From the point of view of neutrons produced per millicurie activity, actinium is twice as good as radium, atomic number 88 and mass number 226, plus its products, and twelve times better than

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radium D plus its products. Since the weight ratio, for equal radioactivity units, of actinium to radium (atomic number 88 and mass number 226) is

$$\frac{13.5}{1590}$$

weight for weight, actinium bears a neutron producing ratio to radium of

$$\frac{3180}{13.5}$$

or approximately 235. This means that, in accordance with our invention, it is possible to use actinium which is approximately 235 times less pure than radium in the same space and with equal results from the point of view of quantity of neutrons produced. Due to the need for less thickness of gamma-radiation attenuation shield by a factor of 10, 100 times as much space becomes available for the source material. Therefore, actinium can have a degree of impurity which is one part actinium in 23,500, so long as the impurities are not gamma rays. Actinium further differs from radium, atomic number 88 and mass number 226, in that the gamma radiation naturally emitted thereby has energies which range from 0.3 to 0.4 m. e. v. in contrast to energies of approximately 2 m. e. v. for radium and its daughter products.

As briefly indicated above, the vertical spacing of the neutron source from the detector is critical for any neutron source. There is a definite range for each type of source beyond the limits of which one cannot go and expect to make a neutron log that can be said, with assurance, truly depicts the lithological properties of the strata penetrated by a well. In order to determine the spacing of a neutron source from a given associated gamma-ray detector it is necessary to take into consideration the number of neutrons emitted per second by the source; the range of the emitted neutrons; the intensity of gamma radiation emitted by the neutron source; the ratio of gamma radiation to neutrons emitted; the type of fluid in the well, the physical characteristics of the formations; the diameter of the well; the ionizing processes which occur in the detector due to neutron-proton or neutron-alpha reactions inside the detector; the relative sensitivity of the detector to gamma radiation resulting from neutron processes in the formations and to gamma radiation emitted from the neutron source and scattered by the formations; the density and quantity of the shield elements comprising a part of the source; and the reactant materials used to produce the neutrons. Although the effects of some of these factors are dependent on one or more of the other factors, the contribution of each factor will be described as far as possible independently.

First, consider the effect of the processes which occur in the detector that are caused directly by neutrons. This effect is evidenced by the fluctuations that occur in the trace of the log at random intervals and which stand out on the trace above the normal background noise that is recorded. These fluctuations are due to neutron-proton and/or neutron-alpha particle reactions occurring inside the detector. They are caused by neutrons travelling directly from the source into the detector and there reacting with some substance, such as the aluminum of which the central electrode of an ionization chamber may be made, to produce a proton or an alpha

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particle, which in its path of travel through the ionizable gas therein produces numerous electrons. These electrons are collected by the collector electrode and result in a burst of current flow in the electrode circuit, which when amplified and recorded produces such random outstanding transitions. This statement is based on numerous experiments and is believed to be correct. Fast neutrons are emitted from the source in all directions and the number which enter a detector having given dimensions, and which have an opportunity to react with a substance therein, varies inversely as the square of the distance between the point where the neutron-producing reactant materials are located and the detector.

This is illustrated in Figures 4a, 4b and 4c. In these figures there are shown three conditions of spacing of neutron source from the detector in a well. These figures show generally the paths k of the neutrons which enter the strata and there produce gamma radiation. The useful gamma radiations so produced reaches the detecting instrument by the paths l . Although the paths k and l are shown only on one side of the instrument, it is to be understood that the neutrons are emitted in all directions and the paths appear on all sides of the instrument. Neutrons which travel directly from the source to the detector follow the paths m . The number of neutrons that follow the paths m and enter the detector vary inversely with the square of the distance between the source and detector. As pointed out above, not all of the neutrons which enter the detector produce protons which contribute, by their ionization processes, a component of current to that flowing in the electrode circuit. For purpose of comparing the effects produced in the detector by the gamma radiation produced by neutrons in the strata and the protons or alpha particles produced in the detector by neutrons which have travelled substantially directly from the neutron source, let us first, for purpose of explanation only, assume that one out of each of n neutrons entering the detector produces an ionizing proton or alpha particle, and assign arbitrary values to the current components that would flow in the electrode circuit. For the spacing shown in Figure 4a, let us assign a value of 3 to the component of electrode current due to gamma rays produced in the strata by neutrons, and .03 to the component of current that would flow in the electrode circuit due to ionizing processes produced by protons or alpha particles. We would then have a ratio between these components of 100 to 1. Now referring to Figure 4b, the spacing between the source and detector shown there has been decreased to a point where that component of current that would flow in the electrode circuit due to gamma rays produced in the strata by neutrons would be doubled. This reduction of the spacing would, under the assumption made in connection with Figure 4a, now increases the current component due to alpha particles or protons to .12, giving a ratio of useful signal to undesired signal of 50 to 1, instead of the 100 to 1 obtained under the condition of Figure 4a. In Figure 4c the source is shown still closer to the detector, spaced therefrom by a distance that will cause the useful signal to increase to 12. That component that would flow in the electrode circuit, the unwanted signal, would increase to approximately .5, reducing the ratio of desired signal to unwanted signal to 24 to 1. The average magnitude of this

phenomenon when plotted against detector-source spacing is an exponential curve such as is illustrated in Figure 7. From this curve it can be seen that this undesired effect increases from that for long or far spacing slowly at first as the spacing decreases and rises rapidly for very short or close spacing. Use of a relatively great spacing thus serves to minimize or effectively eliminate this phenomenon. Too great a spacing, however, results in the decrease of the wanted signal to such an extent that the repeatability of the log is impaired. Thus it is seen that as the spacing between source and detector is varied from very close to very far the repeatability at first improves, as the processes in the detector caused directly by neutrons diminish and later again becomes poor as the intensity of the wanted radiation diminishes. There are therefore maximum and minimum limits of spacing which can be employed with a source of given strength in order to achieve an acceptably repeatable log at a reasonable logging speed. When using sources of scarce or costly materials these limits become of great importance in order that satisfactorily repeatable logs may be obtained with a minimum amount of source material. We have found that when using detectors in which no attempt has been made to minimize or eliminate the direct interaction of neutrons with the materials inside the detector that the satisfactory limits for operation of a weak source, such as one which emits 10^6 neutrons per second, lie between 6 and 14 inches. As the strength of the source is increased, as for example to one which emits 0.5×10^7 neutrons per second, the satisfactory range of spacings increases to 4 to 20 inches. As the effects inside the detector produced by direct interaction with neutrons are reduced the minimum satisfactory spacing decreases. For example, with a detector in which this effect has been reduced by a factor of ten from that of a detector of the type shown in Figure 5 and more fully disclosed in Patent No. 2,390,965, the minimum permissible spacing for a weak source will decrease from 6 to about 3 inches, and with a detector in which this effect has been entirely eliminated a spacing of zero inches, meaning that the neutron source is located within the detector, can be tolerated.

One way to eliminate or reduce the effect caused by direct action of neutrons in the detector is to interpose a substance, such as paraffin or boron for example, which absorbs neutrons, in the direct path between the source and the detector.

We have found that this neutron-proton and neutron-alpha particle effect can be largely eliminated by forming all metallic surfaces that are exposed to the ionizable medium inside the detector of a metal that will not emit heavy ionizing particles, such as protons and alpha particles, when bombarded by neutrons and preferably employing an ionizable medium which also will not emit heavy ionizing particles when bombarded by neutrons. One such detector is shown in vertical section in Figure 5. Although this detector forms a part of the subsurface system that is contained in a capsule, only that fragment of the capsule which houses the detector is shown.

Referring to the Figure 5, the capsule or casing 22 is divided into a plurality of compartments, one of which, compartment 23, contains an ionization chamber that is defined by the inner walls of the casing 22 and top and bottom partitions 24 and 25, respectively. The ionization chamber

thus formed contains an ionizable medium, such as argon, for the detection of gamma radiation. There are concentrically disposed in the ionizable medium within the ionization chamber two electrodes, an outer cylindrical electrode 26 and a central electrode 27. The outer electrode is fixed in spaced relation to the casing 22 by means of a dielectric material 28. Since the ionizable medium in the chamber is under pressure, electrical connection is made to the outer electrode from a point outside the ionization chamber by means of the pressure plug 29. Similarly, connection is made to the central electrode by means of a second pressure plug 30. Pressure plugs 29 and 30 are constructed in much the same manner as spark plugs for an internal combustion engine. Generally speaking, the only differences are the elimination of the electrode that is carried by the outer shell and the elongation of the inner end of the central electrode of the plug.

The bottom end of the ionization chamber central electrode is supported by an insulator 31. The insulator is secured to a tubular element 32 that is adapted to telescopically engage the inner surface of the tubular central electrode 27. Element 32 is adapted to fit snugly inside the electrode but slide freely therein. Insulator 31 is urged downwardly by a spring 33 whose bottom end fits inside of element 32 and presses thereagainst and whose top end butts against a plug 34 that is fixed to the inner surface of the inner electrode 27. Insulator 31 is urged downwardly by the spring 33 to engage a bearing cup 35 that is formed in an upraised portion of the center of partition 25. Passageways 36 are formed horizontally in the upraised portion of partition 25, and these passageways communicate with a central opening 37 in which is secured a valve 38. Valve 38 is provided for the purpose of charging the ionization chamber with an ionizable medium, such as argon.

Such an ionization chamber is more fully disclosed in Patent No. 2,390,965. The novel features of the present invention as applied to such a chamber comprise using an ionizable medium such as argon and forming all metallic surfaces inside the chamber that are exposed to the ionizable medium with a metal, such as tin or tellurium, which medium and metal will not emit heavy ionizing particles, such as proton or alpha particles, when bombarded with neutrons. This can be done by making the metallic elements within the chamber of tin or tellurium, or by coating or plating each of the metallic elements within the chamber with tin or tellurium to a thickness of a few thousandths of an inch. Coating or plating the elements is the most practical of the two methods. When using a coating or plating of tin or tellurium, even though neutrons pass through the coating or plating and react with the plated metals, heavy particles produced thereby are absorbed by the tin or tellurium and thus not allowed to enter the ionizable medium to produce the undesired effect.

The elimination of the undesired effect produced by neutron-proton or neutron-alpha particle reactions in the detector makes it possible to reduce the spacing between the neutron source and detector when desired for advantageous reasons which will be explained hereinafter.

The amount and quality of shielding material used between the neutron source and the detector for the purpose of attenuating primary gamma radiation that is emitted by the neutron producing reactions must be considered when selecting

a spacing for the source from the detector. Although for a given source at a given distance from the detector the effect produced in the detector resulting from processes caused by gamma radiation entering the detector after travelling directly from the source will be substantially constant and will be recorded as background noise, it is desirable to keep it to a minimum. If this were the only effect to be considered the amount of shielding necessary to adequately attenuate the gamma radiation emitted in the direction of the detector would determine the minimum spacing of the source from the detector.

We have found that the desired effect, viz., that produced by gamma radiation which has originated with neutron reactions in the formations, can be augmented by using a source which emits a predetermined large quantity of neutrons per second, for example 0.5×10^7 per second, spaced relatively close to the detector to favor the detection of a maximum intensity of gamma radiation which is produced in the formations by neutron processes therein. The choice of spacing is critical and depends on the type of source used. For example, better performance is secured with strong sources at large spacings. On the other hand, for detectors having a neutron-heavy particle reaction, weak sources have a lower limit of spacing below which the logs will be too inaccurate. Stronger sources perform better in such cases, but not enough better but what there still is a practical lower limit for sources which can economically be secured. Among other things the choice of spacing depends on the range of neutrons in the commonest rocks in the sections to be examined. We have found that the most desirable choice of spacing for oil well logging lies within a range of from 5 to 24 inches. This is illustrated in Figures 6a to 6e. In Figure 6a there is shown a group of curves which have been plotted with spacing of source from detector as abscissa and intensity of gamma rays reaching the detector as a result of neutron processes occurring in the formations as ordinates. The dotted curve represents the intensity of gamma radiation reaching the detector and which has been produced in pure dry coal, such as anthracite. The solid curve represents the intensity of gamma radiation reaching the detector and which has been produced by neutron reactions in limestone, and the dash-dot curve represents the intensity of gamma radiation reaching the detector and which has been produced in wet shale. The range of neutrons in each of the formations represented by these curves is measured from the vertical axis to the right along the horizontal axis and identified respectively by R1, R2 and R3. It is to be understood that these ranges as shown on the curves are not intended to be absolute values but relative values which will serve equally well for purposes of explanation. By comparing the ranges R1, R2 and R3 with the magnitude of the gamma-ray intensity curve at the respective ranges, it can be seen that the maximum intensity of gamma radiation, which originates in the strata, reaching the detector can be detected when the distance between the neutron source and detector is less than, but of the order of this range.

Now consider a detector located at zero of the coordinate system and a source spaced a distance S1 from the detector. Practically all the gamma radiation detected which has arisen from neutron reactions in the formations will be those originating with neutron reactions in the pure

dry coal. The intensity of this detected gamma radiation may be measured as the vertical distance between the horizontal axis and the dotted curve. Next consider the condition where the detector is located at zero and the neutron source is located at the point S2 on the horizontal axis of the coordinate system. Under this condition the magnitude of the intensity of gamma radiation reaching the detector from the coal has more than doubled and the intensity of gamma radiation which has originated in the limestone can also be detected. Making the spacing still shorter by moving the neutron source to the point S3 on the coordinate system, it will be seen that gamma radiation originating in three formations can now be detected, gamma radiation from the dry coal, the limestone and from a wet shale. When the neutron source is moved from S2 to S3 the intensity of gamma radiation from limestone will be the largest and that from dry coal next largest, while the intensity of gamma radiation from the wet shale will be very small. Next consider zero spacing, that is, where the neutron source is located in the center of the effective portion of the detector. It is appreciated that such a condition could not easily be attained due to the unattenuated gamma radiation given off by the neutron source. However, the assumed condition is helpful in illustrating the effect of spacing on the intensity of detected gamma radiation which has originated in the formations as result of neutron reactions therewith. Under these conditions the intensity of the gamma radiation originating in the wet shale will be quite large and will be the most prominent of the detected gamma radiation. The intensity of gamma radiation detected which has originated in the limestone will be next largest, while the intensity of gamma radiation which has originated in the dry coal will be the smallest. These curves serve to illustrate clearly the fact that, from the point of view of intensity of gamma radiation detected which has originated in the formations, the intensity is greatest for a particular formation when the space between the detector and neutron source is less than but of the order of the range of neutrons in that formation.

An important point to be noted is that the three curves representing different geological formations cross as the spacing decreases from a large spacing to a relatively small or zero spacing. This teaches that, if one desires to have the characteristics of dry coal predominate in the log, then the detector-source spacing must be greater than the distance from zero to X1 as measured along the horizontal axis of Figure 6a. If it is desired to emphasize the characteristics of limestone, then a spacing would be used which would lie between the intersection of the solid curve with the dotted curve and the intersection of the solid curve and the dashed curve, i. e., between X1 and X2. If it is desired to emphasize in the log the characteristics of wet shale, then the spacing between source and detector should lie between the intersection of the solid curve and the dashed curve and zero, i. e. between X2 and 0.

Figures 6b, 6c, 6d and 6e serve to illustrate by fragments of logs the manner in which the recorder would be effected when traversing wet shale, limestone and dry coal formations in succession with particular detector-source spacings. Figure 6b shows the manner in which the re-

corder would respond to the intensity of gamma radiation detected with a source-detector spacing of equal to the distance between zero and S₁ in Figure 6a. The magnitude of displacement of the recorder pen is measured from the base line. The recorder, as indicated, would show a single trace offset from the base line an amount proportional to the intensity of that gamma radiation produced in the dry coal and which has reached the detector.

Figure 6c, illustrating the use of a detector-source spacing equal to the distance between zero and S₂ in Figure 6a, shows first a very small displacement from the base line that is caused by the gamma radiation which has originated in wet shale. This offset is followed by a second larger offset corresponding to detected gamma radiation which originated in the limestone. This offset is, in turn, followed by a third and larger offset which represents the detected gamma radiation which originated in the dry coal.

Figure 6d represents the recorder response when these same three formations are traversed in the same order by a detector having a source spaced from it by a distance equal to the distance 0—S₃ in Figure 6a. It is to be noted that the wet shale causes considerable offset in the recorder trace followed by a large offset due to the gamma radiation which originated in the limestone. This last offset is followed by one which is in the opposite direction, showing that the intensity of the gamma radiation reaching the detector and which has originated in the dry coal has become less than that from the limestone. In other words, the critical spacing has been passed for recording predominantly characteristics of coal and now the emphasis is strongly on the gamma radiation which has originated in the limestone.

Under the conditions where the detector and source would coincide or be spaced an extremely short distance apart, the recorder response would be as shown in Figure 6e. In this figure the gamma radiation originating in the wet shale predominates, that is, it would be the formation that would produce the greatest deviation of the recorder pen from the base line. This offset would be followed by a negative offset, that is, one in the direction of the base line. This limestone offset, in turn, would be followed by that for coal, which is also in a negative direction. This figure shows that the critical spacing of source from detector had been passed for limestone, and now the emphasis is on the wet shale. Although three formations have been used for purpose of illustration, it is to be understood that the particular formations that are expected to be encountered in a well are to be taken into consideration when adjusting the spacing between the neutron source and detector. From the picture presented above, it is clear that the closest spacing used need never be less than that point at which the last crossing occurs between the curve for materials of the type ordinarily encountered and that material in which the neutron range is apt to be shortest.

We have found that, in addition to providing a method and apparatus whereby different types of strata can be differentiated, by careful selection of source-detector spacing, we can differentiate between very small percentages of hydrogen content, hence the fluid content, of the formations that are otherwise the same.

In logging oil wells, the type of information which is generally of greatest interest is the varia-

tion of fluid content or other property in a given limestone or sandstone.

Again referring to Figure 6a, for purposes of explanation let the dashed curve be assumed to represent a limestone having 5% fluid content; the solid curve be assumed to represent a limestone having 10% fluid content, and the dash-dot curve represent a limestone having 20% fluid content.

In order that the neutron log respond clearly and definitely to small changes in the fluid content which it is desired to observe it is necessary to so choose the spacing between source and detector that no crossing occurs between the curves of the type of Figure 6a for any of the included varieties of the given limestone or sandstone which are to be differentiated. Best results will be obtained by choosing that spacing which maximizes the rate of change of detected radiation with variation in the property which is to be observed. Such a spacing is appreciably shorter than that at which the first crossing occurs or appreciably longer than that at which the last crossing occurs among the curves of the type shown in Figure 6a for any of the included varieties of the given type of strata.

For example, if it is desired to differentiate, on the log, fluid content in limestone ranging between 5% and 20%, a spacing lying between 0 and X₂ but somewhat less than X₂, or a spacing lying between X₁ and S₂ but appreciably greater than X₁ should be chosen. It will be seen that if a spacing lying between X₁ and X₂ is chosen, an ambiguity results from the fact that curves corresponding with two different fluid contents in the range from 5% to 20% could be drawn which would cross at the spacing chosen. Therefore the gamma ray intensities caused by neutrons for rocks having these particular fluid contents would be equal, and these rocks, though different, would be represented as being the same.

It can be noted from Figure 6a that for a spacing such as S₃ the curve for 5% fluid content of the formations lies between the curves for 20% and 10% and therefore leads to the inconsistency in which the gamma ray intensities are in the following order: The 10% fluid content provides the highest value, and both the 5% less and 20% least fluid contents provide lower intensities of gamma radiation.

The following will serve to illustrate the manner in which source-detector spacing will vary with change of characteristics of formations. First, in order to recognize small differences in fluid content (fluids such as water and petroleum liquid or gas) in some wet shales, for the inside range, a spacing could be used that is from 0-2.5 inches. Second, if it is desired to relatively maximize the secondary gamma radiation from wet shales having suitable water content then a spacing of from 3 to 5 inches could be used. Third, on the other hand, there will be wet shales found for which the outside range of spacing adapted to delineate small differences in fluid content will be 6 to 15 inches.

Additionally, if certain sandstones are being logged the following will serve to show a further variation in the source-detector spacing. First, in order to recognize small differences in fluid content in some tight sandstones, for the inside range, a spacing could be used that is from 0 to 7 inches. Second, if it is desired to relatively maximize the secondary gamma radiation from tight sandstones having suitable water content then a spacing of from 8-11 inches could be used. Third,

on the other hand, there will be found tight sandstones for which the outside range of spacing adapted to delineate small differences in fluid content will be 12 to 25 inches.

In the case of certain very dry limestones, for example, it may occur that the outside range for favorable delineation of small differences in fluid content will extend from 22 to 30 inches.

We have found that the fluid contained in a drill hole plays an important role in neutron logging. The fluids encountered in drill holes are usually oil, water, or fluids containing a large percentage of either oil or water, or both. Oil and water both contain a high percentage of hydrogen, and hydrogen absorbs neutrons. In a well that contains such a fluid fewer neutrons will reach the formations, with the result that fewer photons of gamma radiation will be produced in the formation and a lower intensity of detected gamma radiation will occur. The result would be a weak or poorer log. To those skilled in the art of neutron logging the obvious solution to this problem would appear to be in using a stronger source of neutrons, but, as will be pointed out hereinafter, this is not the solution to the problem.

We have found that a better solution to the problem is to remove the hydrogen containing fluid as by bailing, pumping or displacing it by introducing another fluid containing less to no hydrogen. Also, in certain wells adequate displacement of fluid can be effected by carrying displacement elements on the subsurface instrument. These elements may be formed of materials such as aluminum or carbon.

In wells which have been completed by "shooting" them with nitroglycerine the diameter of the well may be very irregular. In such case the intensity of neutrons reaching the formations, and therefore the intensity of gamma radiation produced thereby, varies in a manner which is not solely dependent upon the characteristics of the formations but is also a function of the well diameter thus giving rise to misleading results. We have found that the effect of the variation in well diameter on the log varies with the spacing between the neutron source and the detector. When the well is empty or filled with a fluid which is very transparent to neutrons, a certain critical spacing can be found for which the effect of well diameter variations is minimized.

When the well contains a fluid, such as oil, water, or any of the drilling fluids normally encountered in wells which are highly absorbent to neutrons, we have found that an extremely great spacing between the neutron source and detector is required to minimize the effect of changes in diameter. In fact we have found that so great a spacing is required that the intensity of the detected gamma radiation is too small to produce a satisfactory log, and that the best solution to the problem is to reduce the amount of absorption of neutrons by displacing or diluting the well fluid with a substance, such as CS_2 , which is more transparent to neutrons in order that the effect of changes in well diameter will be minimum at a closer spacing.

This invention teaches the manner of making a meaningful neutron log of a drill hole under practically any of the conditions that may be encountered. Among the embodiments disclosed are various kinds of substantially gamma-ray free neutron sources; various methods of minimizing the random transitions that occur on the log as

it is made; critically spacing the neutron source from the detector to differentiate between formations; and the elimination of the effect of the well fluid on the neutron log by removing the fluid, displacing it with a fluid that is relatively transparent to neutrons or by altering the density of the fluid to render it more transparent to neutrons. No effort will be made herein to claim specifically all of the embodiments disclosed. A series of additional applications will be filed specifically covering various of the embodiments. The claims herein are not directed to any of the respective individual aspects enumerated in the foregoing portion of this paragraph, but rather are directed to method and apparatus utilizing certain combinations thereof.

We claim:

1. A method of neutron well logging which comprises traversing the formations penetrated by the well with a subsurface instrument containing a gamma ray free neutron source and a detector of radiation containing an ionizable medium, maintaining the source and detector spaced from each other in the direction of the axis of the well while traversing the well with the instrument, maintaining carbon disulfide between the neutron source and the formations, bombarding the formations with neutrons passing from the source and through the displacing medium, detecting gamma radiation resulting from neutron processes in the strata substantially uncontaminated with other gamma radiation by subjecting an ionizable medium thereto and measuring the resultant current.

2. A method of neutron logging a well having significant diameter non-conformities which comprises traversing the formations penetrated by the well with a subsurface instrument containing a gamma ray free neutron source and a detector of radiation containing an ionizable medium, maintaining the source and detector spaced from each other in the direction of the axis of the well while traversing the well with the instrument, displacing the well fluid from between that portion of the instrument which contains the neutron source and the strata with a fluid that is more transparent to neutrons than the fluids normally encountered in wells, subjecting the strata that are of different distances from the vertical axis of the well to neutrons that are substantially free from gamma radiation, detecting gamma radiation resulting from neutron processes in the strata substantially uncontaminated with other gamma radiation by subjecting an ionizable medium thereto and measuring the resultant current.

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