

March 30, 1965

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3,175,608

METHOD AND APPARATUS FOR DIRECTIONAL TUBING PERFORATION

Filed Oct. 21, 1960

4 Sheets-Sheet 1

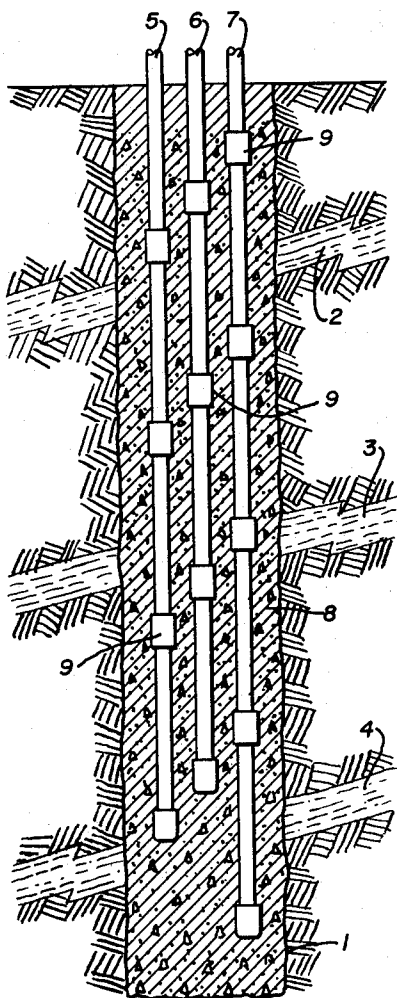


FIG. 1

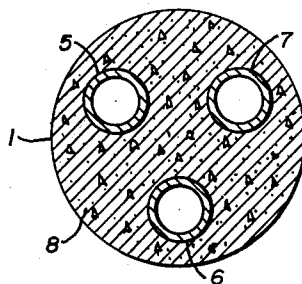


FIG. 2

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4 Sheets-Sheet 2

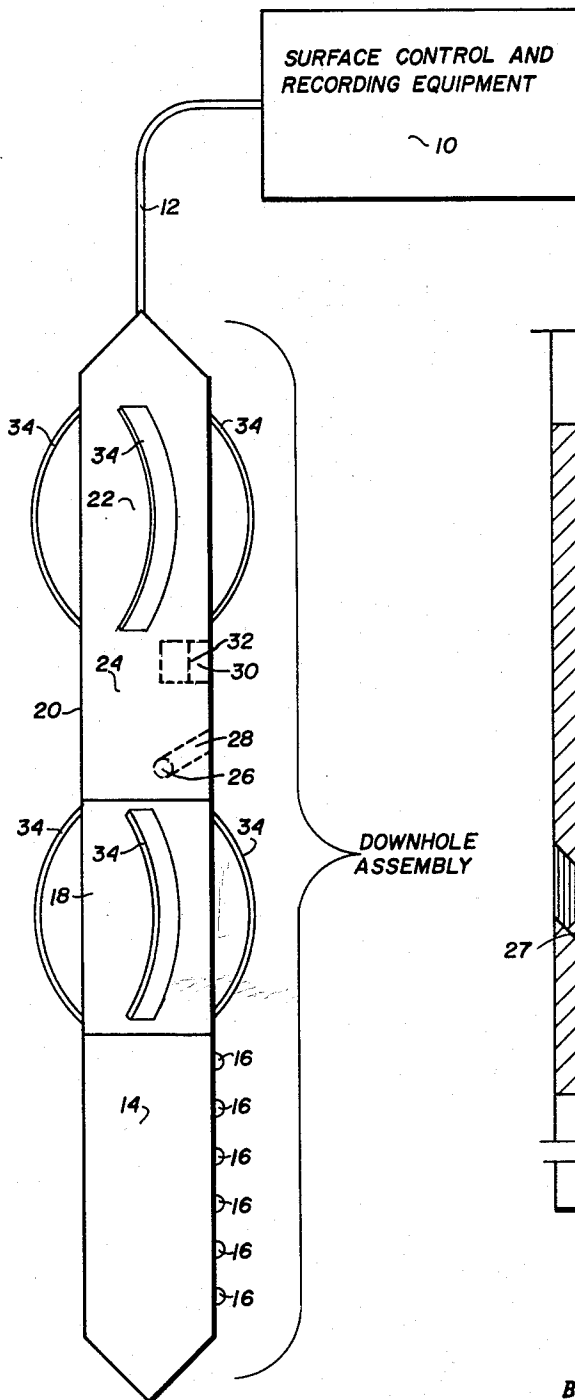


FIG. 3

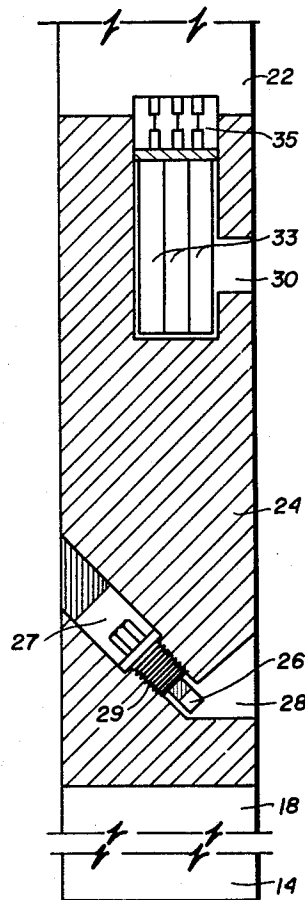


FIG. 4

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4 Sheets-Sheet 3

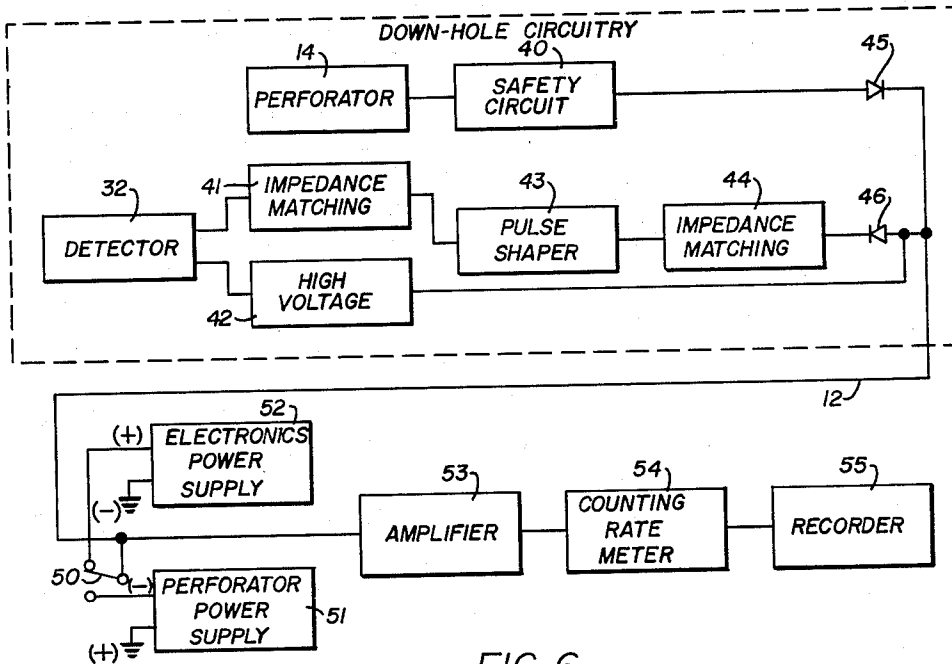


FIG. 6

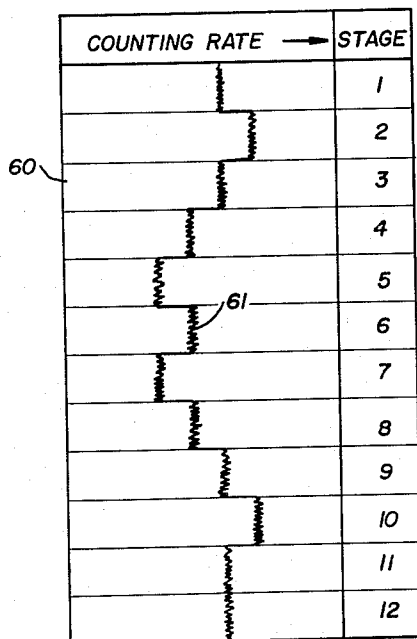


FIG. 7

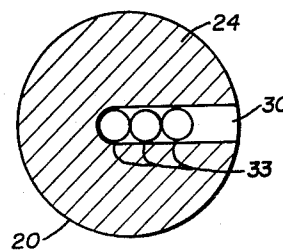


FIG. 5

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4 Sheets-Sheet 4

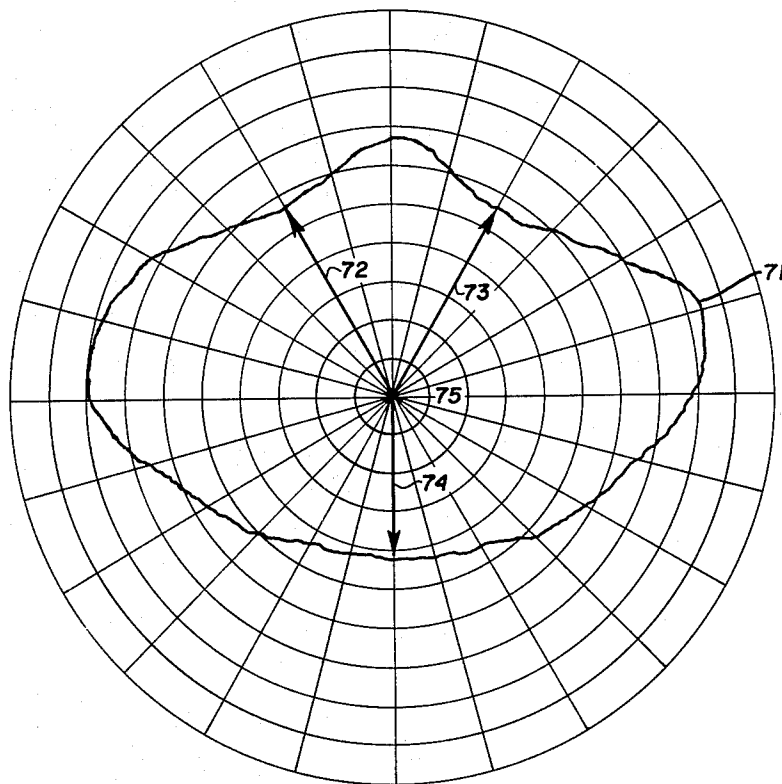


FIG. 8

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METHOD AND APPARATUS FOR DIRECTIONAL TUBING PERFORATION

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Filed Oct. 21, 1960, Ser. No. 64,016

10 Claims. (Cl. 166-4)

This invention is related to the recovery of petroleum from subsurface earth formations, and more particularly relates to methods and apparatus for use in multiple completion of wells for petroleum production.

In its widest sense the term petroleum embraces the whole of the hydrocarbons, gaseous, liquid, and solid, occurring in nature. However, as used herein the meaning of the term is restricted to those gases and liquids which are found in subsurface formations and which are recovered by means of boreholes drilled in the earth. It is well known that such boreholes are often drilled thousands of feet into the earth. It is also well known that, when it is desired that a well be drilled to the deeper formations, one or more formations of promise are often encountered at intermediate depths. It is extremely costly to drill such boreholes. Thus, it is the practice to attempt to recover through a single borehole petroleum from as many formations as may be permitted by other factors. The multiple completion of the well, as it is called, is limited by the restriction that production from one of the formations must not be permitted to mix or mingle with production from any other formation until after delivery to the surface. This requirement is based on the fact that the various formations do not contain petroleum in the same quantities nor under the same pressure. Moreover, one formation may contain gas, whereas another may contain oil. Other formations may contain both.

Thus, many techniques have been developed for achieving completion of a single well in a manner such that a plurality of formations are tapped without such commingling of production. Generally, all such techniques require the installation of casing throughout the entire length of the borehole. A packer is then inserted in the casing at a point above the deepest formation of interest, and one or more packers are thereafter inserted at succeeding levels above the next formations proceeding upwards. In the case of a dually completed well (tapping only two formations) only the one packer is required, and if it is intended that one formation be produced through the casing, a single string of tubing is inserted in the casing and through the packer to a point opposite the deep formation. Then, if the casing is perforated at a point adjacent the higher formation of interest, the shallow formation may be produced through the casing surrounding the tubing, and the deep formation may be produced through the tubing. The packer, of course, serves the purpose of separating the two streams of production in the cased borehole.

Different conditions, of course, call for different techniques. For example, it is usually not practicable to pump a formation that has been completed through casing. In addition, it is often desirable to tap and produce three or more formations through a common borehole. Thus, two or more strings of tubing may be required in the casing. Sometimes it is convenient to arrange these multiple tubing strings concentrically in the casing (one inside another), but more often the strings are arranged side by side. In all cases, however, it has heretofore been the practice to install the aforementioned casing. Recently a new technique has been developed and successfully used which involves inserting the required tubing strings (one per formation) into an uncased

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borehole, side by side, and thereafter filling the borehole with cement to support the tubing. The tubing strings are then individually and separately perforated each at a different depth opposite a particular formation of interest, and the expense of the casing is eliminated.

In order to appreciate the problem of selectively perforating one of a plurality of proximately associated tubing strings, it must be understood that perforation involves piercing the wall of the tubing with one or more holes. Since the perforation must obviously be accomplished from a point within the tubing, there have been made available several types of tools for performing this work. Some employ a series of laterally expanding points which are forced against the interior of the tubing (or casing) wall by the operation of "jars" (free-falling weights), and others employ a series of laterally driven bullets shot through the tubing wall by explosive charges. Another type of perforator employs a series of "shaped charges" to achieve penetration of the tubing. Some perforators have their charges or other puncturing means arranged omni-directionally about their supporting stems. Others have their charges aligned up and down the stem so that perforation is achieved at various levels but in a single lateral direction. In the case of some perforators, the projectiles, charges, etc., may be singly and selectively fired whereas other types of perforators are designed for volley firing.

It is obvious that to perforate selectively one of a cluster of tubing strings a mono-directional perforator must be chosen, and that it must be positioned so that its charges are directed to avoid the other proximately positioned strings. Moreover, it is obvious that, since a laterally directed explosion will penetrate only a limited distance past the punctured tubing, it is desirable to "aim" the perforator towards the nearest part of the borehole wall to insure that the formation is successfully tapped. Heretofore this has been accomplished by attaching a source of radiation to the perforator suspended in the tubing string selected for perforation. This source was enclosed in shielding having an aperture or slot in one side for the purpose of restricting the radiation emitted by the source to a laterally directed narrow beam which was aimed coincidentally with the discharge direction of the perforator. In order to aim the perforator it was also necessary to suspend a radiation detector in each adjacent tubing string, and then to rotate the perforator until the adjacently disposed detectors sensed the least radiation, i.e., direct the beam away from the detectors and therefore away from the adjacent tubing strings. Since this direction-finding equipment can not of itself provide a depth indication, the perforator used for such purposes was usually supplemented with a casing collar locator in addition to its other circuitry.

The chief disadvantage with this method of direction perforation is the necessity for disposing the detectors in the adjacent tubing strings. Not only is an additional hoist truck and cable required for each adjacent tubing string to be avoided, but there is the difficulty and inconvenience of suspending a detector in a tubing string which has previously been perforated and completed as a flowing well. In addition, the casing collar locator is a necessary inconvenience since it is essential that the perforator be correctly positioned with respect to depth, and no other type of equipment has heretofore been satisfactorily substituted for the collar locator for this purpose.

These disadvantages of the prior art are overcome with the present invention and novel methods and apparatus are provided which permit accurate aiming of the perforator, not only to avoid adjacent tubing strings but to select the closest expanse of borehole wall, without the necessity of disposing auxiliary equipment in adjacent tubing strings. Moreover, the new and novel methods and ap-

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paratus hereinafter described also provide accurate detection of casing (tubing) collars without the necessity of auxiliary equipment or any modification whatsoever.

The advantages of the present invention are preferably attained by horizontally scanning with a beam of penetrative radiation the substances surrounding the tubing string selected for perforation, by making a measurement indicative of the scattering effect produced by such substances upon the radiation, and observing the anomalies in the measurement which are attributable to proximity of adjacent tubing strings and the nearest part of the borehole wall. Such a measurement, when made along a vertical axis, also provides observable anomalies indicating the borehole depth of the individual collars connecting the various tubing joints into the selected tubing string. These anomalies are due to the difference in the respective densities of steel and cement, or to the relative atomic numbers of the elements making up these two substances, or sometimes to a combination of both factors since the extent of a particular anomaly will be affected by the nature of the substance contained in an adjacent tubing string. Regardless of the reason for particular anomalies, however, they enable the present invention to provide a reliable indication of the relative positions of the various tubing strings in the borehole.

In one form of the present invention, which was found particularly suitable, a mono-directional tubing perforator, and a rotating means, are combined in a pre-determined angular relationship with apparatus which irradiates the aforesaid surrounding substances with gamma rays having a pre-selected energy, and which measures the scattering effect of the irradiated substances in a manner such as to sense or indicate the aforesaid anomalies. The perforator, rotator, and the anomaly-finding orienter are combined in a manner such that the rotator revolves the perforator-orienter combination as a unit. When so revolved about a vertical axis in the selected tubing string, the orienter signals variations in the aforesaid scattering to indicate the directions in which the anomalies appear. Thus, the perforator may be readily aimed in a direction which traverses the least amount of cement while also avoiding all adjacent tubing strings. Any type of rotating means may be incorporated into the downhole assembly. However, the anomaly-finding means, or orienter, is preferably composed of an assembly which includes a source of gamma rays housed in a shield which collimates the emitted radiation into a narrow beam, a gamma ray detector spaced a pre-selected distance from the source and also housed in a collimating shield, and a radiation opaque body which spaces the source a particular distance from the detector such that maximum sensitivity is obtained for these purposes. When properly arranged as hereinafter further described, the entire assembly is combined in a manner such that the beam of radiation is directed outwardly toward the substances surrounding the tubing in the same direction in which the perforator is aimed. The collimating shield about the detector will permit the detector to sense generally only those source-emitted gamma rays which are scattered in a restricted area outside the tubing and which then return to the interior of the tubing along a restricted but related path. Thus, the number of gamma rays reaching the detector, as determined by surface located counting rate equipment, will be affected primarily by the density and atomic number of the substances in which the scattering occurs. It is therefore preferable that a gamma ray source be chosen which emits generally gamma rays having an energy such that a majority of the emitted rays penetrate past the wall of the tubing containing the downhole assembly but not substantially past the borehole wall. Further, since the orienter must be primarily sensitive to a sharp change in the aforementioned scattering, it is convenient to have the orienter particularly sensitive to the difference in the scattering occurring in the tubing compared with cement. This is preferably accomplished

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by arranging a plurality of Geiger counters in a narrowly slotted shield, as hereinafter explained, and by spacing the detector from the source a particular distance which is functionally related to the pre-selected energy of the gamma rays emitted by the source. Circuitry for establishing electric pulses for each gamma ray sensed by the detector, and for transmitting such pulses to the surface-located counting and recording equipment, and also preferably used in the present invention.

In one preferable embodiment of the present invention, wherein one of a plurality of proximately positioned tubing strings is sought to be perforated, the rotating means, the orienter and of course the aforementioned circuitry, are lowered into the tubing string to approximately the depth at which the formation of interest is thought to be encountered. The means for lowering the assembly into the tubing string is preferably a cable which also affords a means for transmitting detector signal to the surface and firing signals to the perforator. As is well known in the industry, the collars overlap the ends of each joint of tubing, and thus the wall thickness of each tubing string is substantially greater at the collar sections of the strings than between the collars. Accordingly, the location of each collar in the string to be perforated is easily determined by the occurrence of a sudden change in the detector counting rate, each time a collar is traversed by the pipe locator. Since the number of collars and tubing joints is known, as well as the length of the tubing joints comprising the string, the depth of the perforator and pipe locator may be easily determined by merely counting the collars traversed. When located at approximately the desired borehole depth, the assembly may be moved up and down to permit the anomaly-finding orienter to detect a particular tubing collar of particular depth, and the assembly may then be accurately moved to a position adjacent the formation of interest. Next, the entire assembly is rotated about its axis to permit the orienter to scan the substances surrounding the tubing at the selected depth. This scanning operation may be carried out in stages during which the signal provided by the detector indicates the presence or absence of another tubing string in front of the perforator by indicating the number of gamma rays reaching the detector during the selected time interval. The scanning operation is desirably continued through at least two complete revolutions of the perforator and orienter assembly to provide a double check of the positions of all adjacent tubing strings. The assembly may then be rotated to aim the perforator in the direction avoiding the adjacent tubing strings, and the perforator may be "fired."

Accordingly, it is an object of the present invention to provide novel methods and apparatus for multiple completion of oil and gas wells.

It is also an object of the present invention to provide novel methods and apparatus for perforating selectively a plurality of tubing strings suspended in a common borehole.

It is also an object of the present invention to provide an improved method of positioning a mono-directional tubing perforator in a borehole containing a plurality of proximately suspended tubing strings.

It is further an object of the present invention to provide novel apparatus for accurately positioning a mono-directional tubing perforator in one of a plurality of tubing strings proximately suspended in a common borehole, said positioning being achieved with respect to the relative positions of said tubing strings and with respect to borehole depth.

A specific object of the present invention is to provide novel apparatus for selectively perforating one of a plurality of tubing strings proximately suspended in a common borehole, said apparatus comprising a perforator, sensing means attached thereto and responsive to anomalies in radiation absorption by substances adjacent said one tubing string in a direction related in a fixed pre-deter-

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mined manner to the direction of discharge of said perforator, and means in combination therewith for rotating said perforator and said sensitive means as a unit about a generally vertical axis.

Another specific object of the present invention is to provide a novel method for orienting a perforator suspended in one of a plurality of tubing strings proximately suspended in a common borehole, said perforator having a single lateral direction of discharge, said method comprising sensing the relative density of the substances adjacent said perforator and outside said one tubing string, positioning said perforator at a pre-selected depth and such that the lateral direction of discharge of said perforator intercepts the region in said adjacent substances of least density, and operating said perforator.

These and other objects and features of the present invention will be apparent from the following detailed description wherein reference is made to the figures in the accompanying drawings.

In the drawings:

FIGURE 1 is a cross sectional view of a borehole containing a plurality of tubing strings.

FIGURE 2 is an overhead view of the borehole and tubing strings depicted in FIGURE 1.

FIGURE 3 is a view of a tubing perforator equipped in the manner of the present invention.

FIGURE 4 is a detailed view of one form of the present invention.

FIGURE 5 is a detailed view of a part of the apparatus depicted in FIGURE 4.

FIGURE 6 is a block diagram of electronic circuitry useful in one form of the present invention.

FIGURE 7 is a view of a recording of signal indications provided by one form of the present invention.

FIGURE 8 is another view of a recording of signal indications provided by one form of the present invention.

Referring to the drawings in detail, FIGURE 1 shows a single borehole 1 traversing an upper formation 2, an intermediate formation 3, and a lower formation 4. The borehole 1 contains three proximately suspended tubing strings 5, 6 and 7, imbedded in cement 8 along the entire length of the borehole 1. It is readily apparent that any one of the depicted tubing strings may be perforated at a level adjacent any one of the depicted formations. However, it is also readily apparent that, if tubing string 5 is perforated at a level adjacent the lower formation 4, and if tubing string 6 is thereafter perforated adjacent the upper formation 2 in the direction of tubing string 5, then the tubing string 5 would also be perforated and production from both the lower and upper formations 4 and 2 will be commingled in tubing string 5.

Referring now to FIGURE 2, for an overhead view of the borehole 1 depicted in FIGURE 1, it can be seen how tubing string 5 is positioned with respect to tubing string 6 and tubing string 7. If it is desired to perforate one of the tubing strings, it can readily be seen why it is necessary to perforate in a direction away from the adjacent tubing strings.

Referring now to FIGURE 3 for more details of one form of the present invention, there is shown a mono-directional perforator 14 of a diameter small enough to be inserted into any of the tubing strings 5, 6 or 7, shown in FIGURES 1 and 2. The perforator 14 shown includes penetrating means 16 which may be a series of shaped charges arranged in longitudinal alignment so that they achieve perforation of the selected tubing string along a substantial section of the pre-selected formation 2, 3 or 4, and so that exploding the charges 16 will be accomplished all in a single direction (unless the perforator is rotated to a new position between firings). In that form of the invention which was successfully tested, the perforator 14 was equipped with a stepping-type of rotator 18 which was operated by drawing or lowering the perforator 14 a short distance vertically

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in the tubing string to be perforated. Any means for selectively rotating the perforator 14, which may be controlled from the surface, may be used. A variety of such means such as that described in U.S. Letters Patent No. 2,998,068, are well known to those skilled in the art of oil well completion. As shown in FIGURE 3, the rotator 18 is positioned between the perforator 14 and the orienter 20, although this position is not essential to the present invention. The orienter 20, in that form of the present invention shown, consists of a shield 24 of material substantially opaque to radiation, a source 26 of radiation which may be gamma rays, and a radiation detector 32. The source 26 is disposed in a narrow recess or slot 28, and hereinafter termed the "source recess" 28, and the detector 32 is disposed in a similar recess 30, hereinafter termed the "detector recess" 30. Both the source recess 28 and the detector recess 30 are designed to contain respectively the source 26 and the detector 32 in a manner such that the source 26 is spaced a pre-determined distance from the detector 32, as hereinafter further explained. Moreover, as shown in FIGURE 3 both the source 26 and the detector 32 are positioned sufficiently within their respective recesses 28 and 30 so that radiations from the source 26 are emitted in a substantially narrow beam laterally in the same direction as the expected course of penetration by the perforator so that radiations reaching the detector 32 are substantially restricted to those radiations approaching the detector 32 along a relatively narrow path. It is preferable that a source 26 be chosen, for purposes of the present invention, which emits gamma rays having substantially a pre-determined average energy. Therefore, if the energy is sufficient to enable at least a substantial number of emitted gamma rays to penetrate the substances opposite the source recess 28 and outside the wall of the tubing chosen for perforation, a substantial number of gamma rays will be scattered outside the tubing wall. It is preferable that the detector recess 30 be arranged so that the aforementioned narrow path of approach to the detector 32, be in the same vertical plane as the aforementioned beam of radiation emitted by the source 26. Thus a substantial number of gamma rays emitted by the source 26, which penetrate and are scattered in the substances outside the tubing wall, will return to the interior of the tubing along the aforementioned path. If a source 26 is used which emits a relatively stable beam of radiation, then the number of rays incident upon the detector 32 will be primarily affected by the aforementioned absorptive characteristics of the substances penetrated by the beam of radiation. Thus, the number of detected rays will generally be substantially less when the beam is directed into a proximately suspended steel tubing string compared to the number of rays detected (during an identical time interval) when the beam is directed into the relatively less dense cement 8. Similar differences in the rate of occurrence of rays sensed will occur when the orienter 20 and perforator 14 are passed longitudinally through the tubing string and past the collars 9 connecting the points of tubing.

Referring further to FIGURE 3, there is shown a set of bowsprings 34 adjacent both the rotator 18 and the electronics section 22 for the purpose of balancing and centralizing the entire downhole assembly substantially along the central axis of the containing tubing string. This is desirable for neutralizing the effect of the low energy rays, unavoidably emitted by the source 26, which manage to reach the detector 32 after being scattered in the substances within the tubing. Of course an alternative method is to position the bowsprings 34 in a manner such that the side of the orienter 20 having the recesses 28 and 30 is urged against the tubing wall.

In addition to the components hereinbefore mentioned, FIGURE 3 also shows an electronics section 22 containing the downhole circuitry required to convert the detector 32 sensings into indicative and recordable electric

signals. The cable 12, which is used to move the assembly in the borehole 1, is also preferably used to conduct electrical signals to and from the control and recording equipment 10 on the surface of the earth.

FIGURE 4 shows a more detailed cutaway view of the orienter 20 functionally depicted in FIGURE 3. The source 26 is mounted on a source holder 29 to facilitate handling, and is removable from the shield 24 through an access port 27 which is ordinarily plugged to prevent irradiation outside the shield 24 except by way of the source recess 28. The radiation detection means (called the detector 32 in FIGURE 3) can be seen to be composed of three Geiger counters 33, aligned with respect to the detector recess 30, and fastened to connectors 35 which connect them electrically to the electronics section 22 referred to in FIGURE 3. Not shown is an electrical conductor passing through the shield 24 and the rotator 18 to connect to the perforator 14 firing signals originating at the surface and passing through the circuitry contained in the electronics section 22.

FIGURE 5 shows another view of that section of the orienter 20 which contains the Geiger counters 33. As heretofore stated, the three Geiger counters 33 are disposed well within and in axial alignment with the detector recess 30. The advantage of this arrangement is in the fact that few scattered gamma rays approaching the counters 33, along the hereinbefore described narrow path, can escape being counted, and in the fact that few gamma rays approaching the counters 33 obliquely with respect to the detector recess 30 can penetrate the shield 24. In other words, very few of the gamma rays emitted by the source 26, which have energies insufficient to cause them to penetrate the wall of the tubing string, and which are therefore scattered in the interior of the tubing, will therefore have sufficient energy to reach the counters 33 because of the shield 24. On the other hand, since there are three small diameter counters 33 composing the detector 32 instead of one relatively larger diameter counter, there is thus a greater chance of high energy scattered gamma rays being detected instead of merely passing through the detector 32. Moreover, relatively few gamma rays can be expected to approach the detector 32 obliquely with sufficient energy to reach one of the Geiger counters 33 after passing through the shield 24. This last possibility is rendered further remote by the fact that all three Geiger counters 33 are preferably disposed well within the detector recess 30 and away from the mouth of the detector recess 30. The advantage of using three Geiger counters 33 of relatively small diameter rather than one counter of larger diameter, and of aligning the counters 33 in the shield 24 as shown in FIGURE 5, is that such an arrangement obtains with reduced shielding the directional sensitivity necessary for the present invention. This is particularly significant when it is remembered that the present invention is expected to be used in tubing strings having diameters less than 3 inches. In addition, there is a much greater likelihood that the gamma rays sought to be detected (approaching from the cement), which might pass entirely through one Geiger counter of larger diameter, will be counted by one of three small-diameter counters 33 aligned in the direction of expected approach by such rays.

FIGURE 6 shows, in functional form, the circuitry used in the borehole 1 and at the surface of the earth. As hereinbefore stated, the cable 12 is used for communication between the surface of the earth and the apparatus in the tubing, as well as for suspending the apparatus in the tubing. Since the cable 12 must provide means for communicating with both the perforator 14 and the detector 32, and since it is preferable that the cable 12 consist of a single conductor and return, two diodes 45 and 46 are used to permit two separate circuits to be selectively energized by their respective power supplies. The perforator 14 is fired by means of a negative power supply 51 which is selectively connected to the perforator 14, through

a safety circuit 40 and diode 45, by means of a two-position switch 50.

The detector 32, when composed of the three Geiger counters 33 shown in FIGURE 5, is energized by the high voltage supply 42. When energized, the detector 32 provides a pulse for each gamma ray sensed. Since the Geiger counters 33 have high impedance characteristics, the pulses are passed through an impedance matching network 41 before being passed to the transistorized pulse shaper circuit 43. Thereafter, in the form of the present invention which was successfully tested, the shaped pulses are sent to another impedance matching network 44 composed of a transformer before being passed through diode 46 to the surface via the cable 12. There, the pulses are passed through an amplifier 53 to a counting rate meter 54, and the output signal from the counting rate meter 54 is sent to the recorder 55. The electronic power supply 52, which supplies a positive current to operate the transistorized impedance matching network 41 and the pulse shaper circuit 43 and high voltage supply 42, is connected to the downhole circuitry through diode 46 by means of the two-position switch 50. As shown, the switch 50 provides that the positive power supply 52 be disconnected when negative power supply 51 is connected to the downhole circuitry, and vice versa, to avoid having both power supplies connected in opposition to each other.

Referring now to FIGURE 7, assume that the downhole assembly depicted in FIGURE 3 has been inserted in tubing strip 7 (see FIGURES 1 and 2) and positioned adjacent the formation of interest. The assembly may then be rotated by means of the rotator 18, in convenient stages which may be 30 degrees each. As the collimated beam of gamma rays sweeps the surrounding substances the displacement of the trace 61 on the recorder strip 60 will indicate the anomalies in the scattering effect provided by such substances. As heretofore discussed, the steel in the proximately suspended tubing strings 5 and 6 is substantially more dense than the cement 8. Thus, the displacement of the trace 61, during rotational stages 5 through 7, readily indicates the relative location of tubing strings 5 and 6 since in these stages the trace 61 shows the direction towards the greatest density by showing the lowest gamma ray counting rate. On the other hand, the displacement of trace 61 in stages 1, 11 and 12 suggests the closest part of the borehole 1 wall, and thus indicates the preferable direction for perforation.

Of course, one important factor affecting the proper use of the present invention is the proximity of the borehole 1 wall. In many cases the materials composing the formation, such as limestone or dolomite, have a density substantially similar to the steel tubing insofar as the present invention is concerned. Thus, since it is desirable to perforate in the direction where the borehole 1 wall is closest to the downhole apparatus, as well as essential to avoid the adjacent tubing strings, it is preferable to distinguish the formation from the adjacent steel tubing strings. Referring now to FIGURE 8, there is shown by means of a polar plot, a counting rate trace 71 obtained with one complete revolution of the downhole apparatus in tubing string 7 (see FIGURE 2). The relative positions of the nearest borehole 1 wall and the adjacent tubing strings 5 and 6, relative to the axial center 75 of tubing string 7, are indicated by vectors 74, 72, and 73, respectively. It is assumed that the zero of the polar plot depicted is at the axial center 75 of tubing string 7, and that the distance of each point on the trace 71 indicates the gamma ray counting rate obtained during the rotation of the downhole assembly depicted in FIGURE 3. Thus, the counting rate at the points indicated by vectors 72, 73 and 74, are the directions in which the lowest counting rates are obtained, and since the rate decreases sharply at the points indicated by vectors 72 and 73, rather than gradually as at the point indicated by vector 74, the adjacent tubing strings 5 and 6 may be located. Thus, it is thereafter comparatively easy to direct the perforator

14 in the direction which is toward the nearest area of borehole 1 wall, and also which avoids the adjacent tubing strings 5 and 6.

As heretofore stated, it is desired that the orienter 20 respond to the difference in the radiation absorptive characteristics of steel compared to cement. This is preferably attained in the present invention by relating, in a critical manner, the two parameters of source 26 energy and the source 26 to detector 32 spacing. Since it is also preferable that the source 26 be collimated, regardless of the type of radiation used, the first limitation on source energy is the amount of shielding material permitted. The average tubing used for the subject purposes measures less than three inches in diameter; and although the shield 24 may be composed of material such as uranium 238 or lead, the maximum radiation energy should be less than that capable of penetrating the shield 24 in order that the shield may produce the requisite degree of collimation of the radiations.

The second critical limitation on the energy of a source 26 emitting gamma rays is provided by the fact that the present invention is primarily concerned with anomalies in gamma ray absorption rather than anomalies in scattering. This is due to the fact that the average density of that part of the borehole 1 occupied by the adjacent tubing string may not vary significantly from the density of an equivalent cement-filled section of the borehole 1, depending of course upon the type of cement and the nature of the substances (air, liquids, etc.) contained in the tubing. However, it should be remembered that gamma ray absorption is a summation of the functions of the photoelectric effect and pair production, as well as the Compton effect (scattering). Of course, since pair production occurs only with gamma rays having energies greater than 1-mev., this aspect may be disregarded for the purpose of the present invention. On the other hand, the function of the photoelectric effect becomes significant depending upon the energy of the gamma ray when penetrating the substances sought to be identified. This is due to the fact that the photoelectric effect is strongly dependent upon the atomic number of the substance irradiated, as well as upon the energy of the gamma rays. Thus, when iron and calcium (which constitutes almost half of the cement) are respectively irradiated by gamma rays having 500 kev. energy, their total absorption coefficients have been computed (in units of 10^{-24} cm.² per atom) at 7.6 and 5.8 respectively, of which only 0.19 and 0.05 may be respectively allotted to the photoelectric effect. However, when the irradiating rays are reduced to 100 kev., the total absorption coefficients for iron and calcium are 33.3 and 16.7, of which 20.5 and 6.9 are respectively allotted to the photoelectric effect. Thus, to obtain the largest possible anomaly in the counting rate of returning radiation, it is preferable that the emitted rays be slowed (by scattering before entering the wall of the adjacent tubing) to speeds nearer the lower end of the energy spectrum, rather than nearer the higher end, in order to emphasize this atomic number effect. Of course, since the returning radiation must penetrate the wall of the tubing string containing the perforator 14, the source 26 must emit rays which, when scattered in the cement 8, will still return with energies of at least 30-40 kev. In those forms of the present invention depicted and described herein the energy of gammas emitted by the source 26 should preferably be limited to a range of 250 kev. to 750 kev., and the source 26 should preferably be spaced from the detector 32 a distance ranging from approximately four to eight inches, depending upon the selected source energy. In that form of the invention, which was successfully built and tested, a source 26 composed of iridium¹⁹² was spaced a distance of 5½ inches from a detector 32 composed as shown in FIGURE 5. The distance was measured between the center of the source 26 and the near or bottom ends of the active lengths of the depicted Geiger counter 33 tubes.

As hereinbefore stated, the detector 32 is also prefer-

ably collimated in order to provide mono-directional sensitivity to the returning radiation. To improve the mono-directional sensitivity of the detector 32 to the low energy rays hereinbefore described, it is preferable that the detector 32 be composed of a plurality of Geiger counter 33 tubes aligned as shown in FIGURE 5. Relatively short Geiger counters 33 have been found to be superior for these purposes to those of greater length. In one form of the present invention which was successfully tested, Geiger counters 33 having active lengths of two inches each were found to be particularly suitable when spaced a distance of 5½ inches (measured as hereinbefore described) from a 400 millicurie gamma ray source composed of iridium¹⁹².

Referring again to FIGURE 3, the downhole assembly there depicted is shown having two sets of bowsprings 34 for the purpose of centralizing and balancing the assembly in the tubing string sought to be perforated. A decentralized assembly has been determined to be successful for purposes of the present invention, although difficulty is sometimes encountered in rotating a decentralized instrument in the tubing string. During the testing of that form of the present invention which was reduced to practice the orienter 20 was arranged to scan always in the same direction as the perforator 14. In other words, the detector recess 30 and the source recess 28 were aligned with the penetrating means 16 of the perforator 14. Of course, the present invention is not limited to such an arrangement since the orienter 20 may be arranged in any rotational angle with respect to the penetrating means 16 of the perforator 14, so long as this angle is known. For example, in one very useful form of the present invention the orienter 20 was rotated 180 degrees from the direction in which the penetrating means 16 were aimed. In addition, a perforator which may be selectively fired in a plurality of directions may be used, provided the various directions are related in a known manner to the aiming direction of the orienter 20.

Numerous other variations and modifications may obviously be made without departing from the concept of the present invention. Accordingly, it should be clearly understood that the forms of the invention herein before described, and shown in the figures of the accompanying drawings are illustrative only and are not intended to limit the scope of the invention.

What is claimed is:

1. Apparatus for perforating in a cement-filled well bore containing a plurality of juxtaposed pipe strings eccentrically arranged therein, said apparatus comprising: a monodirectional gun perforator adapted to be inserted in one of said pipe strings; a monodirectional pipe location indicating means attached in fixed angular relationship to said gun perforator, said indicating means comprising a collimated monodirectional source of gamma rays having substantially an energy sufficient to penetrate said one pipe string and the nearest portion of the wall of said borehole but insufficient to penetrate the most laterally remote portion of said wall of said borehole, and a collimated gamma ray detector arranged and adapted to preferentially detect source-emitted gamma rays scattered in substances immediately confronting said collimated source, said detector also being spaced from said source substantially a distance functionally related to the energy of said source such as to provide a maximum anomaly in the detection rate of scattered gamma rays when another of said pipe strings is immediately before said collimated source; and means for rotating said gun perforator and said pipe location indicating means in said one pipe string.

2. The apparatus as described in claim 1, wherein said source of gamma rays have an average energy of greater than 250 kev. and not greater than 750 kev., and wherein said detector is spaced from said source a distance greater than 4 inches and not greater than 8 inches.

3. Apparatus for selectively perforating one of a plurality of juxtaposed pipe strings eccentrically arranged in

a cement-filled borehole, said apparatus comprising: a monodirectional gun perforator adapted to be inserted in said one pipe string; a monodirectional pipe location indicator means attached in fixed angular relationship to said gun perforator, said indicator means comprising a collimated monodirectional source of gamma rays of substantially 350 kev. average energy, a collimated gamma ray detector arranged and adapted to preferentially detect source-emitted gamma rays scattered in substances immediately confronting said collimated source, said detector also being spaced from said source substantially at a distance functionally related to the energy of said source-emitted gamma rays so as to provide a maximum anomaly in the detection rate of scattered gamma rays when another of said pipe strings is immediately before said collimated source; and means for rotating said gun perforator and said pipe location indicator means in said one pipe string.

4. The apparatus described in claim 3, wherein the source of gamma rays is an encapsulated quantity of iridium.

5. Apparatus for selectively perforating one of a plurality of juxtaposed pipe string eccentrically arranged in a cement-filled borehole, said apparatus comprising: a monodirectional gun perforator adapted to be inserted in said one pipe string; a monodirectional pipe location indicator means attached in fixed angular relationship to said gun perforator, said indicator means comprising a substantially radiation opaque body having two longitudinally spaced-apart and aligned lateral recesses, an encapsulated quantity of iridium disposed in one of said recesses in a manner to provide a beam of low energy gamma rays, a plurality of relatively short Geiger-Müller counter tubes aligned in said other recess in a manner to provide a monodirectional gamma ray detector, said two recesses being spaced-apart a distance such that said iridium is disposed approximately 5% inches from said detector; and means for rotating said gun perforator and said pipe location indicator means in said one pipe string.

6. A method of locating in a first tubing string disposed in a cement-filled borehole the relative position of a second tubing string in said borehole, said method comprising: at a first point in said first tubing string laterally scanning the substances in said borehole with a substantially monoenergetic beam of low energy gamma rays substantially capable of penetrating said first tubing string and substantially incapable of penetrating the most laterally remote portion of the wall of said borehole, simultaneously and in fixed angular relationship therewith laterally scanning said substances with a substantially monodirectional gamma ray detector at a second point axially spaced in said first tubing string a distance which is functionally related to the average initial energy of said gamma rays, and deriving a recordable electric signal composed of pulses functionally related to detected gamma rays.

7. The method described in claim 6, wherein said scanning is performed in predetermined angular increments of rotation, and wherein said recording graphically displays a linear indication displaced from one edge of a recording strip according to the rate of occurrence of said pulses.

8. The method described in claim 6, wherein said scanning is performed in a rotary manner, and wherein

said signal is graphically recorded as a linear indication displaced from a single polar plot according to the rate of occurrence of said pulses.

9. A method of locating in a first tubing string disposed in a cement-filled borehole the relative position of a second tubing string in said borehole, said method comprising: laterally scanning at a first point in said first tubing string the substances in said borehole with a beam of gamma rays of substantially 350 kev. average energy, simultaneously and in fixed angular relationship therewith laterally scanning said substances with a substantially monodirectional gamma ray detector at a second point axially spaced approximately 5% inches in said first tubing string from said first point, deriving a recordable electric signal composed of pulses functionally related to detected gamma rays, and recording said signal in correlation with an indication of the relative angular direction of said scanning.

10. A method for perforating a tubing string in a well bore having a plurality of tubing strings arranged therein in side-by-side relationship comprising the steps of:

laterally scanning with a beam of gamma rays from within one of said tubing strings the substances in said well bore through at least one complete revolution at a first point in said one tubing string, simultaneously and in fixed angular relationship with said beam laterally scanning through at least one complete revolution said substances with a substantially monodirectional radiation detector at a second point within said tubing string spaced axially in said one tubing string from said first point, deriving a recordable electrical signal from the scanning of said detector composed of pulses functionally related substantially to detected gamma rays scattered only in substances in said well bore in radial directions throughout said complete revolution, graphically recording said signal as a linear indication displaced in radial directions throughout a complete revolution from a single point according to the rate of occurrence of said pulses in a manner to locate the other of said tubing strings in said well bore, positioning a monodirectional tubing perforator in said one tubing string at a third point axially spaced from said first and second points, directing said perforator as indicated by the manner of displacement of said linear indication to avoid the other of said tubing strings, and actuating said perforator.

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