

Aug. 4, 1953

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2,648,056

WELL LOGGING METHOD AND APPARATUS

Filed Nov. 1, 1948

2 Sheets-Sheet 1

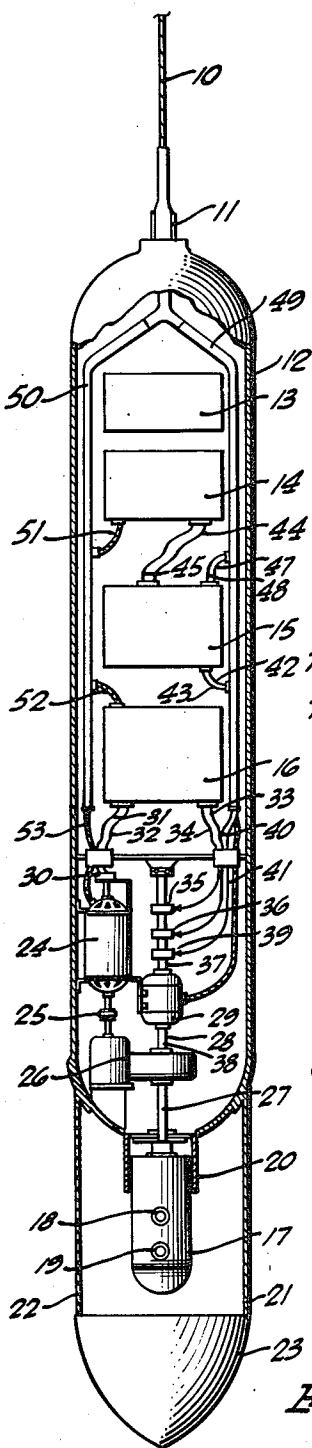


FIG. 1.

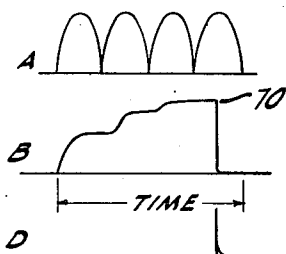


FIG. 3

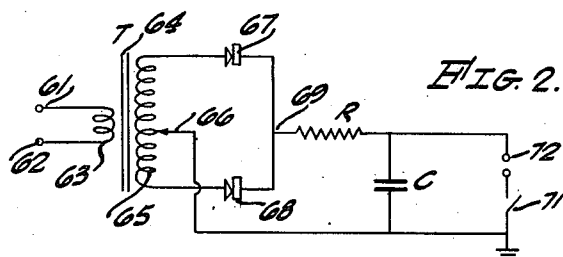


FIG. 2.

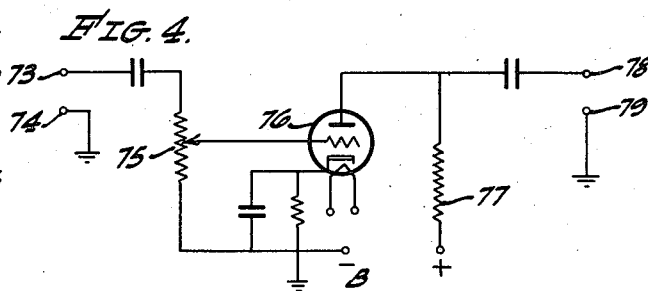


FIG. 4.

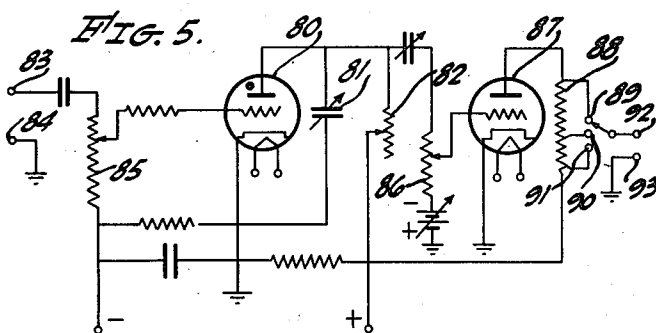


FIG. 5.

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FIG. 8.

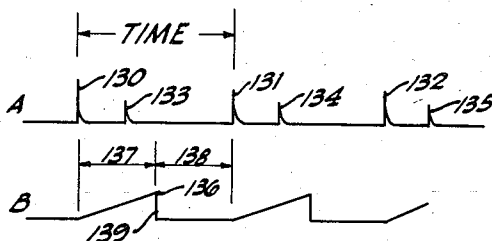
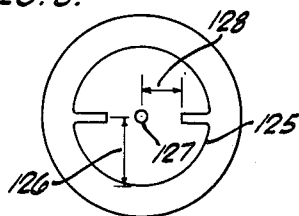


FIG. 9.

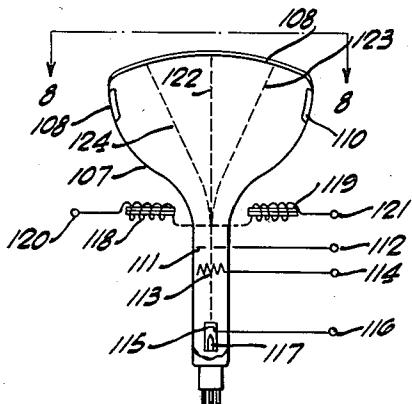


FIG. 7.

FIG. 10.

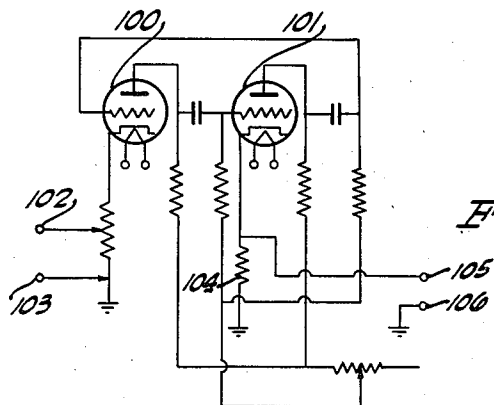
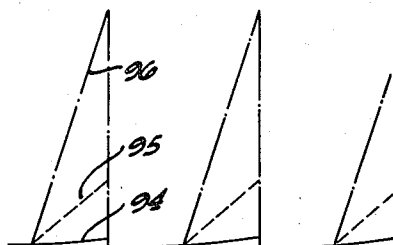


FIG. 6.

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2,648,056

WELL LOGGING METHOD AND APPARATUS

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Application November 1, 1948, Serial No. 57,732

15 Claims. (Cl. 340—18)

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This invention relates to a method for the logging of well bores or other subsurface openings by means of which the size of the bore may be determined. More specifically this invention relates to a method for determining the diameter and the variation in the diameter of well bores by timing the difference between a sonic impulse generated within the well bore and the echo of such an impulse received from the surface of exposed rock.

During the drilling of a well, the size of the borehole varies with a number of factors, among them being: nominal size of drill bit, hardness and composition of the formations penetrated, amount and nature of the material suspended in the mud, pressure on drill bit, type of drilling equipment, and rate of drilling. The size of the hole may be many times that which would be expected from the bit being used in the drilling operation. The amount of this unpredictable change in effective diameter varies from strata to strata, and affects the subsequent cementing and other well completion steps. It is most desirable that the approximate diameter of the borehole be known for each foot of depth of the well. Various methods have been proposed for caliper-ing boreholes, the most commonly used being an instrument which comprises essentially a series of movable fingers, which are hinged at their lower end, and so arranged that they will swing outward until the outer end contacts the side of the borehole. The greater the diameter of the borehole, the greater will be the angle of movement of these fingers. By connecting each of these movable fingers to a variable resistance, and the necessary electrical bridge circuit, it is possible to record the angle of movement of these fingers, versus the depth of the borehole. This method is subject to considerable difficulty due to mechanical maintenance, slow operation, and its inability to measure: (1) enlargements which may have small vertical height, but appreciable horizontal extension, and (2) enlargements in the borehole which are greater than the effective length or motion of the moving fingers.

The present invention therefore is directed to an improved method by means of which a continuous log of a borehole diameter may be obtained as well as a continuous record of the variation in the shape of the cross sectional area of the borehole with depth.

It is an object of this invention to provide an improved method for measuring the dimensions of subsurface openings such as boreholes drilled for the production of oil and gas, and the like, from the subsurface.

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An additional object of this invention is to provide a process which is readily amenable to the rapid and highly accurate determination of well bore diameters through the generation of a series of sonic impulses and measuring subsurface distances by determining the time elapsing between the impulse and its echo from the adjacent reflecting surfaces.

It is a further object of this invention to provide a method for determining the depth at which lost circulation of drilling fluid may occur or the depth at which thieving occurs in a producing well.

Another object of this invention is to provide a well bore caliper method which is highly accurate and which is independent of the medium present in the bore at the time of the determination.

It is an additional object of this invention to provide an apparatus adaptable to carry out the aforementioned objects and which is capable of differentiating well bore diameters to an accuracy of less than 0.1 of an inch, and is also capable of measuring subsurface distances as high as 1,000 feet or higher.

Other objects and advantages of this invention will become apparent to those skilled in the art as the description and illustration thereof proceeds.

Briefly, the present invention comprises a method for logging subsurface openings such as well bores to effect a continuous determination of the average well bore diameter, the variation in the well bore diameter, and to obtain a clear indication of the cross sectional area and its variation with depth in subsurface bores drilled for the purpose of recovering valuable fluids from underground strata. To obtain this information the method of the present invention utilizes a continuous series of sonic impulses or pressure waves of minute duration having a constant frequency. Such pulses are emitted within the well bore and pass through the fluid present therein to rebound from reflecting surfaces in the subsurface and return. A determination of the distance over which these sonic impulses travel is effected by accurately measuring the time elapsing between an emitted pulse and its echo. The impulses are spaced in time at a frequency dependent on the magnitude of the distances being measured so that returning echoes are not confused by the following pulse. The method of this invention is based upon the phenomenon of constant sonic velocities of pressure impulses or sonic impulses through fluids. In gases these sonic velocities vary with pressure and with tem-

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perature and have a magnitude of between 800 and 1500 feet per second. In liquids the sonic velocities are higher varying from 3,000 to 6,000 feet per second depending upon the temperature and composition. The method permits the accurate measurement of subsurface distances such as those in well bores by the highly accurate timing of impulses and echoes to below one microsecond (one-millionth of a second). At a sonic velocity of 6,000 feet per second a sound wave of such a sonic velocity travels 0.072 inch in one microsecond thus permitting a measurement of a well bore radius to within that degree of accuracy.

An apparatus has been devised as herein described which is extremely well adapted to performing the method of this invention. The apparatus comprises an emitter by means of which a sharp sonic impulse or transient is obtained such as from a condenser discharged through a low resistance. This impulse has a controllable duration which may be as low as or lower than one microsecond and may be obtained by discharging a condenser at closely controlled intervals through a low resistance circuit including a spark gap. The emitter produces a sharp pressure wave in the fluids present in the well bore and which is reflected from surfaces surrounding the well bore. Near the emitter is placed a sound sensitive device or receiver such as a microphone by means of which the impulse and its echo are picked up. These impulses and the corresponding echoes are amplified in an audio-amplifier to permit their transmission to the surface where they may be reamplified if necessary and introduced into a timing circuit which will be hereinafter more fully described. In measuring larger distances in which case the echoes are of low intensity, the impulses are not amplified with the echoes. At the surface, the highly accurate measurements of the echo times are made and the distance over which the sonic impulse travels is determined. The apparatus operates continuously and may be either lowered or raised through the well bore or other subsurface opening at a substantial rate which may be as high as 60 feet per minute or higher while still permitting a highly accurate well diameter determination.

It is to be understood, however, that the foregoing brief description of the method and apparatus of this invention is but one modification thereof and that the broad method comprises logging a well bore to determine its diameter and associated properties by measuring the time elapsing between sharp sonic impulses and their echoes. The apparatus broadly contemplated by this invention comprises a sonic emitter which may be of several types hereinafter described, a receiver for picking up sonic impulse echoes as well as the sonic impulses themselves, a power supply to provide power for the emitter, an amplifier to increase the intensity of the impulses and echoes received by the receiver, and a constant speed means for rotating an assembly which houses the receiver and emitter within the well bore. The above apparatus is placed within a housing and provided with means for raising or lowering the complete instrument through the well bore at a predetermined rate. The remainder of the apparatus may be positioned at the surface or adapted to be placed in the instrument and comprises means for suspending the aforementioned apparatus within the well bore, means for measuring the depth of the apparatus from the surface and means for

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timing the echoes received from the emitted impulses to permit rapid and accurate distance determination and depth.

The emitted impulses may be made to be very sharp transient pressure waves having very small oscillatory tendencies and which are of very short duration. The echo received by reflection of such a pulse from the surface against which it is directed may be a sharp pulse very similar to that emitted, or it may be a complex flat top pulse having the characteristics of a distorted wave and it also may be of considerably longer duration than the emitted pulse. A one microsecond pulse emitted along all radii from the axis of a bore of uniform diameter will produce an echo of approximately the same intensity and of approximately the same duration. The reception of such an echo indicates a bore of uniform diameter and the time elapsing between the impulse and the echo indicates the diameter of such a bore. The reception of a flat top or distorted wave indicates a bore of irregular shape since the paths traveled are of different lengths. The initial part of the pulse denotes the arrival of the first echo over the shortest distance while the longest part of the pulse denotes the return from the furthest reflecting surfaces. The emitter may be centrally located in the well bore and operate with a sonic receiver by means of which a sonic pulse and a composite wave of reflected echoes are received, or a series of receivers may be employed which are oriented in different directions and which receive different echoes. Also a series of emitters and receivers may be employed if desirable and in one modification emitters may also function as receivers particularly in the case where a flexible diaphragm actuated by magnetic means is employed. A further modification consists in the utilization of a series of emitters oriented in different directions which are preferably actuated independently of each other in sequence and the echoes received at a centrally located single receiver.

The preferable modification of the apparatus, and one which is subsequently described in conjunction with a series of drawings, comprises a single emitter and a single receiving mechanism which are positioned in a rotatable assembly and by means of which the emitted impulse is carefully directed in a single direction from the emitter to the reflecting surface and in which the receiver is adapted to receive echoes from that same direction. Such a modification simplifies the nature of the echo pulse to one approximating the emitted pulse.

The character of the reflections present an indication of the hardness of the reflecting surface. By interpretation of the echoes obtained differentiation is made between strata upon which an appreciable filter cake is deposited and the harder non-porous rocks where no filter cake is deposited by the drilling mud during drilling. This technique permits differentiation between porous and nonporous strata and in turn indicates the permeability of the formations.

The apparatus employed for measuring elapsed times between impulses and echoes may be an oscillograph with a camera for recording the oscillograph indications or other visual device such as a cathode ray tube oscilloscope well known in the art. By synchronizing the electron beam deflection of such a cathode ray tube with the initiation of the emitted pulse, the return of the echo and the emitted pulse may be visually reproduced on the cathode ray tube screen in

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which form the distance across the tube face between the indications of the emitted and the returning pulses is a direct determination of the time elapsing between them and a measure of the distance. This recorder is preferably geared to the suspension cable by means of which the device of the present invention is suspended in the well bore or other subsurface opening. Such a combination permits the direct correlation of well bore diameter with bore depth.

Because of the short distance between the emitter and the well bore wall and the accompanying short time between the emitted pulse and the received echo, there exists a maximum number of emitted pulses of a given duration.

The pulse duration is preferably very short such as between about 0.01 microsecond to as high as about 100 microseconds or higher. Preferably the pulse duration varies between 0.1 and 10 microseconds and pulses of about 1 microsecond are readily obtained by the discharge of a 1 microfarad condenser through a system having a resistance of 1 ohm. This system may comprise a spark gap, a magnetically operated diaphragm, a magnetic sounder or other device adaptable to the generation of very short sonic pulses.

The apparatus of the present invention in one of its preferred modifications will serve to assist in an understanding of the method of this invention and is shown clearly in the accompanying drawings in which:

Figure 1 presents a cross sectional elevation view of the device which is suspended within the well bore or other subsurface opening, the dimensions of which it is desired to determine,

Figure 2 is a schematic circuit diagram of an electrical apparatus to provide short pulses to the emitter and having a predetermined frequency,

Figure 3 shows a schematic illustration of the voltages and their time relation present during the condenser charge and discharge during the emitter operation,

Figure 4 shows a schematic wiring diagram of an audio-amplifier adaptable to amplifying the emitted pulse as well as the received echo to an intensity sufficient to carry it through suitable conductors to the surface for analysis,

Figure 5 shows a simplified wiring diagram of a saw-tooth wave oscillator used in conjunction with the cathode ray type of recorder,

Figure 6 shows a simplified wiring diagram of a square wave oscillator also employed in conjunction with the cathode ray recording device,

Figure 7 shows a schematic cross section view of magnetically deflected cathode ray tube employed for recording borehole diameters and the like,

Figure 8 shows a schematic view of the screen of a cathode ray tube on which a pattern is described by the cathode ray tube electron beam indicating a borehole of uniform diameter.

Figure 9 is a representation of the various pulses received from the subsurface and generated at the surface for the purpose of operating the cathode ray tube indicator, and

Figure 10 shows the variation in saw-tooth wave oscillator deflection voltage by means of which the range of the instrument and the indicating device may be altered.

Referring now particularly to Figure 1, cable 10 is attached by means of connection 11 to exploration instrument housing 12 which latter housing comprises preferably an elongated steel

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shell closed with gas tight fittings for disassembly and assembly of the sounding device. Cable 10 serves a dual purpose of suspending the device in the subsurface as well as carrying the necessary electrical conductor by means of which the various components of the sounding device are connected to indicating devices when such are maintained at the surface. Within housing 12 is provided gyro 13 by means of which the entire device is maintained in a given position with respect to surface directions, such as for example magnetic north. The device is further provided with power supply 14 which may be a bank of storage batteries, dry cells or a transformer-rectifier-filter system to supply power for operation of audio amplifier 15. The power necessary to generate the emitted pulses is provided by emitter supply 16. The emitter supply 16 may comprise storage batteries or a rectifier system such as that shown schematically in Figure 2 and subsequently described. At the lower end of housing 12 is suspended rotatable assembly 17 provided with emitter 18 and receiver 19. Emitter 18 comprises a spark gap in this preferred modification while receiver 19 comprises a microphonic device of the condenser type, dynamic type, the crystal type or other adapted types to convert received pressure waves to corresponding and electrical impulses. Rotatable assembly 17 is provided with collar 20 which functions to prevent foreign materials from impeding the steady rotation of assembly 17. The outside of assembly 17 is preferably provided with a covering or coating of sound absorbent material to eliminate re-echoes therefrom which confuse the desired first echo. Below assembly 17 and suspended by members 21 and 22 is guard 23 to provide a rest for the sounding instrument at the bottom of the well bore or other subsurface cavity. Suspension members 21 and 22 serve a further purpose in providing an echo from an object of known distance which is employed as subsequently described in calibrating the instrument in various fluid media which may have sonic velocities of considerable variation.

Rotatable assembly 17 is actuated by constant speed motor 24 which is connected by means of coupling 25 to reduction gear 26. Shaft 27 connects assembly 17 with reduction gear 26 and shaft 28 connects Selsyn generator 29 to reduction gear 26. In the preferred modification of these pieces of apparatus, constant speed motor 24 is an alternating current synchronous motor having a synchronous rotary speed of 1800 R. P. M., or 30 revolutions per second. Reduction gear 26 reduces the rotary velocity of synchronous motor 24 from 1800 R. P. M. to 60 R. P. M. or one revolution per second and consequently rotatable assembly 17 turns one complete revolution per second as does Selsyn generator 29. Synchronous motor 24 operates rotary switch 30 which contains a rotor and a stator which contact each other for a period of time which may be equivalent to about one degree or less of arc per revolution. The contact time for an 1800 R. P. M. synchronous motor is therefore 92½ microseconds under these conditions. By decreasing the arc over which contact of the rotary switch is made, shorter contact times may be had. It is not necessary to have such short contact times since the pulse duration is determined by the capacitance and resistance characteristics of the emitter circuit shown in Figure 2. Switch 71 closes the circuit

shown in Figure 2 and causes condenser C to discharge generating the pulse transmitted from emitter 18. In this manner 30 such spark impulses are generated per second during one revolution of rotatable assembly 17.

Obviously, however, other constant speed devices such as a Selsyn motor or the like, together with suitable speed reducers may be employed in the manner and for the function shown.

The transmitted impulse is of very short duration, of the order of one microsecond. However, with other emitters such as mechanical vibrators, and the like, longer pulses may be generated and are satisfactory provided a maximum pulse duration is not exceeded. The maximum pulse duration is dependent upon the distance from the emitter to the reflecting surface from which the echo is obtained as well as upon the sonic velocity. The maximum pulse time T_p in microseconds is given by the following equation:

$$T_{p \text{ max.}} = \frac{2L}{V} \times 10^6$$

where L is the distance from the emitter to the reflector, and V is the sonic velocity in a given fluid present between the emitter and the reflector. Should this pulse duration be exceeded, the initiation of the subsequent pulse will confuse the determination of the end of the echo from the first pulse. In the above equation T_p is the time necessary for the leading wave of the pulse to travel from the emitter to the reflector and return to the receiver which is placed in the immediate vicinity of the emitter.

The maximum pulse frequency, $f_{p \text{ max.}}$, which may be employed is dependent upon the distance from the emitter to the reflector, the sonic velocity, and the pulse duration. The maximum number of pulses per second which may be emitted and from which complete echoes may be recorded is given by the following equation:

$$f_{p \text{ max.}} = \frac{1}{\frac{2L}{V} + (T_p)(10^{-6})}$$

the symbols having the significance given above.

A pseudo maximum instrument range may be defined as the distance between the emitter and reflector for which the echo just precedes the following pulse for given conditions of f_p , T_p , and V. This maximum range L is given as:

$$L_{\text{max.}} = \frac{V}{2} \left[\frac{1}{f_p} - (T_p)(10^{-6}) \right]$$

It is desirable to operate the instrument at pulse frequencies and durations so that the actual distances being measured are below $L_{\text{max.}}$. It is possible to extend the instrument range beyond $L_{\text{max.}}$ by receiving an echo from pulse 1 following emission of pulse 2, pulse 3, or more. Under such conditions great care must be taken at the initiation of pulse emission to determine just which pulse the first echo follows and closely following the relationship between the echo and the pulses immediately preceding and following it.

In Figure 1, rotation of rotary switch 30 periodically closes a circuit in emitter power supply 16 by means of which a condenser is discharged rapidly through a low resistance circuit including emitter 18. Connections 31 and 32 connect rotary switch 30 to the proper circuit in emitter power supply 16 while connections 33 and 34 conduct the discharged energy from

emitter power supply 16 through commutator segments 35 and 36 from which conductors, now shown, but running through hollow shafts 37, 38 and 27 conduct the discharged energy to emitter 18. The sonic impulse thus generated, as well as its echo obtained from a reflecting surface, actuates receiver 19 which is connected by a pair of conductors one of which is common to those of emitter and the two pulses are carried via commutator segments 36 and 39 through conductors 40 and 41 as well as conductors 42 and 43 to amplifier 15. Power for operation of this amplifier is obtained from amplifier power supply 14 via conductors 44 and 45. The amplified signals, comprising the emitted pulse and its echo, are conducted via conductors 47 and 48 to the surface through cable 10.

The exploration instrument is further provided with conductor cables 49 and 50 by means of which the wiring of the instrument is enclosed within housing 12. Conduit 50 in particular carries the alternating current conductors from the surface and from which branches 51 supply alternating current power to amplifier power supply 14, conductors 52 supply alternating current power to emitter power supply 16 and conductors 53 supply alternating current power to synchronous motor 24.

Referring now to Figure 2, a schematic wiring diagram of an apparatus suitable for use as emitter power supply 16 is shown. Alternating current power is supplied by means of connections 61 and 62 to primary winding 63 of transformer 64. Secondary winding 65 is provided with center tap 66 which may be grounded to the instrument. Rectifiers 67 and 68 which may be of the selenium disc variety are connected in series opposition and the two are connected in parallel with secondary winding 65. The rectifying action of the system converts A. C. voltage of secondary winding 65 to a pulsating direct current voltage existing between center tap 66 and point 69. The wave form of this pulsating voltage is shown in curve A of Figure 3. The pulsating D. C. voltage thus generated is applied to condenser C in Figure 2 through resistance R whereby the charging current from the rectifier to the condenser is limited to a safe value. During the first pulses shown in curve A of Figure 3 the charging current through resistor R of Figure 2 causes the voltage to build up in a series of steps in condenser C of Figure 2. The condenser charge rises in a manner shown in Figure 3 as curve B until a maximum shown at point 70 is reached. The time elapsing for the four pulses shown in Figure 3 as curve A amounts to $\frac{1}{30}$ of a second when a 60 cycle 1800 R. P. M. synchronous motor 24 in Figure 1 is used. The same principle, however, may be applied to systems having other than a 60 cycle fundamental frequency.

Within the fourth pulse of curve A in Figure 3, rotary switch 30 of Figure 1 (switch 71 of Figure 2) closes causing the condenser C in Figure 2 to discharge through gap 72. When switch 71 of Figure 2 closes the full voltage charged into condenser C appears across gap 72, causes the dielectric between the electrodes of the gap to break down and the gap to conduct which in turn dissipates the major proportion of energy saturated in condenser C. The voltage across gap 72 during the discharge is shown plotted as curve D in Figure 3.

During this brief short circuit period the power supply as well as the condenser is short

circuited. However, current flow through the rectifiers is limited by resistance R.

The duration of the pulse thus obtained by condenser discharge through gap 72 is determined by the capacity of condenser C as well as the electrical resistance of the circuit which includes condenser C, switch 71 and spark gap 72 shown in Figure 2. The one microsecond pulse is readily obtained by employing a condenser of approximately one microfarad capacity and designing the remainder of the circuit including switch 71 and gap 72 to have an electrical resistance of about one ohm or less. Spark gap 72 while conducting generally has a resistance of between 0.01 and 0.1 ohm as the spacing within electrodes within the gap need be close enough so that the voltage build up is sufficient to break down the dielectric between the electrodes of gap 72 of initiating current flow. The relationship between the capacitance of condenser C and the resistance of the remainder of the circuit in determining the impulse duration is given by the following equation:

$$T=RC$$

in which T is the time in microseconds for a condenser of C microfarads capacitance discharging 63% of its energy through a resistance of R ohms. The end of the pulse occurs when the gap voltage falls below the ionization voltage of the dielectric between the gap electrodes.

It is to be understood that the emitter described in the foregoing description is not intended to limit this invention to the use of spark gaps but is only illustrative of the preferred modification of this portion of the apparatus. By varying the capacitance of condenser C and the resistance of the gap circuit, spark impulses may be emitted having any desired intensities and any duration which may be desired. The values of resistance and capacitance given above are intended to illustrate rather than limit this particular part of the apparatus.

Referring now more particularly to Figure 4, a schematic circuit diagram is shown of an audio amplifier which is suitable to amplify the intensity of the electrical impulses obtained from receiver 19 shown in Figure 1. The electrical impulses obtained by receiver 19 correspond to the sonic impulses of the emitted pulse and the echo and are applied to contacts 73 and 74 by means of which a current is caused to flow in resistor 75. This change in current flowing through resistor 75 changes the grid bias of amplifier tube 76 which in turn effects a considerable variation in plate current passing through resistor 77. An amplified voltage is developed across resistor 77 which corresponds to the sonic impulses and which is applied to contacts 78 and 79 for transmission to the surface where the impulses are further amplified, if necessary, in similar types of equipment.

In Figures 5 through 10 schematic wiring diagrams of typical apparatus are shown which enables the amplified impulses obtained from the amplifier described in Figure 4 to be placed on the screen of a cathode ray tube where they appear as a bright line traced thereon which corresponds with a cross sectional view of the borehole at the depth of the instrument. It is to be understood, however, that this type of indicating apparatus is not to be considered limiting the present invention to the use of this specific type indicator since other types may be used to show the data obtained to good advantage such

as comparing the impulse and echo on an oscilloscope screen wherein spacing is indicative of the elapsed time. The type of apparatus herein described in conjunction with Figures 5 through 10 is the preferred type, however, in that it permits translation of the data obtained by the instrument into a highly effective and readily interpreted form which is also very simply recorded photographically.

In Figure 5 is shown a schematic wiring diagram of a relaxation type oscillator and an amplifier which generates a saw-tooth sweep voltage similar to that shown in curve B of Figure 9. Vacuum tube 80 is a gas-filled triode or similar type which has a particular plate voltage above which the gas in the tube ionizes and permits the plate current to flow. The frequency of the oscillation is dependent upon the capacitance of condenser 81 and resistance 82. In order to synchronize the saw-tooth oscillation with the frequency of pulses being emitted by the emitter described above, synchronizing voltage obtained from the emitter is introduced by means of contacts 83 and 84 across resistance 85. The pulses of voltage of the emitter generate corresponding pulses of current through resistor 85 which keeps the frequency of the saw-tooth oscillation in step with the frequency of the emitted pulses. The output voltage of the saw-tooth oscillator is impressed on the grid resistor 86 connected to amplifier tube 87. In one modification this amplifier may be a class A amplifier operated so that an output voltage is generated across amplifier load resistor 88 having a wave form of that of curve B shown in Figure 9. Load resistor 88 is preferably provided with a series of contacts 89, 90 and 91 to permit a series of different voltages to be removed from the saw-tooth amplifier. In this manner the amplitude of the saw-tooth oscillation may be varied so that changes in the scale of the pattern presented on the cathode ray tube screen may be effected. For example, when the output saw-tooth voltage impressed by means of contacts 92 and 93 on the magnetic deflection coils of the cathode ray tube to be described subsequently is taken from contact 89 the maximum amplitude of saw-tooth voltage is obtained and the scale of pattern present on the cathode ray tube screen is the smallest. By carefully controlling the magnitude of this voltage and by using a cathode ray tube having a screen of about 12 inches in diameter an exact reproduction of the contour of the cross section of a borehole may be reproduced on the screen of the cathode ray tube. If areas in the borehole are encountered where the diameter is considerably increased over that of the nominal size of the bit employed to drill the bore, a saw-tooth voltage which permits a longer range is obtainable by connecting contact 92 to contact 90 on load resistor 88. By adjusting the voltage obtained at contacts 92 and 93 when the former connects to point 89 so that it corresponds to a distance of, for example, one foot, then the voltages obtained from contacts 90 and 91 represent increases in distance range to 10 feet and 100 feet, respectively, for example. The variation in saw-tooth voltage appearing across contacts 92 and 93 under such conditions as described above are shown in Figure 10 wherein saw-tooth curve 94 corresponds to the 100-foot range, curve 95 corresponds to a 10-foot range, and curve 96 corresponds to a one-foot range, the ranges being equal to the maximum distance from the emitter to the reflecting surface which may be repro-

duced on the cathode ray tube screen. The amplitude or the peak voltage of the saw-tooth oscillations shown in Figure 10 bears an inverse ratio to the range of distance reproducible on the cathode ray tube screen, that is, the one-foot range is obtained on the screen by using 100 times the maximum deflection voltage at the same frequency that is used on the 100-foot range setting.

As the electron beam is deflected from the center of the screen radially toward the edge under the instrument of the saw-tooth voltages described above, the audio-signals obtained from the audio-amplifier are impressed on the cathode ray tube in such a way as to cause the electron beam intensity to increase and the indication of the electron beam on the cathode ray screen to brighten when echo impulses are received. The saw-tooth oscillation is synchronized with the sonic pulses in such a manner that the electron beam is in the exact center of the cathode ray tube screen when the sonic pulse is emitted and the electron beam is bright at that instant. It begins to move radially from the center, darkening at the end of the emitted pulse, and brightens when an echo is received. The appearance of the screen under such conditions shows two bright spots, one in the center and one radially from the center at a distance proportional to the distance of the reflecting surface from the emitter. When the electron beam reaches the periphery of the tube a third oscillation is impressed on the tube to decrease the electron beam intensity, if necessary, to a sufficiently low level to prevent the formation of bright lines or spots on the screen during the return of the electron beam from the periphery of the tube screen to its center. The oscillation, called a blanking wave or oscillation, necessary for this function is a square wave oscillation which also is synchronized with the emitted pulses, and has the wave form shown in curve C of Figure 9.

In Figure 6 a schematic wiring diagram of a multivibrator type oscillator is shown by means of which a square wave oscillation may be obtained. This oscillator employs two tubes designated as 100 and 101. The output circuit of tube 100 is resistance coupled to the input circuit of tube 101 and the output circuit of tube 101 is resistance coupled to input circuit of tube 100. Synchronization of the oscillations obtained is effected by injecting a voltage obtained from the emitter circuit into contacts 102 and 103 whereby the cathode bias of oscillator tube 100 is controlled. The initiation of oscillation of tube 100 is regularly controlled therefore in accordance with the emitted pulses. The square wave oscillator circuit shown in Figure 6 is strictly conventional and well known to those skilled in the art. The output voltage is obtained from a cathode resistor 104 of oscillator tube 101 and is connected to the cathode ray tube by means of contacts 105 and 106. The wave form of voltage oscillation thus obtained is that of curve C shown in Figure 9.

In Figure 7 is shown a schematic drawing of a magnetically deflected cathode ray tube into which amplified pulse and echo voltages, the saw-tooth deflection oscillations and the square wave blanking oscillations are impressed. In Figure 7 cathode ray tube 107 is provided with a phosphorescent screen 108, anode ring 109 provided with contact 110, first anode 111 provided with contact 112, control grid 113 provided with contact 114, cathode 115 provided with contact 116 and filament 117. Filament 117 is heated

by the passage therethrough of an electric current which in turn heats cathode 115 causing the emission of a cloud of electrons. A positive voltage is applied to first anode 111 through contact 112 which accelerates the electrons from cathode 115 toward screen 108. Along this route the electron beam passes through control grid 113 exerting a powerful control over the quantity of electrons, that is, the intensity of the electron stream and consequently the brilliancy of the spot on screen where the electron beam impinges. Placed around the neck of cathode ray tube 107 is a pair of rotatable deflection electromagnet coils designated as 118 and 119. These electromagnet coils are provided with a single winding having contacts 120 and 121. Electromagnet coils 118 and 119 are suspended on a ring gear, not shown, so that they may rotate about the neck of the cathode ray tube at a carefully controlled rotary velocity. The function of electromagnet coils 118 and 119 is to deflect electron beam 122 radially from the center of the tube toward the periphery in the plane of the electromagnets in synchronism with the deflection voltage generated by the saw-tooth oscillator described in conjunction with Figure 5 and having a variable peak amplitude as shown in Figure 10.

The mechanical rotation of the electromagnet coils 118 and 119 about the cathode ray tube produces a rotation of the deflected electron beam around the center of the cathode ray tube screen 108 in synchronism with the rotation of assembly 17 shown in Figure 1. Electromagnet coils 118 and 119 are rotated by a Selsyn motor, not shown, electrically connected to a Selsyn generator 29 shown in Figure 1. Thus, as rotatable assembly 17 rotates while emitting pulses and receiving echoes from surrounding reflecting surfaces, electromagnet coils 118 and 119, in Figure 7, are rotated in synchronism therewith to trace out a pattern in the form of a closed line or a series of spots about the center of cathode ray tube 108. The radial distance of any point on the tracing thus obtained from the center of the screen corresponds to the time required for the sonic impulse to travel from the emitter to the reflecting surface and back to the receiver. The received echo is amplified, injected into the cathode ray tube circuit to cause the electron beam to brighten at a point on a radius from the center to the periphery of the cathode ray tube.

In Figure 8 is shown a schematic view of the cathode ray tube screen in which a pattern line 125 is shown corresponding to the short range adjustment described above. The pattern shown corresponds to one obtained in a borehole of uniform diameter. In order to obtain a desirable presentation of the borehole cross section on the screen, the persistence of the electron-induced image on the screen must be great enough to retain the echo image for about one revolution of the emitter in the hole. In Figure 8 the distance 126 from the center 127 corresponds to a measurement of the distance from the emitter to the borehole while distance 128 corresponds to the distance from the emitter to either one of supports 21 or 22 shown in Figure 1. The cathode ray tube screen may thus be readily calibrated to read directly in terms of distance or borehole diameter. Distance 128 from the emitter to supports 21 or 22 shown in Figure 1 permits rapid adjustment of the instrument to changes in sonic velocity which occur during the survey. The distance between the emitter and the supports is

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constant and may be readily determined and adjustment of the saw-tooth deflection voltage may be made to bring distance 128 on the cathode ray tube screen to identity with the distance from the emitter to the supports and thus calibrate all ranges of the instrument to direct readings of distance.

In Figure 9 is shown the phase relationship between three of the characteristic wave forms upon which operation of the apparatus of this invention is dependent. Curve A represents the variation in audio amplifier output voltage obtained during operation showing sonic pulses 130, 131 and 132 followed by impulse echoes 133, 134 and 135. The time between impulses 130 and 131 in the present modification is controlled as above described to a value of 1/30 of a second. A presentation of impulses and echoes may be placed on a cathode ray tube screen as an image like that shown in Figure 9, curve A if desired. Lower emitter velocities are desirable in this case. Pulse 130 synchronizes the oscillation of the saw-tooth oscillator in the square wave generator so that wave forms shown in curves B and C are obtained. The timing of the saw-tooth wave indicated by distances 137 and 138 may be changed by making those distances in any proportion to each other. The magnitude represented by distance 139 may be varied as shown in Figure 10.

Following pulse 130 the voltage of the saw-tooth oscillator output rises as shown in curve B of Figure 9 causing electron beam 122 of Figure 7 to deflect radially to point 123. At this point echo 133 of Figure 9 is received and amplified and introduced into the cathode ray tube control grid 113 causing cathode ray tube screen 108 of Figure 7 to brighten at a point corresponding to point 123. In Figure 9, curve B when the saw-tooth voltage amplitude reaches point 136 electron beam has been deflected to the periphery and is returned to the center to be deflected in the same manner only along a different radial direction under the rotary influence of the deflection coils. During the fly back of the deflected electron beam to the center of the tube the intensity of the electron beam is decreased to a nonvisible value so that it traces no line on the screen. If the steepness of curve B of Figure 9 below point 36 is sufficient and the intensity of the electron beam is adjusted so that except for the time of the initial pulse and the time of the echo no bright spot or trace appears on the screen the saw-tooth blanking pulse may not be necessary.

The saw-tooth wave form shown in curve B of Figure 9 has an increasing amplitude which is linear with time. In magnetically deflected cathode ray tubes the variation in amplitude of the deflecting voltage must be adjusted somewhat from the linear variation shown in curve B to compensate for inductive effects presented by magnet coils 118 and 119 shown in Figure 7. This is necessary in order that a linear deflection of electron beam 122 to position 123 or position 124 shown in Figure 7 will result along a radius of the tube screen. To effect such a linear electron beam deflector with magnetic deflection coils the variation of the amplitude of the deflection voltage or the deflection current must assume a trapezoidal shape.

Referring now particularly to Figure 10 the variation in deflection voltage necessary to obtain various amplifications of tube pattern corresponding to different scales of distance is shown

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and have been previously described. The change in the amplitude of the deflection voltage with time governs the rate at which the electron beam sweeps radially across the cathode ray screen so that the electron beam is effectively deflected far beyond the periphery of the screen when the amplitude of the deflection voltage rises according to curve 96 of Figure 10. Thus, only echoes from near reflectors will be represented on the screen and the range of the instrument is low.

This method disclosed for changing the range of the instrument is perhaps the simplest. However, other methods may be employed which comprise changing the deflection voltage frequency and using the same maximum amplitude so that the electron beam is deflected from the center along a radius toward the periphery of the cathode ray screen at higher frequencies for measuring short distances and at lower frequencies for measuring longer distances.

In the apparatus described above, a magnetically deflected cathode ray tube was used. However, the well known electrostatically or voltage deflected tubes may be used in which the horizontal deflection plates are impressed with a sinusoidal voltage having the same frequency but 90° out of phase with the voltage impressed on the vertical plates. A circular pattern will be traced out and a spiral sweep results.

In actual logging operations the suspension of the instrument of this invention in a well bore, or the like, is carried out in conjunction with other continuous recording operations, namely that of measuring the depth of the instrument from the surface and the photographing of the cathode ray tube pattern at various depths.

The rate at which the instrument may be moved through the hole depends upon the rapidity with which the character of the borehole changes. In drilling certain formations a borehole is obtained which is a fairly uniform diameter and consequently a diameter log of such a bore may be obtained quite rapidly. In other formations and particularly those which are being logged for the first time the logging operation is preferably carried out more slowly in order to clearly define the depths of any cavities which tend to enlarge the mean diameter of the hole drilled through them. The average rate of movement of the instrument would be about one foot per second. The instrument may be lowered at rates as low as 10 feet per minute or less to as high as four or five hundred feet per minute depending upon the complexity of the data desired. In actual well logging operations the operation of the instrument is such that about 30 impulses and as many echoes are normally transmitted and received per second and are sufficient to give adequate well logging data at an instrument velocity of 60 feet per minute, a 6,000 foot borehole may be logged in a little less than two hours including all operations.

The present invention has been described in considerable detail with respect to the preferred modification which involves the emission of sonic impulses of short duration within the borehole or other subsurface opening to be logged and the reception and amplification of the emitted pulse and the received echo. The dimensions of the subsurface opening are then determined by comparing the time of the emission and the time of reception of a given impulse and its echo.

A particular embodiment of the present invention has been hereinafter described in consider-

able detail by way of illustration. It should be understood that various other modifications and adaptations thereof may be made by those skilled in this particular art without departing from the spirit and scope of this invention as set forth in the appended claims.

I claim:

1. A method for measuring subsurface openings containing fluids of variable sonic velocities which comprises suspending an impulse emitter and a sound sensitive receiver into said opening, emitting sonic impulses of short duration and constant frequency from said emitter, receiving echoes of said impulses reflected from subsurface reflectors in said sound sensitive receiver, simultaneously reflecting impulses from a reflector spaced a known distance from said emitter to determine the sonic velocity in the ambient fluid and measuring the time elapsing between respective sonic impulses and their echoes as a measure of the subsurface opening.

2. A method for obtaining a continuous caliper log of bore holes which may contain fluids of widely variant sonic velocity which comprises passing an impulse emitter and a receiver through the borehole, emitting sonic impulses of between 0.01 and 100 microseconds duration and at constant frequency from said emitter simultaneously, measuring the sonic velocity of fluids present in said borehole by measuring the time elapsing between an impulse and its echo from a reflector spaced at a known distance from said emitter, and determining the distance between said emitter and the wall of said borehole by measuring the time elapsing between an impulse and its echo from the borehole wall.

3. A method for determining the configuration of the cross section of a subsurface opening containing fluid phases of different sonic velocities which comprises emitting a series of sonic impulses of controlled frequency and of about one microsecond duration in the subsurface from a sonic impulse emitter, directing said impulses each in a different direction by rotating said emitter in the plane of said cross section, receiving echoes of said impulses from subsurface reflectors, determining the sonic velocity in fluids present in the subsurface opening by reflecting an impulse from a reflector of known distance from the emitter, and measuring the time elapsing between said impulses and said echoes for one complete rotation of said emitter in said plane to determine the configuration of said cross section.

4. A method according to claim 3 wherein a continuous log of the configuration of said cross section is obtained by passing said emitter at a predetermined velocity through said subsurface opening, said velocity being synchronized with the rotary velocity of said emitter.

5. In a method for logging variations in the diameter of a bore hole containing fluids of widely variant sonic velocity which comprises emitting a series of sonic impulses of controlled frequency and of about one microsecond duration in the subsurface from a sonic impulse emitter, directing said impulses each in a different direction by rotating said emitter in the plane of the cross section of said bore hole, receiving echoes of said impulses from subsurface reflectors, determining the sonic velocity in fluids of variant sonic velocity present in the subsurface opening by simultaneously reflecting an impulse from a reflector of known distance from the emitter, and measuring the time elapsing between said impulses and

said echoes during rotation of said emitter in said plane to determine the configuration of said cross section, the improvement in presenting the bore hole diameter variation information thus determined which comprises synchronizing the deflection of the electron beam in a cathode ray tube with the emitter pulse frequency and causing the echo impulse received by reflection from the bore hole walls to affect the electron beam thereby obtaining a visual representation of the bore hole diameter and its variation with respect to said known distance.

6. A method according to claim 5 in combination with the step of photographing the visual representation on said cathode ray tube screen to obtain a permanent record of the bore hole diameter and its variation.

7. In a method for logging variations in the diameter of a bore hole containing fluids of widely variant sonic velocity which comprises emitting a series of sonic impulses of controlled frequency and of about one microsecond duration in the subsurface from a sonic impulse emitter, directing said impulses each successively in a different direction by rotating said emitter in the plane of the cross section of said bore hole, receiving echoes of said impulses from subsurface reflectors, determining the sonic velocity in fluids present in the subsurface opening by reflecting an impulse from a reflector of known distance from the emitter, and measuring the time elapsing between said impulses and said echoes during rotation of said emitter in said plane to determine the configuration of said cross section, the improvement which comprises synchronizing the deflection of the electron beam in a cathode ray tube radially on the tube screen with the emitter pulse frequency, causing the echo to vary the intensity of the electron beam and rotating the radial deflection of said electron beam in synchronism with the emitter rotation and thereby obtaining a visual representation of the bore hole diameter and its variation.

8. An apparatus for logging the diameter of boreholes which comprises an elongated fluid-tight housing and a suspension means therefor for passing said apparatus through said borehole, said housing having an impulse emitter and an echo receiver attached thereto, said emitter being adapted to direct impulses toward the walls of said bore hole, a reflector fixed a known distance from said emitter, and means for determining the distance between said emitter and said reflector and said bore hole walls by measuring elapsed time between respective impulses and echoes.

9. A bore hole caliper instrument which comprises an elongated closed housing provided with fluid tight fittings for disassembly and assembly thereof, a rotatable assembly attached to said housing and provided with a sonic impulse emitter and receiver, means within said housing for rotating said assembly around the longitudinal axis of said elongated housing and at a constant predetermined velocity, gyroscope means within said housing for preventing rotation of said instrument with respect to its surroundings, power supply and impulse generating means connected to said emitter for the generation of sonic impulses of predetermined duration and frequency, suspension means for passing said instrument at a predetermined velocity through the subsurface, a reflecting surface positioned a known distance from said emitter and suspended from said instrument and means for measuring

time elapsing between an impulse and its echo to determine the distance from said emitter and the bore hole walls and said reflecting surface.

10. An apparatus according to claim 9 wherein said emitter comprises a spark gap adapted to the emission of unidirectional transient pressure waves.

11. An apparatus for the measurement of the variation in cross sectional configuration of a borehole along its length which comprises an elongated fluid tight housing provided with a suspension for passing said housing through said borehole, said housing having an assembly depending therefrom provided with a sonic impulse emitter and a sound sensitive echo receiving device, a reflecting surface positioned adjacent to said emitter and at a known distance therefrom, means within said housing for rotating said assembly at a predetermined velocity, an emitter power supply means for generating electrical energy supplied as impulses to said emitter for conversion to sonic impulses, amplifier means for amplifying sonic echoes and impulses received by said sound sensitive device, a cathode ray oscilloscope connected to said amplifying means, means for deflecting the electron beam of said oscilloscope in one direction a distance proportional to the time elapsing between respective impulses and echoes whereby spaced indications of respective impulses and echoes are obtained on the screen of said oscilloscope, said deflection being synchronized with the frequency of impulse emission.

12. An apparatus according to claim 11 wherein said cathode ray oscilloscope is provided with means for rotating the deflected electron beam about the center of the cathode ray tube screen in synchronism with said rotating assembly in the subsurface, said amplifier means being adapted to increase the intensity of the deflected electron beam simultaneously with the received echoes whereby each impulse is depicted as a bright spot in the center and each echo is represented by a bright spot thereon located on a radius of the cathode ray oscilloscope

screen whereby the cross sectional configuration of the borehole is depicted thereon.

13. An apparatus according to claim 11 in combination with an electrical oscillator adapted to the generation of an oscillating voltage having a wave form of the saw-tooth type in synchronism with the frequency of said sonic impulses, to deflect said electron beam, said electrical oscillator being further provided with means for varying the amplitude of the saw-tooth voltage applied to said oscilloscope thereby varying the range of distance between emitter and reflector reproducible upon the screen thereof.

14. An apparatus according to claim 11 in combination with a photographic recorder operating in conjunction with said oscilloscope to obtain a continuous photographic log of the configuration of the cross section of the borehole as the exploration instrument is moved through the borehole.

15. An apparatus according to claim 11 in combination with a coating of sound absorbent material covering the external surfaces of said assembly to eliminate re-echoes.

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