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(54) Analysis of constituents of earth formations

(57) The composition of an earth formation is investigated by repetitively irradiating the formation with bursts of neutrons from a source 22 and measuring an energy spectrum of the scattering gamma rays resulting from such irradiation e.g. by photomultiplier or solid state detector 24. The measured spectrum is thereafter analyzed by comparing it with a composite spectrum, made up of standard spectra, measured in a controlled environment, of constituents postulated to comprise the formation. As a result of such analysis, the proportions of the postulated constituents in the formation are determined. Since the measured spectrum is subject to degradation due to changes in the resolution of the detector, a filtering arrangement effects modification of the standard spectra in a manner which compensates for the changes in the detector and thereby provides for a more accurate determination of the constituents of the formation. Temperature is measured by sensor 46 to compensate for temperature dependence of detector resolution.

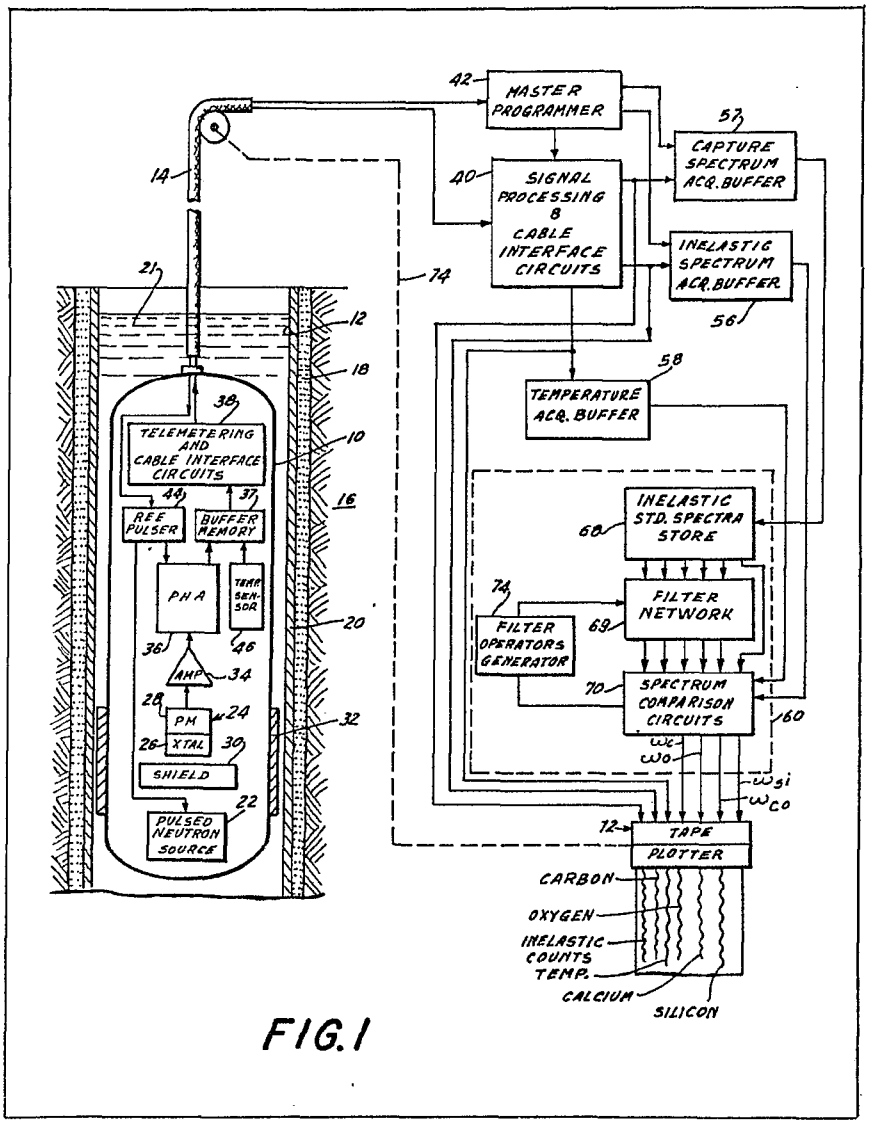

FIG. 1

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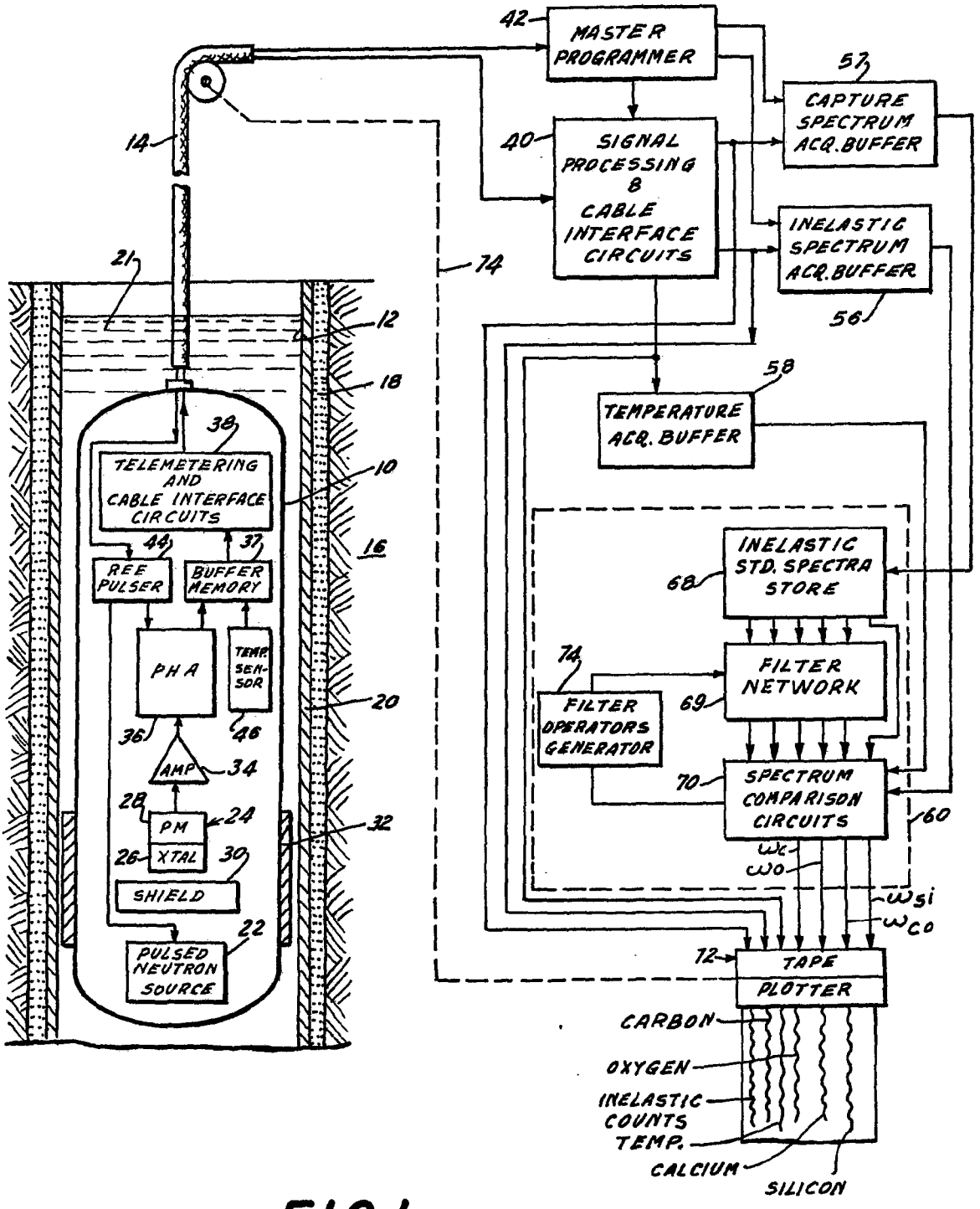
42
MASTER PROGRAMMER
57
CAPTURE SPECTRUM ACQ. BUFFER
40
SIGNAL PROCESSING & CABLE INTERFACE CIRCUITS
INELASTIC SPECTRUM ACQ. BUFFER
56
74
14
21
12
18
10
16
38
TELEMETERING AND CABLE INTERFACE CIRCUITS
44
REE PULSER
37
BUFFER MEMORY
PHA
TEMP. SENSOR
20
36
46
AMP
34
28
PM
24
26
XTAL
30
32
SHIELD
22
PULSED NEUTRON SOURCE
58
TEMPERATURE ACQ. BUFFER
INELASTIC STD. SPECTRA STORE
68
74
FILTER NETWORK
69
FILTER OPERATORS GENERATOR
70
SPECTRUM COMPARISON CIRCUITS
60
ω_c
ω_o
ω_{si}
ω_{Co}
72
TAPE PLOTTER
CARBON
OXYGEN
INELASTIC COUNTS
TEMP.
CALCIUM
SILICON

FIG. 1

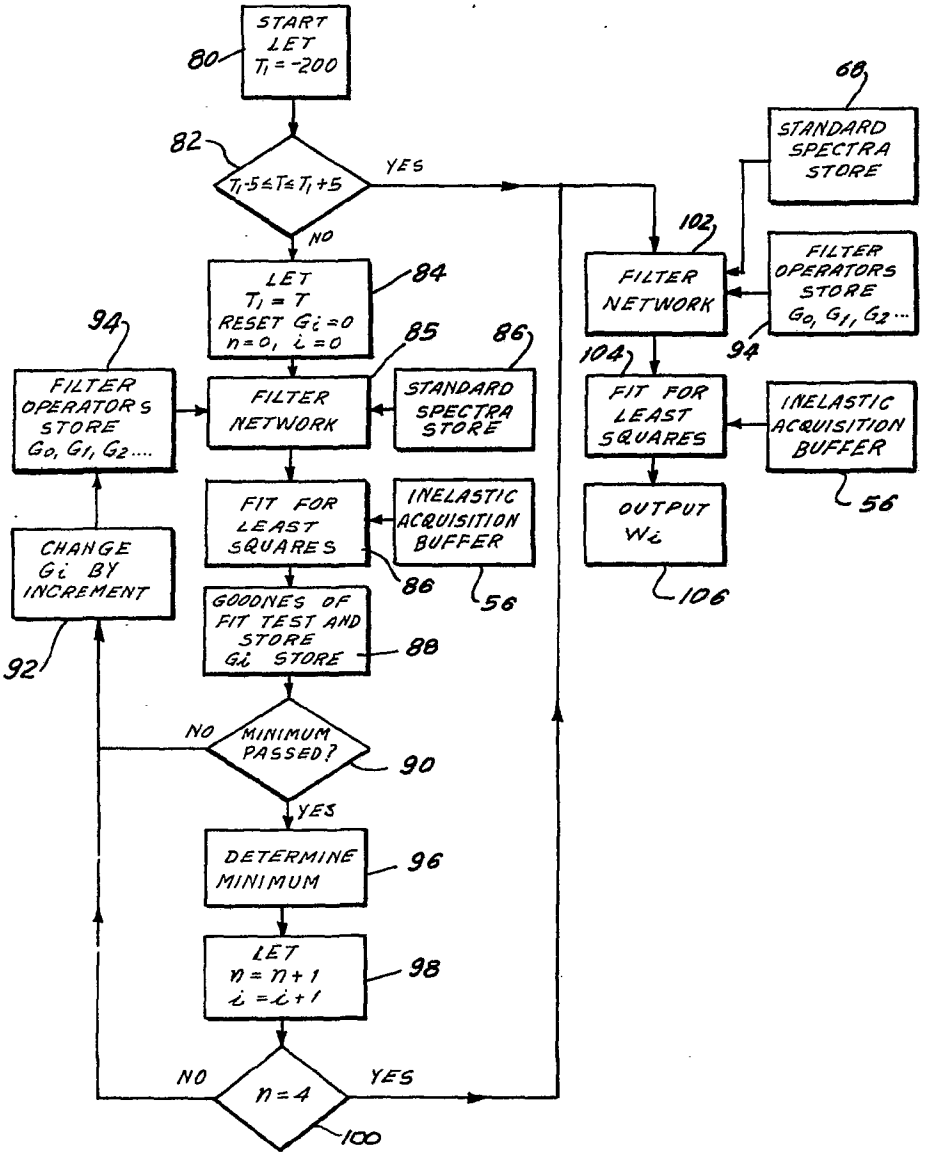
START
LET
$T_1 = -200$
80
82
$T_1 - 5 \leq T \leq T_1 + 5$
YES
NO
LET
$T_1 = T$
RESET $G_i = 0$
$n = 0$, $i = 0$
84
85
FILTER NETWORK
86
STANDARD SPECTRA STORE
94
FILTER OPERATORS STORE
$G_0, G_1, G_2 \ldots$
FIT FOR LEAST SQUARES
INELASTIC ACQUISITION BUFFER
56
86
CHANGE G_i BY INCREMENT
92
GOODNES OF FIT TEST AND STORE G_i STORE
88
NO
MINIMUM PASSED?
90
YES
DETERMINE MINIMUM
96
LET
$n = n + 1$
$i = i + 1$
98
NO
$n = 4$
YES
100
68
STANDARD SPECTRA STORE
102
FILTER NETWORK
FILTER OPERATORS STORE
$G_0, G_1, G_2 \ldots$
94
104
FIT FOR LEAST SQUARES
INELASTIC ACQUISITION BUFFER
56
OUTPUT W_i
106

FIG. 2

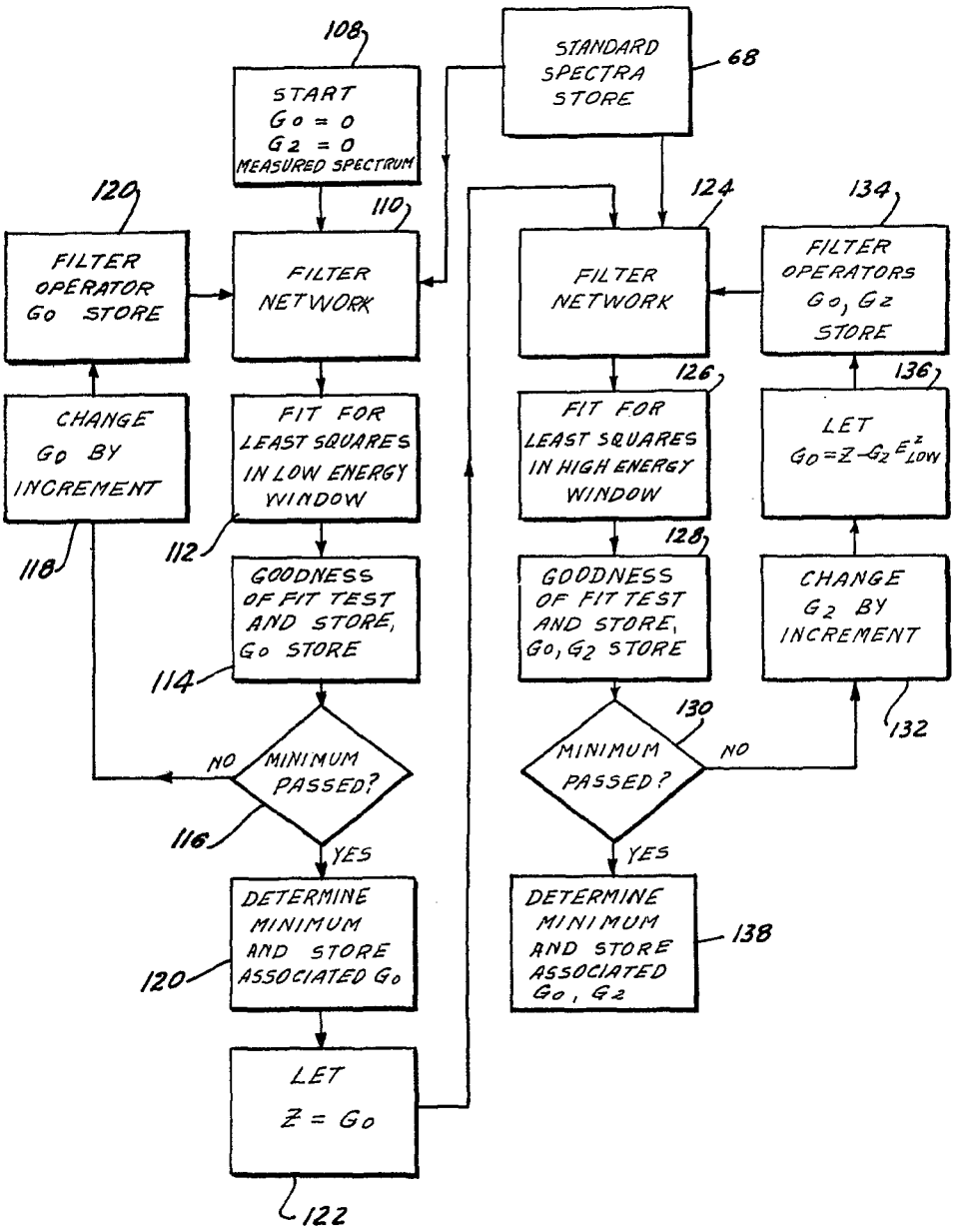
108
START
$G_0 = 0$
$G_2 = 0$
MEASURED SPECTRUM
STANDARD SPECTRA STORE
68
120
FILTER OPERATOR G_0 STORE
110
FILTER NETWORK
124
FILTER NETWORK
134
FILTER OPERATORS G_0, G_2 STORE
CHANGE G_0 BY INCREMENT
118
FIT FOR LEAST SQUARES IN LOW ENERGY WINDOW
112
126
FIT FOR LEAST SQUARES IN HIGH ENERGY WINDOW
136
LET $G_0 = Z - G_2 E^Z_{LOW}$
GOODNESS OF FIT TEST AND STORE, G_0 STORE
114
128
GOODNESS OF FIT TEST AND STORE, G_0, G_2 STORE
CHANGE G_2 BY INCREMENT
132
NO
MINIMUM PASSED?
116
130
MINIMUM PASSED?
NO
YES
YES
DETERMINE MINIMUM AND STORE ASSOCIATED G_0
120
DETERMINE MINIMUM AND STORE ASSOCIATED G_0, G_2
138
LET $Z = G_0$
122

FIG. 3

SPECIFICATION

Methods and apparatus for constituent analysis of earth formations

The present invention relates in general to nuclear well logging, and pertains in particular to improved methods and apparatus for analysing inelastic scattering gamma ray energy spectra to provide more accurate information of the composition of earth formations surrounding a well borehole.

Heretofore, various techniques have been utilized to process gamma ray energy spectra for formation constituent analysis. In the case of inelastic scattering gamma ray energy spectra, it is known that analysis of the spectra to identify the contributions thereto due to carbon and oxygen provides useful information of the presence of oil in a formation. Additional information concerning the composition of the formation, such as its lithology for instance, is however frequently required before an unambiguous determination of the presence of oil can be made. A suitable lithology indicator for this purpose might comprise the ratio of inelastic scattering gamma ray contribution for calcium and silicon.

The derivation of the foregoing information concerning carbon, oxygen, calcium and silicon, and possibly other constituents of the formation, depends upon accurate constituent analysis of the formation gamma ray spectra. An important and basic technique for performing such analysis is disclosed in U.S. Patent No. 3,521,064. In accordance with the teaching of this patent, a detected gamma ray energy spectrum for a formation of unknown composition is compared with a composite spectrum made up of weighted standard spectra of the constituents postulated to comprise the formation. The weight coefficients for the standard spectra which give the best fit of the composite spectrum to the unknown spectrum, as determined, for example, by the method of least squares, represent the relative proportions of the constituents in the formation. By appropriate selection of the standard spectra, the proportions of the constituents of interest, such as carbon, oxygen, calcium, silicon, etc., may be obtained, from which the desired information regarding oil content may be derived.

It has further been proposed in U.K. Patent Application No. 2,012,419 filed January 16, 1978, that a background energy spectrum be generated from gamma rays detected during periods between neutron bursts and be utilized to provide one or more standard background spectra for use in the analysis of the inelastic scattering gamma ray spectra. The standard background spectra are then updated on a repetitive basis to reflect the current background component in the detected inelastic scattering gamma ray spectrum. The measured inelastic spectrum is thereafter analysed by comparing it with a composite spectrum, made up of standard spectra of constituents, including the background spectra, postulated to comprise the formation, to determine the proportions in the formation of the postulated constituents.

The spectral standards, except for a background standard, as employed in the aforementioned application are generated illustratively, in known laboratory formations or test pits at standard conditions of temperature, pressure and detector resolution. The measured spectrum, on the other hand, is obtained in borehole wells having temperatures which vary from borehole to borehole as well as along the length of any one borehole. As a result of such temperature variations and the age of the detector crystal, the output of gamma-ray detectors employed in obtaining the measured spectrum is subject to variation and deterioration in resolution. For example, where a sodium iodide (NaI) detector is employed, the spectral resolution of the output is known to deteriorate (peak width increase) from a measured seven percent peak full width at half maximum (0.662 Mev) at 20°C (room temperature) to over ten percent peak full width at half maximum at 150°C.

Since the derivation of the foregoing information concerning constituents of the formation, depends upon accurate constituent analysis of the formation gamma ray spectra, the weight coefficients for the standard spectra which give the best fit of the composite spectrum to the unknown spectrum, e.g., as determined in accordance with the technique of the aforementioned U.S. Patent No. 3,521,064, will not, in effect, represent the relative proportions of the constituents in the formation if detector resolution is significantly different when the standard spectra are generated and when the measured spectrum is obtained.

According to one aspect of the invention, there is provided a method for investigating the composition of an earth formation traversed by a well bore through comparison of a measured spectrum of radiation received from the formation with standard spectra, said measured spectrum being observed by means including a detector, said standard spectra being related to constituents postulated to have contributed to said measured spectrum and generated by means including a detector, said method comprising the steps of a) deriving said measured spectrum, and b) comparing the standard spectra with the measured spectrum to obtain a satisfactory fit of the standard spectrum to a linear combination of the standard spectra, further comprising; prior to step b), modifying said standard spectra in a manner which reduces the difference between the detector resolution extant during detection of said measured spectrum and the detector resolution extant during generation of said standard spectra.

According to another aspect of the invention, there is provided apparatus for investigating the composition of an earth formation traversed by a well bore through comparison of a measured spectrum of radiation received from the formation with standard spectra, said measured spectrum being observed by means including a detector, said standard spectra being related to constituents postulated to have contributed to said measured spectrum and generated by means including a detector, said apparatus

comprising a) means for deriving said measured spectrum, b) means for comparing the standard spectra with the measured spectrum to obtain a satisfactory fit of the standard spectrum to a linear combination of the standard spectra, and c) means for modifying said standard spectra in a manner which reduces the difference between the detector resolution extant during detection of said measured spectrum and the detector resolution extant during generation of said standard spectra.

The invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1 is a diagrammatic representation of nuclear well logging apparatus in accordance with the present invention;

Figure 2 is a flow diagram useful for illustrating the operation of part of the apparatus of Figure 1; and

Figure 3 is another flow diagram useful for illustrating the operation of an alternative implementation of part of the apparatus of Figure 1.

In Figure 1, a representative embodiment of the invention includes a fluid-tight, pressure and temperature resistant well tool or sonde 10 that is adapted to be suspended in a well bore 12 by an armored cable 14 for investigating a subsurface earth formation 16. The well bore 12 is illustrated as cased, including the usual annulus of cement 18 and steel casing 20, and as containing a well fluid 21. Although no tubing is shown in the well bore, the tool if desired may be sized for through-tubing use. It will be understood that the invention has application also to open hole logging.

The sonde 10 includes a pulsed neutron source 22 and a radiation detector 24. The neutron source 22 is preferably of the accelerator type described in U.S. Patents No. 3,461,291 and No. 3,546,512. This type of neutron source is particularly adapted to generate discrete bursts of high energy or fast neutrons, e.g., at 14 MeV, of controlled duration and repetition rate.

The detector 24 may be of any construction appropriate to the detection, illustratively, of gamma rays and to the production of a pulse signal in response to each detected gamma ray having an amplitude representative of the energy detected gamma ray. Generally, such a detector includes a scintillation crystal 26 which is optically coupled to a photomultiplier tube 28. The crystal is preferably of the thallium-activated sodium iodide type, though other suitable crystal types such as thallium sodium-activated cesium iodide, may be used. Alternatively, a solid state detector, having for example a germanium crystal, might be employed. A neutron shield 30 may be positioned between the source 22 and the detector 24 to reduce bombardment of the detector by neutrons emanating directly from the source.

Electrical power for the sonde 10 is supplied through the cable 14 from a source of power (not shown) at the surface. Suitable power sources (not shown) are also included in the sonde 10 for the purpose of driving the neutron source 22, the detector 24 and other downhole electronics. The sonde 10 may be surrounded by a boron carbide impregnated sleeve 32 located generally in the region of the source 22 and detector 24. The sleeve 32 acts as a shield to minimize the detection of gamma radiation originating from neutron interactions in the immediate vicinity of the source and detector.

An amplifier 34 acts on the output pulses from the photomultiplier 28. The amplified photomultiplier pulses are thereafter applied to a pulse height analyzer (PHA) 36, which may be of any conventional type such as a single ramp (Wilkinson rundown) type. It will be understood to include the usual pulse height discriminators, for selection of the gamma ray energy range to be analyzed, and linear gating circuits, for control of the time portion of the detector signal train to be analyzed.

PHA 36 segregates the detector pulses into predetermined channels according to their amplitude and supplies signals in suitable digital form representing the amplitude of each analyzed pulse. The digital outputs of PHA 36 are stored in a buffer memory 37 and then transferred to telemetering and cable interface circuits 38 for transmission over cable 14 to the surface. At the surface, the cable signals are received by signal processing and cable interface circuits 40. It will be understood that the circuits 38 and 40 may be of any suitable known construction for encoding and decoding, multiplexing and demultiplexing, amplifying and otherwise processing the signals for transmission to and reception by the uphole electronics. Appropriate circuits are described, for example, in U.S. Patent No. 4,012,712.

The operation of the sonde 10 is controlled by signals sent downhole from a master programmer 42 located at the surface. These signals are received by a reference pulser 44 which, in response thereto, transmits control signals to the neutron source 22 and to the PHA 36.

Upon receipt of the reference pulses, the pulsing circuit generates a sharp fire pulse thereby causing the source 22 to emit a corresponding sharp burst of fast neutrons. For purposes of constituent analysis of inelastic scattering gamma ray spectra in accordance with the present invention, the neutron bursts are preferably of short duration, e.g. 18 microseconds, and are repeated at short intervals, e.g. every 100 microseconds, so as to provide satisfactory statistics in the spectrum analysis procedure.

The control signals transmitted from the reference pulser 44 to the PHA 36 enable the linear gating circuits of the PHA during at least two different time intervals in relation to each neutron burst, a first interval, an inelastic gate substantially coincident with the respective neutron bursts and the second interval a capture gate at a time between neutron bursts.

The detector pulses applied to the PHA 36 during the inelastic gate correspond predominantly to inelastic scattering gamma rays and the detector pulses applied to the PHA 36 during the capture gate

correspond predominantly to gamma rays resulting from neutron interactions other than inelastic scattering interactions. For the high burst-rate timing sequence usually employed the detector pulses generated during the capture gate will include components due to gamma rays produced by (1) thermal neutron capture of neutrons from preceding bursts and by (2) capture neutrons which are generated in the borehole environment by the slowing fast neutrons.

The sonde 10 further includes a temperature sensor 46 which may be of any construction appropriate to the detection of borehole temperatures and to the production of an output signal representative of such temperature. Advantageously, such sensor 46 supplies its output signal in suitable digital form to telemetering and interface circuits 38 for transmission over cable 14 to the surface.

The inelastic scattering gamma ray spectrum and the neutron capture gamma ray spectrum are generated by data acquisition buffers 56 and 57, respectively, which, under the control of the master programmer 42, accumulate the appropriate counts-per-channel signals from the signal processing and cable interface circuits 40. Additional buffers may be provided to accumulate other spectra, for example, two capture acquisition buffers may be provided, one to accumulate an epithermal capture spectrum and the other to accumulate a thermal capture spectrum. Specifically, the inelastic spectrum acquisition buffer 56 accumulates the inelastic scattering gamma ray counts-per-channel signals for a period long enough to give a statistically satisfactory spectrum, e.g., of the order of 18 microseconds, and is then instructed by the master programmer 42 to output the spectrum, recycle to zero, and accumulate a new spectrum for a like period. Similarly, the capture spectrum acquisition buffer 57 accumulates the capture gamma counts-per-channel data for a specified period. Where the capture spectrum is to be used as a standard in the analysis procedure for the inelastic scattering spectrum, it is desirable that the capture spectrum have greater statistical reliability than the inelastic spectrum. The counting time of the capture acquisition buffer 57 may therefore be longer than the counting time of the inelastic scattering acquisition buffer 56. For example, the accumulation time for the capture spectrum might be four times as long, e.g., of the order of 80 microseconds, as the accumulation time for the inelastic spectrum. Generally, the accumulation time for the capture spectrum should be selected to maintain the background spectrum as current as possible, while at the same time counting for a sufficiently long time to reduce statistical errors to permissible limits. It will be appreciated, therefore, that the background spectrum is repetitively updated as the sonde 10 is moved through the well bore, and thus automatically takes into account variations in such factors as sonde environment, sonde performance, source strength and the like which affect the shape of the capture spectrum.

A temperature acquisition buffer 48, also under the control of the master programmer 43, accumulates the temperature data from the signal processing and cable interface circuits 40. Desirably, the temperature data is accumulated on a continuous basis during the inelastic spectrum accumulation process and an average value associated with each measured inelastic spectrum provided as an output.

Following accumulation in the acquisition buffers 56, 57 and 58, the inelastic scattering spectrum, the capture spectrum and the average temperature value are transferred to storage buffers (not shown) in a circuit arrangement 60. The arrangement 60 may comprise a general purpose digital computer, such as the PDP—11 computer manufactured by the Digital Equipment Corporation, Maynard, Mass., or, alternatively, it may comprise an analog computer. In either event, it will be understood that the arrangement 60 is suitably constructed to perform the spectrum matching and constituent proportions determining functions described in the aforementioned U.S. Patent No. 3,521,064. In addition, the arrangement 60 includes circuits capable of carrying out certain spectrum processing and pre-analysis steps, as described hereinafter, preparatory to the analysis of the inelastic scattering spectrum.

Within the arrangement 60, storage buffers 68 provide output signals representing the previously obtained standard spectra which are applied, through a filter network 69, to the spectrum comparison circuits 70 for comparison with the inelastic scattering spectrum in the manner of U.S. Patent 3,521,064. Prior to inclusion in the standard spectra, the signals representing the capture spectrum where such spectrum is to be used for background correction, however, may be first applied to spectrum processing circuits for selectively carrying out a number of operations on the capture spectrum signals as described in the aforementioned U.K. Patent Application. Typically, the signals representing the capture spectrum are normalized to the same total count as the other standard spectra to be used in the comparison analysis of the inelastic spectrum. Where the capture spectrum is to be used directly as one of the standards, it will be appreciated that it is already "normalized" to the same detector resolution as the inelastic scattering spectrum, a transmittal path is provided therefore which by-passes the filter network 69.

As described in the aforementioned U.S. Patent No. 3,521,064, the signals representing the unknown inelastic scattering gamma ray spectrum, as accumulated in acquisition buffer 56, are compared with signals representing the weighted standard inelastic spectra to determine the proportions of the constituents which provide the combination; i.e., the composite spectrum, which most nearly matches the unknown inelastic scattering spectrum. This comparison is made in the spectrum comparison circuits 70. Preferably, the "lease squares" criterion is used to determine when a best fit has been obtained between the composite spectrum and the unknown spectrum. The weights (w_1) for the respective standard spectra which produce the best fit represent the proportions of the

corresponding constituents in the formation. As indicated in the drawing, the comparison circuits 70 generate the constituents weights (w_1) and transmit signals representative thereof to a recorder 72.

The recorder 72 includes the conventional visual and magnetic tape components for making the customary record of logging signals as a function of depth. The usual cable-following mechanical linkage 74 for driving the recorder 72 in synchronism with the cable 14 is provided for this purpose. Advantageously, suitable ratios of such constituent weights, e.g., the carbon/oxygen ratio and the calcium/silicon ratio, may be formed and recorded as a function of tool depth. The output signals from the signal processing and cable interface circuits 40 may also be recorded directly on tape in the manner indicated in the drawing for further processing and review.

In order to better understand the principles of the present invention represented in the accompanying drawing, detector resolution and factors affecting it will be presently examined in some detail.

The peak-full-width-at-half-maximum resolution (R) of a detector response at a given energy (E) and temperature (T) can be generally expressed as:

$$R(E,T)^2 = A_0(T) + A_1(T)E + A_2(T)E^2 + \ldots + A_n(T)E^n \quad (1)$$

where the coefficients A_i are temperature dependent constants that describe the detector resolution dependence on the incident gamma ray energy E. For any one particular detector, the coefficients A_i will also be dependent on the degradation of the resolution due to the age of the detector crystal. It will be appreciated that for a typical, undamaged detector at room temperature, only the first two terms of equation (1) will contribute significantly to the expression describing detector resolution.

Equation (1) provides a general expression for detector resolution with temperature dependency. The resolution of a given spectrum measured for example at T_o can be expressed as $(R(E,T)_o)$. It will be appreciated, however, that this expression of resolution becomes inadequate in describing detector resolution at other temperatures which differ significantly from T_o. Therefore, to derive an expression of detector resolution at temperatures which differ significantly from T_o, some filtering process which reflects the changes in resolution becomes desirable.

In the practices of the present invention, advantage is taken of the general Gaussian shape of the peaks of a detector measured spectrum to effect a convolution of the spectrum obtained at T_o by a Gaussian of resolution G(E, T) to produce a new spectrum at the new temperature (T) with a resolution given by the expression:

$$R(E,T)^2 = R(E,T_o)^2 + G(E,T)^2 \quad (2)$$

where

$$G(E,T)^2 = G_o(T) + G_1(T)E + G_2(T)E^2 + \ldots + G_n(T)E^n \quad (3)$$

and the coefficients G_i are temperature dependent constants.

Therefore, given a set of standard spectra measured by a detector and having respective spectra obtained at T_o by a detector having an output spectrum resolution expressed as $R(E,T_o)$, one is able to effect a modification of those spectra for any temperature condition through a filtering process which effects a Gaussian convolution of the obtained spectra. Of course, a determination of the appropriate values of the filter operators G_i becomes essential for effecting the desired modification.

The energy spectrum of any one of the standard spectra exists in a digital or analog computer as 256 contiguous channels, with the particular shape of the spectrum defined by the counts stored in locations corresponding to respective channels. This spectrum can be effectively degraded (i.e., broadened), by convoluting a broadening function with the stored spectrum. The broadening function is generally of the form

$$F(\Delta E, E, T) = \mathrm{EXP}\,((2.77\,\Delta E^2)/G(E,T)^2) \quad (4)$$

where ΔE is a variable energy interval defined over an integral number of contiguous spectral channels.

The new broadened spectrum is obtained from the following relationship:

$$S_{new} = \left(\sum^{\Delta E} S_{old}(E+\Delta E)\,F(\Delta E,E,T)\right)/\left(\sum^{\Delta E} F(\Delta E,E,T)\right) \quad (5)$$

where

$S_{new}(E)$ is the new average count rate in a spectral channel centered about the energy E;

$S_{old}(E+\Delta E)$ is the average count rate of the existing spectrum, in a spectral channel centered about the energy $E+\Delta E$; and

ΔE is an integral multiple of the channel width. The sum over ΔE in equation (5) includes all ΔE values for which $F(\Delta E, E, T)$ is greater than a given limit, such as 0.1.

With reference again to the drawing, circuit arrangement 60 represents one embodiment of the present invention. For purposes of illustration we may assume that a detected radiant energy spectrum conveyed from inelastic spectrum buffer 56 to spectrum comparison circuit 70 is to be analyzed for the formation constituents contributing thereto. We will further assume that this spectrum is measured by a detector of unknown resolution and at a given temperature T as provided to the spectrum comparison circuits 70 by the temperature acquisition buffer 58. Since this is an initial analysis of the measured spectrum, we may further assume that the filter operators generator 74 is in a reset state and therefore provides an output to filter network 69 such that the standard spectra provided from the inelastic standard spectra store 68 through filter network 69 to spectra comparison circuits 70 undergo no modification. In comparison circuits 70 the measured spectrum is compared with a composite spectrum made up of weighted standard spectra, as provided from the inelastic standard spectra store 68, of constituents postulated to comprise the formation. The weight coefficients (w_i) for the standard spectra which give the best fit, i.e., reduce the fit discrepancy of the composite spectrum to the measured spectrum, as determined, for example, by the method of least squares, provides one measure of the relative proportions of the constituents of the formation. It will be appreciated of course that one may then obtain a difference indication corresponding to the fit discrepancy between the measured spectrum and the composite spectrum. This difference indication is thereafter compared with a value chosen as being satisfactory for the spectral analysis process. If the difference indication is of a magnitude which is larger than that chosen value then an output of the spectrum comparison circuits 70 is applied to the filter operators generator 74 so as to generate filter operators representing the effects of detector resolution degradation on an obtained spectrum. The generation of these filter operators will be subsequently discussed in more detail. For purposes of the present discussion, it will be sufficient to note that the output of filter operators generator 74 when applied to filter network 69 effects a modification of the standard spectra passing through the filter network from the inelastic standard spectra store 68 to the spectrum comparison circuits 70. It will be appreciated therefore, that after the generation of these operators spectrum comparison circuits 70 will receive a new set of standard spectra which are modified to reflect detector resolution changes. This new set of spectra is then employed, in spectrum comparison circuits 70, in the constituent analysis process to provide yet another set of weight coefficients for the modified standard spectra as a measure of their relative proportions of the constituents of the formation. A difference indication between this new composite spectrum and the measured spectrum can then be obtained and compared to the chosen value. It will be appreciated then that this process, of generating modified standard spectra is further repeated until a set of weight coefficients for a particular modification of the standard spectra is found which gives the best fit of the composite spectrum to the measured spectrum, i.e., the difference indication for that particular set of standard spectra is less than the chosen value. This set of weight coefficients then represents a measure of the relative proportions of the constituents in the formation which is adjusted for variations in detector resolutions between the measured spectrum and the standard spectra. These weight coefficients are thereafter provided as an output from the spectrum comparison circuits and applied to the recorder 72.

As discussed above, the degradation in resolution of a spectrum measured by a crystal is dependent on the energy of the incident radiation; i.e., the degradation response is dependent on energy. Furthermore, this energy dependency is not fixed for any one crystal but is further subject to variations as a function of temperature and the age of the crystal. It will be appreciated, therefore, that knowledge of a particular energy dependency of the resolution of a crystal at a given temperature and time in the life of the crystal, is of little use when either the temperature or the age of the crystal changes. Therefore, it is incumbent, for a more accurate analysis of formation constituents, in accordance with the practices of the aforementioned U.S. Patent No. 3,521,064, that spectral shapes of the standard spectra reflect a detector resolution which is relatively close to the detector resolution extent when the measured spectrum is obtained.

Filter operators G_i, which in effect, determine the extent of spectral broadening and the energy dependence of such broadening, may be generally determined by sequentially, upon a command from the spectrum comparison circuits to the filter operators generator 74, changing one of the filter operators while holding the other of the filter operators constant and performing a minimum chi-square search for the optimum set of operators which reduces the difference between the measured spectrum and a composite spectrum formed of weighted, modified standard spectra. Obviously, this process is relatively time consuming since it depends on the sequential changing of the operators and often requires that the whole process be repeated for each filter operator until the difference between the measured spectrum and the best modified composite spectrum is less than a given desirable value. This process will have to be further repeated for significant changes in temperatures to which the detector is subjected during measurement intervals in which the radiation spectrum is obtained.

Once these filter operators are obtained, it will be appreciated that, for a given temperature range, for example $\pm 5°C$, these same filter operators will effect the desired normalizations of the spectral standards with respect to the measured spectrum. Should be sonde temperature, as communicated by buffer 58, during a measurement interval exceed the temperature range of the previously determined set of filter operators, a new set of operators is generated by the above mentioned process. Basically,

the spectrum comparison circuits 70 include means for determining an initial temperature range and for modifying that temperature range whenever the temperature at which a new spectrum is measured differs from the limits set for that range. Once a new spectrum is measured at a temperature T_2 which differs from the limits previously defined, e.g., $T_1 + 5°C$, $T_1 - 5°C$, the spectrum comparison circuits 70 provide an output to filter operators generator 74 to effect generation of a new set of filter operators which will effect, in network 69, the desired "normalization" between the measured spectrum and the standard spectra. These operators remain unchanged for all subsequent spectra measured at temperatures T which are within the limits $T_2 + 5°C$, $T_2 - 5°C$.

In order to avoid the time consuming process of determining filter operators for the normalization process outlined above, the appropriate set of filter operators, which provides the desired normalization of the standard spectra, comprising a linear combination of coefficients, associated with respective, monotonically increasing functions of the energy of the incident gamma rays which modify the standard spectra, may be determined by examining only two of the filter operators, a first one not associated with any energy dependence and a second one associated with a term corresponding to the square of the incident gamma ray energy. An initial set of filter operators which modify the standard spectra, is determined by varying only the first coefficient and performing a minimum chi-square search for the optimum filter operators over a low energy portion or window of the measured spectrum. These low and high windows have width of the order of 30 and 80 channels respectively and are therefore small relative to the width of the whole measured spectrum. This initial set of filter operators is thereafter finalized by varying the second coefficient and performing yet another minimum chi-square search for the optimum filter operators over a high energy portion of the measured spectrum. During this second search operation care is taken to ensure that the finalized set of filter operators provide the same or similar modification result for the standard spectra over the low energy portion of the spectrum as did the initial set of filter operators, for example, by varying the first coefficient.

The optimum filter operators generated for the analysis of a particular measured spectrum are, thereafter, employed for the analysis of subsequent measured spectra over an interval of the well borehole where changes in temperature do not exceed certain limits. Where changes in temperature exceeding the certain limits are detected during spectrum measurement, a new set of filter operators is generated, as discussed above, so as to improve the accuracy of the earth formation constituent analysis process.

With reference now to Fig. 2, a simplified flow diagram is shown as illustrative of the operations performed within arrangement 60, in accordance with one embodiment of the present invention. These operations consist mainly of three major paths. A first path reflects the search of filter operators, G_0, G_1, G_2 . . . etc. which provide for a minimum chi-square fitting of a modified composite spectrum to a measured spectrum. A second path effects a search for weight coefficients which provide for a least squares fitting of a measured spectrum to a composite spectrum formed from standard spectra modified in accordance with a filtering process dependent on the filter operators derived in the first path. And finally, a third path which bypasses the first path wherever certain temperature conditions are met.

At the start of operations at 80, it will be appreciated that values for the filter operators correspond to zeros so that operations of filter network 69 will effect no modification of the standard spectra. Also an initial temperature T_1, illustratively, $-200°C$, is chosen so as to assure that the first cycle of operations is conducted thru the first path. Therefore, when at 82 the temperature T of the borehole at a given depth corresponding to that at which a measured spectrum is obtained is compared to a range of temperatures, $T_1 - 5°C$ to $T_1 + 5°C$, it will clearly fall without that range. The following step at 84 designates T_1 equal to T and resets all filter operators G_i, variables i and n equal to zero. Variable i is the subscript of the filter operators and identifies the correspondence of the operator to an incident energy term E which is raised to the power i. The variable n corresponds to the total number of operators to be considered, it being appreciated that the term n may be as large as is desired even though in practice only the first three terms G_0, G_1 and G_2 significantly contribute to the spectra modification process. The filtering process at 85 operates on the standard spectra from store 68, which in this initial cycle will pass through the filtering process unmodified. Subsequently, the measured spectrum from buffer 56 will be compared at 86 with a composite spectrum made up of weighted spectra of constituents postulated to have contributed to the measured spectrum in accordance with the aforementioned U.S. Patent No. 3,521,064. Thereafter, at 88 a measure of the goodness of fit between the composite and measured spectra is derived and stored along with the filter operator subject to variation, in this case G_0. At 90, the goodness of fit derived at 88 is observed to determine whether or not it has passed through a minimum. Since this is the first cycle of operation, the filter operators generator will incrementally change G_i, i.e., in this case G_0, at 92, store this value at 94, and apply the "new" set of operators to filter 85. Of course, this time around when the standard spectra from store 68 are convoluted in filter 85 so as to be modified in accordance with set of filter operators, the result of least squares fitting at 86 and the goodness of fit measure at 88 will be different from that previously obtained.

Once the goodness of fit measure passes through a minimum, that minimum is determined at 96 by means of well known techniques such as by fitting a parabola through the points defining the pass

through the minimum and then determining the minimum of the parabola. The G_0 associated with such minimum is then stored at 94. Thereafter, n and i are incremented at 98 and the process is sequentially repeated through the first path for G_1, G_2 and G_3 and these values stored in their respective terms at 94. It will be appreciated that when n equals 4 this will signify that all the operators needed for the filtering process have been determined. Therefore at 100 the process is continued through the second path through a filter 102 which effects a modification of the standard spectra from store 68 by convoluting the spectra with a function determined from the output of filter operators store 94, i.e., G_0, G_1 and G_2. A composite spectrum formed of weighted, modified standard spectra is then compared to the measured spectrum from buffer 56 to provide a least squares fit therebetween. The weights w_i, of the standard spectra which provide the best fit of the composite spectrum to the measured spectrum is thereafter provided as an output at 106 which output may be supplied to a recorder or plotter such as 72 in Fig. 1.

For subsequent measured spectra having associated temperatures T within $\pm 5°C$ of the previous measured spectrum, it may be safely assumed that the already determined filter operators will provide the desired modification of the standard spectra. Therefore, the process bypasses the first path and directly passes through the filter at 102, the least squares fitting at 104 to the output at 106. Where the temperature of the measured spectrum exceeds that of the previously determined limits, the filter operators will have to be determined anew by the method outlined above with reference to the first path.

With reference now to Fig. 3, a simplified flow diagram illustrates yet another embodiment of the present invention which simplifies the process of obtaining filter operators, i.e., the first path illustrated in Fig. 2, which would effect the desired modification of the standard spectra. In this embodiment only portions of the measured spectrum are employed in the determination of the operators, mainly a low energy window from 1.59 MeV to 2.55 MeV and a high energy window from 5.73 MeV to 7.33 MeV. Moreover, in accordance with this embodiment not all of the operators need be determined. Illustratively, only two operators G_0 and G_2 or G_0 and G_1, may be sufficient for effecting the desired modification of the standard spectra. Of course, more than two operators may be needed and this illustration of the embodiment of the invention is not intended to limit the practice of the invention to any selection of operators. We will assume, for purposes of illustration, that the two operators to be determined are G_0 and G_2. Initially at 108 G_0 and G_2 are set equal to zero so as not to effect any modification of the standard spectra when such spectra is convoluted in filter network 110. At 112 the portion of the spectrum in the low energy window is compared with a composite spectrum formed of weighted spectra of constituents postulated to have contributed to the measured spectrum. Thereafter, at 114 a measure of the goodness of fit between the measured spectrum and the composite spectrum is determined and stored along with the associated G_0. At 116 this measure of the goodness of fit is monitored for indications that it has passed through a minimum. If it has not passed through a minimum, G_0 is incrementally changed at 118 and the new value stored at 120 where it is supplied to filter network 110. This process is repeated, as discussed with reference to Fig. 2, until the measure of the goodness of fit passes through a minimum. This minimum is then determined at 121 as previously discussed and a quantity Z is set equal to G_0 at 122. The process is then repeated for the determination of G_2 in the high energy window of the measured spectrum. Filter network 124, the least squares fitting step at 126, the measure goodness of fit derivation at 128, the passage through a minimum test at 130, the incremental changes of G_2 at 132 and the filter operator stored at 134, correspond to their counterparts discussed in reference to the determination of G_0 and will not be further discussed. However, it will be appreciated that since the desired filter operators should provide the same or similar modification of the standard spectra for the low energy window as the G_0 determined at 120, i.e., Z, a new G_0 is determined at 136 from the relationship:

$$G_0 = Z - G_2 E^2_{Low}$$

Where E_{Low} is the energy at the mid point of the low energy window.

Once a G_2 has been determined, i.e., the G_2 associated with a goodness of fit measure which is at a minimum, the associated G_0 will also be readily identified. These filter operators may then be stored at 138 and further employed in the determination of the formation constituents in accordance with the process discussed above and shown in the second path of Fig. 2.

Although the invention has been described herein with reference to a specific embodiment, many modifications and variations therein will readily occur to those skilled in the art. For example, the gamma ray energy spectrum analysis of the present invention may be carried out by comparison of gamma ray spectra obtained in other ways than by inelastic scattering of fast neutrons, such as those produced by thermal or epithermal neutron capture, or by other ways than by neutron irradiation such as natural gamma ray spectra. Accordingly, all such variations and modifications are included within the intended scope of the invention as defined by the following claims.

CLAIMS

1. A method for investigating the composition of an earth formation traversed by a well bore through comparison of a measured spectrum of radiation received from the formation with standard

spectra, said measured spectrum being observed by means including a detector, said standard spectra being related to constituents postulated to have contributed to said measured spectrum and generated by means including a detector, said method comprising the steps of a) deriving said measured spectrum, and b) comparing the standard spectra with the measured spectrum to obtain a satisfactory fit of the standard spectrum to a linear combination of the standard spectra, further comprising: prior to step b), modifying said standard spectra in a manner which reduces the difference between the detector resolution extant during detection of said measured spectrum and the detector resolution extant during generation of said standard spectra.

2. The method of claim 1, wherein said standard spectra modifying step comprises the steps of:

— generating a set of filter operators and modifying said standard spectra by said filter operators so as to provide a set of filtered standard spectra;

— generating a composite spectrum made up of weighted, filtered standard spectra using weights chosen to provide the best fit between the composite spectrum and the measured spectrum;

— comparing the measured spectrum and the composite spectrum to provide a difference indication corresponding to the fit discrepancy between the measured spectrum and the composite spectrum; and

— repeating said set of filter operators generating step, said composite spectrum generating step, and said comparing step for a plurality of different sets of filter operators to identify an optimum set of filter operators associated with a difference indication having a magnitude which is as small as possible.

3. The method of claim 2, further comprising the steps of:

— obtaining an indication of the temperature of the formation associated with said measured spectrum; and

— effecting said set of filter operators generation step, said comparing step and said repeating step only where said obtained temperature indication differs by more than a chosen amount from an indication of temperature associated with a preceding measured spectrum for which an optimum set of filter operators has been identified.

4. The method of claim 1, wherein said standard spectra modifying step comprises the steps of:

— performing a first search over an energy independent operator, said search minimizing chi-square calculated over a low energy portion of the measured spectrum to generate and initial set of filter operators; and

— performing a second search over an operator dependent on the square of the energy, said second search minimizing chi-square calculated over a high energy portion of the measured spectrum to generate a final set of filter operators, said second search insisting that the finalized set of filter operators provide the same modification result over the low energy portion of the spectrum as the initial optimum set of filter operators.

5. The method of claim 4, further comprising the steps of:

obtaining an indication of the temperature of the formation associated with said measured spectrum; and

effecting said set of filter operators generation steps only where said obtained temperature indication differs, by more than a chosen value, from an indication of temperature associated with a precedent measured spectrum for which an optimum set of filter operators has been identified.

6. Apparatus for investigating the composition of an earth formation traversed by a well bore through comparison of a measured spectrum of radiation received from the formation with standard spectra, said measured spectrum being observed by means including a detector, said standard spectra being related to constituents postulated to have contributed to said measured spectrum and generated by means including a detector, said apparatus comprising a) means for deriving said measured spectrum, b) means for comparing the standard spectra with the measured spectrum to obtain a satisfactory fit of the standard spectrum to a linear combination of the standard spectra, and

c) means for modifying said standard spectra in a manner which reduces the difference between the detector resolution extant during detection of said measured spectrum and the detector resolution extant during generation of said standard spectra.

7. The apparatus of claim 6, wherein said means for modifying said standard spectra comprises:

— means for generating a set of filter operators and modifying said standard spectra by said filter operators so as to provide a set of filtered standard spectra;

— means for generating a composite spectrum made up of weighted filtered standard spectra using weights chosen to provide the best fit between the composite spectrum and the measured spectrum;

— means for comparing the measured spectrum and the composite spectrum to provide a difference indication corresponding to the fit discrepancy between the measured spectrum and the composite spectrum; and

— means for repeating said set of filter operators generation, said composite spectrum generation, and said comparison for a plurality of different sets of filter operators to identify an optimum set of filter operators associated with a difference indication having a magnitude which is as small as possible.

8. The apparatus of claim 7, further comprising:

— means for obtaining an indication of the temperature of the formation associated with said measured spectrum; and

— means for enabling said set of filter operators generation means only where said obtained temperature indication differs by more than a chosen amount from an indication of temperature associated with a preceding measured spectrum for which an optimum set of filter operators has been identified.

9. The apparatus of claim 6, wherein said standard spectra modifying means comprises:

means for performing a first search over an energy independent operator, said search minimizing chi-square calculated over a low energy portion of the measured spectrum to generate an initial set of filter operators; and

means for performing a second search over an operator dependent on the square of the energy, said second search minimizing chi-square calculated over a high energy portion of the measured spectrum to generate a final set of filter operators said second search insisting that the finalized set of filter operators provide the same modification result over the low energy portion of the spectrum as the initial optimum set of filter operators.

10. The apparatus of claim 9, further comprising:

means for obtaining an indication of the temperature of the formation associated with said measured spectrum; and

means for effecting said set of filter operators generation steps only where said obtained temperature indication differs, by more than a chosen value, from an indication of temperature associated with a precedent measured spectrum from which an optimum set of filter operators has been identified.

11. A method of investigating an earth formation, the method being substantially as herein described with reference to Figure 1 of the accompanying drawings.

12. A method of investigating an earth formation, the method being substantially as herein described with reference to Figures 1 and 2 of the accompanying drawings.

13. A method of investigating an earth formation, the method being substantially as herein described with reference to Figures 1 and 3 of the accompanying drawings.

14. Apparatus for investigating an earth formation, the apparatus being substantially as herein described with reference to Figure 1 of the accompanying drawings.

15. Apparatus for investigating an earth formation, the apparatus being substantially as herein described with reference to Figures 1 and 2 of the accompanying drawings.

16. Apparatus for investigating an earth formation, the apparatus being substantially as herein described with reference to Figures 1 and 3 of the accompanying drawings.

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