

March 13, 1962

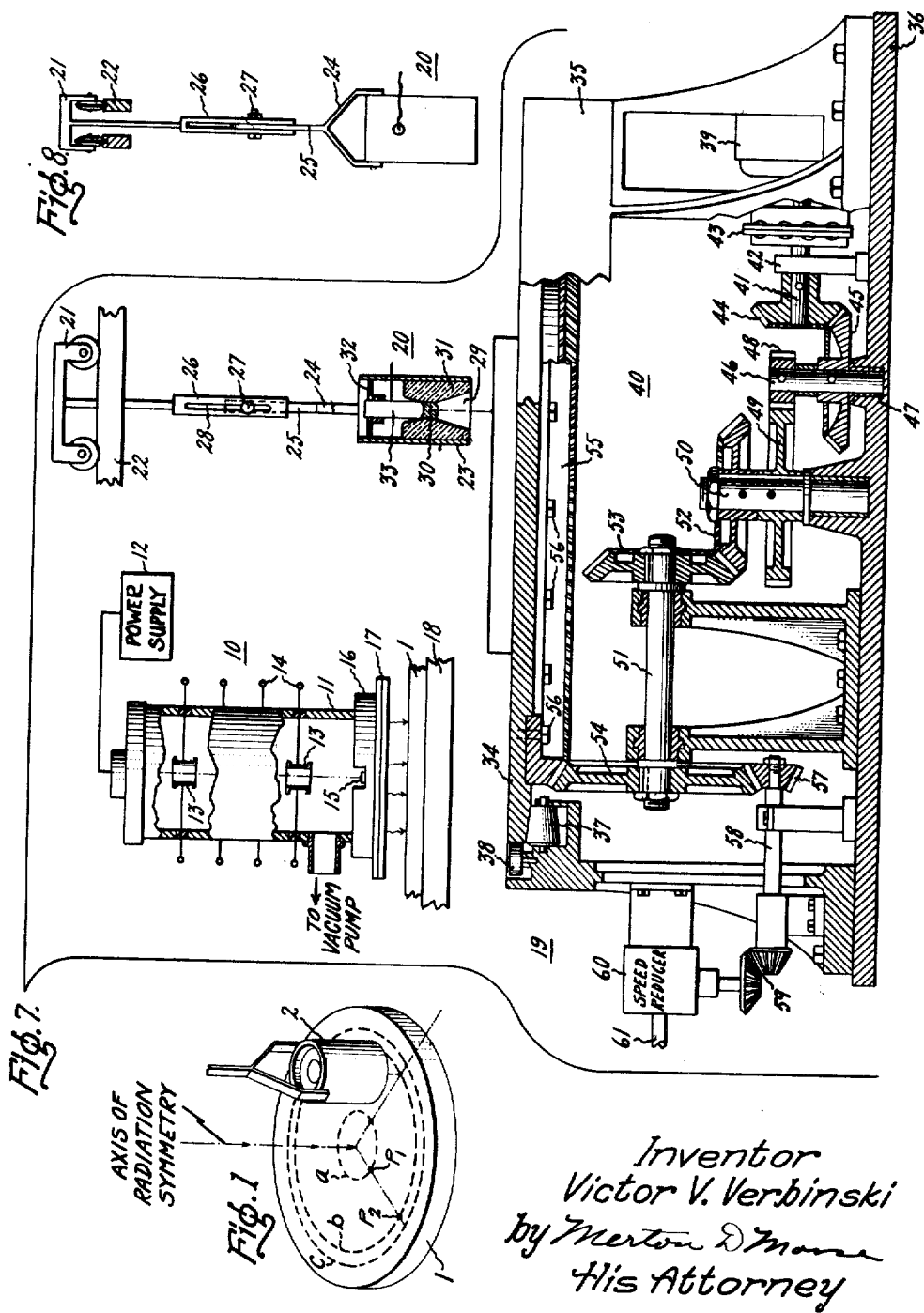
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3,025,399

FLAW DETECTION

Filed Oct. 31, 1958

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Fig. 4.

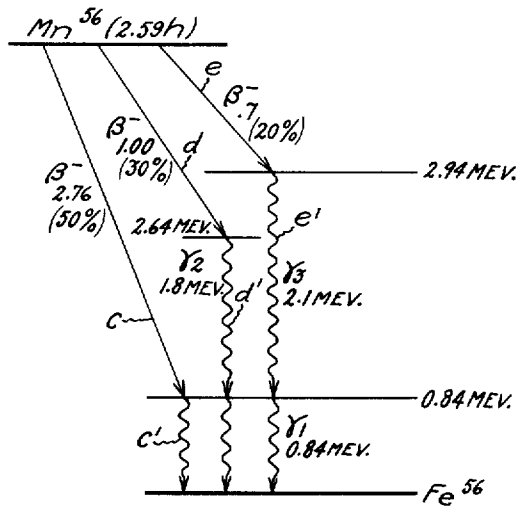
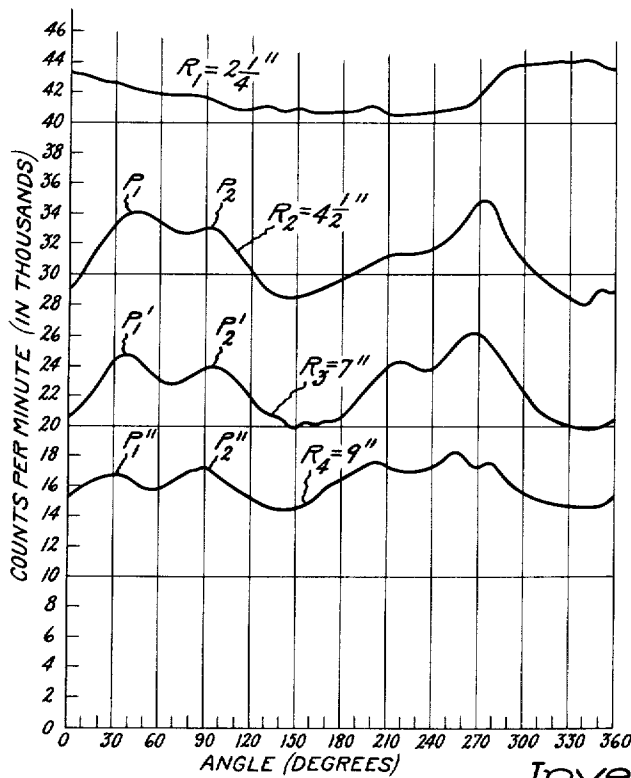


Fig. 2.



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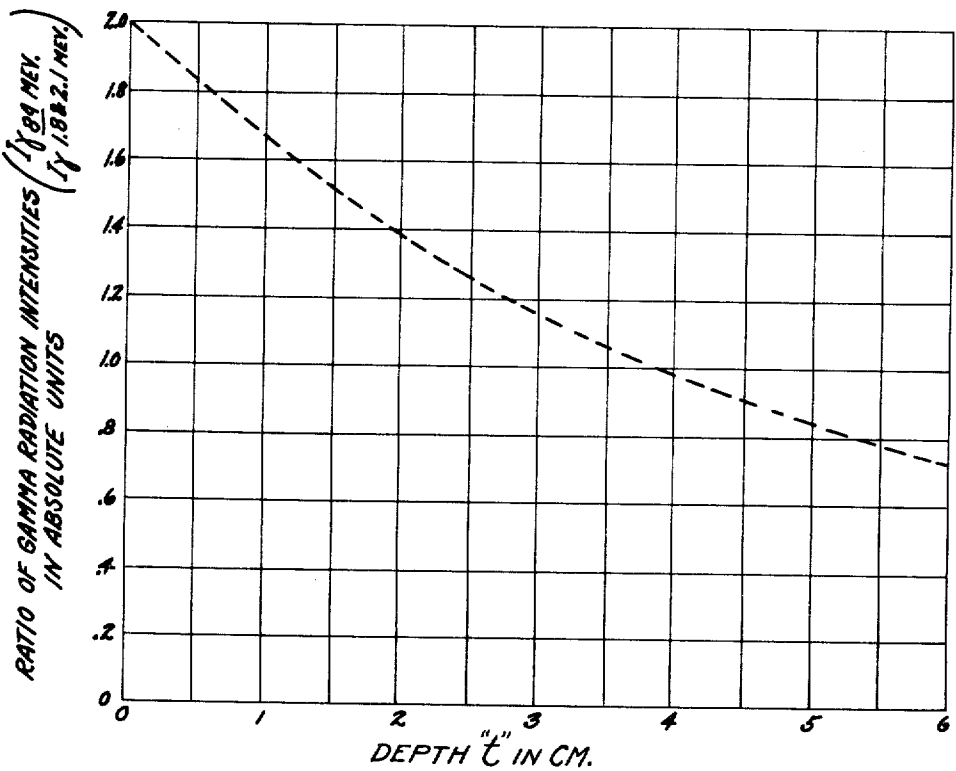
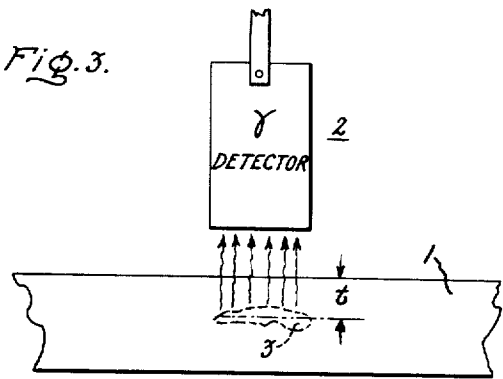


Fig. 6.

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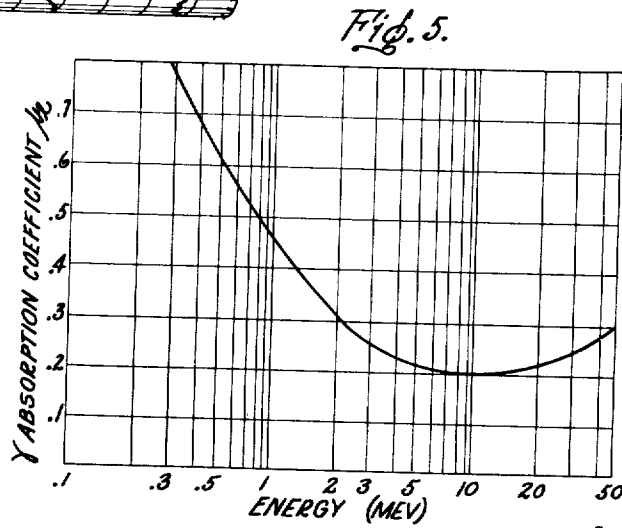
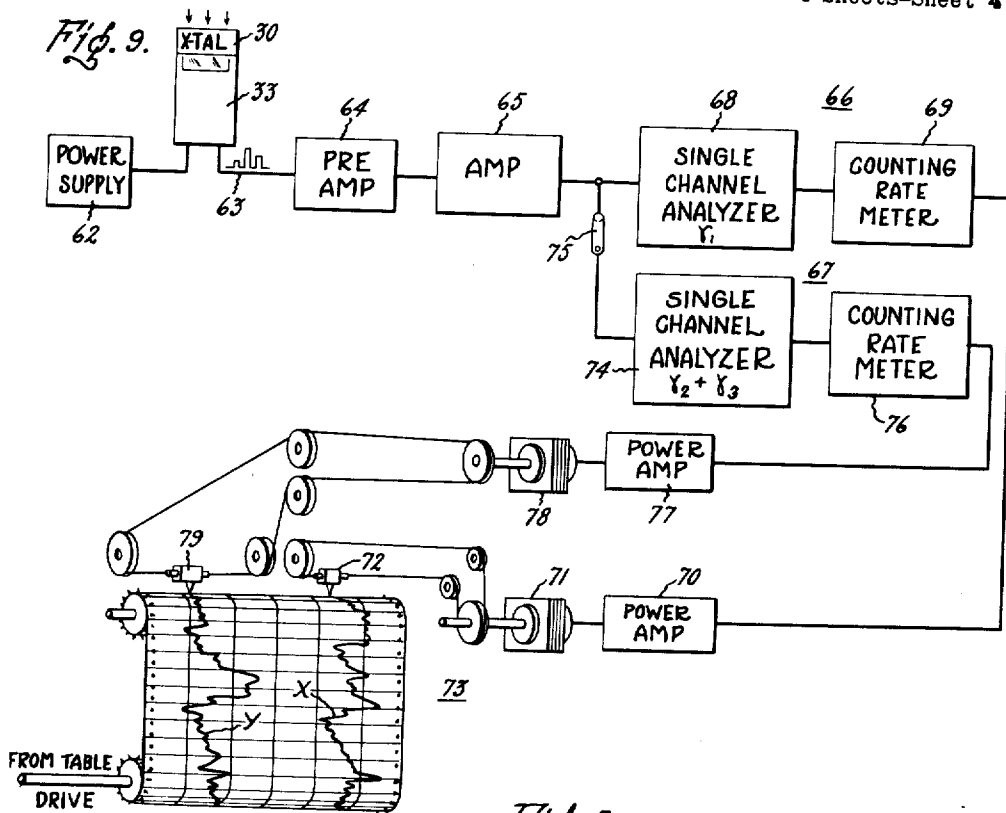
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4 Sheets-Sheet 4



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FLAW DETECTION

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Filed Oct. 31, 1958, Ser. No. 771,118
8 Claims. (Cl. 250-83.3)

This invention relates to a non-destructive test method for locating material flaws, and more particularly, flaws characterized by inhomogeneous inclusions of an element of a mixture.

Many of the physical characteristics of a metallic alloy such as manganese steel, for example, are significantly affected by the manner in which a constituent element, such as manganese, is distributed. Hence, information about the manner in which the constituent elements of an alloy are distributed is of great importance in evaluating the performance of the alloy under load. The need for such information is especially acute where the material is used in an environment in which it is subject to large static or vibratory stresses since any inhomogeneous concentration of the element is a structural weakness which may result in failure under load conditions.

The importance of the problem can be easily understood in connection with rotating machine elements such as generator rotors, steam turbine rotors, etc., which are often fabricated of manganese steel alloys containing a given percentage of manganese ostensibly distributed homogeneously throughout the steel. Often, however, the manganese is not homogeneously distributed but contains randomly distributed manganese inclusions. The presence of such manganese inclusions may be considered a structural flaw in the rotating element although no actual physical discontinuity may exist. Under condition of high rotational speeds and vibration such inclusions may cause the element to rupture or fail in operation. Hence, it is desirable to test the steel before fabrication to obtain information about the presence and the location of such inclusions without destroying the material in the course of testing.

Recent investigations have shown that information about the homogeneous distribution of an element such as manganese in a steel alloy may be obtained by subjecting the steel specimen to a nuclear or charged particle flux in such a manner that the manganese in the steel is activated in a symmetrical manner about some arbitrary axis of the specimen. The manganese is thus converted into a radioactive isotope which emits beta and gamma radiations having discrete energy levels characteristic of the isotope. By measuring the intensity of these gamma radiations along various paths of the activated specimen and noting the variations in said intensity, information relating to the content and distribution of the manganese in the steel may be obtained. Such a non-destructive method for determining the homogeneity of a mixture such as manganese steel is disclosed in an application entitled "Homogeneity Measurement," Serial No. 771,119, W. W. Schultz, filed October 31, 1958, concurrently with the instant application and assigned to the assignee of this application.

However, when a manganese inclusion is detected in the manner described in the above identified application, it is also desirable to learn as much as possible about the extent of this inclusion, and particularly the depth and location of such an inclusion below the surface of the specimen, in order to establish more meaningful criteria for evaluating such a specimen. To provide a non-destructive test method for determining the location and depth of such inclusions is the purpose of the instant invention.

Accordingly, it is an object of this invention to pro-

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vide a method and apparatus for determining the location and depth of an inclusion in a solid mixture of materials.

A further object of this invention is to provide a non-destructive method for determining the location and depth of an inclusion which utilizes radioactive techniques.

Yet another object of this invention is to provide a non-destructive method for determining the location and depth of manganese inclusions in a manganese steel alloy.

A still further object of this invention is to provide a non-destructive method for determining the depth of an inclusion by means of radioactive techniques which is independent of absolute values of the radioactivity.

Other objects and advantages of this invention will become apparent as the description thereof proceeds.

To carry out the novel method, a specimen of the mixture, such as the manganese alloy referred to above, is irradiated by a neutron or charged particle flux in such a manner that the elements, and particularly the manganese, of the specimen are symmetrically activated, i.e., made radioactive, about some arbitrary axis of the specimen. The activated elements emit characteristic radiations of different energy levels and in known proportions. Thus in the case of manganese, gamma radiations of three distinct, discrete energy levels (0.84 mev., 1.8 mev., and 2.1 mev.), are emitted. Furthermore, the individual gamma radiations of different energy levels are emitted in a known proportion with twice as many 0.84 mev. gammas being emitted as 1.8 and 2.1 mev. gammas combined. Similarly, for elements other than manganese the energy of the characteristic radiations as well as their proportions are characteristic of and particular to the isotope produced therefrom.

Because of the symmetric nature of the specimen activation, the intensity of the total radiation from the radioactive elements is proportional to the content of that element along any given path which has been uniformly activated. By detecting the magnitude of the radiation along a number of such paths, variations in the content of one or more of the constituent elements over the entire mixture may be determined from the variations in the radiation intensity. Once an inhomogeneity or inclusion has been located by noting the variation in radiation intensity, information about the location and depth of such an inclusion may be obtained by noting the change in the relative proportions of the individual gamma radiations of different energy levels. That is, the rate at which the gamma radiations from an inclusion located below the surface of the specimen are absorbed or attenuated in the specimen varies not only with the depth of the inclusion but also with the energy level of the radiation. Hence, the lower energy radiations will be absorbed faster than the higher energy radiations and the proportionate amounts of these radiations appearing at the surface of the specimen varies with thickness. Since the proportionate amount of these radiations emitted from the inclusion is known, the change in proportion at the surface of the specimen provides a measure of the depth of the inclusion.

The novel features which are believed to be characteristic of this invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in which:

FIGURE 1 is a perspective view of an irradiated specimen illustrating the paths of activation symmetry;

FIGURE 2 is a graph illustrating variations in total radiation intensity and is useful in carrying out the method of the invention;

FIGURE 3 is a schematic illustration of a test speci-

men and an inclusion therein and is useful in understanding the method of the invention;

FIGURE 4 is a diagram illustrating the decay scheme of a manganese radioactive isotope showing the diverse emitted gamma radiations as well as the proportionate amounts thereof;

FIGURES 5 and 6 are curves useful in understanding the invention;

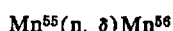
FIGURE 7 shows a preferred embodiment of a portion of an instrumentality for carrying out the novel methods;

FIGURE 8 is an end view of the radiation detector mounting illustrated in FIGURE 7;

FIGURE 9 is a schematic block diagram of a circuit connected to the output of the radiation detector of FIGURE 7.

The distribution of the constituent elements throughout a mixture and the location and depth of any inclusion may be determined without destroying the test specimen by rendering one of the constituent elements radioactive and detecting the intensity and distribution of the characteristic radiations emitted by the radioactive elements. As disclosed in the above identified Schultz application, a specimen of a mixture of elements such as a manganese alloy, is exposed to a neutron flux converting the manganese, by a neutron induced reaction, into a radioactive isotope of the manganese. In decaying, the isotope emits, among other radiations, gamma rays having discrete and distinct energy levels characteristic of the manganese isotope. This process of forming the radioactive isotopes by irradiation is commonly known as neutron activation and the elements rendered radioactive are referred to as activated elements.

Thus, if the manganese steel alloy is subjected to a thermal neutron flux, that is, one composed of neutrons having energies of the order of one fortieth ($\frac{1}{40}$) of an electron volt, the manganese, and particularly the naturally occurring stable isotope manganese 55, in the alloy is converted by the neutron induced reaction:



to the radioactive isotope manganese 56 which has a half life of 2.59 hours and decays to the stable isotope iron 56 (Fe^{56}) with the emission of beta particles as well as gamma rays of three discrete energy levels, i.e., 0.84, 1.8 and 2.1 million electron volts (mev.) respectively. However, in order to obtain meaningful information from the radiation intensities of these gamma radiations, it is necessary that the specimen is activated symmetrically so that the degree of activation along a given path is constant and the characteristic radiations emanating from the activated elements along any such path is a measure of the element content.

Merely placing a specimen to be tested in a neutron flux will under normal circumstances not produce the desired symmetric irradiation since, as a practical matter, the distribution of a neutron flux is normally neither constant nor symmetrical. As a result, the specimen is not activated uniformly or symmetrically. This introduces ambiguities into the radiation intensity readings, since it cannot be determined whether the variations in the radiation intensities are due to a variation in the content of the element or a variation in the degree of activation.

A preferred manner of irradiating the specimen to produce the symmetrical activation is by producing relative rotational movement between the activating neutron flux and the specimen. Thus, even if the neutron flux distribution is neither symmetrical nor constant, any path on the specimen symmetric about the axis of rotation is subjected to an average flux which is constant over the path. Consequently, the activation of the specimen is symmetric about the axis of rotation and the intensity of the characteristic radiations emitted by the activated element of the specimen along any such path is proportional

to the content of the element and provides an indication of any inhomogeneities or inclusions.

FIGURE 1 of the accompanying drawing illustrates by the way of example, a cylindrical specimen 1 which has been irradiated symmetrically about an arbitrary axis, identified by the legend "axis of irradiation symmetry," producing a multiplicity of concentric paths a, b, c , etc., each of which has been activated to a known constant degree. Hence variations in the characteristic radiation intensity along any given path, measured by means of a radiation detector 2 suspended above the specimen 1, provides an indication of the abundance of the element along that path. Furthermore, if the relative degrees of activation for the different paths is known, the radiation intensities at corresponding points P_1 and P_2 , etc., on different paths may be utilized to determine variations in content at various points over the entire surface.

The radiation intensities along any given path symmetric to the axis of radiation may be plotted graphically and variations in the intensity observed to locate the inhomogeneities or inclusions. FIGURE 2 illustrates graphically by means of the curves R_1, R_2, R_3 , and R_4 the variations in radiation intensity along a number of paths spaced different distances ($2\frac{1}{4}, 4\frac{1}{2}, 7$ and 9 inches) from the axis of radiation symmetry. The radiation intensity, plotted along the ordinate in counts per minute, at various points along each path, plotted along the abscissa in degrees, provides an indication of the relative content of the manganese in the specimen along that path. Thus, it is clearly apparent from curve R_1 that the distribution of the element along this path is non-homogeneous and that a severe condition or inhomogeneity exists along a portion of the path and extends approximately from the 270° point through 120° to approximately the 30° point; a condition shown by the abrupt rise in the counting rate at the 270° point.

It is to be noted further from the remaining curves R_2, R_3 , etc., that this homogeneity along the first path extends radially outward in the specimen since the corresponding 270° point of the remaining curves similarly show abrupt rises in the radiation intensity. In addition to this rather large area of inhomogeneity, curves R_2 — R_4 also indicate that another portion of the specimen contains a high concentration or inclusion of manganese as indicated by the radiation intensity peaks centered around the 40° and 90° points respectively and labeled $P_1, P_1', P_1'', P_2, P_2', P_2''$. It will be understood that the more abrupt the change in counting rate the more severe the boundary condition. Thus three major inhomogeneities in the form of manganese inclusions are present in the sample.

It is to be noted that the curves R_1 — R_4 illustrated in FIGURE 2 are displaced vertically along the ordinate. This displacement of the curves does not represent a major change in manganese distribution between the various paths, but is due to varying degrees of activation along different paths. If desired, the radiation intensities in counts per minute for each of the curves may be corrected to compensate for the variations in the degree of activation. Such a correction factor may be obtained by irradiating known reference quantities of manganese along with the specimen at various distances from the axis of radiation symmetry. The activity per unit weight of the reference quantity is then plotted against distance and any variation in activity of the reference quantities with distance is thus directly attributable to variations in neutron flux density. Hence, a simple ratio of the activity of such a reference quantity at any given distance from the axis to the activity at the axis provides a correction factor from the readings obtained along the various paths. By dividing each of the curves illustrated in FIGURE 2 by the appropriate correction factor, four curves may be made to vary about the same counting rate reference level whereby variations in the

counting rate and hence the radiation intensity may be more accurately determined.

Having located a manganese inclusion from the radiation intensities along the various paths on the specimen, it is desirable to know whether the inclusion lies at the surface or beneath, and if the latter, what the depth of the inclusion is. One mechanism for determining the depth of such an inclusion in a specimen contemplates measuring the amount of absorption or attenuation of the gamma rays emitted from the activated inclusion in passing through the steel to the surface of the specimen. FIGURE 3 illustrates schematically a fragment of the specimen 1 having a manganese inclusion 3 located at a depth t below the surface of the specimen 1. The gamma rays emitted by the activated manganese inclusion are attenuated in passing through the specimen 1, and measured by a radiation detector 2. The intensity of the gamma rays appearing at the surface of the specimen 1 varies exponentially with the thickness of the material through which the gamma rays must pass, and hence the intensity of these rays at the surface will vary with the depth of the inclusion. However, since the absolute magnitude of the gamma radiations emitted at the activated inclusion is usually not known, it is difficult if not impossible to determine the thickness of the flaw from the absolute magnitude of the gamma radiation intensity at the surface of the specimen 1.

Fortunately, however, the gamma radiations from the inclusion 3 are of three discrete energy levels and are emitted from the inclusion in known proportions. That is, it is known, that the radioactive isotope manganese 56 emits gamma radiations at 0.84 mev., 1.8 mev., and 2.1 mev., in a known ratio. FIGURE 4 illustrates the decay scheme of the radioactive manganese 56 to the stable isotope iron 56 (Fe^{56}) and demonstrates the nature and proportion of the emitted radiations. Thus the manganese 56 decays with the emission of beta (β) particles to one or more intermediate excited energy levels of the stable nucleus and emits gamma rays in the transition from the excited levels to the stable nucleus Fe^{56} . Thus for a given quantity of Mn^{56} , represented by the uppermost solid line, 50 percent decays, as shown by the solid arrow c , by emitting a 2.76 mev. negative beta particle, or negatron, to reach the excited energy level, represented by the solid line labelled "0.84 mev.," and then reaches the unexcited ground state of the stable nucleus Fe^{56} by the emission of 0.84 mev. gamma radiations (γ_1) shown by the undulating arrow c' . 30 percent of the manganese 56 isotope decays by the emission of a negatron of different energy level (1.05 mev.), as indicated by the solid arrow d , to an intermediate excited state shown by the line labelled "2.64 mev." This intermediate excited state of the nucleus decays by the emission of gamma radiations (γ_2) having energy level of 1.8 mev. to the lower energy 0.84 mev. energy level and then decays to the stable isotope Fe^{56} with the additional emission of 0.84 mev. gamma rays. Thus far, it can be seen that 80 percent of the manganese isotope by weight decays with the emission of 0.84 mev. gammas and 30 percent with the emission 1.8 mev. gammas. The remaining 20 percent of the manganese 56 isotope decays with the emission of a negatron of .7 mev. energy to yet a third intermediate excited energy level, shown by the line labelled "2.94 mev.," and then decays to the lower 0.84 mev. energy level with the emission of yet a third gamma radiation $\gamma_3=2.1$ mev. This remaining 20 percent of the nuclei in the 0.84 mev. excitation level then decays to the stable isotope Fe^{56} by the further emission of 0.84 mev. gamma radiations. Thus it can be seen that 100 percent of manganese 56 disintegrations result in the emission of 0.84 gammas, 30 percent of Mn^{56} disintegrations produce 1.8 mev. gammas, and 20 percent produce 2.1 mev. gammas. In conclusion, it is apparent that twice as many 0.84 mev. gamma radiations (100% of the disintegrations) are

emitted per unit weight of manganese 56 as of the 1.8 and 2.1 mev. gammas combined. This ratio of emitted gammas is constant and may be utilized, in the manner presently to be described, to determine the depth of an inclusion.

It will be apparent from the previous description, therefore, that should an inclusion of the type illustrated in FIGURE 3 be located directly at the surface of specimen 1 of that figure, the radiation intensity of the 0.84 mev. gammas passing through the radiation detector 2 will be twice the intensity of the sum of the radiation intensities of the 1.8 and 2.1 mev. gammas.

It is also known that the rate at which gamma radiations are absorbed by a given material varies with the energy level of the gamma radiations. That is, low energy gamma radiations tend to be absorbed at a faster rate than high energy radiations. Hence the ratio of the intensities of the 0.84 and 1.8 and 2.1 mev. gammas at the surface of the specimen 1 will decrease in known increments with increasing increments of the absorbing material through which they pass. Hence, knowing the original emission ratio from the decay scheme of the Mn^{56} , reductions in the ratio of the intensities at the surface of the specimen represents passage through a given thickness of the absorbing material thus locating the depth of the inclusion.

The relationship of the radiation intensity at the surface of the specimen, to the depth of the flaw, and the energy level of the gamma radiations is defined by the following equation:

$$I = I_0 e^{-\mu_1 t} \quad (1)$$

where:

I = the intensity of the gamma radiation at the surface of the specimen

I_0 = the intensity of the gamma radiation emitted by the inclusion

μ_1 = the linear absorption coefficient of iron for gamma rays

t = the depths of the inclusion.

From this equation it is apparent that the gamma intensity at the specimen surface varies exponentially both with the depth of the inclusion t and the absorption coefficient μ_1 of the particular material. As was noted above, the absorption coefficient μ_1 for any given absorbing material such as iron varies with the energy level of the gamma radiation. FIGURE 5 shows graphically the relationship of the gamma absorption coefficient μ_1 for iron, plotted along the ordinate, to gamma radiation energy, plotted along a logarithmic scale along the abscissa. From the curve of FIGURE 5 it can be seen that the linear absorption coefficients μ_{11} , μ_{12} , μ_{13} for the 0.84 mev., 1.8 mev. and 2.1 mev. gammas are $\mu_{11}=.49$, $\mu_{12}=.33$, $\mu_{13}=.29$ respectively.

Thus let it be assumed that the intensity of the 0.84 mev gammas (γ_1) emitted by an inclusion of a given size and dimension is of a magnitude K . From the decay scheme of manganese 56, illustrated in FIGURE 4, it is known that the sum of the 1.8 and 2.1 mev. gammas ($\gamma_2 + \gamma_3$) from the inclusion is one half the magnitude of the 0.84 gammas (γ_1); or $K/2$. The intensity of the γ_1 radiations appearing at the surface of the specimen may now be defined by the equation:

$$I_{\gamma_1} = I_0 e^{-\mu_1 t} \quad (2)$$

The intensity of the sum of the $\gamma_2 + \gamma_3$ radiations at the surface may be similarly defined by the equation:

$$I_{\gamma_2+\gamma_3} = I_{02+3} e^{-\mu_{12} t} \quad (3)$$

For the condition of $t=0$, i.e., the inclusion is located at the surface of the specimen:

$$e^{-\mu_1 t} = 1 \text{ and } I_{\gamma_1} = I_0 \quad (4)$$

and

$$e^{-\mu_{12+3} t} = 1 \text{ and } I_{\gamma_2+\gamma_3} = I_{02+3} \quad (5)$$

However, it has been postulated that I_{01} (the amount of γ_1 emitted) is equal to K and I_{02+3} (the amount of γ_2 and γ_3 emitted) equals $K/2$. Therefore the ratio of $I_{\gamma_1}/I_{\gamma_2+3}$ with the flaws at the surface of the specimen is equal to 2. From the Equations 2 and 3 the relationship of the gamma intensity ratios at the surface of the specimen can be established for various depths of the inclusion.

Hence,

$$\frac{I_{\gamma_1}}{I_{\gamma_2+3}} = \frac{K e^{-\mu_1 t}}{\frac{K}{2} e^{-\mu_{2+3} t}} \quad (6)$$

Equation 6 may be converted to the form:

$$\frac{I_{\gamma_1}}{I_{\gamma_2+3}} = 2 \frac{e^{-\mu_1 t}}{e^{-\mu_{2+3} t}} \quad (7)$$

which may be rewritten as:

$$\frac{I_{\gamma_1}}{I_{\gamma_2+3}} = 2 e^{(\mu_{2+3} - \mu_1) t} \quad (8)$$

Thus it can be seen that the ratio of intensities at the various depths t varies exponentially with the differential values of the linear absorption coefficients of the gamma radiations. Substituting the values for μ_{11} , the μ_{12+3} , and taking a weighted average of μ_{12} and μ_{13} , the equation takes the form:

$$\frac{I_{\gamma_1}}{I_{\gamma_2+3}} = 2 e^{(0.32 - 0.49) t} = 2 e^{-0.17 t} \quad (9)$$

From Equation 9 it is apparent that the ratio of the two gamma intensities is reduced incrementally by the factor

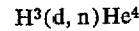
$$\frac{1}{e^{0.17 t}}$$

per unit of thickness t through which the gammas pass. Consequently, the ratios of the radiation intensities for various depths of the inclusion may be plotted from the above Equation 9 for various values of t to produce a curve, such as that illustrated in FIGURE 6, wherein the ratio of the gamma radiation intensity in absolute values is plotted along the ordinate and the depth t of the inclusion is plotted along the abscissa in centimeters. The dashed curve of FIGURE 6 indicates that the ratio of the gamma radiation intensity decreases exponentially with depth t from a maximum value of 2, for $t=0$, i.e., the inclusion located at the surface of the specimen. Hence the absolute value of the ratio of intensities measured at the specimen surface is a measure of the depth of inclusion.

Referring now to FIGURE 7 of the accompanying drawings there is illustrated one form of an apparatus for carrying out the various steps of the novel method. Thus the manganese alloy specimen 1 is activated by irradiation in a neutron flux from a linear accelerator 10 of the Cockroft-Walton type. The accelerator 10 produces the neutron flux by causing a beam of charged particles to impinge on a suitable target which emits neutrons. Linear accelerator 10 comprises an evacuated envelope 11 containing a source of deuteron particles positioned at one end thereof, not shown, energized from a source of operating potential shown in block diagram form at 12 and labelled "power supply." The beam of deuterons is accelerated down the axis of the envelope 11 by means of a multiplicity of cylindrical accelerating sections 13 which are energized by having a direct current accelerating voltage applied to suitable high voltage terminals 14. The accelerating voltages applied to the terminals 14 may be supplied from a high voltage direct current supply, not shown, which customarily includes voltage doubling circuits to provide the necessary high voltages. One typical power supply circuit for this purpose is known as a Cockroft-Walton circuit and is described in detail on

pages 249-251 of Nuclear Radiation Physics, by R. E. Lapp and H. L. Andrews, second edition, Prentice-Hall Inc., New York (1954).

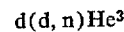
The deuteron beam strikes a tritium target 15 positioned at the opposite end of the housing 11 producing nuclear disintegrations in the target and converting the tritium, which is a heavy hydrogen isotope H^3 , into helium He^4 by the reaction



The conversion of H^3 into He^4 is accompanied by the emission of neutrons which irradiate the specimen 1. Since both thermal and fast neutrons are produced from the tritium target 15 a paraffin moderator 16 and a plastic moderator 17 is positioned on the underside of the envelope 11 and surrounds target 15 to slow down or thermalize the fast neutrons so that the specimen is irradiated by a thermal neutron flux.

To achieve the symmetric irradiation of the specimen 1 and consequently the symmetric activation of the elements, the specimen is supported on a table 18, only partially shown, which table may be rotated by any suitable means, including manual, so that the specimen 1 is rotated at a fixed velocity in the neutron flux subjecting the specimen to symmetric activation about the axis of rotation of said specimen.

It is to be understood and will be apparent to those skilled in the art, that instrumentalities other than the illustrated Cockroft-Walton linear accelerator and the tritium (H^3) target may be utilized to produce the neutron flux. For example, a zirconium target having deuterons adsorbed therein may be used to interact with a deuteron beam to convert the adsorbed deuterons to helium 3 (He^3) by means of the reaction



Furthermore, particle accelerators of various types, such as cyclotrons, synchrocyclotrons, etc., may be utilized in place of the Cockroft-Walton linear accelerator to produce a particle beam to interact with a suitable target to produce the neutrons.

Nor is it necessary in carrying out the invention that particle accelerators of any sort be utilized to produce the neutron flux since the neutron activation of a specimen may take place in a nuclear reactor; this approach being limited only by the relative sizes of the specimen and the available area within the reactor. In addition, it is also possible to utilize sealed naturally radioactive neutron sources such as radium-beryllium or polonium-beryllium, for example. It is clear, therefore, that the step of irradiating the specimen in a neutron flux to produce the symmetric activation may be carried out by means of many different instrumentalities and devices.

The characteristic gamma radiations from any manganese inclusion in the now activated specimen are detected at various points along selected paths of the specimen to determine the distribution of the manganese in the specimen. To this end, the symmetrically activated specimen 1 is removed from neutron flux and positioned so that various portions thereof may be scanned by radiation detecting instrumentality to determine the intensity of the characteristic radiations from the manganese along various symmetrically activated paths. The specimen 1 is positioned on a rotating table assembly 19 beneath a radiation detecting scintillation counter 20 which may be positioned at various distances from the axis of radiation symmetry of the specimen 1 by moving a carriage 21 to which it is secured along suitable rails 22.

The radiation detector assembly 20 comprises an open ended cylindrical housing 23 supported in a Y-shaped yoke 24, seen most clearly in FIGURE 8. The yoke 24 has a stem portion 25 which is retained in a split guide member 26 by means of a bolt 27 extending through the stem 25 and a pair of vertical slots 28 in the guides 26. In this manner the entire housing 23 may be raised

or lowered by securing the stem 25 in any desired position within the guide 26.

Positioned within the housing 23 and at the apex of a collimating slit 29 is a thallium activated sodium iodide scintillating crystal 30 surrounded by a lead shield 31 to eliminate background radiation and to insure that only the characteristic gamma radiations from the specimen 1 impinge upon the crystal. The sodium iodide crystal 30 in a well known manner produces minute light flashes or scintillations in response to impinging gamma rays with the intensity of the light scintillations being proportional to the energy of the gamma rays and the rate of their occurrences, i.e., the number per unit time, being proportional to the intensity of the radiation. Adjacent to one side of the crystal 30 and supported in the housing by means of a bracket 32 is a photomultiplier device 33 which intercepts the light scintillations from the crystal and converts them into electrical impulses, the magnitudes of which are proportional to the intensity of light scintillations and hence to the gamma ray energies. Photomultiplier devices are old and well known in the art and need not be discussed here in detail except to point out that they convert the light scintillations from the crystal into electrical impulses.

The table assembly 19 which rotates the activated specimen 1 underneath the radiation detector 20 includes a specimen supporting rotating table 34, which is driven at a constant rotational speed to permit scanning of the specimen. The table 34 is mounted in a frame 35 secured to a base member 36 and is supported for rotation in the horizontal plane on a multiplicity of tapered rollers 37 secured to the frame 35 and distributed along the underside of the table. A number of cylindrical rollers 38 rotatable about a vertical axis and secured to the frame 35 frictionally engaged the periphery of table 34 to permit rotational movement thereof while yet preventing end play or level movement of the table. The table also includes a clamping mechanism, not shown, for rigidly securing the specimen 1 to the table during rotation.

The table 34 is driven by a constant speed synchronous motor 39 and a speed reducing gear train, indicated generally at 40, at a constant rotational speed. The gear train 40 is so constructed that the speed at which the table is driven is very low, in the order of $\frac{1}{2}$ r.p.m. or less, whereby the surface of the specimen 1 is slowly scanned by radiation detector 20. The motor 39 drives a shaft 41 journaled in a bearing supported in a suitable bracket 42 through disengaging clutch mechanism 43. A bevel gear 44 is secured to the shaft 41 and engages a similar bevel gear 45 fastened to a vertical stub shaft 46 mounted for rotation in a sleeve bearing 47 retained in the base 36. Rotation of the shaft 46 by means of the bevel gears 44 and 45 causes a spur gear 48 mounted on the shaft 46 to mesh with a corresponding spur gear 49 to transmit motion to a second vertical shaft 50 journaled in a sleeve bearing retained in the base 36. In addition to transmitting power from the motor 39 to the shaft 40, the diameters of the respective gears 44, 45, 48 and 49 are so proportioned that the driving speed is reduced and the shaft 50 is rotated at some desired fraction of the motor driving speed.

The remaining portion of the gear train 40 transmits motion from the shaft 50 with further reduction in speed to the table 34 to rotate the specimen at the desired constant rotational speed. Thus, rotation of the vertical shaft 50 is transmitted to a horizontal shaft 57 through a pair of bevel gears 52 and 53 which are fixed to the respective shafts. The shaft 51 is journaled in a pair of sleeve bearings mounted in suitable bearing brackets and drives a bevel gear 54 secured to one end thereof. Gear 54 engages a ring gear 55 secured to the underside of the table 34 by means of fastening bolts 56 and drives the table 34 supported on the rollers 37 at a constant low speed.

A bevel gear 57 fastened to a third horizontal shaft 58 is driven by the gear 54 and drives an output shaft 61 through a bevel gear assembly 59 and a speed reducing mechanism 60. The gears 57 and 59 and the speed reducer 60 are so constructed that the output shaft 61 is driven at the same rotational speed as the table 34 and in turn drives the strip chart takeup drive of a suitable strip chart recorder at the same speed as the table 34 so that the output signals from the radiation detecting device 20 suspended above the table may be recorded directly on the chart at various positions corresponding to the rotation of the specimen.

FIGURE 9 illustrates in block diagram form a two-channel gamma ray scintillation spectrometer for measuring and indicating both the intensity of the total characteristic gamma radiations from the manganese inclusions as well as the ratio of the 0.84 mev. and the sum of the 1.8 and 2.1 mev. gamma radiation intensities. As pointed out previously, gamma radiations impinging on the crystal 30 mounted in the housing 23 produce light scintillations, the intensity of which are proportional to the energy of the gamma rays and the number of which per unit time represent the intensity of the radiation. The crystal 30 is positioned adjacent to the photosensitive electrode of a photomultiplier device 33, such as an RCA 5819 photomultiplier tube, which converts the light scintillations into variable amplitude output pulses. A regulated high voltage power supply 62 may supply operating voltage for the photomultiplier 33 which thus produces on output lead 63 a series of pulses varying in amplitude with the energy of the impinging gamma rays and in frequency with the intensity of the gamma radiation. The output pulses appearing on the lead 63 are applied successively to a preamplifier 64 and an amplifier 65 to amplify the output pulses from the photomultiplier 33 to produce pulses of a magnitude suitable for analyzing. The amplified pulses appearing at the output of the amplifier 65 are applied to two analyzing channels 66 and 67 wherein the pulses are segregated according to amplitude and counted to determine the number of pulses of a given amplitude, or range of amplitudes, per unit time. Accordingly, the analyzer channel 66 is preset in such a manner that it accepts only pulses representative of 0.84 mev. gamma radiations (γ_1) whereas channel 67 accepts only pulses in a range representative of 1.8 and 2.1 mev. gamma radiations.

Analyzer channel 66 thus includes a single channel analyzer 68 of well known construction such as the Radiation Instrument Development Laboratory Model RIDL-3300 analyzer which accepts only those pulses of an amplitude representative of the 0.84 mev. gamma rays (γ_1) and counts their rate of occurrence. A counting rate meter 69 is coupled to the output of the analyzer 68 and produces a variable direct current output the magnitude of which is proportional to the pulse rate from the analyzer. This output current is applied to a power amplifier 70 to energize a pen drive motor 71, which actuates a marker pen 72 in one channel of a two-channel strip chart recorder 73 to produce a trace, such as the illustrated curve X, representative of the radiation intensity in counts per minute of the 0.84 mev. gammas.

Channel 67 in a similar fashion includes a single channel analyzer 74 connected to the output of the amplifier 65 through a manually operated switch 75 which may be opened to de-energize the channel 67. The function of switch 75 will be explained in detail later in connection with a description of the operation of this circuit. The channel analyzer 74 is preset to accept and count only pulses having amplitudes representative of 1.8 and 2.1 mev. gamma ray energies ($\gamma_2 + \gamma_3$). The output from the analyzer 74 is similarly applied to a counting rate meter 76, which produces an output signal proportional to the pulse rate. The output signal from the counting rate meter 76 is amplified in a power amplifier 77 which energizes a pen drive motor 78 actuating a marker pen 79 in

the second channel of the strip chart recorder 73 to produce upon the strip chart a second trace, such as the curve Y, representing the radiation intensities of the 1.8 and 2.1 mev. gamma rays. The depth of the manganese inclusion may thus be determined directly from the two curves X and Y by noting the change in the γ_1 to the sum of $\gamma_2 + \gamma_3$ radiation intensities. In this fashion a simple and effective way of locating the depth of the inclusion is provided.

In carrying out the method of the instant invention, an irradiated specimen is positioned on the rotating table assembly 19 and various paths on the surface thereof are scanned by means of the radiation detecting element 20 suspended above the sample. During this portion of the operation the switch 75 in the second analyzing channel 67 is open disabling the channel, and the single channel analyzer 68 of channel 66 is preset to accept and count all the total number of pulses representative of all three different energy level gamma radiations γ_1 , γ_2 , and γ_3 to produce an indication upon the strip chart similar to the curves of FIGURE 2, which illustrate the total radiation intensity. Once an inclusion has been located from such a curve by virtue of an abrupt rise in the counting rate, switch 75 is closed placing the second channel 67 in operation and the two single channel analyzers 68 and 74 in the respective channels are preset to accept only pulses representative of the 0.84 mev. gamma radiations (γ_1) and the sum of the 1.8 and 2.1 mev. gamma radiations ($\gamma_2 + \gamma_3$) respectively. The various paths on the sample 1 are again scanned by the radiation detecting device 20 in order to determine the variations in the γ_1 to the sum of $\gamma_2 + \gamma_3$ radiation intensities in order to determine from this the depth of the manganese inclusion. In this manner, valuable information has been provided about a specimen mixture such as a manganese alloy which is useful in determining and evaluating many of the physical characteristics of these specimens.

It is to be understood that the instant invention is not limited to measuring the ratios of the 0.84 and 1.8, 2.1 mev. gammas intensities simultaneously by means of a two-channel analyzer such as is illustrated in FIGURE 9. It is obvious that a single channel analyzer may be utilized which measured the intensities of the respective gamma groups sequentially to provide an indication of their ratio. In such an eventuality provision must be made to compensate for decay of the Mn^{56} during the interval between such measurements.

While a particular embodiment of the invention has been described and shown, it will of course be understood that it is not limited thereto since many modifications and variations in the method and the circuit arrangements for carrying out the method may be made. It is contemplated that the appended claims cover any such modifications as fall within the true spirit and scope of this invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. In a non-destructive method for determining the depth of an inhomogeneous inclusion in a mixture of elements, the steps of irradiating the mixture in a particle flux to form radioactive elements from the inhomogeneous inclusion of one of the mixture constituents, said radioactive elements emitting characteristic radiations of different energy levels, detecting and measuring the relative amounts of the radiations of different energies to establish their ratio as an indication of the depth of the inclusion.

2. In a non-destructive method for determining the depth of an inhomogeneous inclusion in a mixture of elements, the steps of irradiating the mixture in a particle flux to form radioactive isotopes from one of the constituent elements distributed in the mixture, said constituent element being characterized by the emission of at least two characteristic radiations of different energy levels when radioactive, and producing an indication of

the depth of an inclusion from the ratio of the intensities of said characteristic radiations due to the different degree of attenuation of the radiations of different energy levels.

3. In a non-destructive method for determining the depth of an inhomogeneous inclusion in a specimen, the steps of irradiating a specimen in a particle flux to activate the included element causing it to become radioactive and emit characteristic radiations of different energy levels, determining the depth of such inclusions from the relative attenuation of the radiations of different energy levels including the step of detecting and measuring the relative intensities of the respective radiations of different energies at the surface of the specimen to establish thereby the ratio of their intensities as a measure of the depth of said inclusion.

4. A non-destructive method for determining the depth of a continuous but non-homogeneous inclusion in a specimen by the differential absorption of radiations of different energies, comprising the steps of irradiating a specimen in a particle flux to activate the included element and transform it into a radioactive isotope which emits characteristic radiations of different energies, detecting the intensities of the characteristic radiations of different energies at the surface of the specimen to establish a ratio of their intensities and provide an indication of the depth of said inclusion from the variation of said ratio due to the different degrees of absorption in said specimen.

5. In a non-destructive method for determining the depth of an element inclusion in a matrix of a different element, the steps of irradiating a specimen in a particle flux to activate the included element so that it emits characteristic radiations of different energy levels in known proportionate amounts, detecting and measuring the relative amounts of radiations of different energies at the surface of the specimen to establish thereby the ratio of their intensities for determining the depth of the inclusion from the change of said ratio due to the differential absorption of the radiations of different energy levels in the matrix material.

6. In a non-destructive test method for determining the depth of an element inclusion in a matrix of a different element, the steps of irradiating a specimen in a neutron flux to activate the included element whereby it emits gamma radiations of different energy levels in amount of known proportions, detecting and measuring the relative amounts of the different gamma radiations emitted at the surface of the specimen to establish the ratio of their intensities for determining therefrom changes in the depth of the inclusion due to differential absorption in the matrix element in accordance with gamma energy levels.

7. In a non-destructive test method depth of manganese inclusion in a manganese steel alloy, the steps of irradiating a specimen of the manganese steel in a neutron flux to form the radioactive manganese isotope Mn^{56} which emits 0.84, 1.8 and 2.1 mev. gamma radiations, the relative proportions of the gammas emitted by said isotope being such that twice as many 0.84 mev. gamma radiations are emitted at the inclusion as 1.8 and 2.1 mev. gamma radiations combined, detecting and measuring the relative amounts of 0.84 mev. gammas and the combined 1.8 and 2.1 mev. gammas at the surface of the specimen to establish the ratio of their intensities to determine the depth of the inclusion from changes in the ratio due to differential absorption with energy level.

8. In a non-destructive test method for determining the depth of an element inclusion in a matrix of different element, the steps of irradiating a specimen in a particle flux to activate the included element causing it to become radioactive and emit characteristic radiations of different energy levels and in known proportions, rotating said specimen in the neutron flux to activate symmetrically about the axis of rotation, detecting and measuring the intensity of the characteristic radiations about the axis

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of activation symmetry to locate inclusions of said element in said specimen, and detecting and measuring at the surface of the specimen the ratio of the individual radiations of different energy to determine the depth of an inclusion from changes in said ratio the individual radiations of different energy levels.

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