DOSE DETERMINATION ALGORITHMS FOR A NEARLY TISSUE EQUIVALENT MULTI-ELEMENT THERMOLUMINESCENT DOSIMETER*

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ABSTRACT

In a continuing effort to develop dosimetric systems that will enable reliable interpretation of dosimeter readings in terms of the absorbed dose or dose-equivalent, a new multi-element TL dosimeter assembly for Beta and Gamma dose monitoring has been designed. The radiation-sensitive volumes are four LiF-TLD elements, each covered by its own unique filter. For media-matching, care has been taken to employ nearly tissue equivalent filters of thicknesses of 1000 mg/cm^2 and 300 mg/cm^2 for deep dose and dose to the lens-of-the-eye measurements respectively. Only one metal filter (Cu) is employed to provide low energy photon discrimination. A Thin TL element (0.09 mm thick) is located behind an "open window" designed to improve the energy under-response to low energy beta rays and to provide closer estimate of the shallow dose equivalent.

The deep and shallow dose equivalents are derived from the correlation of the response of the various TL elements to the above quantities through computations based on previously defined relationships obtained from experimental results. The theoretical formalization for the dose calculation algorithms is described in detail, and provides a useful methodology which can be applied to different "tissue-equivalent" dosimeter assemblies. Experimental data has been obtained by performing irradiation according to the specifications established by DOELAP, using 27 types of pure and mixed radiation fields including Cs-137 gamma rays, low energy photons down to 20 keV, Sr/Y-90, Uranium, and Tl-204 beta particles.

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1. INTRODUCTION

Although the need for improving the quality of personnel dosimetry systems is well recognized by the health physics community members and by the various authorities, there is no overall agreement about techniques and methodology which are required to achieve this goal. Some of the inconsistencies between the different dosimetry programs and systems have been recently demonstrated in a pilot performance test conducted by the Department of Energy Laboratory Accreditation Program (DOELAP) where as a group, the participants met the test criteria in only 38% of the tested categories[1]. All the participants experienced difficulties in any category that required low energy photons or mixtures of low energy photons with beta fields. The main reasons for the large variations in the test results and the poor performance in some of the test categories were identified as follows: 1) lack of evaluation and preparation of the system; 2) calibration problems; and, 3) dose calculation algorithms and dosimeters not designed to accommodate a wide range of radiation types and energies. This paper presents an improved multi-element TL dosimeter together with dose calculation algorithms which are designed to resolve those problems and to meet the ever growing demands of modern personnel dosimetry and obtain DOELAP[2] accreditation. In this paper we present the philosophy behind the dosimeter design, the dose calculation algorithm formalism, a comprehensive step-by-step methodology, and the results from a detailed experimental study that was conducted to calibrate and characterize this system.

2. DOSIMETER DESCRIPTION

The dosimeter is composed of two parts, a TLD card and a holder which carries the radiation modifying filters. The TLD card consists of four LiF:Mg,Ti TL elements of different thicknesses and compositions mounted between two PTFE sheets (0.0635 mm thick) on an aluminum substrate. Each TL element is covered by its own unique filter which provides different radiation absorption thicknesses to allow dose estimation for the various organs in risk. The element in position 3 is a thin (0.09 mm) solid TLD-700 chip protected from the environment by a thin, aluminized Mylar sheet (0.0625 mm thick). The shallow dose estimation is based on the response of this element; and, as a result of its reduced thickness (a factor of 10 thinner than the standard 3x3x0.9 mm TLD ribbons), the energy-dependent response to the low energy beta rays is improved. The elements in positions 1 and 2 are a thicker (0.4 mm) TLD-700, covered by a 1000 mg/cm^2 tissue equivalent filter and by a Copper filter respectively. The deep dose estimation is based on the response of element 1. The ability of the dosimeter to act as a crude energy spectrometer for low energy photons is based on the variation with energy of the photon attenuation characteristics of the Copper filter located in position 2. Position 4 is occupied by a neutron sensitive TL element, TLD-600, shielded by a tissue equivalent filter of 300 mg/cm^2 thickness, to enable dose estimation to the lens of the eye and to measure neutron dose in the absence of

thermal neutrons. Since the scope of this study was limited to deep and shallow dose estimation in the presence of mixed photon beta fields, the response of the dosimeter in neutron fields and the dose estimation to the lens of the eye are not discussed here. This configuration is a modification of the dosimeter described by Storm et al,[3] and which has been used since 1982 in the Los Alamos National Laboratory (LANL) Personnel Dosimetry Program. Care has been taken to use nearly tissue equivalent TL elements and tissue equivalent filters. A plastic filtration of 1000 mg/cm^2 for the deep dose estimation was preferred over lead filters which are commonly used[4]. Lead filters introduce severe mismatch[5] between the sensitive dosimetric material (LiF) and the filter medium (Pb), which complicates the dose reading interpretation and reduces the TL signal per unit dose for low energy photons due to the strong attenuation of low energy photons in Lead. Those difficulties are further demonstrated in reference 6.

3. EXPERIMENTAL

The TL measurements were performed using the Model 8800 Automatic TLD Card Reader developed by Harshaw. The Model 8800 utilizes a non-contact heating technique based on pre-purified hot nitrogen gas. However, unlike any other hot gas TLD reader known to date, the Model 8800 employs a programmable, precisely controlled, linear time temperature profile. One of the most important requirements of a TLD reader is that the heating of the dosimeter elements should be reproducible. The reason is that the amount of radiation-induced Thermoluminescence is dependent on the thermal history of the material as well as on the heating rate during readout. A fully controlled heating cycle is therefore important, especially for low dose measurements. Usually a controlled heating cycle is accomplished by contact ohmic heating of the TL element. The contact heating method has some disadvantages, such as relatively short dosimeter life and large infrared signals associated with the heating element. The most important advantage of the contact heating method is its ability to continuously control the heating cycle using various feedback techniques. The "Time Temperature Controlled" non-contact heating technique applied in the Model 8800 shares this advantage of the contact heating approach without sharing its disadvantages.

For this series of tests, glow curves were recorded to a maximum temperature of 300^{o}C at a heating rate of 25C^{o}/sec. No high temperature annealing was applied and the preparation of the dosimeters prior to irradiation consisted of subjecting each dosimeter to one readout cycle through the reader. The residual TL signals using this reader anneal technique were found to be less than 0.5% at the Sr/Y-90 one rad level. All the irradiations to determine the Element Correction Coefficients and the Reader Calibration Factor were performed in the reader using an internal 0.5 mCi Sr/Y-90 irradiator with an automatic shutter. The reproducibility of the irradiator was found to be within 1% (one

standard deviation of 10 repeated irradiations) at the Sr/Y-90 500 mrad level. Also, no significant changes in the glow curve structure were observed due to repeated irradiation and readout. The TL signal is accumulated simultaneously from four TL elements via the charge integration technique using four thermoelectrically cooled Hamamatsu photomultipliers (Bialkali photocathode).

4. THE ELEMENT CORRECTION COEFFICIENT METHOD

Since not all TL elements can be manufactured to have exactly the same TL efficiency, where TL efficiency (TLE) is defined as the emitted TL light intensity per unit of absorbed dose, individual Element Correction Coefficients (ECCs) have been applied. The method of ECC generation is based on relating the TL efficiency of each TL element of the entire dosimeter population (Field Dosimeters) to the mean TL efficiency of a small subset of this population which is used only for calibration purpose (Calibration Dosimeters). When the ECC is applied to the response of each individual TL element of any of the Field or the Calibration Dosimeters, its TL efficiency is virtually identical to the mean value of the Calibration Dosimeters group. The Element Correction Coefficient, ECC_{ij}, for element i in calibration card j is given by:

$$ECC_{ij} = \langle Q \rangle_i / Q_{ij} \qquad (1)$$

when $\langle Q \rangle_i$ is the average TL response for element i of the calibration card population and Q_{ij} is the response of TL element i in card j. Similar to (1), we define the Element Correction Coefficient ecc_{ij} for Field Cards as follows:

$$ecc_{ij} = \langle Q \rangle_i / q_{ij} \qquad (2)$$

when q_{ij} is the TL response of element i in a field card j. For a detailed discussion of this concept see reference 7. Throughout this process, the inherent sensitivity of the Calibration Cards must remain constant. However, as we have shown in a previous publication[9], the TLD cards used here can be subjected to hundreds of reuse cycles without any noticeable change in their TL efficiency.

5. THE REFERENCE SOURCE AND THE CALIBRATION LABORATORY

To maintain a known relationship between the ability of the reader to convert stored TL information to measurable electric signals (charge or counts), it is convenient to express the ratio between the average TL response of the Calibration Cards and the delivered radiation quantity L in terms of one variable. Since the numerical value of this variable will be mainly dependent on the condition of the reader at a given date and time, it is appropriate

to name this variable "Reader Calibration Factor" (RCF), defined as follows:

$$RCF_i = \langle Q \rangle_i / L \qquad (3)$$

when $\langle Q \rangle_i$ is the TL response of a set of Calibration Cards exposed to a known quantity of radiation L.

The radiation quantity L can be expressed in any convenient units. We define the unit gU (generic unit) as the unit to express the quantity L. For example, 1 gU can be equal to the amount of irradiation delivered during a period of one second by a specific source with specific geometry to a dosimeter located at a set distance from the source. Since the definition of gU is somewhat arbitrary, once it is defined for a specific source and geometry, it will have any meaning only for this source, which is called the Local or Reference Source.

The last step of the system calibration consists of establishing the link to a set of various NBS calibrated sources located at a calibration laboratory. The calibration laboratory performs the irradiations and reports the delivered quantity in terms of Shallow dose and Deep dose for various radiation fields (10). The method that was used to establish this link is described in the following sections.

6. SUPERPOSITION OF RADIATION FIELDS AND THE MIXTURE IDENTIFICATION FORMULAS

Since the dosimeter may respond differently (different gU/rem values) to different types of radiation fields or mixtures, its response has been experimentally characterized. The results of this characterization are used in the interpretation of the dosimeter readings for unknown dose and radiation field combinations. This requires knowing the type of radiation field or mixture that the dosimeter was subjected to, and to use this information to calculate the specific dose equivalent values. The only direct data from the dosimeter reading which is available for determining the radiation field type are the responses in units of gU from the different dosimeter positions, L_1, L_2, L_3 and L_4. The TL element in position 4 is sensitive to neutrons and is reserved for applications involving neutron fields. The remaining three elements form two independent ratios, L3/L1 and L3/L2. Let us define a function f(x) to be the ratio L3/L1 (f) as a function of the ratio L3/L2, (x).

The key issue in the dosimeter's ability to discriminate different radiation fields or to determine the relative contribution of components in mixed fields is the shape of this function and its rate of change for different energies and compositions. For a mixture of 2 model radiation fields "a" and "b" we assume that the

response of each TL element is the weighted sum or superposition of its individual response to fields "a" or "b" as if the other field did not exist. This assumption means that there is no interaction between the induced TL effects when the dosimeter is subjected to two or more different radiation fields. Although this assumption may seem to be straightforward, there are evidences in the literature that in some cases the TL response resulting from mixtures of radiation fields may not be additive. This effect is particularly noticeable with fast neutrons, where a decrease of 10% in the gamma TL signal was observed as a result of the tendency of fast neutrons to release the stored gamma induced signal from previous or simultaneous gamma irradiation[11]. However, if non-additivity effects exist for mixed beta gamma fields, they are expected to be small, and in fact our data shows that the assumption of superposition of radiation fields is valid to within few percent.

The superposition principle can be applied to determine f(x). Let N be the relative contribution of field "a" to the mixed field and assuming that only two fields exist, 1-N will be the relative contribution of field "b". If the delivered quantities are expressed in terms of Roentgen or rad in air, N and 1-N will be the weighting factor assigned to each field. The relative response, a_i, b_i (i=1..4) of each element to pure field "a" or "b" is defined as the response of the particular element in units of gU per unit of delivered dose in air when only one field is being used. Using the superposition principle, the relative response $(ab)_i$ of element i to a mixture of fields "a" and "b" is as follows:

$$(ab)_i = Na_i + (1-N)b_i \qquad (4)$$

Based on (4), the L3/L1 and L3/L2 ratios in a mixed field become:

$$L3/L1 = (ab)_3/(ab)_1 = [Na_3+(1-N)b_3]/[Na_1+(1-N)b_1] \qquad (5)$$

and similarly,

$$L3/L2 = (ab)_3/(ab)_2 = [Na_3+(1-N)b_3] \,/\, [Na_2+(1-N)b_2] \qquad (6)$$

Using x for L3/L2, we can then rewrite (6) in the form:

$$N = [b_3-xb_2]/[x(a_2-b_2)-(a_3-b_3)] \qquad (7)$$

Substituting N from (7) into (5) and using f(x) for L3/L1, we can then write (5) in the form:

$$f(x) = [b_3a_2-a_3b_2]x/[(b_1a_2-a_1b_2)x+(a_1b_3-b_1a_3)] \qquad (8)$$

Formula (8) is used to identify the mixture as follows: all the calibration constants a_i and b_i are determined once by performing calibration irradiations at an NBS traceable calibration laboratory for all the radiation fields of interest (all the possible a's and b's). The value of x (the ratio L3/L2) is then computed from the

response of the dosimeter, and f(x) computed for this particular x and for all the possible radiation field mixtures "a" and "b", which are used as model fields to simulate possible different model responses of the dosimeter to various radiation fields. Then the measured L3/L1 value is compared to all the calculated f(x) (all the possible computed L3/L1 ratios for the particular measured L3/L2 ratio) and the calculated value which is nearest to the measured L3/L2 ratio is selected to represent the required type of model radiation fields mixture, i.e. the identity of "a" and "b". Once "a" and "b" have been identified, (7) can be used to calculate the relative contribution of each component, N and 1-N for fields "a" and "b" respectively. If none of the computed L3/L1 ratios is in close agreement with the measured one, the reading may have resulted from radiation fields different from those covered by the calibration, or the dose was too low to provide an accurate measure of the value of N. In this case, the dose is calculated based on the average value of the calibration constants shown in Table 2.

7. DEEP AND SHALLOW DOSE DETERMINATION

Once the value of N has been determined, the Deep and the Shallow dose are calculated from the TL response in units of gU, R_1 and R_3 for elements 1 and 3 respectively. Let Ra_1 be the response of element 1 in units of gU when the dosimeter is exposed to d rem of deep dose and Ra_3 the response of element 3 in units of gU when the dosimeter is exposed to s rem of shallow dose using model field "a". Similarly, the variables Rb_1 and Rb_3 are defined for model field "b". The "model field calibration values" r_{a1}, r_{a3} in terms of gU per "deep rem" and gU per "shallow rem" for field "a", are defined as follows:

$$r_{a1} = Ra_1/d \quad [gU/rem] \tag{9}$$

and

$$r_{a3} = Ra_3/s \quad [gU/rem] \tag{10}$$

similarly we define r_{b1} and r_{b3} for model field "b":

$$r_{b1} = Rb_1/d \quad [gU/rem] \tag{11}$$

and

$$r_{b3} = Rb_3/s \quad [gU/rem] \tag{12}$$

Using the superposition principle, we can now define the "mixed field calibration factors" r_{ab1} and r_{ab3} for deep and shallow dose respectively, to be:

$$r_{ab1} = Nr_{a1} + (1-N)r_{b1} \quad [gU/rem] \tag{13}$$

and,

$$r_{ab3} = Nr_{a3} + (1-N)r_{b3} \quad [gU/rem] \tag{14}$$

Finally, we can compute the deep and shallow dose from the TL response in units of gU, R_1 and R_3 for elements 1 and 3 respectively and using (13) and (14) as follows:

$$\text{DEEP DOSE} = R_1/r_{ab1} \quad [\text{rem}] \qquad (15)$$

and,

$$\text{SHALLOW DOSE} = R_3/r_{ab3} \quad [\text{rem}] \qquad (16)$$

8. RESULTS AND DISCUSSION

To implement and test the methodology described in the previous sections, a batch of 145 dosimeters was supplied to the calibration laboratory to be exposed to various types and amounts of beta and gamma radiation following the Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems[2] (DOE/EH-0027) irradiation procedures. Forty dosimeters, five in each field, were exposed to eight different "pure" radiation fields as specified in DOE/EH-0027 and summarized in Table 1. The responses of those dosimeters were used to generate the various calibration factors as described in the previous sections. Ten other dosimeters were exposed to the accident categories (I and II). However, the dosimetry at the high dose level and the fading corrections required are still under investigation. The remaining 95 dosimeters were irradiated using 19 different mixtures of photons and beta rays. The responses of both groups of dosimeters were used to test the dose calculation algorithm. The deep dose levels were in the range of 420 - 2000 mrem.

The calibration Factors r_{ai} and a_i were calculated using the response of the dosimeters to the pure fields and the delivered deep dose, shallow dose and delivered exposure, or dose, supplied by the calibration laboratory. The results of this calculation for r_{ai} are shown in Table 2. Each calibration factor was computed averaging the response of five dosimeters which were exposed simultaneously to the same radiation field. The uncertainties shown in Table 2 represent one standard deviation from the average. and the percentage standard deviation is given in parentheses. When the L3/L1 ratio is plotted as a function of L3/L2, each mixture type is identified by its own unique pattern, i.e., Mixture Identification Curve (MIC). Typical results for various mixtures are shown in Figure 1, which illustrates a family of curves calculated using (8).

The ability to discriminate between photon and beta fields has been well demonstrated. However, there is no discrimination ability among M150, H150, and Cs-137 photon fields. From Table 2 we can see that the over-response of the dosimeter relative to Cs-137 is approximately 20-25% with M150 and about 10% with H150. Since there is no clear discrimination among these 3 sources, whenever one of them is identified in a mixture, the calibration factors (r_{abi}) are set to the average of the individual r_{ai} values for those three photon fields. This procedure will overestimate the reported dose

from the M150 source by approximately 10-13% and underestimate the response to the Cs-137 and the H150 sources by approximately 10% and 3-5%, respectively. Although less pronounced, a similar situation may occur in some mixtures involving Tl-204 or Depleted Uranium. If we reexamine Table 2, we see that the shallow dose responses of these two beta sources are within 20%. Again, if the average of the individual calibration factors (r_{a3}s) is used whenever Tl or DU are identified in a mixture, the maximum "built-in" overestimation or underestimation of the DU or Tl-204 dose respectively will be 10%.

The Mixture Identification Curve method was applied to all of the 135 dosimeters that were involved. Each dosimeter was treated as if it was exposed to a mixed field and the mixture components were identified and the relative contributions of each field, N and 1-N were calculated. The measured N values were compared to the N values as reported by the calibration laboratory ("delivered") for the mixed fields. The results of this comparison are shown in Table 3, and demonstrate good agreement between the measured and the actual contribution of the various radiation fields. No comparison was made for the two mixtures of Cs-137 with M150 or with H150 since no meaningful N values can be computed due to the overlap of their MICs. The reported Deep and Shallow doses were calculated from the dosimeter responses using formulas (9) to (16) and the calibration factors from Table 2. The results for each category were compiled using the guideline given in the DOELAP handbook for Personnel Dosimetry Systems[12], when the "Bias", B is given by:

$$\overline{B} = 1/n[\sum_{i=1}^{n} P_i] \qquad (17)$$

where P_i is the fractional difference between the reported and delivered absorbed dose or dose equivalent for the i^{th} dosimeter, given by:

$$P_i = (\text{Reported}_i - \text{Delivered}_i)/\text{Delivered}_i \qquad (18)$$

and the standard deviation:

$$S = [\sum_{i=1}^{n}(P_i - \overline{B})^2 /(n-1)]^{1/2} \qquad (19)$$

The $|B|+S$ values for all of the 27 radiation fields involved are represented graphically in Figure 2 and compared to the current (solid line) and future (dotted line) DOELAP tolerance levels.

9. CONCLUSION

It has been shown that the dosimeter response can be used to identify the mixture type in a mixed beta-gamma field and to estimate the relative contribution of major components. Furthermore, it has been demonstrated that the accuracy of the system can be well within DOELAP tolerance limits.

10. REFERENCES

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Table 1. Calibration Irradiations

	Radiation Field	Energy
1	x-ray NBS filtered Technique - M30	20 keV
2	x-ray NBS filtered Technique - S60	36 keV
3	x-ray NBS filtered Technique - M150	70 keV
4	x-ray NBS filtered Technique - H150	120 keV
5	Gamma Cs-137	662 keV
6	Beta (Point geometry) Tl-204	760 keV (max)
7	Beta (Point geometry) Sr/Y-90	2300 keV (max)
8.	Beta (Slab geometry) Uranium	2300 keV (max)

Table 2: Pure Field Calibration Factors - gU/rem

	Source	Deep Dose - r_{a1}	Shallow Dose - r_{a3}
1	M30	693.0 ± 11.1(1.6%)	837.6 ± 19.7(2.4%)
2	S60	942.9 ± 15.1(1.6%)	1008.1 ± 22.0(2.2%)
3	M150	805.4 ± 16.3(2.0%)	848.1 ± 10.9(1.3%)
4	H150	726.5 ± 39.6(5.5%)	737.2 ± 20.3(2.8%)
5	Cs-137	659.8 ± 14.5(2.2%)	667.7 ± 11.7(1.8%)
6	Tl-204	----	498.0 ± 7.6(1.5%)
7	Sr/Y-90	----	716.0 ± 10.9(1.5%)
8	Uranium	----	408.6 ± 10.1(2.5%)

Table 3: Comparison Between Delivered and Measured N values

Mixture Components		Relative Contribution of Field "a" - N	
Field "a"	Field "b"	Delivered	Measured
M30	Cs-137	0.696	0.674 ± 0.012
S60	Cs-137	0.491	0.441 ± 0.096
M30	Tl-204	0.483	0.561 ± 0.028
S60	Tl-204	0.466	0.458 ± 0.021
M150	Tl-204	0.416	0.515 ± 0.088
H150	Tl-204	0.415	0.464 ± 0.071
M30	Sr/Y-90	0.474	0.471 ± 0.043
S60	Sr/Y-90	0.458	0.470 ± 0.052
M150	Sr/Y-90	0.407	0.457 ± 0.011
H150	Sr/Y-90	0.406	0.410 ± 0.023
M30	Uranium	0.483	0.385 ± 0.061
S60	Uranium	0.466	0.500 ± 0.041
M150	Uranium	0.416	0.421 ± 0.026
H150	Uranium	0.415	0.438 ± 0.034
Cs-137	Tl-204	0.493	0.441 ± 0.075
Cs-137	Sr/Y-90	0.484	0.402 ± 0.056
Cs-137	Uranium	0.493	0.406 ± 0.087

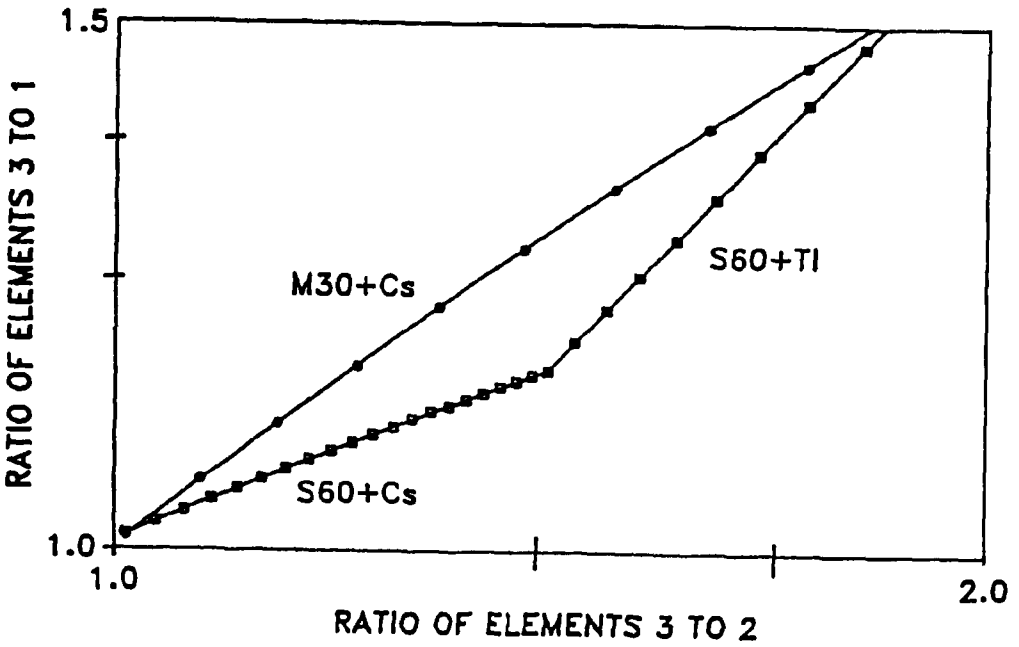

Figure 1

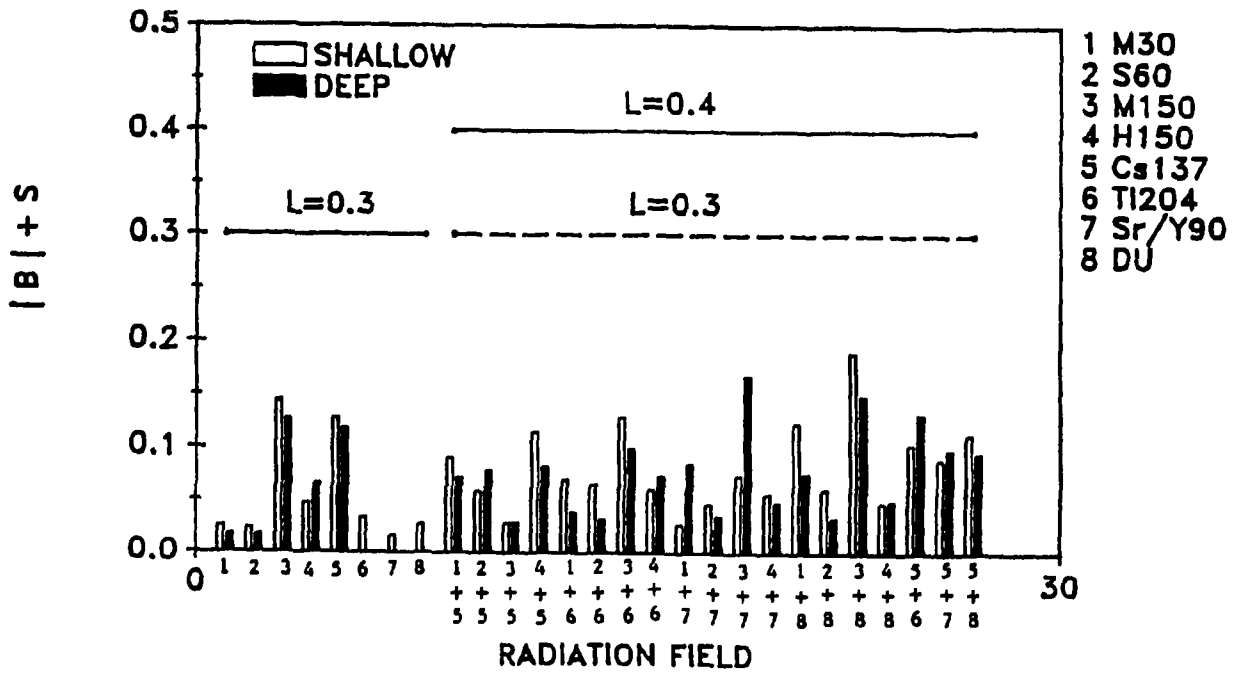

Figure 2