PROCEEDINGS SERIES

ADVANCES IN PHYSICAL AND BIOLOGICAL RADIATION DETECTORS

PROCEEDINGS OF A SYMPOSIUM ON
NEW DEVELOPMENTS IN
PHYSICAL AND BIOLOGICAL RADIATION DETECTORS
HELD BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Radiation dosimetry is a fundamental part of all radiation protection work. The measurements are made with a variety of instruments, and health physicists, after professional interpretation of the data, can assess the levels of exposure which might be encountered in a given area or the individual doses received by workers, visitors and others at places where the possibility of radiation exposure exists. The types of radiation concerned here are photon radiations, ranging from soft X-rays to gamma rays, and particulate radiations such as β-rays, α-particles, protons, neutrons and fission fragments. The type of technique used depends not only on the type of radiation but also on such factors as whether the radiation is from a source internal or external to the body.

Radiation dosimetry is not only used at nuclear facilities; it has diverse applications, for example in determining doses when radiation sources are employed for medical diagnostics and therapy, in safeguarding workers in any industry where isotopes are used, and in assessing the effect of both naturally occurring and man-made radiations on the general public and the environment. The advances of modern technology have increased the variety of sources; an example can be given from colour television, where the high potential necessary in certain colour cathode-ray tubes generates a non-negligible amount of X-rays.

The Symposium on New Developments in Physical and Biological Radiation Detectors was one of a continuing series of meetings in which the International Atomic Energy Agency furthers the exchange of information on all aspects of personnel and area dosimetry. The Symposium was devoted in particular to a study of the dose meters themselves — their radiation-sensitive elements (both physical and biological), their instrumentation, and calibration and standardization.

Several speakers suggested that the situation in the standardization and calibration of measuring equipment and sources was unsatisfactory, and saw an important role for the Agency in furthering international intercomparison studies. This would in particular help the developing countries who were not able to set up specialized standards laboratories, while providing a check for all Member States on the reliability of quoted measurements and their associated accuracies.

The final section on biological dosimetry evidenced the growing interest in this topic. The use of physical dosimeters has certain shortcomings: it is, for example, difficult to determine the dose received by one part of the body from a reading of a dosimeter worn on another part. It is possible that biological changes in the body could be used as a direct measure of the radiation insult received, without the need for interpolating data obtained by physical dosimeters. Biological dosimetry is, however, already being used a a "null indicator" in cases of suspected high exposure. This section is rounded off by a brief discussion on general topics related to biological dosimetry.

The Symposium was attended by 170 participants from 29 Member States and 5 international organizations. The papers are given in full together with the discussions.

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H. FRANÇOIS (France)
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LUMINESCENCE AND EXOELECTRON DOSIMETRY IN PERSONNEL MONITORING *

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Abstract

LUMINESCENCE AND EXOELECTRON DOSIMETRY IN PERSONNEL MONITORING.

The acceptance of luminescence (especially thermoluminescence) dosimeters for routine γ- and β-ray monitoring has been progressing in a number of establishments, and the development of automatic read-out equipment will no doubt accelerate this process. A number of useful dosimeter phosphors are available for this application; however, lithium fluoride continues to be the most widely employed. In the area of neutron dosimetry, luminescent dosimeters have not been so successful, because they are insensitive to fast neutrons. Various methods have been tried to overcome this deficiency, and these are discussed. It is pointed out that it should be possible to achieve a useful luminescent dosimeter for registering the combined γ-ray + intermediate neutron dose by adjusting the thermal-neutron/γ-ray response ratio. Several recent attempts at achieving a more acceptable fast-neutron response are discussed, including one based on an exoelectron emission dosimeter.

1. Introduction

In preparing this paper I was faced with a choice between a rather broad and detailed survey of the virtues and faults of the principal luminescence and exo-electron dosimetry systems, and a selective discussion of certain problem areas. I found myself attracted to the latter approach because the former has been done so many times before, and I feel that more can be gained at this time from reviewing specific aspects in depth. In particular I will devote most of this paper to a discussion of the neutron dosimetry problem, since this has been the area where luminescent dosimeters have been least successful so far.

2. Thermoluminescence Dosimeters

Lithium fluoride [1] is clearly in the lead among the TL phosphors, as evidenced by the fact that about half of all the TLD publications abstracted during 1969 dealt with that material (see Fig. 1). This results partly from its early start as a commercially available product, but there are other reasons as well. Table I summarizes some important characteristics of the principal TLD phosphors. It will be seen that only lithium fluoride, lithium borate [2], and beryllium oxide [3] approximate tissue in atomic number, thus not requiring a shield to avoid over-response for γ rays below 100 keV. Of course the techniques are well known for designing such shields, to provide a nearly constant response per

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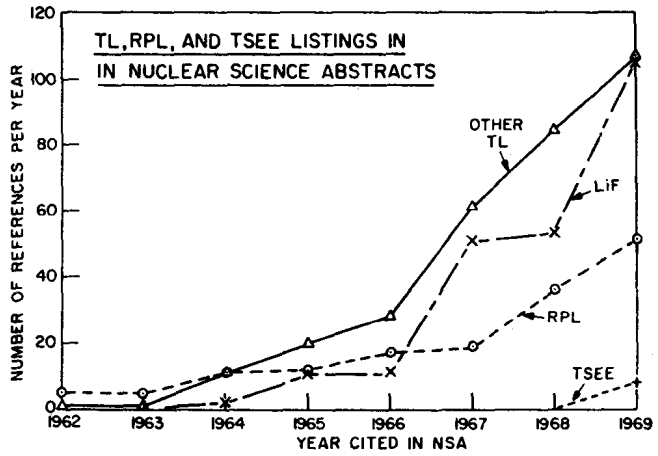

FIG. 1. Scientific publications on thermoluminescence (TL) radiophotoluminescence (RPL), and thermally-stimulated exoelectron emission (TSEE) dosimetry, as cited by the Nuclear Science Abstracts Subject Index for 1962-1969. References including specific mention of lithium fluoride thermoluminescence are represented by the "LiF TL" curve; "Other TL" includes all the others.

TABLE I. RESUMÉ OF CHARACTERISTICS OF PRINCIPAL TLD PHOSPHORS

Phosphor	Low Z	Utility at 10 mR	Low Fading	Low n_{th} Response	High n_{th} Response
LiF TLD-700	X	X	X	X	
LiF TLD-100,600	X	X	X		X
CaF_2:Mn		X	X	X	
CaF_2 (Fluorite)		X	X	X	
CaF_2:Dy		X		X	
$Li_2B_4O_7$:Mn	X	X	X		X
$CaSO_4$:Mn		X		X	
BeO	X	X	X	X	
$2MgO \cdot SiO_2$:Tb		X	X	X	

roentgen from 1.2 MeV down to about 40 keV for the TLD phosphors of higher atomic number. However such shielding has disadvantages in the context of personnel monitoring: (a) increased unit cost, (b) increased size and weight, (c) exaggerated dependence of response upon direction of incident radiation, especially at low γ-ray energies, and (d) elimination of β-ray response, whether desired or not.

Again referring to Table I, these three low-Z phosphors are all sensitive enough to measure 10 mR by normal procedures, and their signal-storage stability is generally adequate for personnel monitoring [3-6], although Scarpa [7] has reported 20% fading in three days with one specific type of hot-pressed BeO.

Lithium borate shows a strong response to thermal neutrons, comparable with that of LiF TLD-100. It probably cannot be manufactured sufficiently free from ^{10}B to allow its use for γ-ray dosimetry in the presence of thermal neutrons without the dose contribution from the latter being greatly exaggerated. Since low thermal-neutron sensitivity has been regarded as an important requirement for many personnel monitoring applications [8], lithium borate would be handicapped in this respect. However it has been studied in a number of laboratories [6,9, 10] and found to be generally competitive with LiF, and even to offer certain advantages: (a) ease of phosphor manufacture in the laboratory, with resulting economy, although it is also commercially available, and (b) even less x-ray energy dependence than LiF. Hence for personnel β-γ dosimetry in the absence of significant thermal neutron fields, one may expect lithium borate to be more widely used in the future, especially where initial material cost is a strong consideration. Its possible use in mixed n-γ fields will be discussed later.

3. The Neutron Dosimetry Problem

Having brought up the subject of neutron response, I would like now to pursue the matter at some length in an attempt to clarify the significance of the neutron data quoted in the literature for various TL dosimetry phosphors. It seems to me that the most important part of the problem of finding neutron dosimeters among the luminescent materials is to define our goals. Otherwise we may fail to recognize useful neutron capability even when it exists.

Table II summarizes the thermal neutron response of several phosphors, as measured in three different laboratories [3,7,11]. It is interesting to note that CaF_2:Mn, fluorite, and BeO all have even less thermal neutron sensitivity than does LiF TLD-700. Ayyangar and his co-workers [11] have clearly demonstrated that this phosphor typically contains about five times as much ^6Li as the 0.007% originally specified by the manufacturer, which accounts for its slightly elevated thermal neutron sensitivity.

The significance of the data in Table II for personnel dosimetry applications can best be seen with the aid of Figs. 2A and 2B. In Fig. 2A "small" masses of LiF(TLD-700), LiF (TLD-100), BeO, and soft tissue are shown being irradiated in free space by a combined field of 4×10^{10} thermal neutrons per cm^2 and 1.04 roentgens of ^{60}Co γ rays. The usual charged-particle-equilibrium considerations apply.

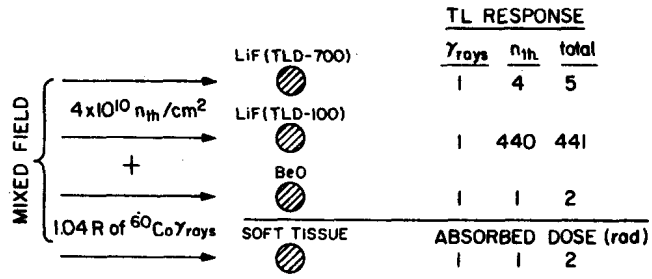

FIG. 2A. Response of TL dosimeters to mixed γ-ray + thermal neutron fields in free-space geometry. TL dosimeter-reader is calibrated for each type of dosimeter to give a meter reading of one scale unit for ^{60}Co γ-ray exposure of 1.04 R, or a kerma of 100 erg/g in a small mass of tissue (= 1 rad under charged-particle-equilibrium conditions).

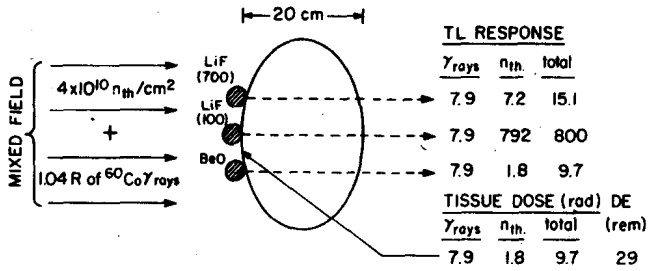

FIG. 2B. Response of TL dosimeters to same mixed fields as in 2A, but worn on the front of the body. TL dosimeter-reader calibration is the same as in Fig. 2A, for each type of dosimeter. Mean quality factor for n_{th} capture in the $^{14}N(n,p)^{14}C$ reaction is assumed to be 11.9 [12], to compute the dose equivalent (DE). The ^{60}Co γ-ray dose in tissue at the surface is 1.1 rad.

In the soft tissue the absorbed dose due to the ^{60}Co γ rays is 1 rad. The dose deposited by the thermal neutrons, primarily by secondary protons from the $^{14}N(n,p)^{14}C$ reaction, is also 1 rad. The 2.2-MeV γ rays from the $^{1}H(n,\gamma)^{2}D$ reaction essentially all escape without local energy deposition. Thus the total tissue dose is 2 rad.

The TL dosimeters in Fig. 2A are each assumed to be calibrated to give a response of one scale unit per 1.04 R of ^{60}Co γ rays (i.e., 1 tissue rad in free space). Table II then tells us how they will respond to the thermal neutrons, and thus what their total readings should be in the mixed field (assuming no synergism takes place). The spread of thermal neutron response values shown in Table II for LiF(TLD-100) and BeO suggests variability in the degree of self-shielding and of sample impurities, respectively. We will assume the average values 4.4×10^{2} for LiF(TLD-100) and 1.0 for BeO, for present purposes. It will be seen that the BeO dosimeter then gives nearly the correct value for the total n_{th} + γ absorbed dose in tissue, with the LiF TLD-700 2.5 times higher, and the

TABLE II. THERMAL NEUTRON RESPONSE OF TLD PHOSPHORS

^{60}Co γ-ray tissue dose in rad required to give the same TL response as $4 \times 10^{10} n_{th}/cm^2$ (≈ 1 rad in small tissue mass).

Phosphor	Tochilin et al.[3]*	Ayyangar et al.[11]**	Scarpa [7]†
LiF TLD-700	4.0	3.8	4.0
LiF TLD-100	6.1×10^2	4.4×10^2	2.6×10^2
CaF_2:Mn	2.2	0.8	-
CaF_2 fluorite	-	-	0.64
CaF_2:Dy	-	2.8	-
$Li_2B_4O_7$:Mn	-	2.2×10^2	-
BeO	0.76	-	0.68-2.8

*Peak height measurements **Integrated light output up to 300°C

†Integrated light output up to 400°C

TLD-100 much higher still, because of its natural 7% ^{6}Li content. Note also that the TLD-100 and TLD-700 dosimeter readings, together with the knowledge of the relative sensitivity of each for γ rays and thermal neutrons, allows the straightforward algebraic calculation of the D_γ and $D_{n_{th}}$ values in tissue.

Next we consider (in Fig. 2B) what these dosimeters would read when worn on the front of a body exposed to the same mixed field of radiation. The thermal neutron flux density, and the associated γ-ray field due to the $^1H(n,\gamma)^2D$ neutron-capture reaction, are taken from the measurements of Boot and Dennis [12]. The TL reader calibration is the same, for each type of dosimeter, as in Fig. 2A. It will be seen that the γ-ray dose in tissue at the surface is about eight times greater than for the small tissue sample, primarily due to capture γ rays. Backscattering from the body nearly doubles the flux density of thermal neutrons, and the tissue dose they produce, at the surface.

The BeO dosimeter still provides a direct measure of the total surface dose in tissue, while the LiF(TLD-700) dosimeter reads about 3/2 of this value. Neither phosphor has negligible response to thermal neutrons, as called for by Saxby and White [8]; instead their thermal neutron response is comparable with that for γ rays. However the γ-ray dose may be easily deduced from simultaneous measurements made with a dosimeter of relatively greater thermal-neutron sensitivity, such as LiF TLD-100.

4. Luminescent Dosimeters for Intermediate-Energy Neutrons + γ Rays.

Let us now explore the possibility of adjusting the ^{6}Li/^{7}Li ratio in LiF (e.g., by mixing some LiF TLD-100 powder in with TLD-700) to make a personnel dosimeter which would read