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HIGH RADIATION DOSE LUMINESCENT AND OPTICAL DOSIMETRY SYSTEMS

by

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ABSTRACT

An investigation of the characteristics of radiophotoluminescent, thermoluminescent and optical absorption dosimeters has indicated that they are suitable for use as radiation damage dosimeters in high energy particle accelerators. An introduction is given to their respective modes of operation and to their integration into a practical dosimetry system.

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1. INTRODUCTION

During the operation of high energy particle accelerators and storage rings, the bombardment of targets with proton beams as well as unintentional beam losses during machine operation result in complex and intense radiation fields. In high beam loss areas of presently running accelerators the annual accumulated dose can be as high as 5×10^8 rad, and this will undoubtedly increase when future accelerators of higher energy and beam intensity come into operation. The absorbed doses at the hot and quiet radiation areas along the beam line at the CERN 28 GeV Proton Synchrotron (PS) and its associated pair of Intersecting Storage Rings (ISR) differ by up to a factor of 10^3 with a further factor of 10^3 between the beam line and the tunnel walls. A dosimeter for use in such an environment must therefore possess a very large dose range.

Dosimetry is performed on a routine basis around the CERN accelerators and storage rings in order to maintain a constant check on radiation damage to machine components. The result of radiation damage up to 10^5 rad is apparent in electronic components⁽¹⁾ and glasses such as semiconductors, photomultiplier tubes, TV camera lenses and scintillator blocks. Further up the dose range damage becomes increasingly important for organic materials^(2,3) used, for example, as insulators in magnet pole face windings, magnet coils and electrical cables, O-rings in vacuum systems and cooling water hoses.

It is desirable that a dosimeter responds to a radiation field in the same way as the numerous materials under investigation. This cannot be completely achieved in practice because, although glass and crystalline dosimeters suffer from lattice defect formation in the same way as glass and semiconductor components, organic materials undergo molecular degradation. However, for engineering applications, an optimum condition can be achieved by using a glass dosimeter with a low effective atomic number (Z) which will be a good match to the (Z) of the organic materials. These requirements are satisfied by glass radiophotoluminescent (RPL) dosimeters. Crystalline thermoluminescent (TL) and glass and plastic optical absorption dosimeters are suitable for providing an independent check on the RPL dosimeters.

An introduction is given to the pertinent electronic mechanisms involved in these processes and to their application to radiation dosimetry. The requirements of a good radiation damage dosimeter for accelerators are then considered in relation to the restrictions that they place on the dosimeter materials.

2. LUMINESCENT DOSIMETERS⁽⁴⁻⁷⁾

2.1 Electronic Mechanisms of Luminescent Dosimetry Systems.

2.1.1 RPL Dosimeters

Crystal lattice imperfections are always present due to thermodynamic considerations, one of the most common in alkali halides being occasional positive and negative ion vacancies situated throughout the

lattice. These defects play a significant role when the crystal is exposed to ionising radiation. For example, halide ion vacancies are regions of localised positive charge and can therefore trap electrons stripped from lattice ions by ionising radiation. Such an electron-vacancy system or colour centre, termed an F-centre for an alkali halide, possesses discrete allowed energy levels. The absorption of a photon of the appropriate frequency does not destroy the centre by electron liberation but allows excitation and radiative transitions between these energy levels. The constant intensity of luminescent emission resulting from constant optical stimulation is a function of the radiation dose absorbed by the crystal. This is the basis of the radiophotoluminescent (RPL) radiation dosimetry system. An advantage of such a system is that read-out of the dosimeter does not destroy the stored dose information, thereby enabling repeated read-out of the dosimeter to be performed.

The use of pure crystals for RPL dosimeters is not practicable due to the poor reproducibility and low luminescent efficiency of the F-centres. Doping of crystals allows the formation, on irradiation, of centres which are reproducible, stable and luminescent, examples of such systems being $\text{NaCl:Ag}^{(8)}$, $\text{NaCl:Pb}^{(8)}$ and a range of phosphate glasses: $\text{Ag}^{(9-11)}$ as shown in Table 1. For a practical dosimetry system, the reproducible preparation of the material in large quantities and its fabrication into various geometries favours glass as a more suitable matrix than crystals.

2.1.2 TL Dosimeters^(12,13)

The exposure of many undoped and doped alkali halide⁽¹⁴⁻¹⁶⁾ and metalpolyborate⁽¹⁷⁾ crystals to ionising radiation induces peaks into their optical absorption spectra and are due to the trapping of charge carriers at defect energy levels. These peaks have been shown to be independent of the doping ions because of the similarity in their shape and photon energy position for a given crystal doped with various elements⁽¹⁸⁾. Subsequent heating of such a crystal completely bleaches these radiation induced peaks and is interpreted as the thermal excitation of charge carriers from their trapping states. These charge carriers then make transitions to the appropriate continuous energy band and migrate through this band before undergoing radiative recombination with doping ions situated in the energy band gap. The luminescent emission increases as more charge carriers are thermally released, reaches a maximum, then decreases as the traps become progressively emptied. Figure 1 shows the resulting luminescent output as a function of temperature, the "Glow Curve", for a typical LiF crystal.

The area under, or the height of, the glow curve is a function of the absorbed radiation dose and this forms the basis of the thermoluminescent (TL) dosimetry system. A disadvantage of a TL as opposed to an RPL dosimeter is that it can be read only once, as reading destroys the stored dose information.

2.2 RPL Materials

The composition of some of the principal RPL dosimeters are given in Table 1, with Tables 2 and 3 summarising their characteristics which need to be considered for operational purposes.

2.2.1 Dose Range and Dose-Rate Dependence

Unfortunately, there are no adequate primary or absolute dosimeters available for calibrating Megarad dosimeters in the complex radiation fields of particle accelerators. However, a large number of different dosimeters, including RPL dosimeters, have been irradiated under various exposure conditions in pure gamma sources (^{60}Co and ^{137}Cs), nuclear reactors (ASTRA at Seibersdorf, DIDO at Harwell and SILOE at CEN Grenoble) and high energy accelerators (NIMROD at RHEL and the CERN PS⁽¹⁹⁾). The gamma source doses were measured mainly by chemical dosimeters and the reactor doses mainly by calorimeters. After analysis of the experimental data, the majority of the Toshiba FD-R1-1 RPL dosimeters were found to agree within a factor of two with the other dosimeters, and Figure 2 shows the resulting optimal calibration curve for the Toshiba FD-R1-1 dosimeters.

Dose is a linear function of luminescent emission intensity for Toshiba FD-R1-1 rods up to approximately 10^4 rad, above which dose the glass becomes increasingly coloured⁽²⁰⁾ ranging from pale yellow at 2×10^4 rad to dark brown at 10^8 rad. Due to the form of the calibration

curve the dosimeters must be divided into two batches, uncoloured ones to the low dose branch and the coloured ones to the high dose branch. It is recommended that a second type of dosimeter, e.g. optical absorption, is used to aid the interpretation of glasses whose absorbed doses fall in the least sensitive area of the calibration curve, i.e. between 10^4 and 5×10^5 rad.

The total accumulative dose absorbed by RPL glass dosimeters does not depend on the dose rate within a large range. Toshiba⁽²¹⁾ quote a range from 6×10^{-3} rad h⁻¹ to 6×10^9 rad h⁻¹ for their complete range of RPL glasses, which agrees with our experimental observations.

2.2.2 The Response of RPL Dosimeters to a Mixed Gamma-Neutron Field^(22,23)

In order to obtain a better insight into the response of RPL dosimeters to a well defined mixed gamma-neutron field, a series of Toshiba FD-R1-1 rods was exposed in the Standard Neutron Irradiation Facility (SNIF) at the ASTRA Reactor, Seibersdorf-Vienna. The rods were divided into three groups shielded by respectively 1 mm thick plastic as this is used for routine packaging purposes, 1 mm thick Cd to provide a thermal neutron shield and 1 mm thick Sn in order to match the energy response characteristics of the Cd. A second series of plastic covered FD-R1-1 rods was exposed in a ⁶⁰Co γ-source for comparison purposes. The irradiation conditions are given in Table 4.

⁶⁰Co γ-Irradiations

The expected absorbed dose in the glass rods is taken as 0.88 of

the dose measured by a Frické dosimeter from consideration of the mass energy coefficients⁽²⁴⁾ of FDI glass and water.

Reactor Irradiations

The expected absorbed dose in the glass rods is defined as :

$$D_e = \sum_i D_i^g \cdot f_i^{\text{let}}$$

where D_i^g = absorbed dose in the glass from radiation of type i,

f_i^{let} = the efficiency (RPL signal per unit energy imparted in the glass) of the radiation of type i as compared to ^{60}Co γ -rays.

The components of the reactor field are a) gamma-rays, b) thermal neutrons and c) fast neutrons.

a) Gamma-Rays

$$D_{e\gamma} = D_{\gamma}^g \text{ as } f_{\gamma}^{\text{let}} = 1.$$

b) Thermal Neutrons

The main thermal neutron reactions to be considered in the calculation of the glass thermal neutron sensitivity are given in Table 5a. Due to the small size of the glass rods (6 mm x 1 mm $\emptyset$), most of the γ -rays escape without being absorbed, therefore the predominant portion of the thermal neutron response is induced by the α and β -particles and the recoil nuclei. The various components of the calculated absorbed dose in FD-R1-1 dosimeters due to thermal neutrons are shown in Table 5b.

c) Fast Neutrons,

We have found the fast neutron response of FD-R1-1 dosimeters to be in the order of 0.5 % of that of ^{60}Co γ -radiation, which is in good agreement with previously published values⁽²⁵⁾.

Luminescent intensity values of the reactor irradiated FD-R1-1 dosimeters are plotted against the expected gamma and thermal neutron absorbed dose in Figure 3. A good correspondence exists between this independent set of results and the curve obtained from the ^{60}Co γ -irradiated FD-R1-1 dosimeters, whose absorbed dose was measured by Frické dosimeters. This indicates a correct assessment of the expected gamma and thermal neutron dose absorbed by the dosimeters.

2.2.3 Stability of RPL Emission

The increase and decrease of RPL emission intensity are both functions of temperature and time, and therefore have to be considered with respect to the interpretation of RPL intensity into absorbed dose value.

The principle process to be considered is that of RPL build-up. A considerable fraction of the electrons liberated from normal lattice ions by ionising radiation are captured in shallow traps to form centres which absorb exciting ultra violet light but do not subsequently fluoresce. In an Ag^+ doped phosphate glass, these electrons are subsequently thermally released from such traps and become retrapped at Ag^+ ions to form stable Ag^0 luminescent centres⁽⁸⁾. The effect, as shown in Figure 4,

for FD-1 RPL glass, is a gradual increase of RPL emission intensity as a function of time.

A second, though very small contribution of RPL build-up in phosphate glass, is the β -particle emission from the reaction $^{31}\text{P}(n,\gamma)^{32}\text{P}$ which has a half life of 14.3 days. Reactor irradiated Toshiba FD-R1-1 rods, which contain 33.44 % ^{31}P , were counted for induced β activity and, within ± 30 %, a linear relationship was found between count-rate and thermal neutron fluence.

It can be seen from Figure 4 that at a storage temperature of 25° C, approximately two days are required for the maximum luminescent intensity to be reached for dosimeters irradiated to 10^4 rad. However, this time interval can be reduced by supplying heat energy to the lattice in order to accelerate the thermal ionisation of the unstable intermediate traps.

Tests have been conducted to determine a suitable stabilisation schedule for dosimeter glasses which have received doses in the Megarad range. A series of Toshiba FD-R1-1 rods, with absorbed doses in the range 5×10^3 to 10^6 rad, were read out 10 days after irradiation and again 7 days later. The post irradiation storage temperature was ambient. A final read out was made the same day after annealing the dosimeters for 1.5 h. at 110° C. The effect of RPL build-up on the luminescent emission versus dose curves is shown in Figure 5. The emission intensity as a function of time for dosimeters with the same range of absorbed dose is shown in Figure 6. For doses up to 5×10^4 rad, annealing for 15 min. at

110°C results in approximately maximum emission intensity, but for similar results at higher doses the time must be extended to 1.5 h. If the annealing time is prolonged, a fading of emission intensity is observed for all dose values, while for doses of 10^5 rad and upwards, a slight increase occurs again after 6 h. annealing. When the annealing temperature is raised to 160°C (see Figure 7), the emission intensity increases initially in the same manner as for the 110°C anneal. For doses of 10^5 rad and above, the increase continues, although at a slower rate, if the annealing time is extended. However, such an annealing schedule, to maximise the emission intensity, is undesirable as the occupied electron traps corresponding to low absorbed doses will be subjected to thermal bleaching after approximately 15 min.

The fading of the RPL emission intensity as functions of time and temperature is utilised to regenerate the dosimeters for further use. Details concerning the regeneration⁽²⁶⁾ and post regeneration cleaning procedures⁽²⁷⁾ for the dosimeters is given in Table 3.

2.2.4 Pre-Dose

The natural fluorescence from an unirradiated RPL material, when illuminated with UV light, is termed the "Pre-Dose"⁽²⁸⁾. By the use of ultra-pure materials, from which those elements which exhibit luminescence in the orange-red spectral region such as Mn^{2+} , Fe^{3+} and certain lanthanides⁽⁸⁾ have been removed, and by careful control of the preparation techniques, it is now possible to produce RPL dosimeters with an extremely

low pre-dose, as shown in Table 3. Further sources of pre-dose are the remanent radiation induced absorption bands after regeneration, and surface contamination.

2.3 TL Materials

Comprehensive surveys of the development of materials suitable for TL dosimetry have been published in the last decade⁽²⁹⁻³³⁾, therefore in Tables 1, 2 and 3 only the composition and principal characteristics of the TL dosimeters used at CERN are given.

2.3.1 The Response of TL Dosimeters to a Mixed Gamma-Neutron Field

The response of TL dosimeters to a gamma field⁽³⁴⁾ differs widely to that of a neutron field. Data concerning thermal neutron reactions with Li has been considered in Tables 5a and b, and Table 6 gives additional information concerning the isotopic ratios in LiF, which is one of the main TL materials. ⁷Li has a negligible thermal neutron capture cross-section (1.4 Barn), therefore ⁷LiF will respond primarily only to the gamma component of a mixed gamma-thermal neutron field. The ratios for the response of TLD-100* and TLD-700* to ⁶⁰Co γ-rays and thermal neutrons, defined as

$$m = \frac{\text{response per neutron tissue rad}}{\text{response per } ^{60}\text{Co } \gamma\text{-ray tissue rad}} \quad (35)$$

and with the tissue dose per unit thermal neutron fluence taken as 2.4×10^{-11} rad⁽³⁶⁾ are shown in Table 7.

* TLD-100, -600 and -700 are trade names of the Harshaw Chemical Company.

The response of LiF to fast neutrons⁽³⁷⁾ (rad rem⁻¹) is negligible, as shown in Table 7 for TLD-100 and TLD-600 exposed to a fast neutron fluence of 4×10^9 n cm⁻² (about 150 rem)⁽³⁸⁾. This obvious insensitivity accounts for the difficulty in using this system directly for fast neutron dosimetry without the aid of a neutron moderating material in order to slow down the fast neutrons to thermal energies.

2.3.2 The TL Glow Curve and Fading

It is important to consider the fading of the TL glow curve when choosing the most suitable area to use for dose measurement. Fading refers to the loss of stored signal when a TL dosimeter is maintained at room temperature after irradiation. At a constant post-irradiation temperature the number of remaining trapped electrons (holes) related to a given glow curve peak as a function of time is given by :

$$n = n_0 \exp [-s \exp(-E/kT) t] \quad (39)$$

where: n_0 = initial number of trapped electrons (holes),

E = electron (hole) thermal activation energy (eV),

s = attempt to escape frequency (t⁻¹).

Usually, electrons (holes) are trapped at more than one defect level, and fading is due to the release of charge carriers from only a proportion of these traps. Traps which fade quickly, i.e. those which have a lower thermal activation energy, are those normally associated with the lower temperature glow curve peaks.

TL LiF possesses five main peaks in its glow curve structure, as shown in Figure 1, which are associated with traps having thermal activation energies of 0.9, 1.04, 1.11, 1.19 and 1.35 eV, respectively⁽⁴⁰⁾. After irradiation, the peaks decay with the following approximate half lives, 5 min., 10 h., 0.5 yr., 7 yrs. and 80 yrs.⁽⁴¹⁾, which indicates that peaks four and five are the most suitable for dosimetry purposes.

3. OPTICAL ABSORPTION DOSIMETERS

The irradiation of glass produces vacancies and interstitials, together with a large number of free electrons which may become trapped at negative ion vacancies. Such processes create centres, as discussed in section 2.1.1, with a typical optical absorption of their own. If the absorption is in the visible spectral region, an impression of colour is given. The exposure of polymers to ionising radiation also induces colour changes due to electron trapping, as in glass, together with the formation of conjugated double bonds.

In order to utilise this change in colour as a function of absorbed dose, the change in optical density is measured spectrophotometrically. Initial absorption is defined by an unexposed reference dosimeter, and different dose ranges can be covered by using dosimeters of different thicknesses or by changing the wavelength of the measuring light to correspond to a spectral region of different optical absorption.

Both glass⁽⁴²⁾ and plastic⁽⁴³⁾ systems are used at CERN for supplementary radiation damage dosimeters, details of which are given in Tables 1, 2 and 3.

4. CONCLUSIONS

A radiation dosimeter for use around high energy particle accelerators for routine survey and radiation damage purposes should possess the following characteristics : Have a dose range of at least six decades, be independent of dose rate from 10^2 rad h⁻¹ upwards, have an overall accuracy of dose measurement to within a factor of two, and respond to a radiation field in a similar manner as do both inorganic and organic materials. Other general requirements are that it should be small, solid, re-usable and that the read-out system be simple to operate. Combinations of RPL, TL and optical absorption dosimeters satisfy these conditions.

Of the two luminescent dosimetry systems, RPL is more advantageous than TL as an overall radiation damage dosimeter. Apart from its dose range extending to higher values, 5×10^8 rad as compared to 10^5 rad for the TL, its mode of luminescence allows repeated read-out of a dosimeter should this be necessary. However, it is advantageous to adopt a combination of RPL and TL systems in order to provide an independent check on low dose measurements. Pairs of RPL and optical absorption dosimeters are necessary in the range 10^4 to 5×10^5 rad due to the possibility of misinterpretation of RPL emission intensity into dose because of the insensitivity of the calibration curve in the region of its maximum.

The final conclusion of this report is that RPL dosimeters, with the support of subsidiary TL and optical absorption systems, provide a suitable method for radiation damage dosimetry around particle accelerators.

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		CHEMICAL COMPOSITION %											
ELEMENT		Li	Be	B	O	F	Na	Mg	Al	P	K	Ca	Ag
Atomic No. Z		3	4	5	8	9	11	12	13	15	19	20	47
<u>RPL DOSIMETERS</u>													
TOSHIBA	FD 1	3.67		0.85	53.71				4.64	33.44			3.67
	FD 3	3.58			53.51				5.11	34.53			3.27
	FD 4	3.48			52.74				4.97	34.04			4.77
	FD 5				51.34		8.94		6.08	33.33			0.52
	FD 6				51.40		6.60	1.96	5.49	33.16			1.41
	FD 7				51.16		11.00		6.12	31.55			0.17
CEC	1	2.50	0.50		52.30		4.70		3.50	33.60			2.90
	5	3.20	0.05		52.13		4.70		3.50	33.52			2.90
	31	0.70	1.70		52.80		4.80		3.50	34.10			2.40
	32 - 36	2.50	0.50		52.60		4.70		3.50	33.80			2.40
<u>TL DOSIMETERS</u>													
	LiF	26.75				73.24							
	CaF ₂					42.81						57.19 + Dy	
<u>OPTICAL ABSORPTION</u>													
SCHOTT	PDG-11			0.93	49.68			2.41	4.76	30.76	9.96+1.5% residuals		
PERSPEX *	HX	Polymethylmethacrylate + 0.15 % benzoyl peroxide + 1.00 % residual monomer											
RED PERSPEX *	4034	"	"	+ selected dyes									

* Trade name of ICI LTD.

TABLE 1 : Chemical composition of RPL, TL and optical absorption dosimeters

DOSIMETER	DIMENSIONS (mm)	DOSE RANGE (RAD)	MEASURING LIGHT λ (nm)	READING INSTRUMENT	EMISSION SPECTRA λ (nm)
<u>RPL</u>					
TOSHIBA FD-R1-1	6 x 1 $\emptyset$	1 - 5 x 10 ⁸	365	TOSHIBA FGD-6	610
<u>OPTICAL ABSORPTION</u>					
SCHOTT PDG-11	36 x 12 x 5	1.6 x 10 ⁴ - 5 x 10 ⁵	510	BECKMAN	
	36 x 12 x 1.5	1.4 x 10 ⁵ - 2 x 10 ⁷	510	DB - GT	
PERSPEX HX	40 x 10 x 3	10 ⁴ - 2 x 10 ⁶	305	"	
HARWELL RED PERSPEX	30 x 11 x 3	5 x 10 ⁵ - 5 x 10 ⁶	640	"	
<u>TL</u>			TEMPERATURE AT GLOW CURVE MAX. °C		
TELEDYNE DISCS					
⁷ LiF - TEFLON	12.7 $\emptyset$ x 0.4	10 ⁻² - 10 ⁵	210	CON-RAD 7100	
⁶ LiF - TEFLON	11.3 $\emptyset$ x 0.4	10 ⁻² - 10 ⁵	210	"	350 - 600 Maxima = 400
HARSHAW SOLID CHIPS					
TLD - 600, ⁶ LiF	0.32 x 0.32 x 0.09	10 ⁻² - 10 ⁵	210	"	
TLD - 700, ⁷ LiF	0.32 x 0.32 x 0.09	10 ⁻² - 10 ⁵	210	"	
TLD - 200, CaF ₂ :Dy	0.32 x 0.32 x 0.09	10 ⁻³ - 10 ⁵	140	"	460 - 600 Maxima = 480, 580

TABLE 2 : Dosimeters currently used at CERN - Characteristics (1).

DOSIMETER	POST IRRADIATION STABILIZATION	POST IRRADIATION REGENERATION	PRE-DOSE	POST IRRADIATION FADING	CLEANING
TOSHIBA FD-R1-1	Doses $< 5 \times 10^4$ rad Either 110 °C for 15 min. Or 25 °C for 2 days Doses $> 5 \times 10^4$ rad Either 110 °C for 1.5 h. Or 25 °C for 10 days	370 ± 10 °C for 1.5 h. + 12 h. cooling	Few rad to 200 rad Depends on irradiation history. Measure prior to low dose measurement. 1 rad for new glasses.	1 % per 3 months at 25 °C. Exposure to sunlight accelerates fading.	Ultra-sonic agitation immersed in 5 % detergent solution : 4 min., tap water : 1 min., distilled water : 1 min., pure alcohol : 1 min.
LiF	To eliminate glow curve peaks 1, 2 and 3 80 ± 5 °C for 16 h. ⁽⁸⁾	To restore background and sensitivity ⁽⁸⁾ 80 ± 5 °C for 16 h.	Eliminated by post irradiation regeneration.	Negligible for peaks 4 and 5 (Fig. 1)	-
SCHOTT PDG-11	120 °C for 10 min.	380 ± 10 °C for 10 h. + 12 h. cooling	Negligible in usable dose range.	Up to 25 % in 1st 24 h. at 25 °C.	As for RPL
PERSPEX HX		Discard after use	-	10 % per month for 1st 2 months.	No, prepacked
RED PERSPEX 4034	Pre-irradiation exposure in water for 2 months at 35 °C eliminates effect of air and water content.	Discard after use	-	5 % in 1st 10 days	No, prepacked

TABLE 3 : Dosimeters currently used at CERN - Characteristics (2)

Fast Neutron Flux ($E > 1$ MeV)	5.95×10^9 n/cm ² sec.
Thermal Neutron Flux	4.20×10^9 n/cm ² sec.
Fast Neutron Dose Rate (CH)	48.0 rad/sec.
Gamma Dose Rate (CH)	4.7 rad/sec.
Cadmium Ratio (Au Foils)	2.14
Temperature	~ 30 °C
Irradiation Medium	Air

TABLE 4 : Main characteristics of SNIF reactor position⁽¹⁾

REACTION	ENERGY Q (MeV)	ABUNDANCE (%)	n_t CAPTURE CROSS SECTION (BARNs)
${}^6\text{Li}(n,\alpha){}^3\text{H}$	4.78 ($\alpha = 2.05$, ${}^3\text{H} = 2.73$)	${}^6\text{Li} = 7.4$	${}^6\text{Li} = 945$
${}^{10}\text{B}(n,\alpha){}^7\text{Li}$	2.90 ($\alpha = 1.90$, ${}^7\text{Li} = 0.60$, $\gamma = 0.40$)	${}^{10}\text{B} = 19.6$	${}^{10}\text{B} = 4017$
${}^{107,109}\text{Ag} + n \rightarrow {}^{108,110}\text{Ag} \xrightarrow{\beta,\gamma} {}^{108,110}\text{Cd}$	$\bar{\beta} = 2.00$	${}^{107}\text{Ag} = 51.8$ ${}^{109}\text{Ag} = 48.2$	${}^{107}\text{Ag} = 30$ ${}^{109}\text{Ag} = 84$
α half life = 24 sec. β " " = 2.4 min.			

TABLE 5a : Thermal neutron reactions with Li, B and Ag

ABSORBING COMPONENT	DOSE (${}^{60}\text{Co}$ γ -rad $\text{cm}^2 n_t^{-1}$)
${}^6\text{Li}$	1.68×10^{-8}
${}^{10}\text{B}$	1.48×10^{-8}
${}^{107}\text{Ag}$	7.67×10^{-11}
FD1 rods neglecting Ag	3.16×10^{-8}
Cd covered FD1 rods	1.05×10^{-8} ($\frac{1}{3}$ value of plastic covered rods)
Equivalent γ dose with $f_{nt}^{\text{LET}} = 0.2^{(22)}$	
Plastic covered FD1 rods	6.32×10^{-9}
Cd covered FD1 rods	2.10×10^{-9}

TABLE 5b : Absorbed dose in Toshiba FD-R1-1 glass dosimeters due to thermal neutrons

PHOSPHOR	Isotopic Ratio %	
	${}^6\text{Li}$	${}^7\text{Li}$
TLD - 100 Li natural	7.5	92.5
TLD - 600 Conc. ${}^6\text{Li}$	95.6	4.4
TLD - 700 Pure ${}^7\text{Li}$	0.001	99.99

TABLE 6 : Isotopic ratios of Li in LiF

DOSIMETER	$m = \frac{\text{response per } n_t \text{ tissue rad}}{\text{response per } {}^{60}\text{Co } \gamma\text{-tissue rad}}$	RESPONSE (rad/rem) to fast neutron fluence $4 \times 10^9 \text{ n cm}^{-2}$
TLD - 100	1.46×10^3	0.005
TLD - 600	-	0.010
TLD - 700	5.3	-

TABLE 7 : Response of LiF to thermal and fast neutrons

Fig. 1 TL glow curve of LiF at a heating rate of 2°C s^{-1} .

Fig. 2 Accelerator radiation field calibration curve
for Toshiba FD-R1-1 glass dosimeters.

Fig. 3 RPL signal as a function of expected gamma and thermal neutron dose for FD-R1-1 dosimeters irradiated in a reactor field.

Fig. 4 RPL Build-Up in Toshiba FDL glass as a function of post-irradiation storage time.

Fig. 5 The influence of storage and thermal treatment on
RPL emission intensity of Toshiba FD-R1-1 dosimeters.

Fig. 6b

The RPL luminescent emission from ^{137}Cs γ -irradiated Toshiba FD-R1-1 dosimeters as a function of storage time at 110°C .

Fig. 7a

Fig. 7b

The RPL luminescent emission from ^{137}Cs γ -irradiated Toshiba FD-R1-1 dosimeters as a function of storage time at 160°C .