A STANDARDIZED METHOD FOR MAKING NEUTRON FLUENCE MEASUREMENTS BY FISSION FRAGMENT TRACKS IN PLASTICS. A SUGGESTION FOR AN EMERGENCY NEUTRON DOSIMETER WITH RAD-RESPONSE

S. PRÊTRE,* E. TOCHILIN and N. GOLDSTEIN
U.S. Naval Radiological Defense Laboratory, San Francisco, California 94135

Abstract—A neutron detector is described which consists of a fission foil (^{232}Th, ^{235}U, ^{238}U, ^{237}Np or ^{239}Pu) in contact with a plastic track detector. These detectors were exposed to reactor neutrons and to monoenergetic neutrons with energies between 1.0–18 MeV. Fission fragment tracks registered in the plastic were selectively etched by a hydroxide and counted in an optical microscope. For thick foils of fissionable metals the sensitivity of the system was found to be $(1.16 \pm 3\%) \times 10^{-5}$ $\frac{\text{fission fragment tracks}}{\text{neutron} \cdot \text{barn}}$ which is in good agreement with theoretical calculations. This sensitivity is independent of the fissionable element used, independent of the neutron energy, fairly independent of the material chosen for tracks registration (plastics, glass, mica) and of etching conditions. Since the (n,f) cross-sections are accurately known for most neutron energies, the above constant can be used for standardized measurements of neutron fluences. An application to emergency neutron dosimetry is suggested. The fissionable material must be readily available and have low specific activity while the (n,f) reaction cross section should follow the $\frac{\text{rad}}{\text{n/cm}^2}$ curve for tissue. As first compromise, natural thorium is suggested to measure the "proton-part" of the neutron dose (above 1 MeV). The second compromise is an alloy made of natural thorium and 0.5% (by weight) of natural uranium. Using the technique of track counting, these dosimeters have a practical range between 5 rad and 30,000 rad. To avoid track counting, a direct read-out method using thin Mylar film was investigated. This plastic is opaque in the deep ultra-violet (below 3000Å), and the etching of fission fragment tracks in this plastic film produces holes. Neutron dose is determined by the amount of UV light passing through the etched film.

A. Measurements of Neutron Fluence

INTRODUCTION

A method by which tracks from heavy nuclear particles can be observed visually in materials such as mica, certain glasses and plastics has been described by Fleischer, Price and Walker.[1-5] These solid state nuclear track detectors have already found wide application in many fields including neutron dosimetry. The neutron detector consists of a fission foil in contact with a nuclear track detector. Fission fragments produced by neutron interactions penetrate the detector producing trails of radiation damage. The trails can be chemically etched in a reagent which selectively creates hollow channels or tracks along the damaged regions. The number of tracks per unit area can be counted in an optical microscope and correlated with neutron fluence.[6-8]

Earlier measurements at this Laboratory indicated that, for thick fission foils, the track

* Permanent address: Federal Institute for Reactor Research, Health Physics Division (SU), 5303 Würenlingen, Switzerland.

density produced in mica, certain plastics and glasses could be equated to neutron fluence by a constant, weighted by the fission cross section of the foil material. This suggested that a standardized method for measuring neutron fluence could be developed. The present study investigates over what limits and to what accuracy such measurements can be made.

EXPERIMENTAL MEASUREMENTS

Fission foils thicker than the maximum range of fission fragments in fission materials (about 13 microns) were used primarily in the neutron detector. The thick fission foils consisted of 0.01 in. ^{232}Th, ^{235}U and ^{238}U. The relative sensitivities of thin fission foils and a Mg-Th alloy containing 4 percent ^{232}Th by weight were also established. The thin fission foils of ^{235}U, ^{238}U and ^{237}Np were of mass thickness of about one mg/cm^2 of isotope deposited on a nickel backing over a $\frac{3}{4}$ in. diameter circle. Alpha particle autoradiographs established that the material was uniformly deposited over the active area. Six ^{239}Pu foils weighing approximately 0.02 mg and deposited over a $\frac{1}{2}$ in. diameter circle were found to be highly non-uniform. Small areas of uniform activity were found on three of the plaques. An aperture covering all but the uniform region allowed the ^{239}Pu foils to be used in some experiments.

Two plastic foils, Lexan* and Mylar,† were used as nuclear track detectors. Most of the track counting measurements discussed in this section were obtained with Lexan mainly because of its clear background and the easy discrimination between tracks and non-tracks. Whenever thin detector material was required (see Section B), Mylar films were used. Tracks of good quality were obtained with a solution of potassium hydroxide (KOH) at a concentration of 28% and a temperature of 60°C. Sodium hydroxide which has often been used with Lexan was found to produce less controllable etching along with some undesirable background effects. A typical fission fragment track etched with KOH is represented in Fig. 1. Selective etching is seen to take place along the trail of radiation damage. In both Lexan and Mylar the directional etching proceeds at a rate of approximately 0.55 μ/min. At the same time the surface is being removed at a rate of about 0.05 μ/min. The ratio of track to surface etching speed (eleven for the two plastics) provides a method of expressing the selectivity of this etching process.[9] Figure 2 depicts the formation of a track as a function of developing time while Fig. 3 describes the etching of fission fragment tracks as a function of etching time.

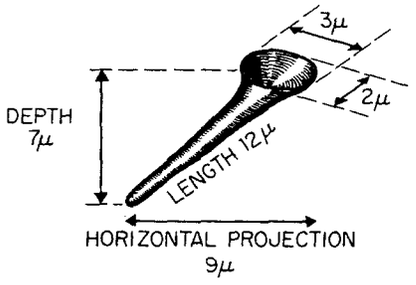

FIG. 1. Typical fission fragment track in plastic etched with KOH.

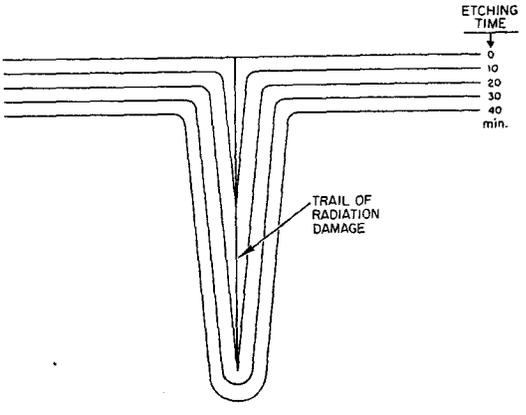

FIG. 2. Cross-sectional view of a typical track after different etching times. In this example, the best etching time is 20 min. With longer etching, the track will no longer increase in length, but only in width.

A regular optical microscope at a magnification of 430 power was used for track counting whenever the track density ranged from 10^4 to 10^6 tracks/cm^2. Optimum etching time was found to be dependent on track density as shown

* General Electric Company, Pittsfield, Mass.
† E. I. duPont de Nemours and Company, Wilmington, Del.

in Fig. 4. For track densities less than 10^4 tracks/cm^2 maximum etching time was used which produced thick tracks that could be readily identified at lower microscope magnifications. For an upper limit it was possible to count as many as 10^7 tracks/cm^2 where minimum etching times and higher microscope magnifications are required for positive track identification. Figure 5 shows the difference in track structure produced when Lexan with a heavy track density is etched for 5 min compared to a lower track density etched for 40 min.

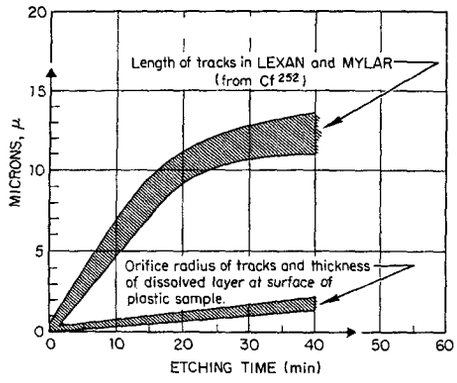

FIG. 3. Etching kinetics of fission fragment tracks in KOH at a concentration of 28% and a temperature of 60°C. In Lexan and Mylar, directional etching speed along the trail of radiation damage is approximately eleven times faster than the volume dissolution speed.

Selective etching with a faster rate at high track density is observed in Lexan. This is particularly noticeable when tracks begin to overlap as in Fig. 5(A). Only a small fraction of all tracks will be seen when Lexan with low track density is etched for 5 min as compared to almost complete track recognition above 10^6 tracks/cm^2. This effect did not occur with any of the other track detectors investigated during this study.

Optimum etching time for Lexan will vary over wide limits whenever track counting is used to determine fast neutron fluence. However if track counting is replaced by other detecting methods in which track length or track width become critical (i.e. densitometry, photometry, etc.) then etching conditions must be more rigidly controlled. Use of the photometric technique described in Section B required several refinements to the simple etching apparatus

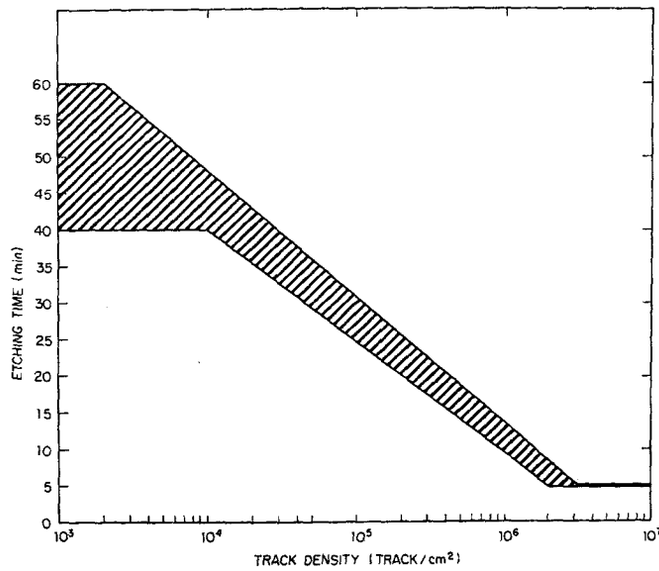

FIG. 4. Optimal etching time for track counting in Lexan. The solution is KOH 28% concentration at 60°C. Recommended etching procedure: etch 5 min to determine approximate track density; continue etching up to the optimal etching time.

used for track counting. The refinements are given as recommendations for others who may have similar requirements:

1. The volume of etching solution should be large in order to minimize changes in concentration during the etching process.

FIG. 5. Fission fragment tracks in Lexan. (A) High track density ($\sim 4 \times 10^6$ cm^{-2}) and short etching time (5 min). (B) Lower track density ($\sim 10^5$ cm^{-2}) and longer etching time (40 min).

2. The concentration of etching solution should be monitored to insure that changes do not occur either because of evaporation or contamination.

3. A cover should be placed over the etching bath to keep down evaporation. For some types of plastics the cold etching technique described by Benton and Collver[10] could be used. (This method was found to improve track definition in cellulose nitrate.)

4. The etching solution should be continuously agitated in order to avoid the formation of density and temperature gradients. Ultrasonic agitation is recommended over other methods.

5. Samples should be placed vertically rather than horizontally in the solution to avoid the formation of small bubbles at the lower surface which may interfere with track formation.

Neutron exposures were made at the USNRDL 2 MeV Van de Graaff accelerator, the Fast Burst Reactor, White Sands Missile Range, New Mexico (WSMR reactor) and the Aerojet-General Nucleonics Industrial Reactor, San Ramon, California (AGNIR reactor). Monoenergetic neutrons were obtained at the accelerator ranging from 1.9 to 5.2 MeV from the D$(d,n)^3$He reaction and from 12 to 18 MeV from the T$(d,n)^4$He reaction; exposures were also made with 1.0 MeV neutrons from the T$(p,n)^3$He reaction. A calibrated long counter was used to measure neutron fluence up to energies of 5 MeV while a sulfur threshold detector was used at energies of 12 MeV and above. The sulfur (n,p) cross section as well as the (n,f) cross-sections for the different foils was taken from the summary cross section data tabulated by Barrall and McElroy.[11] Measurements at the accelerator, made over a wide range of energies, determined the relative efficiency with which Lexan will detect fission fragments at different bombarding neutron energies.

The WSMR reactor has been calibrated with a fission foil technique developed by Hurst *et al.*[12] where the residual gamma ray fission product activity is counted. ^{239}Pu, ^{237}Np and ^{238}U fission detectors are placed in a spherical shell of ^{10}B and together with ^{32}S are exposed to fission neutrons. In this case an intercomparison study (Table 3) was made with the Hurst system and our fission foil-Lexan detectors. A similar intercomparison has recently been described by Kerr and Strickler.[13]

RESULTS AND DISCUSSION

Our preliminary experiments using nuclear track detectors of mica, plastics, microscope glass slides and silver-activated phosphate glass indicated a sensitivity for thick fission foils approximately 10^{-5} fission fragment tracks/

Table 1. *Measured Sensitivity of Thick Fission Foils in the Neutron Energy Range from* 1.0–16 MeV

Fission foil	Neutron energy [MeV]	Sensitivity fission fragment tracks/ neutron · barn
^{232}Th	2.6	1.15×10^{-5}
	3.8	1.19
	5.0	1.14
^{235}U	1.0	1.17×10^{-5}
	2.0	1.23
	5.2	1.13
^{238}U	1.9	1.12×10^{-5}
	2.0	1.14
	2.6	1.07
	3.8	1.20
	5.0	1.11
	5.2	1.19
	12–16 (8 points)	1.17 ± 4.5%
Weighted average		1.16×10^{-5}

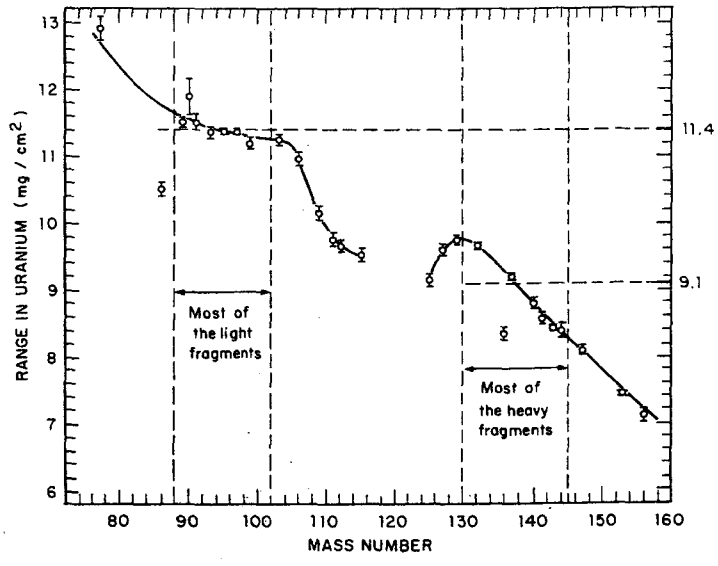

FIG. 6. Integral ranges of fission products of ^{235}U measured in uranium metal (Niday[14]).

neutron·barn independent of neutron energy. Becker's more systematic investigation of fission track detection in silver-activated phosphate glass gave a value of 1.3×10^{-5} fission fragment tracks/neutron·barn with an accuracy of $\pm$ 10%.[8] One objective of the present report was to determine this value for Lexan with sufficient accuracy to allow its use as a direct method for measuring thermal and fast neutron fluence.

A summary of measurements with monoenergetic neutrons from the Van de Graaff accelerator is found in Table 1. Given are the neutron energy, type of foil material and the measured sensitivity in fission fragment tracks/neutron·barn. A weighted average of 1.16×10^{-5} fission fragment tracks/neutron·barn with standard error of 3% was obtained.

Thermal neutron measurements were made at the thermal neutron column of the AGNIR reactor with two groups of uranium foils, one containing 378 ppm ^{235}U and the other 3600 ppm ^{235}U. A cadmium ratio of greater than 100 was obtained at the point of exposure. Measurements made in a Cd shield established that 4% of the tracks from the 378 ppm ^{235}U foil was from fast neutron contamination in the thermal column. With this correction the thermal neutron fluence obtained with the two sets of foils agreed within experimental error. Simultaneous measurements made with gold foil monitors gave values 10% higher than indicated by the ^{235}U fission foils. This difference is within the limits of accuracy of the two measurements.

Measurements by Niday[14] giving the ranges of fission products in uranium metal have been reproduced in Fig. 6.[15] From this data it is possible to calculate the neutron sensitivity of thick fission foils. Consider a uranium target of 1 cm² area and a thickness R equal to the range of fission fragments. This target has $\frac{NR}{A}$ atoms/cm². Thus the number of induced fissions will be:

$$\frac{N}{A} \cdot \frac{R_L + R_H}{2} \cdot r = 2.6 \times 10^{-5} \frac{\text{fissions}}{\text{neutrons} \times \text{barn}}$$

where R_L is the range of light fission fragments in uranium (11.4×10^{-3} g/cm²); R_H is the range of heavy fission fragments in uranium (9.1×10^{-3} g/cm²); N is Avogadro's number (6.025×10^{23} atoms/mole); A is the atomic weight of uranium metal (238.1 g/mole); r is a conversion factor (10^{-24} cm²/barn).

Referring to Fig. 7, if one fission occurs at

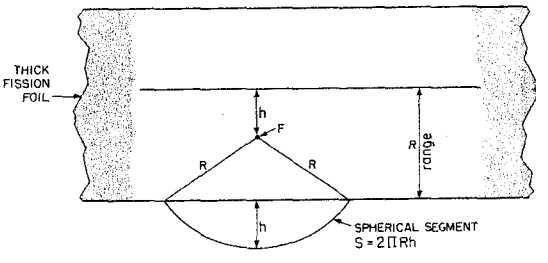

FIG. 7. Geometry factor for thick foils. One fourth of all fission fragments produced within the thickness R, will emerge at the surface.

point F (producing two fission fragments) the probability that one fission fragment will emerge at the lower surface is:

$$\frac{2\pi Rh}{4\pi R^2}$$

Assuming a uniform distribution of the fission events within this foil, the total geometry factor is

$$\frac{\int_0^R 2\pi Rh \cdot dh}{\int_0^R 4\pi R^2 \cdot dh} = \frac{1}{4}$$

The number of fission fragments which will emerge out of this thick fission foil is:

$$\frac{N}{A} \cdot \frac{R_L + R_H}{4} \cdot r = 1.3 \times 10^{-5} \frac{\textit{emerging fission fragments}}{\textit{neutron} \times \textit{barn}}$$

However, not all emerging fission fragments will produce observable tracks. Assuming that the etching process dissolves approximately 1μ of the plastic surface (see Fig. 3) and that the tracks

must be at least 1μ in depth to be observed, we see that, in order to produce an observable track, the emerging fission fragments must have enough energy to penetrate at least 2μ deep in the plastic.

It can be shown that some 90% of the emerging fission fragments will fulfill this requirement. Thus the sensitivity of a thick fission foil can be approximated as:

$$1.17 \times 10^{-5} \frac{\textit{fission fragment tracks}}{\textit{neutron} \times \textit{barn}}$$

registration efficiency is 100%). This was found to be the case for both Lexan and Mylar.

Figure 8 gives the range of neutron fluence over which the different foils were found usable. The solid bars indicate the optimum counting region for each detector while the dashed regions to the right and left indicate the range of upper and lower limits over which track counting to an accuracy of $\pm$ 5% can still be obtained. One could of course identify tracks below the arbitrarily assigned lower limit of 1000 tracks/cm^2 but the times required to obtain good

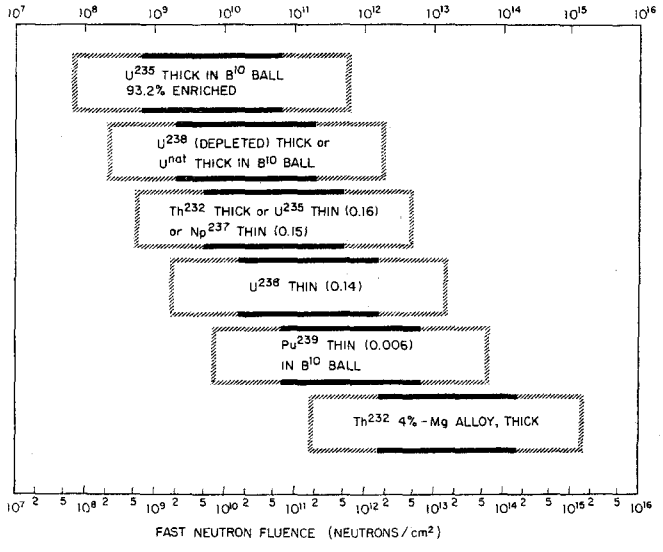

FIG. 8. Range of fast neutron fluence measured with fission foils. The lower limit of measurable track density is given as 10^3 cm^{-2} while the upper limit is 10^7 cm^{-2}. The number given in parenthesis for thin foils is the thickness factor as defined in the text.

Excellent agreement is seen to exist between the experimental and calculated values. Since the (n,f) cross-sections are accurately known for most neutron energies the above constant can be used for standardized measurements of neutron fluences. The advantages offered by using a thick foil are that this constant can be directly applied independent of fission material (^{235}U, ^{238}U and ^{232}Th), independent of neutron energy (no difference was observed between slow fission processes and fast fission processes) and reasonably independent of the track registration material (assuming that the fission fragment counting statistics tend to become excessively long. The upper counting limit will be that point where overlapping tracks begin to make positive track identification difficult.

A "thickness factor" was determined for the fission foils less thick than the maximum range of the fission fragments and has been included, where applicable, in Fig. 8. The relative counting sensitivity of the thin fission foils was established for the monoenergetic neutrons from the NRDL Van de Graaff and compared to the value obtained for thick fission foils. The ratio of the two values is the "thickness factor" and when

Table 2. Calculated Average (n,f) Cross-Sections for Neutron Energy Intervals Measured with Threshold Detectors

Element and corresponding (n,f) average cross-section (barns)	Energy interval (MeV)			
	(ϕPu–ϕNp) 0.01 to 0.60	(ϕNp–ϕU) 0.60 to 1.5	(ϕU–ϕS) 1.5 to 3.0	(ϕS) >3.0
^{235}U	1.5	1.2	1.3	1.2
^{239}Pu	1.7	1.75	2.0	1.9
^{237}Np	0.2	1.2	1.6	1.5
^{238}U	0	0.08	0.5	0.57
^{232}Th	0	0.005	0.11	0.14

combined with the sensitivity factor for thick foils gives a relative sensitivity factor for the thin foil.

The fission foil detectors were also used in an intercomparison study at the WSMR reactor with the standard threshold detector system.[16] Fast neutron fluences were measured by the White Sands group within the four energy regions indicated in Table 2. We have calculated the average fission cross-section of five fission foils in each energy region.[11] These cross-sections were then used to evaluate the neutron fluence above 0.6 MeV with ^{237}Np-Lexan detector and above 1.5 MeV with a ^{232}Th-Lexan detector. Since the thorium foil was exposed bare the sensitivity factor previously determined for thick foils could be directly applied. Additional corrections required for the ^{237}Np foil included a "thickness factor" and a ^{10}B attenuation factor. Results of the intercomparison check is given in Table 3. In both cases the neutron fluence above 3 MeV was independently determined with a ^{32}S(n,p) ^{32}P threshold detector with an assigned effective cross-section of 0.30 barns.[17] Depleted ^{238}U fission foils were exposed together with thorium, but the associated thermal neutron fluence complicated their interpretation.

In any calibrated neutron facility where neutron flux and spectrum have been determined, the sensitivity constant for thick fission foils can also be used for direct measurements of the (n,f) cross-section. An example of such measurements is given in Fig. 9, where the (n,f) cross-section for ^{232}Th was determined between 12 and 18 MeV.[18] Earlier cross-section measurements by Pankratov,[19] over the same energy interval are included for comparison along with the curve drawn through the data points.

Table 3. Intercomparison of Neutron Measurements at the White Sands Missile Range Fast Burst Reactor

Neutron energy	Measured neutron fluence (n/cm^2)			
	WSMR		NRDL	
	61 in.	150 in.	61 in.	150 in.
>0.6 MeV	3.16×10^{11}	1.43×10^{11}	3.18×10^{11}	1.48×10^{11}
>1.5 MeV	0.63×10^{11}	0.26×10^{11}	0.59×10^{11}	0.26×10^{11}

B. A Suggestion for an Emergency Dosimeter with Rad-response

INTRODUCTION

The purpose of an emergency dosimeter is to permit an estimate of any significant radiation exposure which may produce acute biological effects. In most neutron experiments with large animals the midline tissue dose has been used as the reference dose. Bond *et al.*[20] exposed dogs to neutrons of 9 MeV average energy and found an RBE (or QF) of 0.95. Alpen *et al.*[21] made similar exposures with simulated fission neutrons and found a quality factor of 0.9. In both cases the biological effects were compared to that of 250 kVp X-rays. These studies indicate that a dosimeter measuring total midline tissue dose in rads can be directly related to biological effects. One should further note that this is not the case with a detector that records only first collision dose unless additional information on neutron energy is available.

The two major processes by which the body absorbs neutrons is by elastic scattering (the (n,p) reaction) and by thermal neutron capture in hydrogen leading to the $^1H(n,\gamma)D$ reaction. We can thus speak of a "proton-part" and a "gamma part" of the neutron dose. Depth dose curves in tissue giving the neutron and gamma-ray contributions have been calculated by Snyder[22] for neutron energies from thermal to 10 MeV. The absorbed dose in a 30 cm phantom at a depth of zero to 4 cm and at 10 cm is plotted in Fig. 10. If we consider the absorbed dose within this range to be the most significant we see that for neutron energies above 1 MeV the proton dose is predominant while for neutron energies below 0.1 MeV the gamma dose is predominant. Between these energy intervals both components are important.

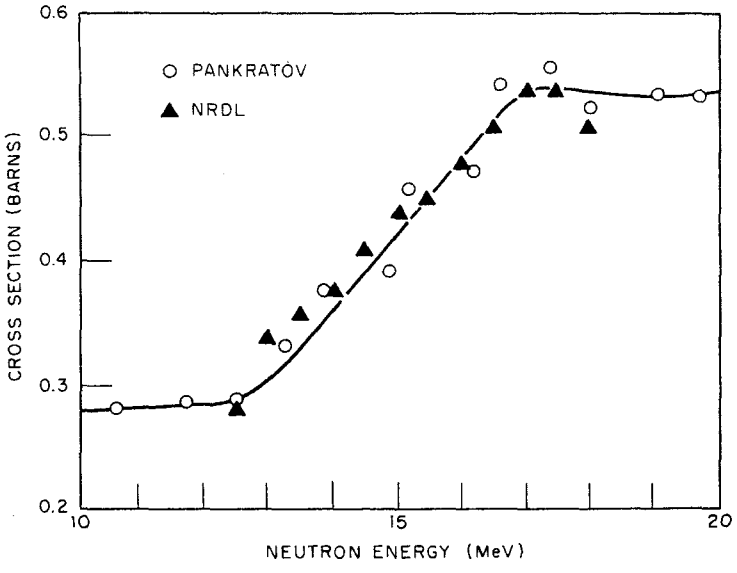

FIG. 9. Fission cross-section of ^{232}Th for neutrons from 12.5–18 MeV measured with Lexan. Earlier measurements by Pankratov[19] are also shown.

The emergency neutron dosimeter considered here is intended primarily for use in the event of a reactor accident or a nuclear explosion. Since it is based on a system of fission foils it is important to know the probable spectrum to be encountered and how the neutron dose is distributed over this spectrum. Braun and Nilsson[23] have examined several representative spectra from infinite homogeneous reactors with different moderators and from a fission plate in a graphite moderator. Ritchie and Eldridge[24] described methods for calculating

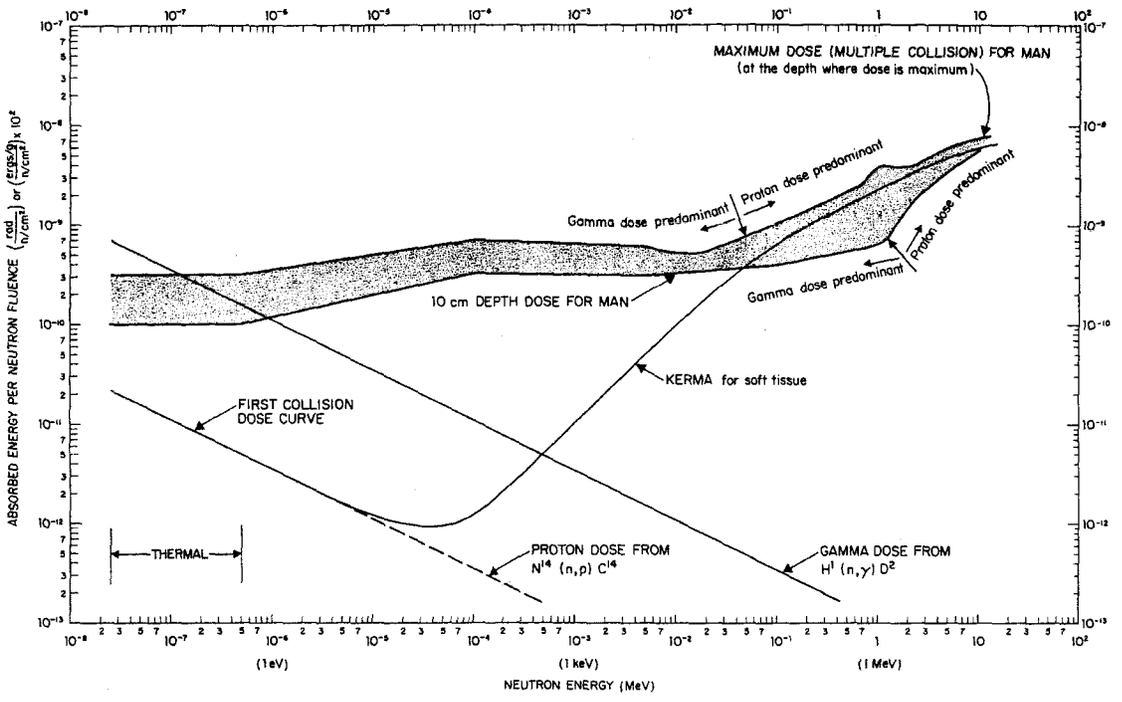

FIG. 10. Absorbed dose in tissue irradiated by neutrons. The depth at which dose is a maximum may be considered to be 4 cm except in the energy region between 0.1–2 MeV. In this region the 4 cm depth dose will be approximately 2/3 the maximum dose. The first collision dose curve is shown for comparison.

neutrons from critical assemblies while Yampolskiy[25] described the probable distribution of neutron dose from fission weapons. While no typical spectrum can be assumed it is possible to say that, except where large masses of non-hydrogenous moderator could exist (> 30 g/cm^2), most of the neutron dose will be from neutrons in the energy range above 0.1 MeV. About 90% of the dose comes from energies less than 4 MeV, 40–60% from energies less than 1 MeV and only about 20% for energies below 0.1 MeV. Under these conditions most of the neutron dose will be in the energy range from 0.1 to 2 MeV.

It should be noted that for a typical fission neutron spectrum approximately half the total midline dose received by the human body will be from capture gamma-rays. Since gamma-ray dosimeters worn on the body will detect this component one already has the capability for recording the gamma portion of the total neutron dose (at the same time there is no way of separating primary gamma dose from neutron produced gamma-rays). The neutron dosimeter should therefore reflect as close as possible the biologically significant radiation dose without remeasuring the gamma contribution and having it registered twice. On the other hand if one could measure the region below 0.1 MeV by matching fission foil response to the midline dose it would be possible to evaluate this gamma-ray contribution and subtract it from the total gamma dose registered by a dosimeter worn on the body.

FISSION TRACK EMERGENCY NEUTRON DOSIMETER

Fission foils in combination with a fission track detector possess many desirable properties to recommend their use as personnel neutron dosimeters. They can be made small and light weight and are completely unaffected by gam-

ma-rays, by environmental conditions or by storage time. Neutron dose can be measured over many orders of magnitude. Where thick foils are used the measured track density can be directly related to neutron fluence. Fission tracks striking the detector leave a permanent record of radiation damage which can be processed at any later time by simple chemical techniques.

While many of the transuranic elements can be used as fission foils practical considerations restrict the choice to readily available materials. This automatically limits present usage to either thorium or natural uranium. However, the fission cross sections of these materials are such that they can be satisfactorily used as emergency neutron dosimeters.

Rad-response of Natural Thorium

In this case we will restrict ourselves to the measurement of the proton part of the neutron dose above the threshold energy of ^{232}Th. To obtain a neutron dosimeter with rad response we require the tracks/cm^2·rad ratio to be constant for all neutron energies. It means that the product of rad·cm^2/n and neutrons/track be independent of neutron energy. In other words, the following three quantities must be proportional: rad·cm^2/n, tracks/neutron and cross-section (barns). Thus a neutron dosimeter will have a rad response if we can match the rad·cm^2/n curve (Fig. 10) with the (n,f) cross-section curve. Assuming that we are only interested in the proton portion of the neutron dose, we see from Fig. 11 that above 1.3 MeV we can match the thorium (n,f) cross-section curve with the rad·cm^2/n curve using a response factor of

$$3 \times 10^{-8} \frac{\text{rad}}{(\text{n/cm}^2)\cdot\text{barn}} .$$

Using the sensitivity obtained in Section A we can rewrite this response factor as

$$390 \frac{\text{tracks/cm}^2}{\text{rad}} .$$

Our minimum and maximum counting criteria of 10^3 and 10^7 tracks/cm^2 give us a practical detection range between 3 and 30,000 rad.

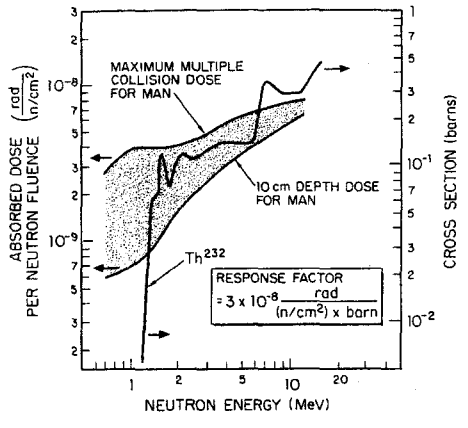

FIG. 11. Response of thorium as an absorbed dose detector. It is assumed that the gamma part of the neutron dose would be detected by usual gamma-ray dosimeters.

Rad-response of a Thorium–Uranium Alloy

If it is important to measure the total absorbed dose from neutrons then we need a fission material having a cross-section curve that will match the rad·cm^2/n curve over all neutron energies.

As a compromise we suggest a thorium alloy containing 0.5% (by weight) of natural uranium (0.5% by weight = 0.3% by atoms). The ratio of ^{235}U atoms to ^{232}Th atoms is thus 1/46000. The (n,f) cross-section for the thorium alloy is plotted in Fig. 12 in a way to best match the midline tissue dose response. One sees that this dosimeter has very low sensitivity in the region 0.1 MeV to 1 MeV which is an important region for fission neutrons. In order to compensate for this deficiency we have given the dosimeter a higher sensitivity above 1 MeV. We assume that $\sim 40\%$ of the fast neutron dose is due to neutrons with $E_n > 1$ MeV, and thus we raise the cross-section curve by a factor 2.5. The response factor becomes:

$$7.5 \times 10^{-8} \frac{\text{rad}}{(\text{n/cm}^2)\cdot\text{barn}}$$

and our sensitivity for the thorium–uranium alloy becomes

$$155 \frac{\text{tracks/cm}^2}{\text{rad}}$$

giving a practical detection range between 6 and 60,000 rad.

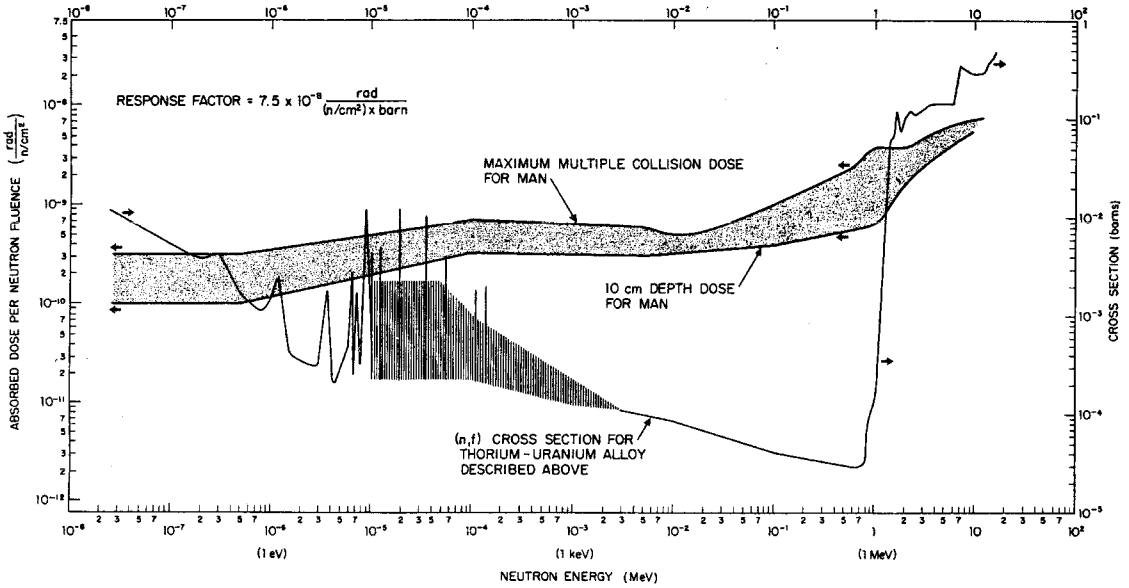

FIG. 12. Response of thorium–uranium alloy as an absorbed dose detector. The (n,f) cross-section for thorium alloy containing 0.5% by weight of uranium is compared to the multiple collision dose curve for neutrons energies from 10^{-8}–10^{2} MeV.

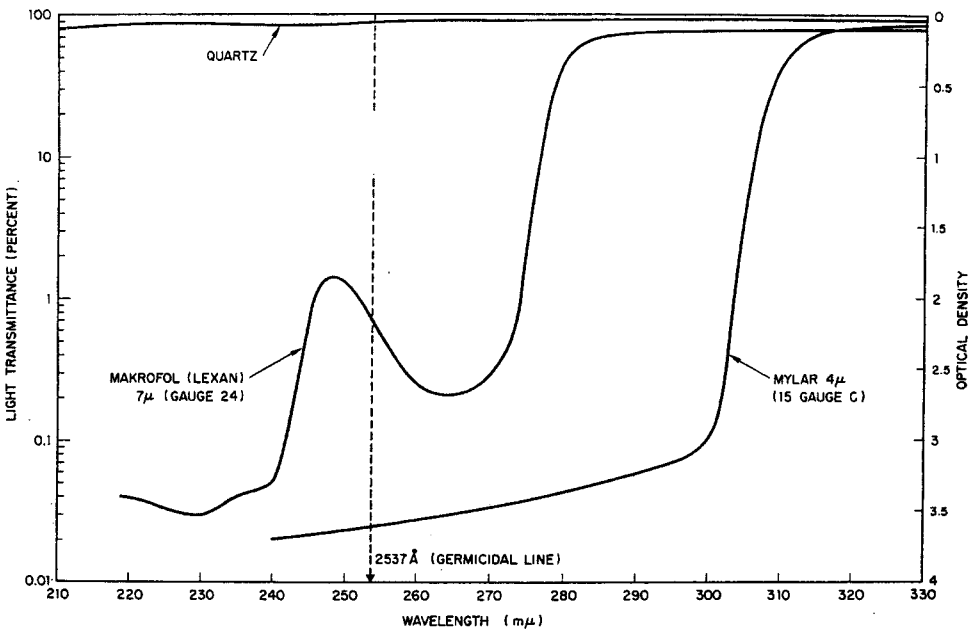

FIG. 13. Transparency of thin plastic foils to ultra-violet light. Measurements were made with a Beckman DU spectrophotometer.

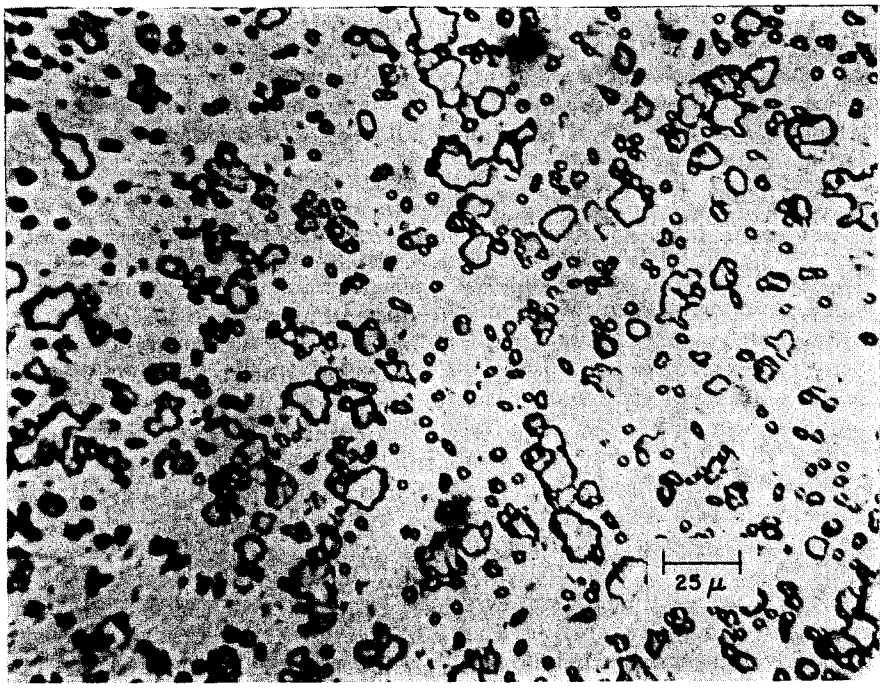

FIG. 14. Holes etched in thin Mylar film. The fission track density was approximately 10^6 cm^{-2} and the etching time was 30 min. in standard KOH solution.

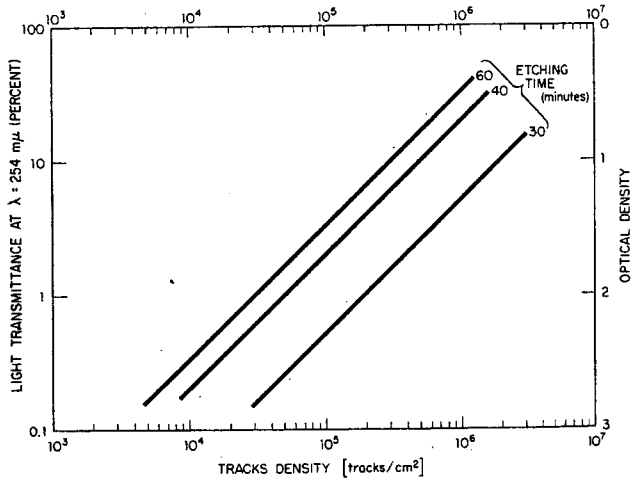

FIG. 15. Transmittance of ultra-violet light (254mμ) through Mylar film exposed to fission fragments and etched in standard KOH solution. The light transmittance is directly proportional to the track density, therefore also proportional to the neutron dose.

NEUTRON DETECTION BY LIGHT TRANSMISSION

Despite the many obvious merits of track counting the process is slow and somewhat tedious. Methods to replace track counting by simpler and more direct measurements have already been described.[6, 8, 26] Another such method is to use a thin opaque plastic film so that the etched tracks will produce holes in the material. The amount of light passing through the film should be proportional to the number of holes. Unfortunately, almost every plastic in very thin layers (4μ–12μ) is transparent to visible light. We discovered only one plastic which was simultaneously thin and opaque (0.5 mil black Tedlar PVF film*) but we could not produce the selective etching in it.

However, plastics such as Mylar, Lexan and Makrofol† are opaque to deep ultra-violet light, even in very thin layers.

Observing Fig. 13, we see that Mylar, even in the thinnest gauge, is more opaque than Makrofol. Mylar is also easier to handle and available in a large variety of thicknesses. We used 15C Mylar 4 microns thick and a working wave length of 2537Å (254mμ) which is called the "germicidal line". The choice of this wave length is based on the easy availability of ultra-violet sources giving most of their energy in that particular wavelength (germicidal lamps).

Etched tracks in thin Mylar (4μ) become holes as illustrated by Fig. 14. Using our standard etching conditions we have found that the light transmittance at 254 mμ is directly proportional to the track density. Figure 15 shows that light transmittance measurements can replace track counting between 5×10^3 and 3×10^6 tracks/cm^2. This track range corresponds to a midline dose between $\sim$ 25 and 10,000 rad. It is thus possible to measure the track density without counting the number of tracks. Unlike track counting, this method requires precise control of etching conditions.

Handling of very thin Mylar film is still a problem. We used concentric rings to mount the Mylar film. Unfortunately preferential etching occurs at the places where the plastic is under strain, and even a relatively short etching time can split the Mylar where it is held between the rings. This difficulty could be eliminated by mounting the plastic film with adhesive on a backing of quartz (see Fig. 13).

* E.I. duPont De Nemours and Co., Wilmington, Delaware.

† Bayer Co., Germany.

CONCLUSIONS

The suggested emergency dosimeter would consist of a fission foil in juxtaposition with a plastic foil. Either thorium or a thorium–uranium alloy could be used as the fission foil. Lexan or any other appropriate detector could be used for track counting while Mylar is recommended for transmitted light measurements. A "germicidal" lamp with an optical filter to eliminate all lines other than 2537Å was found to be a suitable light source.

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DISCUSSION

E. VAN ESPEN (*Belgium*):

The CaF_2 used by MBLE is different from the one commonly called Mn-activated CaF_2.

B. BJARNGARD (*U.S.A.*):

In answer to Dr. Langmead's (rapporteur) question of the light-sensitivity reported by us, the dosimeters had been used before but had not received an accumulated exposure in excess of IR. My opinion is, therefore, that it is a true excitation by light and not a rearrangement of trapped electrons. Similar experiences have been reported in other investigations of LiF. With regard to the different precision attained by us and the British group with LiF-Teflon discs, no influence of the low temperature glow peak is present in our results. This glow peak was minimized in the preirradiation annealing, using 80°C for 2 hr after 300°C for 15 min. Besides, the dosimeters were read out immediately after irradiation. In any case, postirradiation annealing as used by Dr. Ehrlich in one of the papers reported by Dr. Langmead, is the most efficient way to eliminate the low temperature glow peak. I would appreciate it if this point was commented upon by the authors of the other paper concerned.

L. K. BURTON (*U.K.*):

No elimination of the low temperature glow peak was attempted for the measurements recorded. There is some indication that the low temperature glow peak develops only after several irradiation-annealing cycles.

R. L. KATHREN (*U.S.A.*):

Dr. Langmead's comments with respect to not advocating one or another system for personnel dosimetry are well taken. We should endeavour to study both the accuracy and sources of error of all currently used and promising systems. Since untoward effects of environment on film dosimeters have been reported, I would like to inquire of those who reported on comparison studies between film and thermoluminescence systems whether the films used were given appropriate protection from adverse environment. (Apparently those used by Johnson and Attix were not since a faulty air conditioner in their building was stated to be responsible for some spurious effects on film.) A comparison study at our Laboratory indicated reasonably good agreement between film and thermoluminescence dosimeters. However, in a few cases, the TLD read very much higher than the film. This effect, viz. apparently inexplicably high TLD readings, has occasionally been noted in TLD used for other experimental purposes. And, with respect to TLD impregnated in Teflon, studies at our Laboratory also indicated a pronounced reduction in light output per unit dose upon reuse.

J. CAMERON (*U.S.A.*):

I want to comment briefly on several points raised earlier. One of them is the matter of testing or comparing two systems: it is nice to use a new system in practice, but it is almost impossible to make a true test of it, because you are comparing a system, for example thermoluminescence, to film and film has a rather wide inaccuracy in practical use, and the only way you can make a practical test is to do a blind test and to have somebody exposed with the film *and* the new system and to read these out. In the work reported by Dr. Langmead and performed in our laboratory, all of the exposures were unknown. The exposures were made by our health physicist and read out by Suntharalingam. The matter of variability from one laboratory to another can depend upon factors such as the batch of material; this is somewhat variable. The annealing effect is another large variability, for example at the reading of Teflon dosimeters, if you anneal them at 300° for 1 hour, and then anneal them at 80° for about one day, the original response is essentially restored. I think these are the main comments.

G. COWPER (*Canada*):

When Teflon-LiF is used as a finger dosimeter it is required to lie on an approximately cylindrical surface. To be read accurately, it must however lie on a flat surface and must therefore itself be flat to give good heat transfer. Would the authors care to comment on the problem of achieving results which are not subject to error because of this effect?

B. BJARNGARD (*U.S.A.*):

The possible deformation of the discs, as pointed out by Dr. Cowper, is certainly to be taken into consideration when reading them out. Our heating element for the discs has a perforated metal screen attached to a Nichrome planchet, in which the heat is generated. The disc is inserted between the screen and the planchet. Provided the screen is not deformed, it presses the disc to the hot support. No special difficulties result from deformation of the discs if this technique is used.

G. TORI (*Italy*):

Come radioterapista, ho apprezzato molto il valore delle informazioni rese note dai vari sperimentatori. Queste nuove possibilità di accertamento dosimetrico offrono prospettive assai interessanti anche per le applicazioni pratiche sui pazienti in cura e sul personale. Chiedo se, nell'ambito delle determinazioni di confronto fra i differenti sistemi dosimetrici, sono state effettuate prove tra i dosimetri a termoluminescenza (LiF) e quelli a fotoluminescenza, ossia quelli basati sull'impiego di metafosfati misti di Al, Na, ecc., il cui elemento sensibile è rappresentato dall'argento.

K. BECKER (*Germany*):

Es sind sowohl Vergleiche zwischen Film- und Thermolumineszenz-Dosimetern wie auch Vergleiche zwischen Film- und Glasdosimetern durchgeführt worden. Bei letzteren zeigte sich eine gute Übereinstimmung der Glasdosimeteranzeige mit der von Ionisationskammer-Stabdosimetern, dagegen eine schlechte Übereinstimmung mit der Filmdosis. Vergleiche zwischen Glas- und Thermolumineszenzdosimetern sind u. W. in der Praxis noch nicht durchgeführt worden. Aufgrund der dosimetrischen Eigenschaften dieser Systeme wäre jedoch dabei sicherlich mit einer guten Übereinstimmung beider Systeme zu rechnen.

J. BOOZ (*Euratom*):

I want to make a remark on the described comparisons of dose response curves of LiF-dosimeters that had been irradiated with radiations of different energy. I wonder, what might be the influence of the material surrounding the dosimeters during irradiation? The secondary electrons produced by ^{60}Co γ radiation, for instance, are sufficiently energetic to partly penetrate the dosimeters and to contribute to the measured dose, which might be not the case for low energy X-radiation. Therefore, I would like to know what was the surrounding matter that has been used for the measurement shown in Fig. 2.

M. EHRLICH (*U.S.A.*):

At both energies, an electronic-equilibrium layer of polyethylene or an equivalent plastic surrounded the LiF. However, this fact is of no importance to the results shown in Fig. 2, concerned with the change in the shape of the response vs. log exposure curves. A change in the surrounding material would simply cause a shift of the curves parallel to the exposure axis.

W. N. SAXBY (*U.K.*):

Mr. Langmead has given two excellent presentations this morning. I am sure that we all greatly admire this *tour de force*. In his own paper he described how to determine the average dose absorbed by the body, this being the integrated dose over the body volume divided by the body mass.

He did not say why this is a "revealing dose" and in particular he did not say why the integrated dose was chosen. This particular choice needs further justification both from a dosimetric and radiobiological viewpoint and from an ICRP and regulating viewpoint. I would like to have the views of the author and of any radiobiologists or ICRP members who may be present.

W. A. LANGMEAD:

The question is why we wished to know the "average" dose to the body. Recently it has been suggested that certain chromosome aberrations in circulating blood cells are related to the absorbed doses received by the cells. Such a biological indicator of absorbed dose would be helpful in the dosimetry of over-exposed persons and, in the absence of information as to the doses received by the affected cells, the dose value most likely to correlate with the observed chromosome damage is the "average" dose to the body. In the U.K. Atomic Energy Authority, chromosome investigations of this kind are undertaken and hence the need to know the "average" dose to the body of this irradiated person.

K. BECKER (*Germany*):

Einige Autoren haben gefunden, dass die Spaltfragmentregistrierung in Gläsern mit einer geringeren Ausbeute erfolgt als in Kunststoffen. Die ausgezeichnete Übereinstimmung der Empfindlichkeit von $1,2 \times 10^{-5}$ Spuren/Neutron/barn, die Herr Prêtre mit Kunststoffen gefunden hat, mit dem Wert von Unruh et al. für Kunststoffe und dem von uns für Phosphatgläser gefundenen Wert bestätigt unser Ergebnis, dass unter optimierten Ätzbedingungen die Empfindlichkeit für Gläser und Kunststoffe nahe bei 100% liegt.