

## PERSONNEL DOSIMETRY AT ACCELERATOR LABORATORIES

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September, 1975

### I. INTRODUCTION

In the present paper I will attempt to cover a number of more or less complementary topics:

First, I will discuss the various rationales for personnel monitoring practices at accelerator laboratories, including operational considerations which are not directly relevant to dosimetry; second, I will discuss current practices at various laboratories, comparing current realities with our idealized goals, and third, I hope to indicate some possible paths for the future.

Most of what I say here is not original, coming from a number of conference proceedings<sup>1-4</sup> and review articles.<sup>5-7</sup> Many of the points I make here apply equally well to other types of installations; accelerator laboratories are unique primarily in regard to their openness, their large transient populations and the types of radiation present.

### II. ADMINISTRATIVE AND RADIOBIOLOGICAL CONSIDERATIONS

First, let us consider the rationale for monitoring. We know that exposure to large amounts of radiation is known to be harmful, and exposure to lesser quantities might also be deleterious. It is therefore prudent to keep track of what individual exposures are. Thus, we have the first function of radiation monitoring, namely, the measurement and documentation of exposure to potentially hazardous conditions.

Second, if we are even moderately clever and responsible, we also use information on past exposures in order to control future exposures. For example, individuals with high exposures may be assigned different duties to limit their total exposures; jobs which result in large exposures are studied in order to reduce resulting exposures.

Finally, the third function that I see for personnel dosimetry is to tell us what the exposures aren't. That is, a report of a low or minimal exposure for people who should receive no exposure tells us that nothing unusual is happening.

I find it interesting and disturbing that many individuals and groups involved in radiation protection recognize only the first of these reasons for monitoring, namely, record-keeping.

Various scientific bodies, such as the International Commission on Radiological Protection (ICRP) and National Council on Radiation Protection and Measurements (NCRP) have established "maximum permissible occupational exposures".<sup>8,9</sup> These bodies further recommend that individuals be monitored for exposure if it is "likely" that their doses will exceed some fraction--such as one-third--of the occupational limit. Other governmental and regulatory bodies<sup>10</sup> have adopted similar guidelines. Thus, if we were to follow their guidelines, most of the people monitored would have exposures above 50 to 100 mrem per month.

In actual fact, most of the people monitored have monthly exposures close to zero. (At Fermilab, for example, 85% of the people regularly monitored receive a "minimal" exposure each month, and the mean positive exposure is about 60 mrem per month.) I believe this happens for several reasons. First, it is far easier to issue dosimeters to everybody (or everybody entering certain areas) than it is to determine who is "likely" to receive more than a certain exposure. Second, one is protected against errors of judgment if everybody is monitored. And finally, it placates inspectors who become unhappy if they see an unmonitored person even passing through an area of a few mrem/hr. Thus, because of practical considerations, governmental pressures, and public-relation questions, we are monitoring many people who would not be monitored on health physics grounds alone.

The current practice at all major United States accelerators is to monitor anybody who goes anywhere near the accelerator or experimental areas, even though there is no reasonable expectation of his receiving any significant dose under "normal" circumstances.

"Why", asks Klaus Becker, "do we need to monitor to a large extent, and at a relatively high cost people who, as experience has shown, are extremely unlikely ever to receive a significant radiation dose, when for the same price we could indeed increase substantially their average life span by providing them with safety belts for their cars or convince them to smoke less?"<sup>5</sup>

A logical way of dealing with this pressure to monitor everybody would be to use different types of dosimeters for personnel working in "high-risk" and "low-risk" jobs, as suggested by Becker. The former would be sophisticated and read fairly frequently; the latter, inexpensive and read only once or twice a year. In this context, "high risk" could mean either subject to the possibility of a serious radiation accident,

or likely to be exposed to a significant fraction of the "maximum permissible dose". Becker intends the former meaning. However, the latter criterion is used as a basis for assigning monitoring devices by one United States laboratory. Recognizing that most of the monitoring they do is for reassurance purposes, the Stanford Linear Accelerator Center (SLAC) designates such monitors as "accident dosimeters", reads them out once per year, and does not normally enter the results into the person's radiation history file.<sup>14</sup> This saves them a sizable reporting effort under current United States regulations. The employees who are routinely exposed have their dosimeters read quarterly. SLAC is also the only accelerator laboratory to use thermoluminescent dosimeters (TLD's) for routine personnel monitoring. All the other accelerator laboratories treat the casually exposed and the routinely exposed people the same way, and all but one use film for both gamma and neutron dosimetry.

When we examine the sensitivity and accuracy desired (or attainable) in personnel monitoring, we find another contradiction between what logic might tell us should be done, and what is actually being done. In his thought-provoking paper,<sup>5</sup> Becker points out the many logical steps between reading a dosimeter and assigning a dose to a critical organ, or making a meaningful estimate of possible somatic or genetic damage. I will just touch briefly on a few of the questions he raises. For example, how the dosimeter reading relates to the dose received by the critical organ(s) depends on a variety of factors, including where the dosimeter is worn, type, energy and direction of radiation, and which organ is being considered. We may also ask about the various factors needed to make radiobiological sense out of dose measurements. More simply--how well do we know quality (or other modifying) factors and how meaningful are they? Figure 1 shows the RBE for different mammalian systems as a function of LET, and compares an "average" mammalian response with the ICRP Quality Factor recommendations. I would characterize these as conservative educated guesses. To go from an incident neutron flux to a calculation of a quality factor introduces the uncertainties of body composition, and n-p and n-nucleus interactions. Introduction of continuous neutron spectra and bilateral or isotropic irradiations only makes matters even more complicated. (One sometimes wonders at the wisdom or utility of accumulating large collections of numbers which may only be of dubious value.)

Becker then suggests that in normal monitoring situations we recognize and learn to live with the tenuous connection between dosimeter readings and somatic damage, and content ourselves with dosimeters which are stable with time and reasonably reproducible--say  $\pm 20\%$ . (We will see shortly whether such dosimeters in fact exist.) Only in cases of very high and potentially lethal exposures does he feel

it is necessary to have the ultimate in dosimeter sophistication, so that it might be possible to determine the dose to the critical organs to perhaps 25 to 40%. The ICRP recommends<sup>12</sup> that "the uncertainty in assessing the annual dose should not exceed 50% of the recorded dose or 1 rem, whichever is larger"; these two sets of recommendations are generally consistent.

### III. DOSIMETRY TECHNIQUES

#### A. Introduction

Let me start by reviewing the criteria that have been formulated<sup>13, 14</sup> for personnel dosimetry systems. From a technical standpoint, each monitoring element:

- (a) should be sensitive predominately to the type of radiation it is meant to monitor, and insensitive to other types which might be simultaneously present,
- (b) should be stable and its response unaffected by environmental factors,
- (c) should cover the entire dose range desired, preferably linearly,
- (d) should respond well over the entire range of particle energies which will be encountered,
- (e) should provide adequate accuracy.

From an administrative standpoint, the system

- (a) should be easy to use in the field,
  - (b) should have a straightforward readout and dose interpretation,
- and
- (c) should be inexpensive and capable of handling large numbers of people.

With these standards, let us look first at gamma and then at fast neutron dosimetry.

#### B. Gamma Dosimetry

While gamma dosimetry may not be very exciting, it should be remembered that perhaps 90% of the total exposure at accelerator laboratories is due to maintenance of radioactivated machine components.<sup>15</sup> The most widely used method of gamma monitoring is still photographic film. This method has a number of advantages which continue to make it attractive:

1. it has reasonable accuracy and reproducibility ( $\pm 15\%$ ),
2. it has reasonable sensitivity,  $\sim 20$  mrad,
3. it is not expensive--about United States \$1 per unit per reading,
4. it provides a permanent record,
5. examination of the film can provide information concerning conditions of exposure: x or  $\gamma$  rays, frontal or backwards irradiation.

Those who continue to use film may or may not be aware that film is inferior to other means of dosimetry with regard to<sup>5</sup>

1. accuracy and reproducibility,
2. sensitivity,
3. long-term stability under conditions of heat and humidity.

The latter effect, which is widely known for fast neutron dosimetry, also occurs in gamma dosimetry; different authors have had widely varying degrees of success trying to eliminate it with hermetically sealed packaging.<sup>16-19</sup> The systems which are superior to film in these respects are solid-state systems: Thermoluminescent dosimetry (TLD) and Radio-Photo-Luminescent glass (RPL). The former is quite widely used for personnel dosimetry of a number of large facilities. TLD materials ( $\text{CaSO}_4:\text{Dy}$ ) are available which provide sensitivities of a fraction of a mrad. Commercial automated TLD systems exist, although their reliability still leaves something to be desired. Use of a phosphor (such as LiF) with a mean atomic number approximately that of tissue eliminates the need for the various filters needed with film dosimetry. With the small size of TLD materials comes the possibility of dosimeters which are more convenient to wear, and thus less susceptible to loss.

Progress with RPL glass has come more slowly, but recent advances<sup>20</sup> in the understanding and formulation of such glass have made its performance comparable to that of the TLD systems in current use. RPL systems enjoy a greater popularity in Japan than they do in Europe or the United States. For those not familiar with the RPL concept, the dosimeter material is a piece of silver-activated phosphate glass. Under the action of radiation,<sup>21</sup>

- (a) the optical density (opacity) increases over most of the visible and UV spectrum; and
- (b) stable fluorescing color centers are excited in the glass. These emit orange light (5000-7000Å) upon excitation by UV at 3650Å.

Readout is accomplished by stimulating the glass with UV light and measuring the light emitted in the orange region of the spectrum.

As an example of what can be done with this technique, Yokota and others have been able to obtain 15% standard deviation for a 10 mrad  $\gamma$  exposure, and a 2% standard deviation for a 50-mrad exposure, using blocks of glass  $8 \times 8 \times 4.7$  mm<sup>3</sup>. Unfortunately, these glasses are quite sensitive to thermal neutrons because of their Li and B content.

The cost of operating a gamma dosimetry service based on either of these two techniques should be roughly comparable to that for a film service. Operating costs might even be lower, since all the materials are reusable. The crossover point may well depend on the rate at which badges are lost, since their initial cost may be significantly higher than for film badges.

Why, then, have accelerator laboratories lagged behind other institutions in adopting newer and presumably better types of photon dosimetry? I do not believe it is because their health physics personnel have lacked either imagination or the desire to do a better job. Rather, I think it is a combination of two reasons--film has performed sufficiently well under their relatively controlled circumstances to make them reluctant to change, and their neutron dosimetry has kept them tied to film anyway. This brings us to the question of neutron dosimetry.

### C. Neutron Dosimetry

By "neutrons" at an accelerator laboratory I mean fast neutrons, with energies in the multi-MeV range. Figure 2 shows experimentally unfolded neutron spectra from the CERN-LBL-RHEL shielding experiment.<sup>22</sup> Also shown is a calculated spectrum produced by 200-GeV protons under a thick earth shield.<sup>23</sup> The relevant feature of all these spectra is that they are roughly  $1/E$  (up to a sharp drop between 100 MeV and 1 GeV) when expressed in fluence/MeV. This means that they are roughly flat--up to the same break point--when plotted as neutrons per lethargy interval. The dose-equivalent per neutron is a rising function of energy. These factors combine to put most of the dose-equivalent in the multi-MeV range. Rather roughly, for all the spectra shown in the figure, 80% of the dose-equivalent is due to neutrons between 5 MeV and 1 GeV. (Low-energy neutrons diffusing through penetrations in the shielding are an exception to this rule.)

NEUTRON TRACK FILM. Figure 3 shows a measured response curve for NTA film.<sup>14</sup> The low-energy cutoff (roughly 0.5 to 1 MeV) is determined by the number of emulsion grams desired in the shortest acceptable proton recoil track. The film is sensitive to only about 20%

of the dose-equivalent carried by the neutron spectrum because of the high-energy falloff in response. However, interactions of higher energy neutrons with C and N nuclei in the film do give it some response past 15 or 20 MeV.

Figure 4 shows the "fading" of latent proton recoil tracks in NTA film. This fading is caused by the oxidation of the silver grains by atmospheric oxygen in the presence of water vapor. The rate of fading increases rapidly with increasing temperature and humidity.

There is still no uniformity of results concerning the effectiveness hermetically sealing the film prior to use. Best success has resulted from dessicating the film prior to sealing it.<sup>14, 16-18</sup> The best packaging material for this purpose is an aluminum foil--plastic--paper combination ("pipe tobacco pouch paper") in which the aluminum foil is the actual vapor barrier and the plastic is used for sealing.<sup>16</sup> At this time only one commercial film badge service<sup>25</sup> in the United States offers this type of packaging, and no test data is yet available from them. Thus, NTA film is not an intrinsically stable dosimetry medium, and antifading measures are not yet being taken on a large scale.

Further, neutron track film is easily fogged by several rads of gamma radiation, which reduces its sensitivity and ultimately makes it entirely unreadable.<sup>7</sup> Finally, the inherent precision of track film is limited by track-counting statistics, among other things. Current scanning practices yield a precision of perhaps 50% for a 100-mrem dose.

What, then, are the fast-neutron dosimetry systems of the future?

First of all, there is FILM. Two improvements could make this a reasonably satisfactory, although still not ideal system. First, the widespread adoption of a proven system for hermetically sealing the film would eliminate fading in all but tropical climates. Secondly, development of automated scanning equipment<sup>26</sup> might allow a larger field to be scanned easily and thus allow better statistics to be accumulated. Further, automatic measurement of the distribution of proton track lengths could routinely be used to provide information on the incident neutron spectrum, and thus yield a better dose estimate.

Thick emulsions (100-200- $\mu$ m thick) do not suffer from track fading the way 30- $\mu$ m thick NTA film does. Use of such emulsions would also allow higher energy recoil tracks to be recognized. However, they are more difficult and require a much longer time to develop than does conventional film.<sup>27</sup>

SOLID-STATE SYSTEMS--the established solid-state systems are TLD and RPL. The thermally stimulated exo-electron (TSEE) concept is still being developed. All of these detectors have what NTA film lacks: sensitivity, precision, and stability. Unfortunately, none of these systems has an inherent sensitivity to fast neutrons. One therefore has two options: to measure only the low-energy tail of a hard-neutron spectrum and make an educated guess about the shape of the spectrum; or to enhance the sensitivity of these detectors to fast neutrons. The procedure used at SLAC involves measurement of the low-energy tail.<sup>11</sup> They use  $^6\text{LiF}$  and  $^7\text{LiF}$  TLD dosimeters incorporated into a wallet identification card. The system is sensitive primarily to thermal neutrons via the reaction  $^6\text{Li}(n, \alpha)\text{T}$ . It is also sensitive to higher-energy neutrons which are moderated in the wearer's body; the efficiency of this process decreases with increasing neutron energy. This concept will be discussed later.

They assume that, because of their shield thickness, the higher-energy neutrons have reached an equilibrium spectrum. They further assume, for dosimetry purposes, that the ratio of fast to "thermal" neutron flux is constant wherever neutron doses can be received. They measured an average flux ratio of 3.4, but use a factor of 6 for safety. This ratio, when combined with the appropriate flux to dose conversion factors for fast and thermal energies, yields an assigned fast-neutron dose of 200 mrem for every mrem of measured thermal neutron dose.

This scheme works only because the actual neutron spectra are all quite similar, and because the actual neutron doses are small compared to the legal limits. Its pitfalls are illustrated by what happened when a SLAC experimenter worked at BNL and was exposed to a much softer neutron spectrum than was assumed for the SLAC calibration. His dose, as interpreted by the SLAC ID card dosimeter, was some ten times the dose that BNL assigned on the basis of film measurements!<sup>28</sup> Spectral measurements indicated the correctness of the BNL results.

ALBEDO DOSIMETERS. It is possible to reduce the response of a  $^6\text{LiF}$  chip to thermal neutrons and simultaneously enhance its response to higher energy ones by putting it, sometimes along with a small amount of hydrogenous moderator, into a partial or complete cadmium shield. The cadmium blocks the neutrons which were thermalized in the environment or in the user's body. High-energy neutrons which are strongly moderated in the wearer's body ("albedo neutrons"), but are still above thermal energies, are not absorbed by the cadmium. If they are then thermalized by the moderator inside the dosimeter, they may be captured by the  $^6\text{Li}$ . A companion  $^7\text{LiF}$  permits a gamma subtraction. A number of designs for these so-called "albedo" dosimeters exist, and

systems have been used rather successfully in reactor or fuel-processing plants.<sup>29-32</sup>

Unfortunately, measurements made by Hankins<sup>33</sup> and calculations made by Alsmiller and Barish<sup>34</sup> both show that the response of such systems is still strongly dependent on the incident spectrum. As an example, Fig. 5 shows the relative response of a particular albedo dosimeter design as a function of neutron energy. The relative response to a number of typical spectra is shown in Fig. 6. The strong falloff of response with neutron energy above about 100 keV makes this unsuitable for use whenever the neutron spectrum is not uniform. Thus, the albedo dosimeter system now being implemented at LASL will not be used for fast neutron dosimetry around LAMPF; they will continue to rely on NTA film for that area.<sup>35</sup>

There are, however, solid-state systems which are either inherently sensitive to fast neutrons or which can be made to be sensitive. Some of these systems appear to have promise, but I am cautioned by some of the overly optimistic statements made in the past.

In the field of TLD, work at Battelle-Northwest has shown that both  $^7\text{LiF}$  (TLD-700) and  $\text{CaF}_2:\text{Tm}$  (TLD-300) have an intrinsic response to fast neutrons; this occurs via scattering interactions which transfer energy to higher temperature traps.<sup>36</sup> These peaks are unfortunately also about ten times as gamma-sensitive as they are neutron-sensitive, on a rad basis. In the  $\text{CaF}_2:\text{Tm}$  material, the normal glow peak is at 150° C, the neutron peak is 240° C; thus, they are easy to separate. The present detection limit is 100 mrad of  $^{252}\text{Cf}$  neutrons using small chips of thermoluminescent material. If the same phosphor is put into a glass bulb, the indications are that it will be ten or more times as sensitive. This system is still in the early development stage, and all of its problems are not yet known. One known problem is reducing the gamma response. If this type of dosimeter turns out to be successful, it should be very easy to implement, since the automatic readout systems are already available.

Another promising prospect for fast neutron dosimetry involves the measurement of neutron damage in specially prepared silicon diodes. The forward voltage drop across the diode increases with increasing fast neutron dose. The diodes are not sensitive to gamma radiation. Fractional fading effects are easily circumvented. The observed effect is independent of neutron energy over the range tested. The main problem right now is sensitivity, present sensitivities being a major fraction of a rad. This is adequate for use as an accident dosimeter, but it will require some substantial advances in sensitivity before this is a useful system for routine monitoring.

Finally, we come to TSEE in BeO. This is not inherently sensitive to fast neutrons, but can be given an adequate response for many neutron spectra. The sensitive volume in a TSEE detector is right at the surface. If a hydrogenous radiator is placed in front of the BeO disk, recoil protons will deposit energy in the disk. This will give it an enhanced response compared to a similar disk with a teflon or graphite radiator.<sup>6</sup> The TSEE material is also gamma sensitive, thus, in mixed fields, when the neutron dose is obtained as a difference of two dosimeter readings, the neutron dosimetry becomes harder as the gamma component increases. TSEE systems for neutrons are still in the development stage, although a system for gammas is reported to be in use in the Soviet Union.<sup>38</sup>

Before leaving solid-state systems, I would like to talk about the supposed advantages of "tissue equivalence". I have the feeling that the underlying physics of radiation interactions has gotten lost, and that all that remains is a magic phrase, whose application is thought sufficient for success. Consider the following statement:

"The relationship between absorbed dose in silicon and in tissue is a rapidly varying function of neutron energy. Thus, the applicability as a personnel dosimeter will be limited to cases where the neutron spectrum is known and where calibrations have been carried out with neutrons having a similar spectrum."<sup>39</sup> The implied conclusion is that silicon diodes would not make good personnel dosimeters; this is not necessarily true at accelerators.

On the other hand a BeO TSEE dosimeter consisting of a polyethylene radiator and BeO detector is similar in mean atomic number to tissue; but this is not relevant at all neutron energies. At high enough energies it may not work at all.

Consider a typical accelerator neutron spectrum, such as was discussed earlier. Half the dose is delivered by neutrons with energies above about 60 MeV. At these energies, neutron interactions in matter consist of inelastic nuclear events as well as elastic scattering from hydrogen nuclei. Thus, the effect of hydrogen content is partially masked by other interactions. The nuclear effects such as thresholds, etc., in light nuclei reactions become less important at higher energies. At high neutron energies, all shielding materials tend to look rather similar. After going through many interaction lengths, the neutrons have reached an equilibrium spectrum; adding further shielding material simply attenuates the spectrum uniformly at all energies. At these high energies, energy deposition by the neutrons is essentially material-independent; all materials absorb energy about equally well on a per gram basis. It is then not serious that a TLD or Si diode material is

not "tissue equivalent". The only neutrons for which "tissue equivalence" is important are those whose energies are so low that their most important interaction is elastic scattering from hydrogen.

Consider the TSEE system, on the other hand. Its functioning depends on a difference in neutron interactions in carbon and polyethylene, for example. In the high-energy limit, this difference disappears, and with it, the proper functioning of the system. Further, as the neutron energy increases, so does the energy and range of the resulting recoil protons or other secondary particles. This range, which is 1 or more gm/cm<sup>2</sup> at 60 MeV, determines the thickness of the "effective radiator" in front of the BeO disk. At higher energies an even deeper volume provides charged recoils, further diluting the n-γ discrimination of the dosimeter.

TRACK DAMAGE DOSIMETRY. We now come to a type of dosimeter which has reasonable sensitivity, does not fade, is neutron-sensitive but gamma insensitive, is easy to read out, and is in practical use in at least one accelerator. This is the track damage dosimeter. Over 15 years ago it was discovered that highly ionizing particles-- such as α or fission fragments--cause local damage along their tracks when they pass through certain materials. This damaged area may be rendered visible by being etched away at a rate faster than the undamaged areas. Materials which have been found to be sensitive include minerals such as mica, glasses, and organic polymers. This method of registering tracks is now used in a wide variety of scientific applications. <sup>40</sup>

All dosimeter schemes in current use consist of two parts: a fissionable radiator and a track-recording foil. The radiator foil provides highly ionizing fission fragments which cause ionization damage tracks in the recording foil. Different nuclides are used for the radiator foils, depending on the neutron energy range to be covered. For example, <sup>239</sup>Pu and <sup>235</sup>U can be used for thermal neutrons; <sup>237</sup>Np, <sup>238</sup>U, and <sup>232</sup>Th can be used for neutron energies above 1 MeV. Bismuth and gold have fission thresholds at 50 to 100 MeV. Other factors influencing the device of a radiator material include the fission cross section, spontaneous fission rate, associated gamma activity, radio-toxicity of the nuclide, and one's ability to prepare a chemically and mechanically stable foil.

The detector foil is usually mica, polycarbonate (Lexan, Makrofol, Kimfol) or cellulose nitrate, in order of increasing sensitivity. It is "developed" by etching in KOH or NaOH for about one hour. The etching produces pits and eventually holes at the location of each fission track. These holes can then be counted in any of a number of ways. First,

they can be counted visually, using a microscope, as in NTA film scanning. Secondly, they can be counted electronically by the method of spark counting, as developed by Cross and Tommasino.<sup>41</sup> In this method the etched foil is placed between two electrodes, one of solid metal, the other an aluminized plastic film. A high voltage is applied between the electrodes, causing sparks to jump through the holes in the etched detector foil. These sparks are counted electronically. Each spark vaporizes sufficient aluminum from the foil electrode to prevent a second spark through that hole. The method is quite reproducible and is the preferred method of counting.

One can also measure the light transmitted through the holes at a frequency for which the foil is opaque. Finally, in case of a large number of etched holes, it is possible to measure the electrolytic conductance of the foil.<sup>42</sup>

A fission track system has been in use at the Swiss Federal Institute for Reactor Research since 1968.<sup>43</sup> (More recently its use has been instituted at the SIN cyclotron in Switzerland.) Two radiators are used:  $^{235}\text{U}$  for thermal neutrons and Th (2-cm diameter, 20- $\mu\text{m}$  thick) for the fast neutrons (Fig. 7). Makrofol disks are used as accident dosimeters. A calibration of 4-mrad/spark for fast neutrons is used, so there is no lack of sensitivity. (A slightly different calibration would be used at accelerators.) The foil can be spark-counted for doses up to 7 rads; microscope counting of the accident dosimeter extends its range up to 20 krad.

A possible problem with this dosimeter is the dose delivered to the wearer by the natural radioactivity of the dosimeter. Despite some 3-mm of aluminum shielding in the badge, a dose of about 80 mrad/yr is received by the area under the badge. Use of  $^{237}\text{Np}$  instead of  $^{232}\text{Th}$  would considerably reduce the gamma dose of the wearer.<sup>40</sup> Other potential problems involve the question of ownership or distribution of fissionable material, albeit in small quantities. Finally, the authors caution that such a system should not be used at electron accelerators, where high energy bremsstrahlung produces photofission in competition with the neutron fissions used for monitoring. I wish to emphasize that this is an established, functioning system. Costs quoted by the institute to outside organizations for this service seem to be two or three times what a commercial service would charge for film service.

Carl Distenfeld of BNL has combined a Th-fission track detector with  $^6\text{LiF}$  and  $^7\text{LiF}$  TLD's which form a crude albedo dosimeter to get some indications of the hardness or softness of the neutron spectrum, and thereby gain additional dosimetry information.<sup>44</sup> This system is still in the developmental stage.

There is also the possibility of dispensing with the fissionable foil and simply looking for holes due to C, N, or O recoils or  $\alpha$  particles from (n,  $\alpha$ ) reactions from these nuclei in a very thin and sensitive cellulose nitrate foil. This is still in the development stage. <sup>40, 44</sup>

In conclusion, besides NTA film, there is only one proven, operational method of fast neutron dosimetry suitable for use at accelerators. That is fission-track dosimetry. If I had to abandon film today, that is what I would choose. It is remarkable that only one accelerator laboratory, and less than half a dozen installations in the world, have made that change so far.

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- <sup>38</sup> A. I. Beskorskii et al., paper SM-143-69, IAEA Symp. Advances Rad. Detect., Vienna (1970).
- <sup>39</sup> J. F. Fowler, ref. 21, p. 308.
- <sup>40</sup> K. Becker, in Topics in Radiation Dosimetry, Suppl. 1, F. H. Attix, editor; Academic Press, New York (1972).
- <sup>41</sup> W. G. Cross and L. Tommasini, Health Physics 15, 196 (1968).
- <sup>42</sup> W. R. Cross and H. Ing, ref. 4.
- <sup>43</sup> S. Prêtre, ref. 2, Vol. II, p. 99; and S. Prêtre, K. Heusi, EIR-TM-SU-149 (1972).
- <sup>44</sup> C. Distenfeld, BNL-17452 (1972).
- <sup>45</sup> B. J. Tymons, J. W. N. Tvyn, J. Baarli, ref. 2, Vol. II, p. 63; M. Sohrabi, Health Physics 27, 598 (1974).

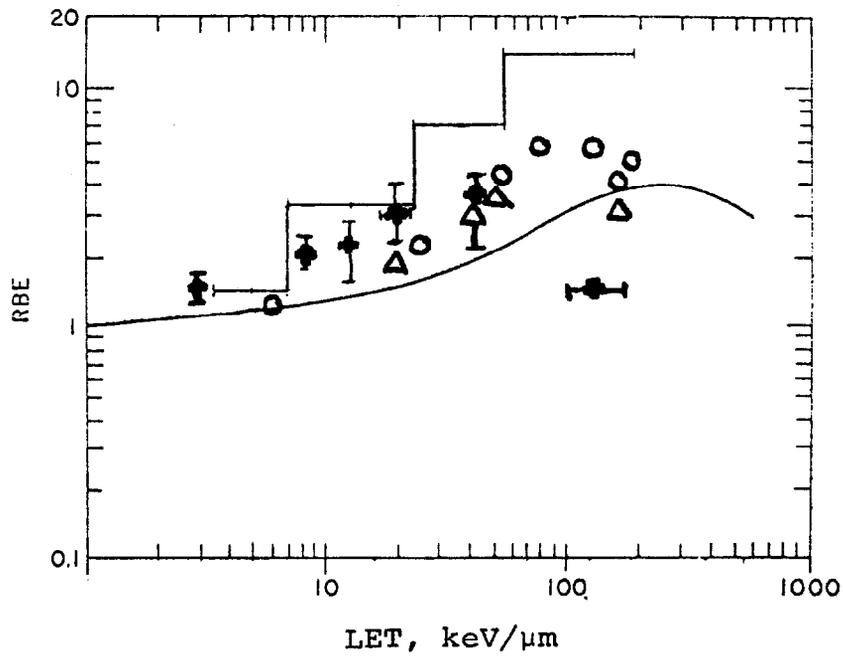


Fig. 1. Schematic curve summarizing the response of mammalian cells to radiation as a function of LET. Some data points are shown. The stepped line represents current values of Quality Factors as recommended by ICRP. From "Dose-Effect Modifying Factors in Radiation Protection", Report of Subcommittee M-4 of NCRP, BNL 50073 (1967).

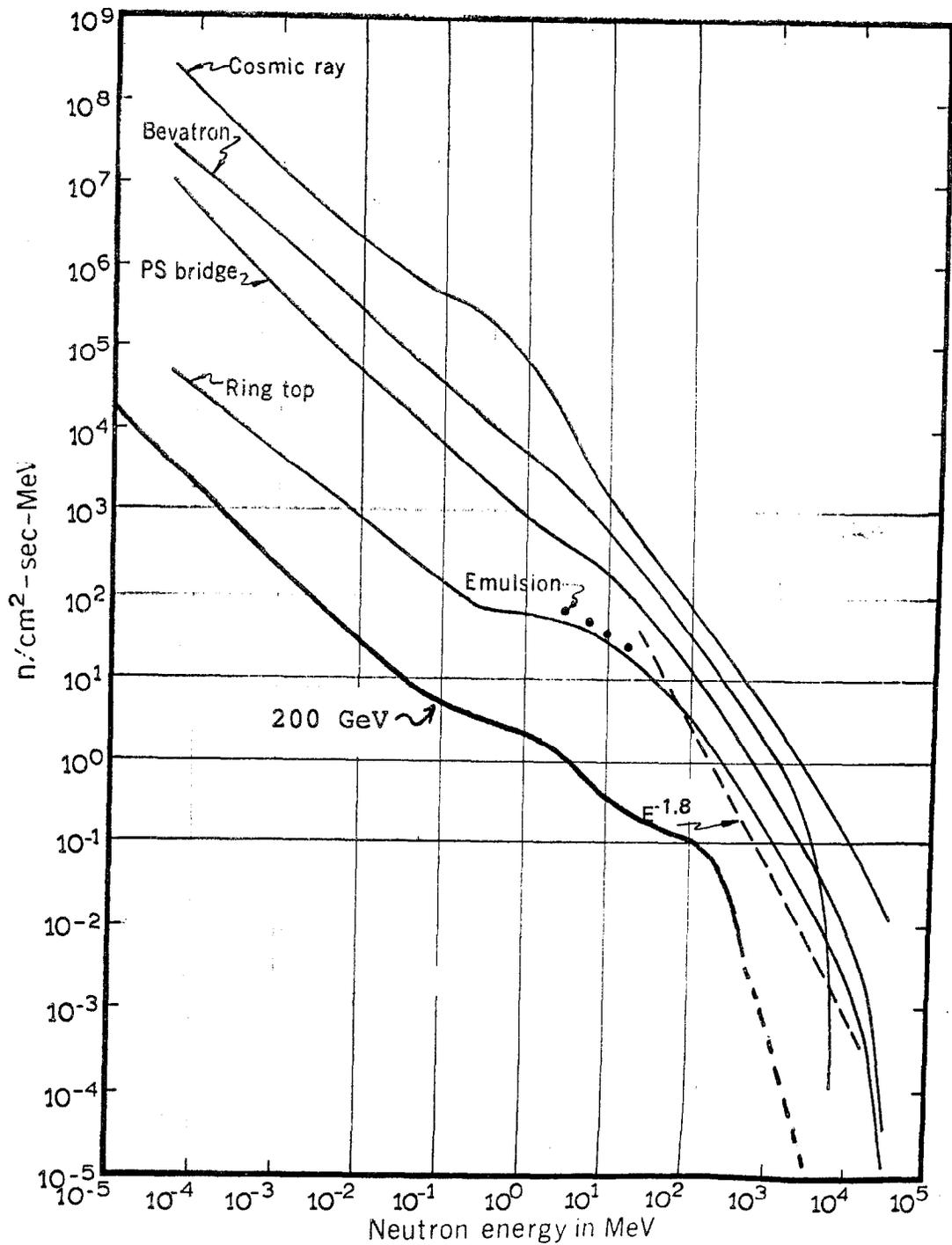


Fig. 2. Typical neutron spectra obtained from CERN-LBL-RHEL shielding experiment and other work (Ref. 22). The curve labelled "200 GeV" is a calculated spectrum due to protons lost on iron magnets behind a thick earth shield (Ref. 23). Relative intensities of spectra are arbitrary.

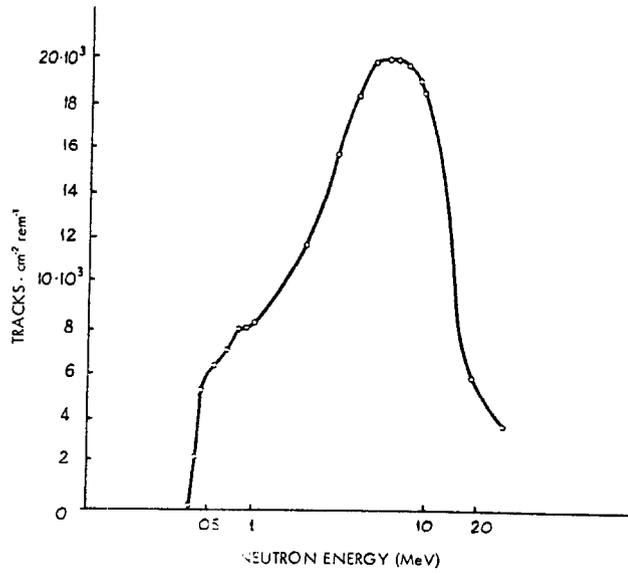


Fig. 3. Energy response of Kodak Personal Neutron Track Film, Type A (from Ref. 14).

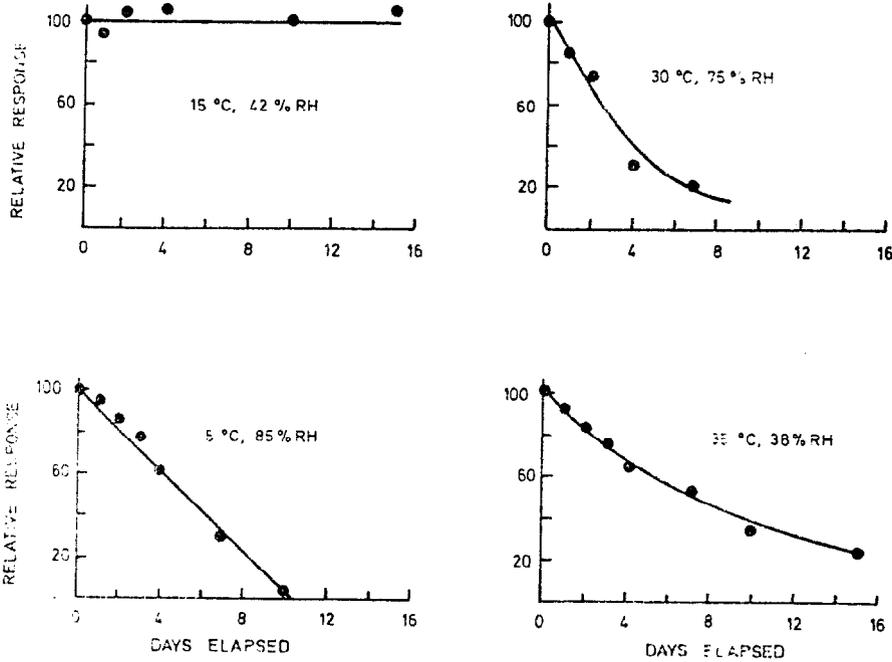


Fig. 4. Post-irradiation fading in NTA films for different temperature and humidity conditions (from Ref. 714).

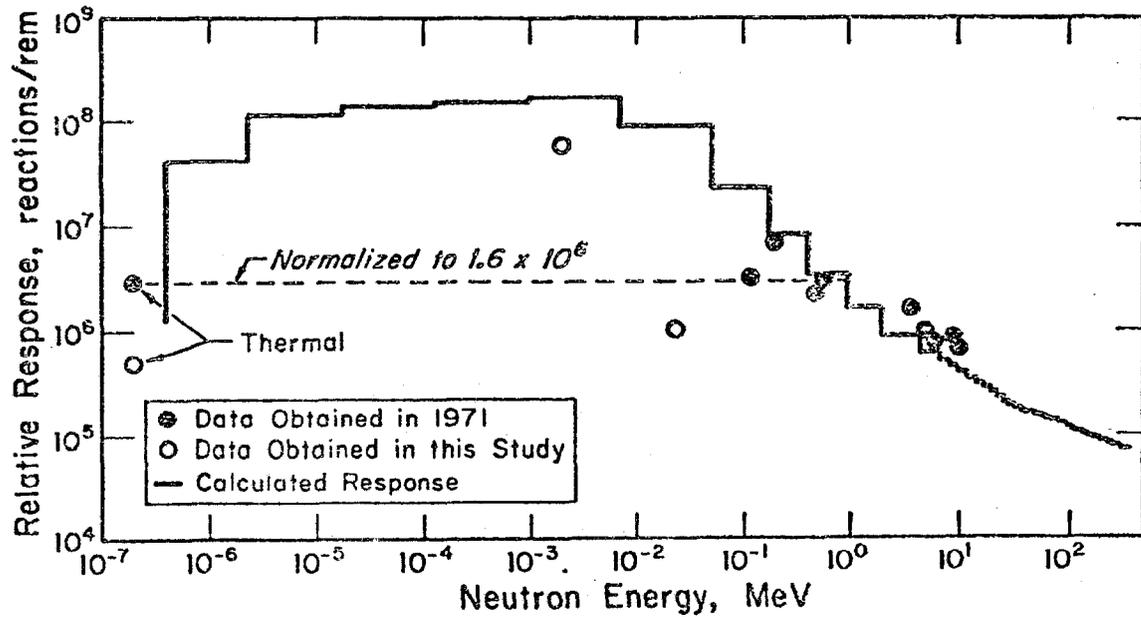


Fig. 5. Relative response of an albedo neutron dosimeter due to J. Hoy [Health Physics 23, 385 (1972)] for monoenergetic neutrons (from Ref. 34).

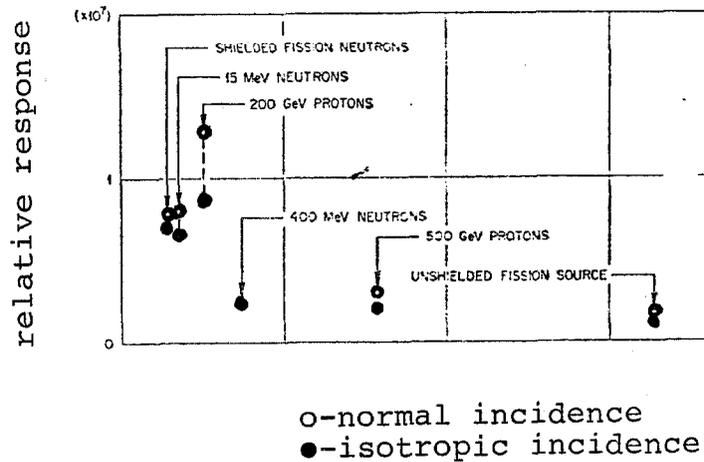


Fig. 6. Relative response of the Hoy dosimeter to various neutron spectra (from Ref. 34).

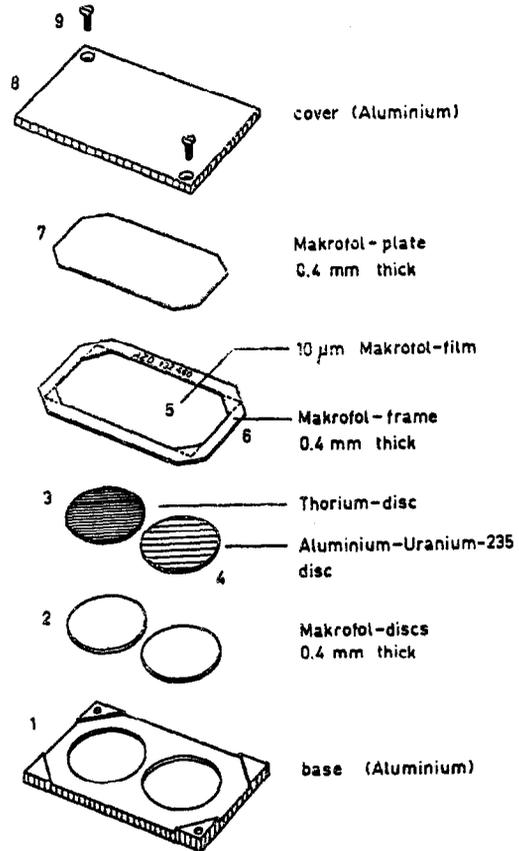


Fig. 7. Fission track damage system developed by Prêtre (Ref. 43).