A COMPOSITE DAMAGE TRACK-ALBEDO
PERSONNEL NEUTRON DOSIMETER FOR GENERAL USE*

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Abstract

No known detector or series of detectors in personnel neutron dosimeters have correct dose equivalent energy-dependence. Useful dosimeter performance is assumed by calibrating dosimeters for the exposure spectrum. This method implies that the exposure spectrum will be constant within a given facility or the wearer will not be exposed to different spectra in other areas. Since exposure spectra are known to vary widely a composite damage track-albedo personnel neutron dosimeter was developed to separately respond to the softer and more energetic parts of various spectra. The relationships of the responses of the elements vary with different spectra and are used to convert dosimeter readings to dose equivalent. Measurements indicate that dose equivalent deviation was less than ~50% for unshielded lucite and steel shielded HPRR spectra, monoenergetic spectra from 4.7 to 15 MeV, a ^{252}Cf spontaneous neutron spectrum and an AmBe spectrum. Dosimeter sensitivity was similar to present NTA film methods. The composite personnel neutron dosimeter was also tested with calculated spectra by simulating badge response through known energy-dependence of the badge elements. Dose equivalent deviation was less than ~20% for 19 significantly different assumed spectra. Thus, the experimental and calculational results support adherence to the dose equivalent for common exposure spectra.

Introduction

The prototype Brookhaven neutron dosimeter, BND, was a composite damage track and thermoluminescent detector. Thorium fission was used to respond to > 1 MeV neutrons and high sensitivity TLD 600 and 700 ribbons responded to softer neutrons. Previous experimental work(1) at the Alternating Gradient Synchrotron, AGS, a 33 GeV proton accelerator, utilized the energy dependence of the ratio of thermoluminescent response, Tℓ, to Thorium response, sparks. This ratio is defined as spectrum softness. Softness variation was related to a correction factor used to adjust a TLD response to properly account for the dose equivalent below 1 MeV.

An invitation was extended to participate in the 1974 ORNL intercomparison of personnel neutron dosimeters. Exposures involved neutron spectra produced by a 14 MeV neutron generator and the Health Physics Research Reactor (HPRR) in its three configurations.

Participation in the study required the determination of different BND calibration constants for the much softer reactor spectra. It was assumed that the neutron energy was limited to ~15 MeV. For this energy, the thorium calibration value was 7.1 mrem · sparks^{-1} and the problem was the interpretation of the TLD response.

Thermoluminescent Response

No known detector or series of detectors in BND or any other personnel neutron dosimeter has correct dose equivalent energy-dependence. Acceptable dosimeter performance is usually assumed by calibrating any dosimeter to the exposure spectrum. A single exposure spectrum reflects few calibrations, while general application requires many spectra calibrations. This study was made manageable by computer simulation of BND response. The method required the energy dependence of the dosimeter elements to be folded with known or assumed spectra producing integral response values for the detector elements. Results were used to determine an energy dependent relationship to correct the elements and thereby provide dose equivalent values.

TLD 600 and TLD 700 consist of nearly pure ^{6}LiF and ^{7}LiF material respectively. The most probable neutron interaction ^{6}Li(n,α) occurs below a few electron volts.(2) Personnel exposures involve the impingement of neutrons on the hydrogen rich torso of man. The back scattered neutrons, albedo, form a continuum tailing to thermal energies. Thus, the Tℓ response was mainly due to albedo neutrons from the wearer's body and incident thermal neutrons. Alsmiller(3) calculated the albedo neutron fraction for neutrons of < 400 MeV (Fig. 1). Since TLD 600 is a thermal neutron detector, and the albedo groups calculated by Alsmiller cover the near thermal and thermal region, a simple Tℓ energy relationship should exist.

*Research carried out at Brookhaven National Laboratory under contract with the U.S. Energy Research and Development Administration.

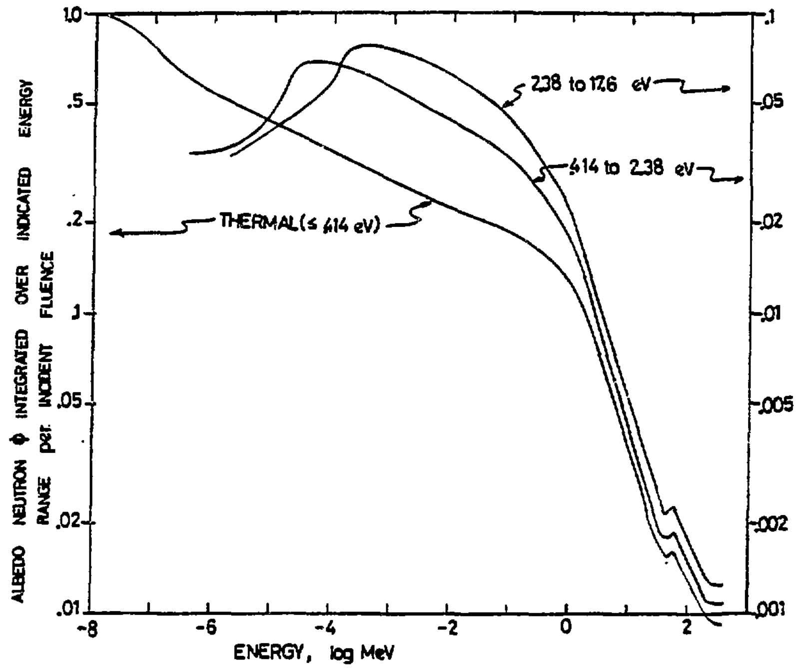

Fig. 1

Thermoluminescent pair, TℓP, is defined as the neutron Tℓ response and is determined as the gamma calibration based difference between TLD 600 and TLD 700 pairs. It is expressed in γ equivalent units, mR (n,γ). In general, the TℓP response to neutrons is:

$$T\ell P = P\,\Phi(E)\,\sigma(E) \qquad (1)$$

where the response constant P equates the differential energy spectrum, Φ(E), and the (n,α) cross section vector, σ(E), to TℓP. TℓP for any spectrum can be related to the thermal response, TℓP(th), as follows:

$$T\ell P\,(a,b) = T\ell P(th) \cdot \frac{\int_a^b \sigma(E)\,dE}{\int_{.01\,eV}^{.4\,eV} \sigma(E)\,dE} \qquad (2)$$

TℓP(th) was measured by two different methods. A direct <u>under cadmium</u> calibration in the BNL sigma pile provided a value of 1.29 E-4 ± 5% mR (n,γ) per unit fluence. The other less direct method utilized a Van de Graaff calibration with 15.5 MeV D-T neutrons contaminated with 10% 3 MeV D-D neutrons. The measured TℓP response was due to the sum of a small incident fluence effect, I,[4] and the effect of the three albedo groups, A_1, A_2, A_3, and of the energy ranges given in Fig. 1. Employing equation (2) and the bound macroscopic cross section data from Sanna[4], TℓP(th) was evaluated to be 1.39 E-4 ± 5% mR(n,γ) as follows:

$$T\ell P = \Phi(15.5) \cdot \theta \cdot T\ell P(th) + \Phi(3.0) \cdot \theta\, T\ell P(th) \qquad (3)$$

where $\theta = \frac{I\sigma(15.5)}{\sigma(th)} + A_1 + A_2 \cdot \frac{\bar{\sigma}(2)}{\bar{\sigma}(th)} + A_3\,\frac{\bar{\sigma}(3)}{\bar{\sigma}(th)}$

TℓP(th) = 1.39 E - 4 ± 7% mR(n,γ) was taken to be the mean of the sigma pile and Van de Graaff measurements.

Three Tℓ configurations were investigated. The first consisted of the TLD 600 and TLD 700 dosimeters shielded by plastic of ~200 mg cm^{-2}. The presence of the plastic was ignored and the Tℓ was considered as unshielded, TℓP.

Cadmium, 0.76 mm, was used to alter the response. Tℓ material placed in front of the Cadmium was termed back cadmium, BCd and Tℓ located behind the Cadmium was termed front Cadmium, FCd.

Tℓ response per unit incident Φ of energy E for three albedo groups considered (Fig. 1) is:

$$T\ell P = T\ell P(th) \times \frac{\sigma(E)}{\sigma(th)} + T\ell P_1 \cdot A_1(E) + T\ell P_2 \cdot A_2(E) + T\ell P_3 \cdot A_3(E) \quad (4)$$

$$FCd = T\ell P(th) \times \frac{\sigma(E)^*}{\sigma(th)} + T\ell P_2 \cdot A_2(E) + T\ell P_3 \cdot A_3(E) \quad (5)$$

$$BCd = T\ell P(th) \times \frac{\sigma(E)}{\sigma(th)} + T\ell P_4 \cdot A_2(E) + T\ell P_3 \cdot A_3(E) \quad (6)$$

$^*E \geq 4 \times 10^{-7}$ MeV   Where $A_1(E)$, $A_2(E)$ and $A_3(E)$ are the spectrum weighted albedo groups.

The TℓP and BCd elements respond equally to incident neutrons while cadmium absorption eliminates $T\ell P_1$ and part of the .4 eV to 2.5 eV albedo group $T\ell P_2$ response. $T\ell P_4$ accounts for this attenuated energy group.

The Tℓ constants used were determined by equation (2) and are:

$T\ell P_1$ = 1.39 E-4 mR $cm^2 \cdot n^{-1}$; E-8 to 4 E-7 MeV

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The three functions (Fig. 2) have some relative energy dependence. FCd and TℓP differ in the thermal energy region. The more extended differences of BCd and TℓP were used to develop a Tℓ correction system as described herein, and FCd was considered unnecessary.

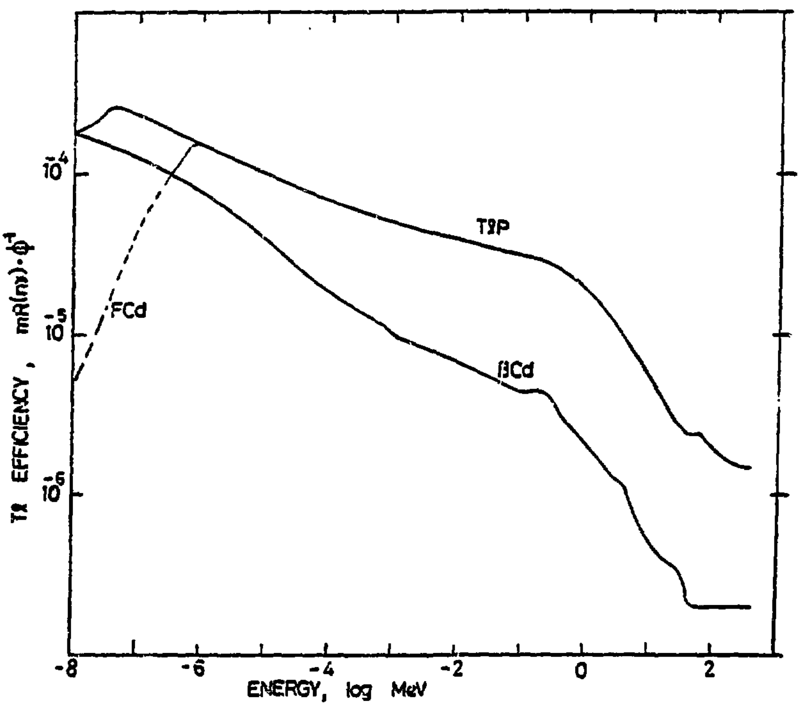
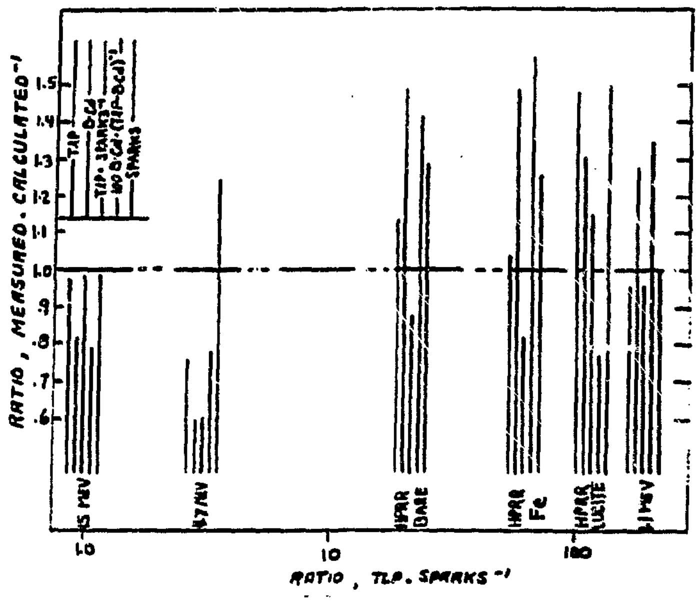


Fig. 2

The value of the computer simulations depends on the quality of the response functions. This was evaluated by comparing six measured cases with the corresponding calculated values (Fig. 3). Five BND parameters per case were considered and all are within a factor of 1.6 of the calculated values.



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Test Spectra

Fifteen hypothetical spectra were generated using the HPRR lucite shielded spectrum[6] as a starting point. One softer and thirteen harder spectra were composed (Fig. 4) and used to calculated the BND constructs. The Tℓ correction, k, is discussed later and was evaluated as follows:

$$T\ell P \cdot mrem^{-1} = k_1 \text{ or } k_2 = MADE - 7.1 \times sparks \quad (7)$$

The hypothetical spectra produced the relationship k_1 vs. TℓP · $sparks^{-1}$, illustrated as points in Fig. 5, and used for the HNL intercomparison measurements. Thorium and unshielded Tℓ pair elements indicated the unshielded HPRR dose equivalent to +5%, steel shielded to -44% and the lucite shielded core to +50%. Softness ratios of >20 reflect a strongly diminishing spark response. Monoenergetic neutron fields of <1 MeV afford nearly zero thorium response, erroneously suggesting a soft spectrum. Additionally, the 56% agreement for the steel shielded HPRR spectrum should be improved. For the above reasons an additional energy dependent relationship was tried.

The BCd element favors the thermal portion of an incident neutron spectrum, while the TℓP gains additional response from the albedo $T\ell P_1$ (equation 4). For this reason, a ratio of BCd to (TℓP - BCd)$^{-1}$ can be used to supplement and replace the TℓP · $sparks^{-1}$ softness ratio. The BCd derived softness values (open circles Fig. 5), scaled by 100, agree closely with the previous TℓP · $sparks^{-1}$ dependence in the softness range of 13 to 20. A smooth curve defines the TℓP correction value for a corresponding TℓP · $spark^{-1}$, k_1, or corresponding 100 BCd · $(T\ell P - BCd)^{-1}$, k_2.

The standard method used to evaluate the Tℓ and thorium elements of the BND badge was,

$$MADE = 7.1(sparks) + T\ell P \cdot k \quad (8)$$

where MADE is the maximum dose equivalent, and k the TℓP correction factor. Values of k_1 were taken from Fig. 5 for TℓP · $spark^{-1}$ values <15. Softness values >20 require the determination of 100 BCd · $(T\ell P - BCd)^{-1}$ and the corresponding k_2 correction. Arithmetic average k corrections, $.5(k_1 + k_2)$, were used for the intermediate TIP · spark^{-1} range between 15 and 20.

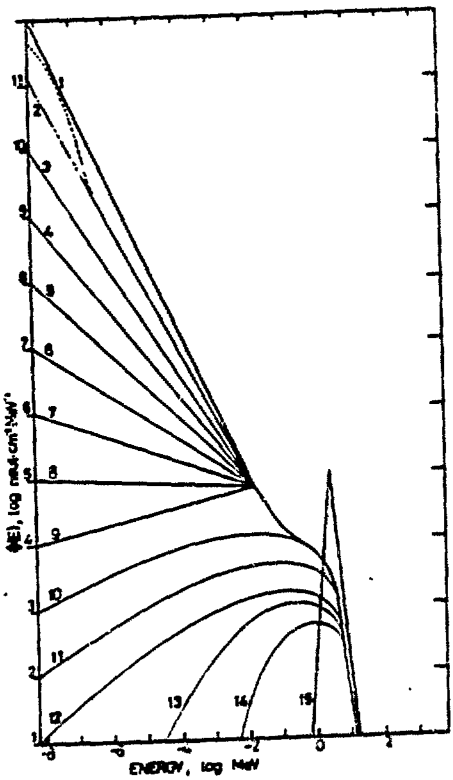

Fig. 4

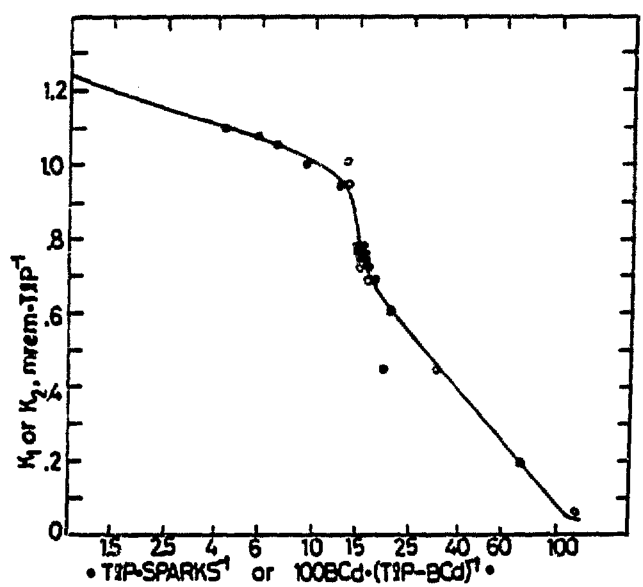

Fig. 5

Discussion and Results

Experimental Exposures

Results are given for 8 real spectra (Fig. 6). The HPRR spectra[5], dosimetry, and exposures were derived from participation in the 1974 Intercomparison of Personnel Neutron Dosimeters. A Bonner multi-sphere spectrometer specified the Californium and AmBe exposures, and a precision long counter and liquid scintillation spectrometer the remaining mono-energetic spectra. NTA film results were computed for every case by folding measured NTA responses with published or measured spectra. BND evaluation was accomplished by applying the standard method.

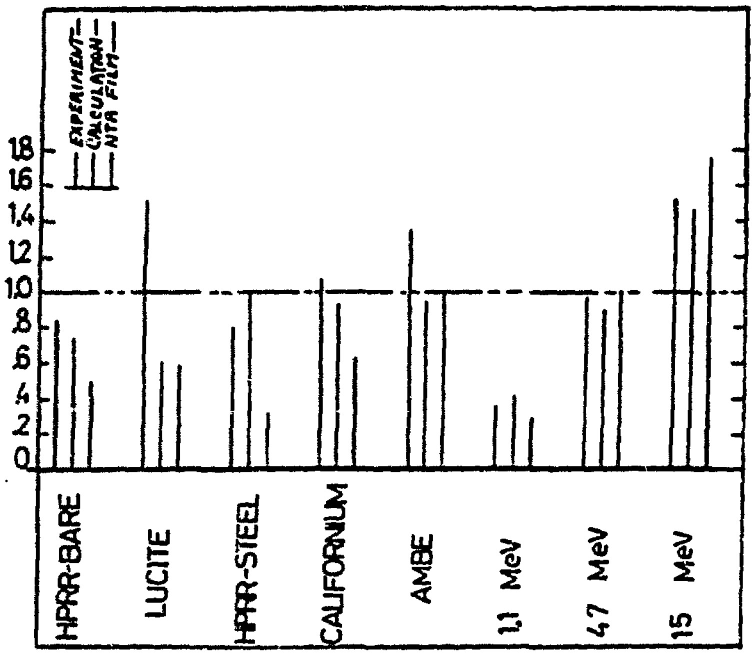

Fig. 6

Good agreement was observed between calculated and measured BND values in all but one case. Considering the lucite shielded HPRR exposure, measurements indicate ~50% excess response while calculations predict an equal under response.

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Poor results were obtained for the 1.1 MeV spectra. This is due to the near zero response of the thorium fission element in BND and the greatly diminished NTA response.

Calculated Exposures

Five criticality[6,7] and the 15 hypothetical spectra (Fig. 7) were used to computer predict TLP, BCd, thorium sparks and NTA film values.

Using the standard method of BND evaluation, results are generally consistent with the experimental exposures. Fission sources, shielded by 2 cm H_2O, 5 cm D_2O and 5 cm iron are similar to the unshielded HPRR case; while the 30 cm H_2O shield roughly corresponds to the lucite shielded HPRR exposure. However, the 50 cm iron shielded synthesis provides a BND over response of a factor of 2 and an NTA under response of ~6. This does not compare with a measured under response of a factor of 1.2 for BND and 3 for NTA film calculated for the 13 cm steel shielded HPRR exposure.

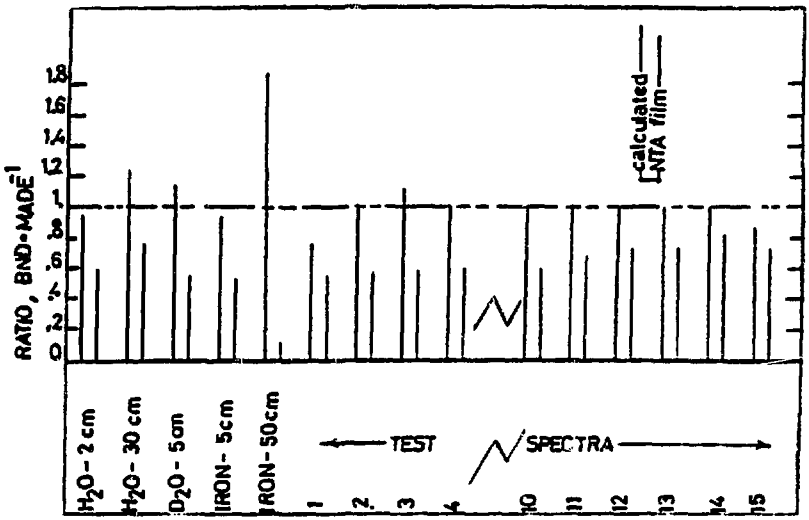

Fig. 7

The 15 hypothetical exposures are expected to afford good agreement since they were used to derive the T&P correction method.

Summary

A. Differences in energy dependence can be used to adjust the interpretation of the TLD dosimeter elements to more correctly conform to the dose equivalent.

B. Computer simulation of badge element response, for any spectra, allow the determination of a system of correction for better adherence to the dose equivalent.

C. Accuracy in personnel neutron dosimetry can be improved by including the different energy dependent dosimeter elements of thorium and TLD in a personnel style badge.

D. The method is general and could apply to any system of dosimeter elements of known response to largely different parts of an exposure spectrum.

References

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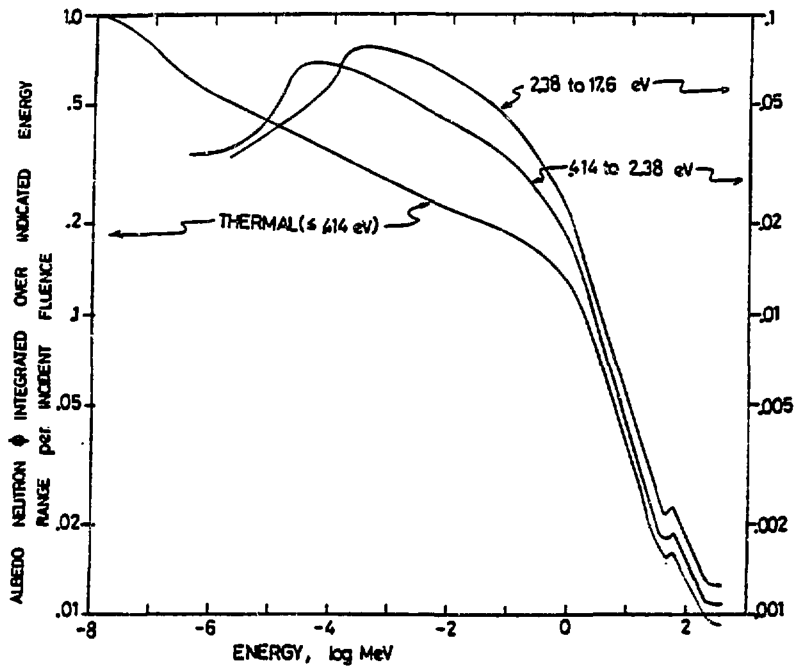

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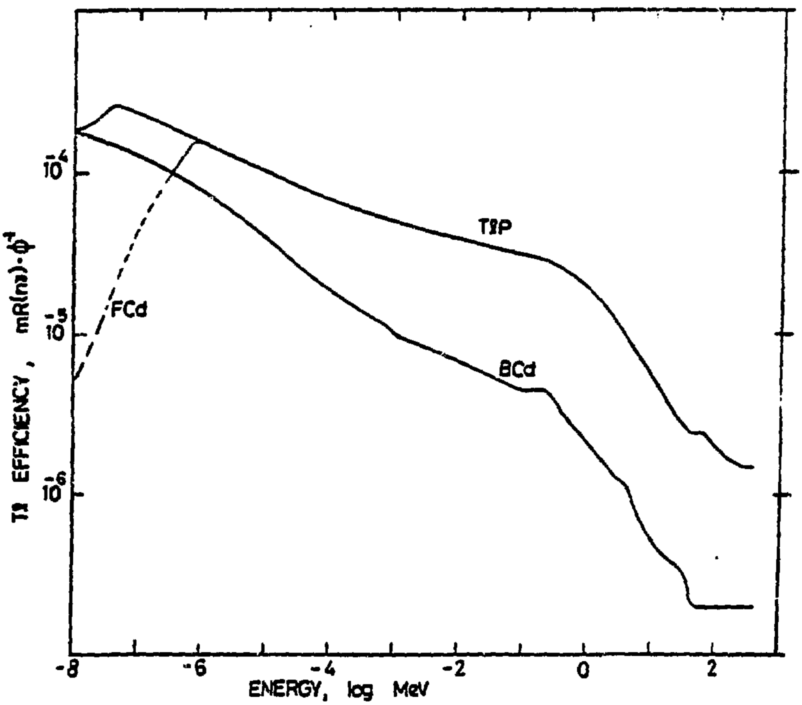

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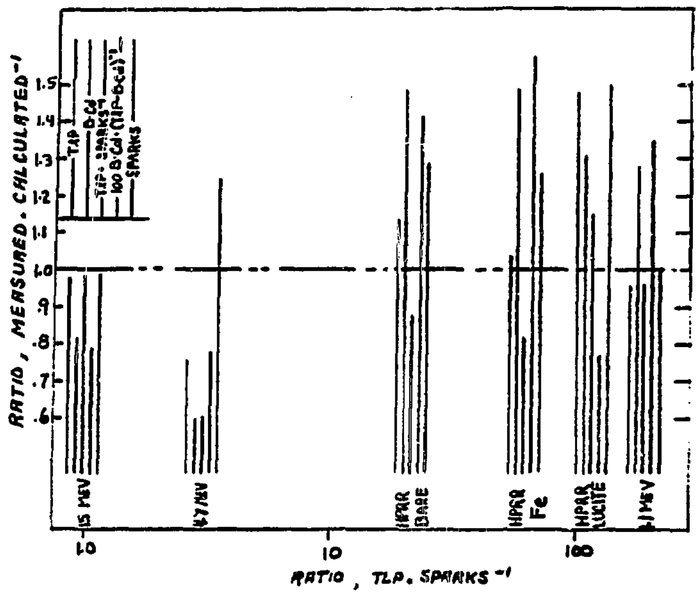

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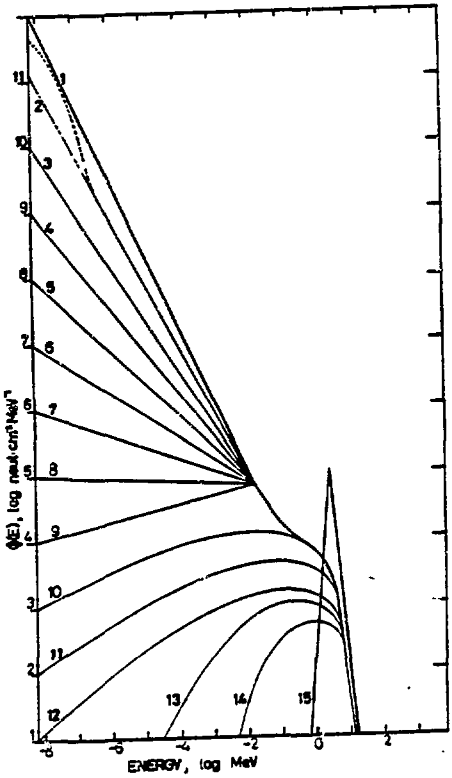

Fig. 4

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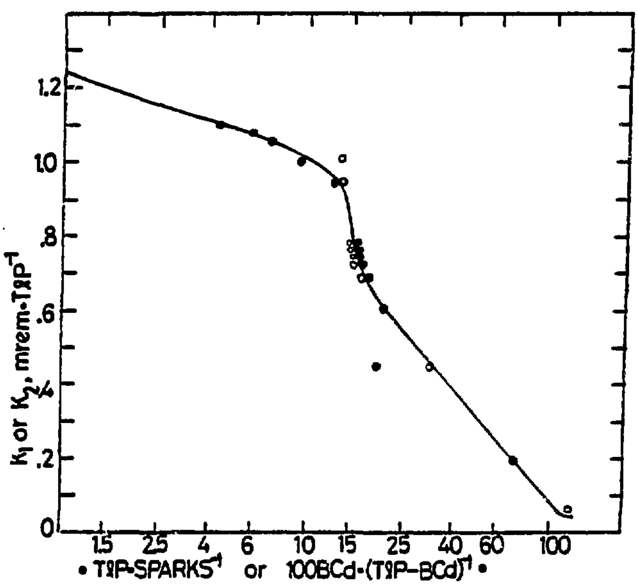

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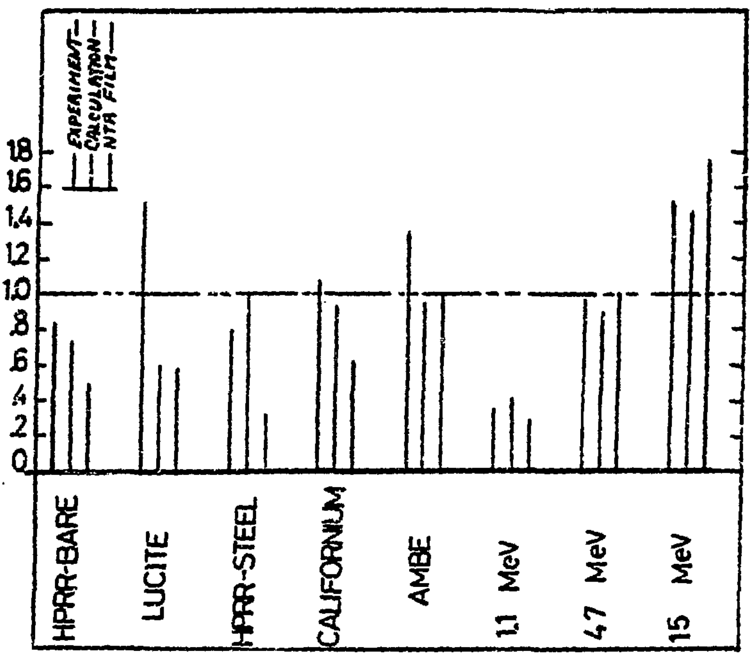

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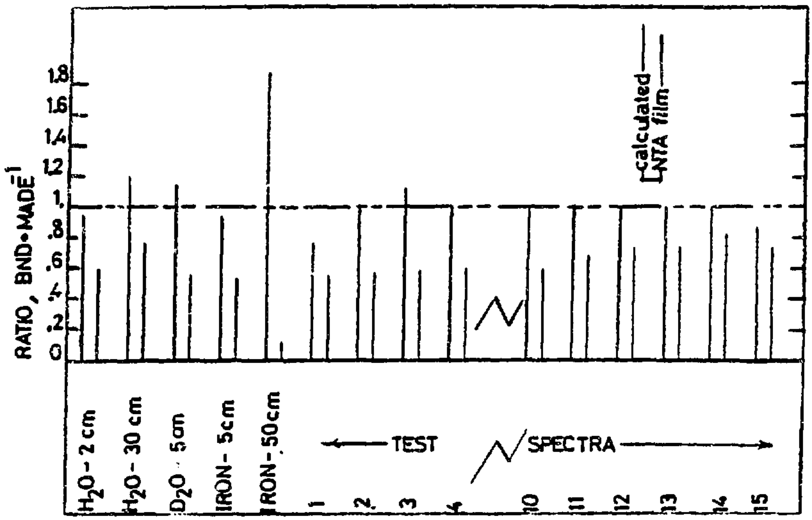

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