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REACTOR DOSIMETRY WITH DIODES, POCKET DOSIMETERS, AND PAIRED CHAMBERS

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ABSTRACT

Paired ionization chambers with nominal volumes of 0.5 cm^3 have been used for measuring the neutron and gamma ray dose components in different AFRRI-TRIGA reactor fields. The results of these measurements have been compared with measurements made with other dosimetry systems such as wide based silicon diodes and pocket dosimeters. The saturation behavior of the pocket dosimeters has been tested by exposures with the AFRRI LINAC. Results indicate that the pocket dosimeters have a lower sensitivity to fast neutrons than to gamma rays, which could probably be improved, and, more important, that the dose rate dependence is very strong. On the other hand, the silicon diode is a very attractive device for measuring neutron doses because of its simplicity of readout, its negligible gamma response and its neutron energy response which does not change if a small shift in the neutron energy spectrum occurs.

I. INTRODUCTION

In previous reports[3, 8, 9] measurements of the neutron spectrum and neutron and gamma ray dose components of the AFRRI-TRIGA reactor, made with threshold detectors and paired ionization chambers (0.05 cm^3 and 50 cm^3 nominal volume), have been described.

The objectives of the research reported herein were to test the newly developed paired ionization chambers with nominal volumes of 0.5 cm^3 by measuring the different AFRRI-TRIGA reactor fields and to compare the results with measurements made with wide based silicon diode fast neutron dosimeters from the Swedish firm AB Atomenergi and fast neutron and gamma ray tissue-equivalent Bendix pocket dosimeters, Type No. 884.

In addition to the measurements with the reactor, some measurements have been performed with the AFRRI electron linear accelerator (LINAC) for studying the saturation behavior of the Bendix dosimeters and with the ^{60}Co and ^{137}Cs irradiation facilities for calibration purposes and for evaluating the lowest dose rate level that can be measured by the ionization chambers.

II. DOSIMETRY SYSTEMS

Paired ionization chambers. With the paired ionization chamber concept, it is possible to measure the neutron and gamma ray dose components in a mixed radiation field separately.[2, 5] In this study, the newly developed ionization chambers with nominal volumes of 0.5 cm^3 have been used. One of the chambers is a tissue-equivalent chamber filled with tissue-equivalent gas (TE chamber), the other is a magnesium chamber filled with CO_2 (Mg chamber). The TE chamber has about the same sensitivity for neutrons as for gamma rays which means this chamber is sensitive to the total dose (kerma); the Mg chamber has a low sensitivity for neutrons and is therefore nearly specific to gamma rays. The TE chamber is illustrated in Figure 1. The Mg chamber is similar in design to the TE chamber.

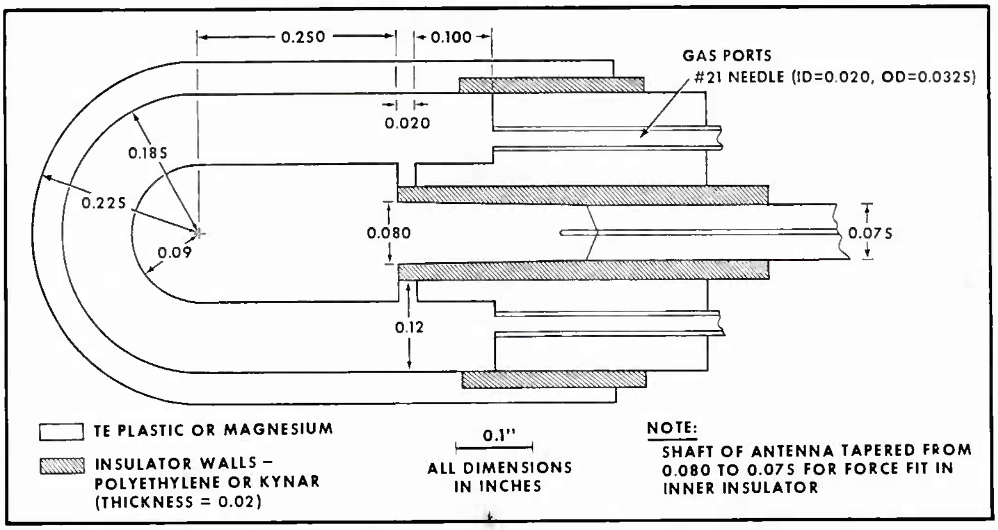

Figure 1. Tissue-equivalent chamber

These chambers have been calibrated with the ^{60}Co and ^{137}Cs facilities of AFRRI. The measured sensitivity coefficients are shown in Table I.

Table I. Sensitivity Coefficients

Chamber	Gas filling	Sensitivity coefficients (R/Cb) (at 760 mm Hg, 22°C)	
		^{60}Co	^{137}Cs
TE	TE	5.21×10^9	5.48×10^9
Mg	CO_2	3.3×10^9	3.42×10^9

These coefficients are mean values of two measurements taken by successive readings at opposite polarities to eliminate cable currents. The leakage current of these chambers has been measured and found to be about 2×10^{-15} ampere. From this leakage current it can be concluded that, if the signal to noisc ratio is 1 and if the noise value is known within 20 percent error limit, the lowest dose ratc that can be measured with these chambers with an accuracy of 20 percent is about 50 mR/h.

Silicon diodes. The bchavior of wide based silicon diodes as fast neutron dosimeters has been studied by Svansson et al.[6] (see also references cited by Svansson et al.). The particular diodes used in these measurements were manufactured by the Swedish firm AB Atomenergi.

The principle of operation of such devices is that when a diode is exposcd to fast neutrons, silicon atoms are displaced from their lattice positions and these recoil atoms often have sufficient energy to displace further silicon atoms. Vacancies and interstitials are thus produced in the crystal which act as recombination centers (Frenkel defects). The result of these displacements is that the forward resistance of the wide based diode is increased.

The simplest method of measuring this effect is to pass a constant forward current through the device before and after irradiation and measure the change in voltage across it (Figure 2). This has been done with a commercially available reading instrument of the Swedish firm with an applied current of 25 mA. The only special feature of this instrument is that the current passes through the diode for a short time (0.2 sec) to avoid heating of the diode.

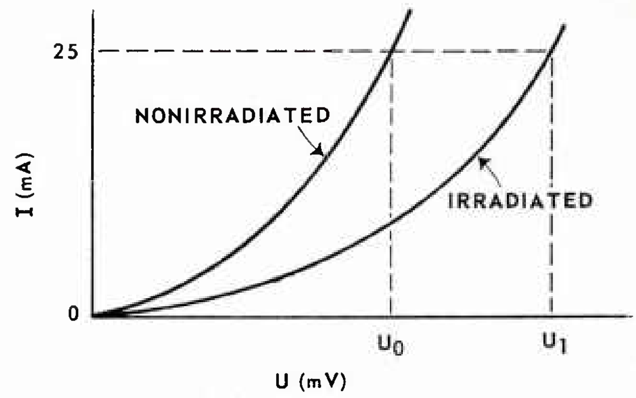

Figure 2. Silicon diode characteristics

Previous work conducted in Germany with ^{60}Co gamma rays and monoenergetic fast neutrons yielded the following results. The diode response to ^{60}Co gamma rays is about four orders of magnitude less than to fast neutrons. The response to 14 MeV neutrons is about 25 percent less than to 3 MeV neutrons. Extensive work has been done to determine the temperature dependence of the diode response for different irradiated dose levels, the fading behavior as a function of time and irradiated dose, and the dependence of the fast neutron response as a function of the predose value U_0 (Figure 2). The results of these measurements will be published in a later report.

Bendix dosimeter. The Bendix device is a pocket type dosimeter with a reading instrument up to 1000 rads. According to the specifications, it should have the same response on a tissue rad for rad basis to fast neutrons as to gamma rays.

These dosimeters were calibrated with ^{60}Co gamma rays and fission spectrum neutrons and the saturation behavior was evaluated with the AFRRI LINAC.

III. RADIATION FIELD OF THE AFRRI-TRIGA REACTOR

The AFRRI-TRIGA reactor has two exposure rooms. All measurements for this report were done in the larger room, Exposure Room No. 1 (20 ft x 20 ft x 10 ft high).

The reactor core is suspended in a cloverleaf-shaped pool of water and the suspension system rests on tracks so that the core can be moved from one of the two exposure rooms to the other (Figure 3). The walls of Exposure Room No. 1 have been painted with a gadolinium-based paint that reduces the thermal neutron fluence by a factor of about 20. Three configurations are regularly used to obtain different mixed neutron-gamma ray radiation fields.

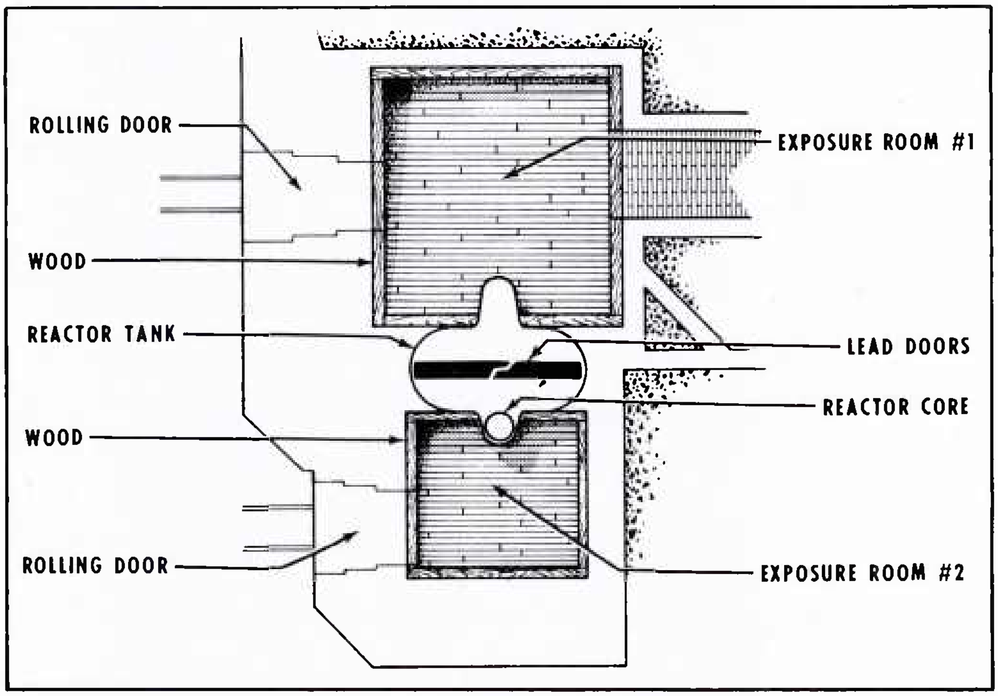

Figure 3. AFRRI-TRIGA cross section

The normal field, characterized by a neutron to gamma tissue kerma rate (n/γ ratio) of about 0.5 which is nearly constant throughout the room, can be obtained by placing the core snugly into the tank protrusion (Figure 4A).

The so-called enhanced neutron field (n/γ ratio ≈ 10 at 1 m) was achieved by rolling a 6" Pb shield in front of the normally positioned core (Figure 4B).

The enhanced gamma field (n/γ ratio < 0.1 throughout the room) occurs when the core has been retracted 5" from its normal position, that means behind a 5" shield of water (Figure 4C).

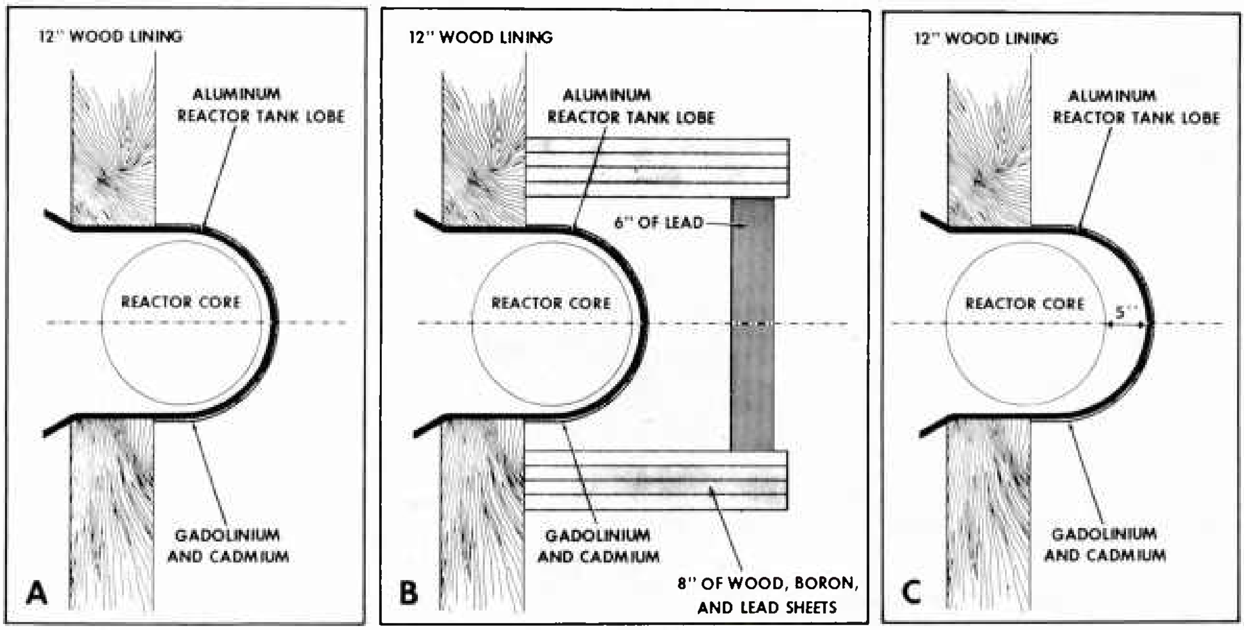

Figure 4. AFRRI-TRIGA exposure arrays. A. Normal field. B. Enhanced neutron field. C. Enhanced gamma field.

Neutron spectra. The neutron spectra for these three configurations have been reported.[8] These spectra, normalized to the total flux, are given in Figure 5. It can be seen that above 1.5 MeV the relative neutron spectrum compared with the normal field is slightly hardened in the case of the water shield (enhanced gamma field) and is softened by the 6" Pb shield (enhanced neutron field).

This hardening or softening of the fast neutron spectrum by the water or by the lead shield can also be seen in the reports by Verbinski et al.[7] and Clifford et al.[1]

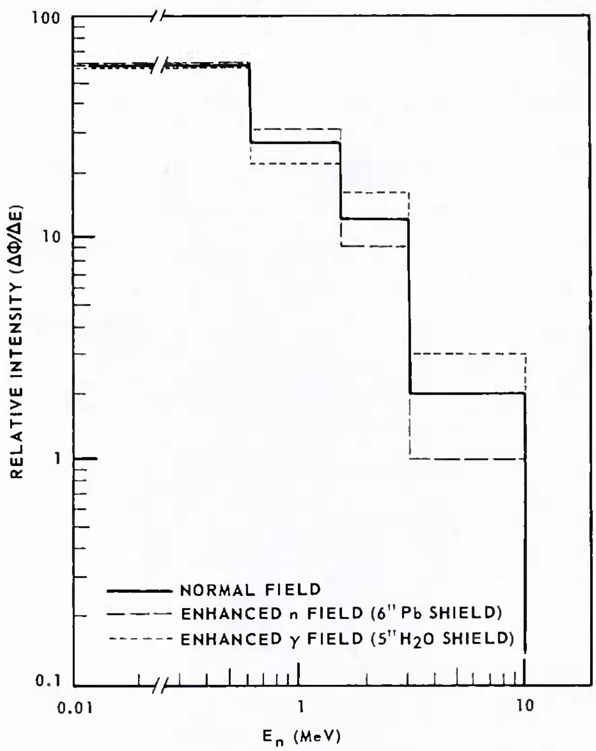

Figure 5. Neutron spectra

Tissue dose measured with the paired chamber technique. With the paired chamber technique, the neutron and gamma dose components were measured for the three previously mentioned reactor configurations. The basic principle of this technique is that for each chamber the radiation-induced charge in a chamber is made up of one component that is linear with the neutron tissue dose and another component that is linear with the gamma tissue dose. The response equations used were

$$A_{TE}\, Q_{TE} = 0.96\, n + 1.04\, \gamma \tag{1A}$$

$$A_{Mg}\, Q_{Mg} = 0.07\, n + 1.04\, \gamma \tag{1B}$$

where Q_{TE} and Q_{Mg} are the charges produced by radiation within the chambers when exposed simultaneously to a neutron dose of n rads (tissue) and a gamma dose of γ rads (tissue). A_{TE} and A_{Mg} are sensitivity coefficients which can be found in a calibration measurement in ^{60}Co or ^{137}Cs gamma fields. These coefficients are a measurement of the gamma exposure in roentgens necessary to produce a charge of 1 coulomb. Details about these techniques were supplied by Shosa.[5] For the enhanced neutron field (6" Pb shield), the second of the previous equations has to be corrected because in this field a large part of the gamma dose component comes from low energetic x rays (88 keV lead x rays) produced in the lead shield. Previous measurements[5] indicate that the Mg chamber is 13 percent more sensitive to the gamma rays in this field than to gamma rays in the ^{60}Co gamma field or in the fields of the other configurations. Equation (1B) is then

$$A_{Mg} \times Q_{Mg} = 0.07\ n + 1.13 \times 1.04 \times \gamma \quad . \tag{2}$$

With these two equation systems, it is easy to calculate the neutron and gamma dose components. Results of these measurements can be seen in Figures 6 - 8.

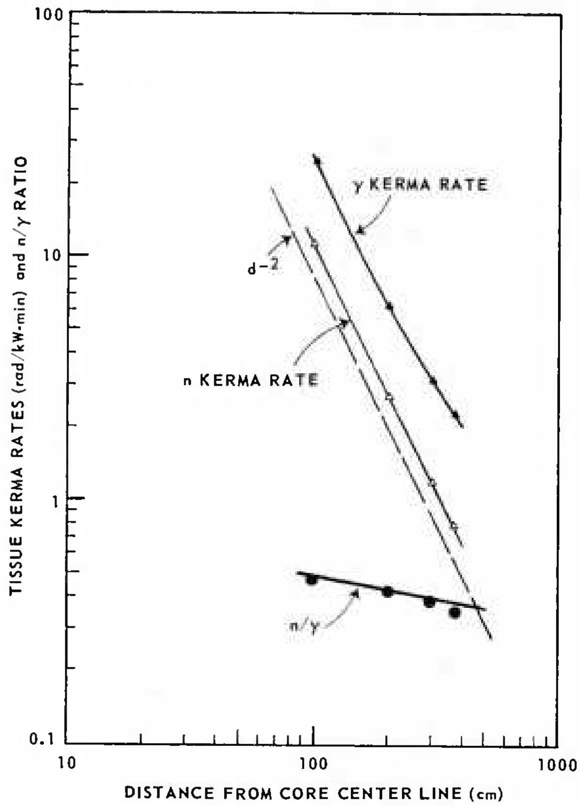

Figure 6. Tissue kerma rates and n/γ ratio for normal field

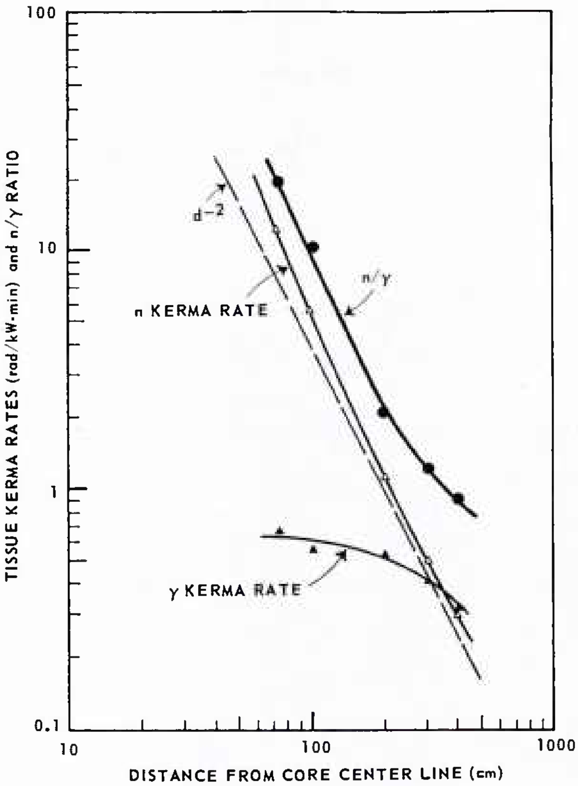

Figure 7. Tissue kerma rates and n/γ ratio for enhanced neutron field

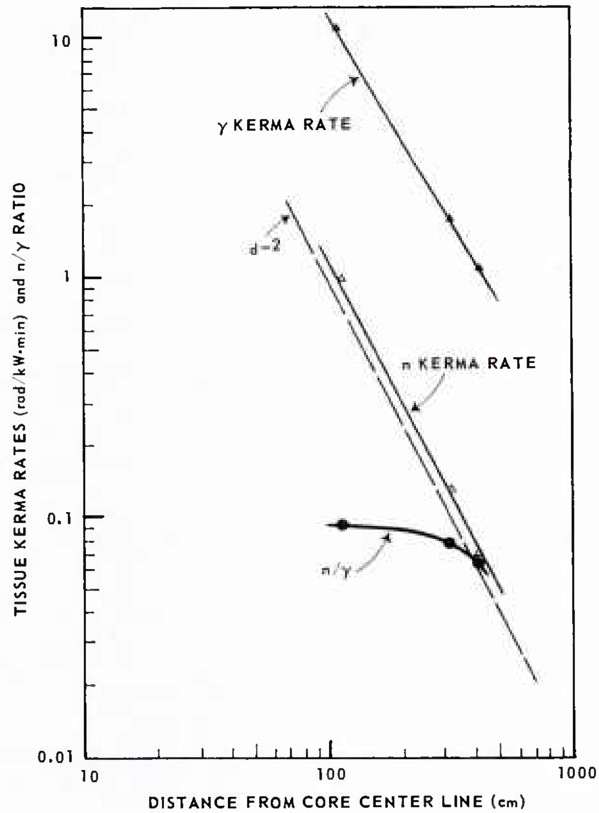

Figure 8. Tissue kerma rates and n/γ ratio for enhanced gamma field

Figure 6 summarizes the results for the free-in-air tissue kerma rates in the normal field. It can be seen that the neutron tissue kerma rate follows the inverse square law well. The gamma tissue kerma rate does not obey this rule so well because the gamma rays coming from the walls of the exposure room contribute a greater part to the gamma tissue kerma rate than the scattered neutrons do to the neutron kerma rate. This difference is reflected in the fact that the n/γ ratio changes only from 0.5 at 1 m to about 0.35 at 4 m.

This situation is quite different for the enhanced neutron field (6" Pb shield). Because the gamma tissue kerma rate is much more depressed by the lead shield (≈ 45 at 1 m) than the neutron tissue kerma (≈ 2 at 1 m), the n/γ ratio is much higher and the part of the gamma rays coming from the walls becomes more important. This results in a slight change of the gamma tissue rate as a function of the distance and in a rapid diminution of the n/γ ratio with the distance from the core (Figure 7).

Figure 8 summarizes the results for the enhanced gamma field (5" water shield). The neutron and gamma tissue kerma rates follow the inverse square law quite well. Therefore, the n/γ ratio is a smooth function of the distance. It has to be mentioned that in this field the error limit for the neutron tissue kerma rate is higher ($\approx$ 20 percent) than in the other configurations ($\approx$ 5 - 10 percent).

Silicon diode measurements. The behavior of these diodes has been tested with the AFRRI-TRIGA reactor and the following results have been obtained.

The diode response to fast neutron irradiation is linear in the dose range from about 400 to 2500 rads. The sensitivity (slope of the curve) in this range is 2.1 mV/rad (Figure 9). In the dose range below 400 rads, the sensitivity became progressively smaller and is about 1 mV/rad at 20 rads (Figure 10).

The diode response to the neutron dose (mV/rad) obtained by the paired chamber technique is, within the statistical error ($\pm$6 percent), the same for the normal field of the reactor (n/γ ratio $\simeq$ 0.5) as for the enhanced neutron field (6" Pb shield, n/γ ratio $\simeq$ 10), and as for the enhanced gamma field (n/γ ratio $\simeq$ 0.1). This means not only that the change of the n/γ ratio has no effect on the diode response but also that the neutron spectrum shift has no effect.

Measurements using the pulse mode of the reactor (up to 1100 rads per pulse, and up to $\approx 1.1 \times 10^5$ rads/sec neutron tissue dose) indicate no dose rate dependence of the diode response (Figurcs 9 and 10).

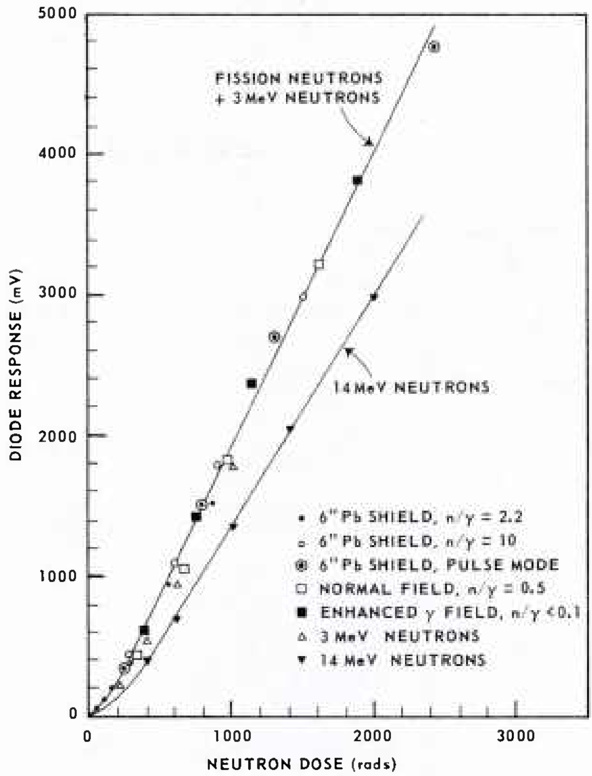

Figure 9. Silicon diode response for fast neutrons

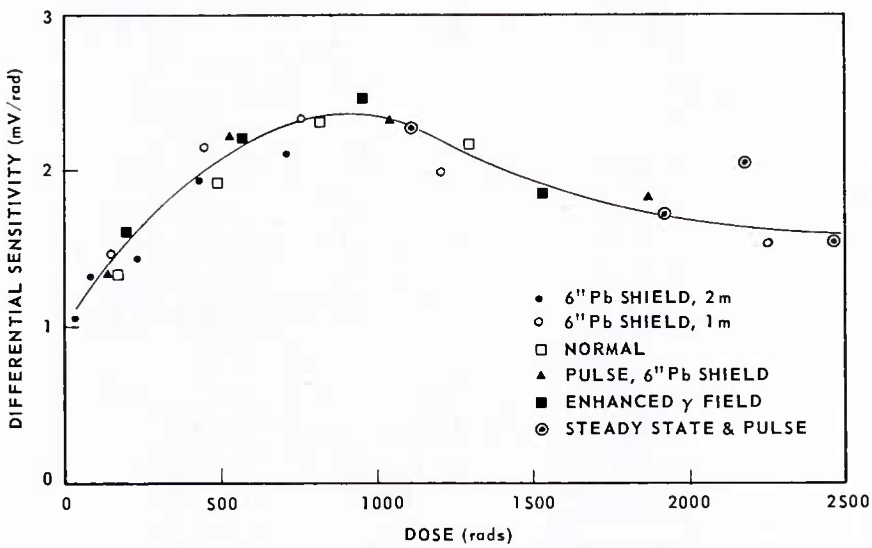

Figure 10. Silicon diode, differential sensitivity

In this report, the diode response has been studied as a function of the neutron tissue dose rather than as a function of the silicon dose because of the intention of using the diodes in radiobiological and health physics studies. This is reasonable because the energy response follows the variation of tissue dose closely over the neutron energy range from 300 keV to 14 MeV.[10]

Bendix pocket dosimeters. These dosimeters were exposed in two reactor configurations with three different n/γ ratios. The purpose of these irradiations was to check for any shift of the sensitivity of these dosimeters dependent on the n/γ ratio.

From Table II it can be seen that the sensitivity, normalized to ^{60}Co exposure, drops with increasing n/γ ratio. That indicates that the sensitivity is lower to fast neutrons than to gamma rays. The first three columns of measurements were made in the steady-state operating mode of the reactor, with dose rates ≤ 3 rads/sec. The values in parentheses were obtained with the "best" two dosimeters of the five dosimeters tested. These values are an indication that it would be possible for the manufacturer to improve the difference between the sensitivity to gamma rays and to fast neutrons.

To study the saturation behavior of these dosimeters, measurements have been performed in the reactor pulse mode field and with the AFRRI LINAC.

In the TRIGA pulse field (525 rads/pulse, 10 msec pulse width, dose rate $\simeq 5 \times 10^4$ rads/sec), the sensitivity drops to 35 percent (Table II).

Table II. Sensitivity (response of the dosimeter/total dose) of Bendix Pocket Dosimeters (normalized to ^{60}Co) for Different n/γ Ratios in Steady-State and Pulse Mode of the AFRRI-TRIGA Reactor

Configuration	Normal	6" Pb shield		6" Pb shield pulse mode (2 m from core)
		2 m from core	1 m from core	
n/γ ratio	0.5	2.0	10.5	2
E/E ^{60}Co (percent)	96 (98)	79.0 (87)	75 (89)	35

A more detailed idea about the saturation behavior can be seen from the measurements with the AFRRI LINAC (Figure 11). In this figure, the sensitivity is drawn as a function of the dose per pulse because this variable enables an easier description of the phenomena.[4] The dose rate in these measurements varied in the range from 6.1×10^4 rads/sec to 1.63×10^7 rads/sec. It can be seen that these dosimeters are useful only to a dose of about 1 rad/pulse.

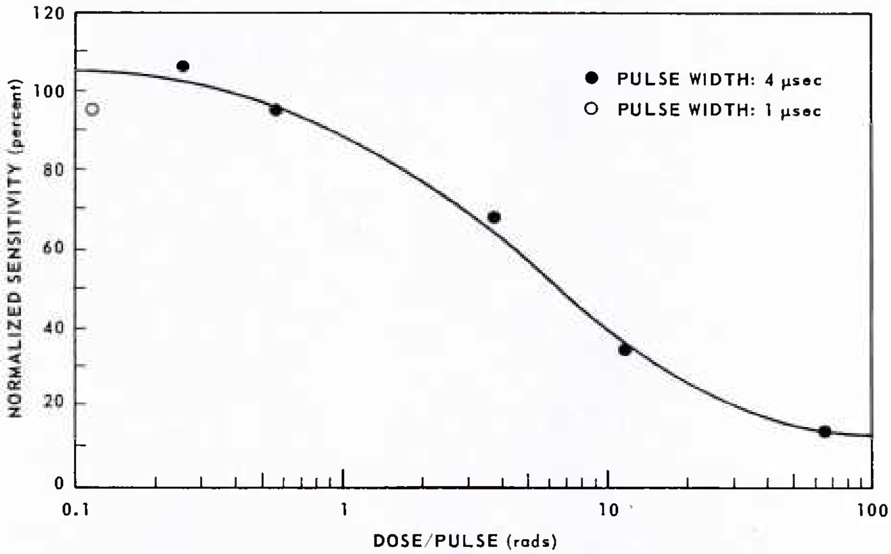

Figure 11. Saturation behavior of Bendix dosimeter

From these results it can be concluded that the Bendix dosimeters are not very useful in the mixed neutron-gamma field with high dose rates.

IV. CONCLUSION

The paired chambers are very efficient devices to measure the gamma and neutron dose components in mixed radiation fields. The measurements with the 0.5 cm^3 paired ionization chambers are in very good agreement with previous results[3, 9] obtained with the 0.05 cm^3 and 50 cm^3 paired ionization chambers.

For measuring the neutron tissue dose alone in a mixed radiation field, the wide based silicon diode is a very attractive dosimetry system because of its simplicity of readout, its negligible gamma response, and its nearly energy-independent neutron response.

The Bendix pocket dosimeter can be used for measuring the total dose in a mixed radiation field only in the steady-state mode of the reactor and then only with certain limitations because of its lower response to fast neutrons than to gamma rays. It cannot be used in the pulse mode of the reactor because of its strong dose rate dependence.

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