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**NEUTRON DOSIMETRY
USING THE FISSION FRAGMENT DAMAGE PRINCIPLE**

**W. V. BAUMGARTNER
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By

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Dosimetry Technology Section
Environmental Health and Engineering Department

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W. V. Baumgartner
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INTRODUCTION

This paper describes the development efforts to incorporate the fission fragment damage principle into a personnel neutron dosimeter. Plastic, glass, and minerals used in conjunction with fissionable materials provide the basis for a full energy spectrum neutron dosimeter. Prototype dosimeter results show marked improvement in dose response when compared to nuclear track emulsion (NTA) neutron dosimeters, which have been used as the basic neutron dosimeter since the start of the nuclear industry twenty-five years ago.

The use of the solid state fission fragment damage principle as a neutron dosimeter was suggested by P. B. Price, R. M. Walker, and P. L. Fleischer⁽¹⁻³⁾ at the General Electronic Research Laboratory in 1963. They proposed placing a neutron fissionable foil next to a piece of plastic sheet, glass, or mica to record the fission events caused by neutrons. After properly etching the surface of the detector material, these events can be recognized by viewing under a microscope as etch pits or tracks. The number of tracks should be related to the dose from neutrons. The Dosimetry Technology Section at Battelle-Northwest accepted the solid state fission fragment damage principle⁽⁴⁻⁸⁾ as a good candidate to

replace the NTA emulsion dosimeters presently in use and began the development of a fission foil neutron dosimeter.

SUMMARY

The fission fragment neutron dosimeters permitted dose evaluation in several neutron energy groups in mixed gamma and neutron radiation fields. This new dosimeter principle used with a single ^{237}Np oxide foil will provide substantially improved neutron dosimetry in mixed radiation fields compared to the commonly used NTA emulsion dosimeters. Fission fragment neutron dosimeters were fabricated with fission foils of metallic ^{235}U (93% enriched) and 20-fold depleted uranium. ^{237}Np oxide foils were fabricated using slow-curing polyester resin as a support base. Uniform surfaces of ^{237}Np oxide were obtained that contained approximately 35 mg/cm^2 of ^{237}Np . Exposure studies of RaBe, PuBe, and PuF4 neutron sources and monoenergetic fast neutrons obtained from a 2 MeV positive ion accelerator characterized the energy and dose response of this device. Comparison studies using fission fragment neutron dosimeters and NTA emulsions were made in field exposure situations. Theoretical and experimental studies indicate that fast neutron doses as low as 150 mRem and thermal neutron doses of 1 mRem can be measured.

MATERIALS AND PRINCIPLES

Of the detector materials suggested, the plastic sheet seemed to be the most promising material since it is readily available and inexpensive, the surface quality can be controlled, and the surface etching process is simple. Many different types of plastic sheet were tested, and Lexan polycarbonate was found to be the most suitable.

Figure 1 shows the general procedure used for processing the fission foil neutron dosimeters. Neutrons strike the fissile foil causing it to fission; fission fragments from the surface penetrate the Lexan causing damage areas. The Lexan, after irradiation, is developed or etched in hot 6N NaOH solution for about 45 min at 60 °C, then rinsed and dried. The Lexan is

then inspected for the etched damage pits or tracks under a microscope using 200 or 400 power depending on the number of tracks in the field. A TV monitor is used to reduce eyestrain.

Attention next focused on the capability of the neutron dosimeter. The criteria for choosing fissile foil materials were:

- The dosimeter should have a fast neutron response that is an improvement over the response of the NTA film emulsion, which has a low energy cutoff at about 0.7 to 0.8 MeV when the direction of the neutron is not known.⁽⁹⁾
- The energy response of the dosimeter should be proportional to the dose response for neutrons of different energies.

FIGURE 1. Fission Foil Neutron Dosimeter

- The dosimeter must have the capability for distinguishing doses from fast and thermal neutrons and should give some indication of the dose from intermediate neutrons.

BNL-325 and UCRL-5226^(10,11) were used to obtain a list of nuclides having fission cross-sections for neutron energies from 0 to 10 MeV. In Figure 2 are shown the fission cross-sections of some of the nuclides at different neutron energies. It is obvious from the figure that no one nuclide by itself will be able to match all the criteria listed above.

Some of the nuclides are difficult to obtain, and others are not chemically stable to be made into thin foils.

Of the metals, only ^{235}U , ^{238}U , and ^{232}Th are suitable for personnel dosimeters. However, the ^{232}Th and ^{238}U cutoff energies are higher than the 0.7 MeV cutoff energy and would therefore not be sensitive to neutrons with energies below 0.7 MeV.

The nuclide ^{237}Np with low energy cutoff of 0.4 MeV was found to be available, but neptunium metal is chemically unstable in air, being spontaneously oxidized. However, it was felt that the ^{237}Np would have to be used to obtain a better fast neutron response than that of the NTA emulsion. Neptunium oxide is chemically stable and was used in place of metallic neptunium.

FIGURE 2. Fission Cross Section for Various Nuclides

Many methods of plating, compacting, and pressing neptunium oxide to form a foil failed to produce a nonsmearing surface or unbreakable foil that could withstand normal wear. A method found to be suitable was to mix the neptunium oxide in a polyester resin plastic and to cure it slowly at room temperature for 24 to 48 hr. This long curing time allows the oxide to settle to the bottom of a flat mold which places the $^{237}\text{NpO}_2$ on the bottom surface of the foil in a form not readily smeared. The amount of neptunium oxide used was about 35 mg/cm^2 of foil surface area. Using this method and amount of $^{237}\text{NpO}_2$, we obtained foils that have a uniform surface distribution and with 100 dis/min or less smearable contamination.

The top half of Figure 3 is a plot of fission cross-section for the nuclides ^{235}U , ^{238}U , and ^{237}Np . The bottom half shows the results of irradiating the foils with neutrons. The foils were 1 cm^2 by 0.02 to 0.05 cm thick pieces of ^{235}U (93%) and ^{238}U (20-fold depleted) and 1 cm^2 by 0.25 cm thick foils of $^{237}\text{NpO}_2$ in polyester resin. The neutron energies were obtained from a 2 MeV positive ion accelerator using different targets and supplemented by PuBe and PuF₄ sources.

The observed $^{237}\text{NpO}_2$ response is less than that of the ^{235}U and ^{238}U responses since the surface of the foil is about 75% polyester resin. The $^{237}\text{NpO}_2$ foil response is about the same as the 20-fold depleted ^{238}U for neutron energies above 1.4 MeV. The sharp cutoff of responses indicate that no correction is necessary for impurities in ^{238}U and $^{237}\text{NpO}_2$.

PROTOTYPE DOSIMETER

Using foils of 20-fold depleted uranium and $^{237}\text{NpO}_2$ and two foils of ^{235}U (93%), one bare and one covered with 1 mm of cadmium on both sides, a prototype dosimeter was fabricated as shown in Figure 4. The overall size is about 2.5 cm by 7.6 cm by about 0.6 cm thick. The foils were glued to the aluminum, which is about 1.2 mm thick. The double bag technique was used in fabrication to avoid spread of contamination. Several hundred measurements were made and no cross contamination of the foil surfaces was detected. As a precaution the Lexan plastic on removal is placed in detergent and sequesterate solutions for cleaning before placing in the etch solution.

FIGURE 3. Comparison of Cross Sections and Results of Fission Foil Exposures

FIGURE 4. *Prototype Neutron Dosimeter*

Prototype badges were used to measure neutrons in mixed radiation fields in several work areas. No employee has worn a prototype badge since there is a radiation level of about 15 mR/hr at the surface, primarily from the $^{237}\text{NpO}_2$ foil. Efforts are being directed at reducing the amount of $^{237}\text{NpO}_2$ in the foils by grinding and lapping the 2.5 mm thick

foils down to about .25 mm. Also, new curing procedures are being tried in attempts to make thinner foils. Shielding materials are also being tried. Using these methods, the dose rate should be reducible to less than 1 mR/hr at the surface, and the fission foil neutron dosimeter may then prove acceptable as a personnel neutron dosimeter.

DOSE EVALUATION EQUATIONS

Using the prototype dosimeter, a method was developed to evaluate neutron doses. The principle for the fission foil neutron dosimeter is essentially the same as for the NTA film neutron dosimeter.

- $\text{Rem} = \text{Rem (n/cm}^2) \times \text{neutron/track} \times \text{track/cm}^2 \text{ of detector}$
- The values for $\text{Rem (n/cm}^2)$ are obtained from the NBS Handbook 63, Figure 13 and Table 2. (13-15)
- The values for neutrons/track are experimentally measured values and are a function of the cross-section for the materials. In general, fissionable metal surfaces yield about 1.2×10^{-5} tracks/neutron/barn.
- Tracks/cm^2 are measured by counting tracks and calculation from the area under the dosimeter foils.
- The foils have overlapping responses to various neutron energies and the general equation required correction terms to properly evaluate the doses. The correction terms have been determined by calibration to known sources.

For neutrons with energies greater than 1.3 MeV:

$$D_{F1} = R_{F1} N_8 (T_8 - 4 \times 10^{-4} T_5) \quad (1)$$

where:

D_{F1} = dose equivalent in Rems

$R_{F1} = 3.9 \times 10^{-8} \text{ Rem/n/cm}^2$

$N_8 = 1.68 \times 10^5 \text{ neutrons/track for } ^{238}\text{U foil}$

T_8 = tracks/cm² for the area under the 20-fold depleted uranium foil

T_5 = tracks/cm² for the area under the bare ²³⁵U foil

$4 \times 10^{-4} T_5$ = correction term for the amount of ²³⁵U in the 20-fold depleted uranium.

The correction term $-4 \times 10^{-4} T_5$ for the ²³⁵U contained in the depleted uranium is an average value and seems to work well for moderated fast and intermediate neutron spectra. For thermal neutrons the value $-8 \times 10^{-4} T_5$ should be used to adjust for the increased number of tracks from ²³⁵U fissions. The value $-8 \times 10^{-4} T_5$ should be used when the ratio T_5/T_{Cd} is much larger than 10 (where T_5 is the number of tracks/cm² under the bare ²³⁵U foil, and T_{Cd} is the number of tracks/cm² under the cadmium-covered ²³⁵U foil).

For neutrons with energies between 0.4 and 1.3 MeV:

$$D_{F2} = R_{F2} [N_{Np} T_{Np} - N_8 (T_8 - 4 \times 10^{-4} T_5)] \quad (2)$$

where

D_{F2} = dose equivalent in Rems

$R_{F2} = 3.1 \times 10^{-8} \text{ Rem/n/cm}^2$

$N_{Np} = 2.03 \times 10^5 \text{ neutrons/track for the } ^{237}\text{NpO}_2 \text{ foil.}$

T_{Np} = tracks/cm² for the area under the ²³⁷NpO₂ foil in the dosimeter.

- The term $N_8(T_8 - 4 \times 10^{-4} T_5)$ is the value (as in Equation 1) for neutrons with energies above 1.3 MeV.

The neptunium oxide foil by itself may be used as a fast neutron dosimeter which will be an improvement over NTA film dosimeters. Equation 2 will then have the form:

$$D_F = R_F N_{Np} T_{Np} \quad (2a)$$

where

$R_F = 3.5 \times 10^{-9}$ Rem/n/cm² and N_{Np} and T_{Np} are as defined for Equation 2.

For neutrons with energies between 0.5 eV and 0.4 MeV;

$$D_I = R_I N_I (T_{Cd} - 2.5 T_{Np}) \quad (3)$$

where

D_I = dose equivalent in Rems

$R_I = 2.7 \times 10^{-9}$ Rem/n/cm²

$N_I = 1.2 \times 10^3$ neutrons/track (experimental) for the cadmium-covered ²³⁵U foil

T_{Cd} = tracks/cm² for the area under the cadmium-covered ²³⁵U foil

T_{Np} = tracks/cm² for the area under the ²³⁷NpO₂ foil, where 2.5

T_{Np} is a correction for neutrons with energies above 0.4 MeV.

In a thermal neutron flux the cadmium covers will depress the flux considerably. Because of this, the fission fragment track density under the center of the cadmium cover is considerably lower than that near the edges. The flux depression can be calculated for Maxwellian neutron energy distributions to correct for this effect. Alternately, the track density at the center of the cadmium cover can be determined, and the flux depression effect included in the calibrations. The latter procedure was used in evaluating Equation 3. For thermal and slow neutrons, Equation 4 is used:

$$D_{Th} = R_{Th} N_{Th} (T_5 - T_{Cd}) \quad (4)$$

where

D_{Th} = dose equivalent in Rems

$R_{Th} = 1.0 \times 10^{-9}$ Rems/n/cm²

$N_{Th} = 7.9 \times 10^2$ neutrons/track if $T_5/T_{Cd} < 10$

$N_{Th} = 4.6 \times 10^2$ neutrons/track if $T_5/T_{Cd} > 10$

T_5 = tracks/cm² for the area under the bare ²³⁵U foil

T_{Cd} = tracks/cm² for the area under the cadmium-covered ²³⁵U foil

The two values of N_{Th} are felt to be necessary to allow for changes in the fission cross-section of ²³⁵U in the thermal to 0.5 eV region. The value 4.6×10^2 neutrons/track is used when the spectrum is known to be composed of only slow and intermediate neutrons (i.e. there is no fast neutron dose as calculated from Equations 1 and 2).

The values for N_g and N_{Np} are averages for the number of neutrons/track derived from free air exposures to neutrons from a positive ion accelerator using the targets and nuclear reactions as shown in Figure 3. The fluences were measured by a Hanford precision long counter.⁽¹⁶⁾ The value of N_I is a calculated value and corresponds to an effective fission cross-section of about 30 barns for ²³⁵U. This value for N_I usually results in a conservative estimate of the dose equivalent from neutrons in the energy range from 0.5 eV to 0.4 MeV. This value for N_I agrees with calculations based upon neutron spectrum⁽¹⁷⁾ data for the number of neutrons in this energy range from plutonium fluoride sources. The values for N_{Th} are based on measurements made in the calibrations unit sigma pile at Battelle-Northwest. The neutrons/track values, N_{Th} , depend upon the size of the foils used in the dosimeter. The values given in the equations compensate for the thermal neutron flux depression effect, and should be conservative for free air exposures.

EXPERIMENTAL BASIS FOR EQUATIONS

If a ²³⁵U foil is placed in an isotropic thermal neutron flux with a Maxwellian energy distribution, the uranium (being approximately a 1/V absorber) will measure the neutron density. Neglecting the effects of spectral hardening caused by the absorption of lower energy neutrons, the effective cross-section for a 1/V absorber is $\sigma_{Th} = (\sqrt{\pi}/2)\sigma_0$, where σ_0 is the 2200 m/sec cross-section. Since ²³⁵U is not exactly a 1/V absorber, we must multiply this effective cross-section by a "not 1/V factor" of 0.98. The effective fission cross-section of ²³⁵U for thermal neutrons is thus

$$\bar{\sigma} = (.98)(\sqrt{\pi}/2) \sigma_0 = 505 \text{ barns.}$$

A 93% enriched ²³⁵U foil with the oxide coating removed was exposed in a graphite sigma pile, and the number of fission fragment tracks/neutron was found to be $3.80 \times 10^{-3} \text{ t/n} \pm 10\%$. This foil was large enough to cause a significant flux depression. The amount of the flux depression can be approximated by a formula developed by Meister.⁽¹⁸⁾ Using Meister's formula, the depressed flux at the surface of the foil was found to be $0.66 \phi_0$, hence the tracks per neutron value corrected for the flux depression is 5.8×10^{-3} tracks/neutron. Dividing this value by the effective fission cross-section of 505 barns gives 1.15×10^{-5} tracks/neutron/barn which agrees quite well with the 1.2×10^{-5} tracks/neutron/barn value established for various

foils exposed to fast neutrons without flux depression effects. Experiments also showed there is no significant difference in the number of tracks/neutron between foils with a thin oxide coating and clean metal foils.

The technique used for track counting will influence the measured values of N , the number of neutrons/track. For the values used in Equations 1 to 4, only the larger, well defined tracks at 200X magnification were accepted. Many of the smaller pits were rejected even though they appear to have been caused by fission fragments. In this way, small surface imperfections are not mistaken for tracks.

RESPONSE CHARACTERISTICS

Table I is a summary of response of the fission foil neutron dosimeter to different calibrated sources. Measurements are included of sources shielded by 1/2 in. lucite, simulating hood exposures. The track/neutron values for the ^{238}U foil are less than that of the $^{237}\text{NpO}_2$ foil for lower energy spectra, but greater at higher energies. The response of the $^{237}\text{NpO}_2$ foil for energies above 2 MeV can be made the same as the ^{238}U foil response by increasing the amount of ^{237}Np at the foil surface. This can be accomplished with slightly longer curing times of the polyester resin, or by using about 40 mg/cm² of $^{237}\text{NpO}_2$ when making the foil. The ratio of tracks is felt to be useful in the absence of spectrum data. For example, a very high ratio for bare ^{235}U to cadmium-covered ^{235}U indicates the spectrum is well thermalized, and is used to

determine the value of N_{Th} in Equation 4. Unusual ratios are useful for adjusting the Rem/n/cm² values in the equations to more accurately define the dose equivalent. Taking the value from the track/neutron columns in Table I and using the Equation 1 through 4, one obtains the values under the column dose equivalent in (Rem/n/cm²) $\times 10^{-8}$ evaluated by dosimeter. The dose equivalent in Rem/n/cm² evaluated by the dosimeter are in agreement with the values taken from Table II and Figure 13 of the NBS Handbook 63. The ratio of fluence data from the dosimeter and calibrated fluence data results in value in the last column of Table I. The ratio of fluences for PuBe + 1.27 cm lucite is probably low due to the statistical error resulting from the small dose received by the dosimeters.

DETECTION LIMITS

Studies were also conducted on detection limit, effects of mixed radiation fields and track fading with time. If one scans 1 cm² of the Lexan plastic from the area under the ^{238}U and $^{237}\text{NpO}_2$ foils, it is possible to detect 150 mRem ($\pm 50\%$ for the 95% confidence level) for neutron energies above 0.4 MeV. A one-tenth mRem dose equivalent from thermal neutrons can be detected by the Lexan from the area under the ^{235}U foils. Exposures to mixed beta, gamma and neutron radiation indicated that the fission foil neutron dosimeter evaluation were not significantly influenced by beta and gamma radiations up to 10,000 rads. Also, no track fading was observed in the Lexan plastic for periods up to one year at temperatures below 50 °C.

TABLE I. Summary of Neutron Exposure

Source	Tracks/Neutron $\times 10^{-5}$ (a)				Ratio of Tracks		Dose Equivalent in (Rem/n/cm ²) $\times 10^{-8}$ Evaluated by Dosimeter	Ratio of ϕ (Fluence) Evaluated by Dosimeter to Calibrated ϕ
	²³⁸ U(b)	NpO ₂ (c)	Cd* ²³⁵ U(d)	²³⁵ U(d)	NpO ₂ / ²³⁸ U	²³⁵ U/Cd* ²³⁵ U		
PuF ₄	0.248	0.476	1.60	5.71	1.9	3.6	3.3	1.06
PuF ₄ + 1.27 cm Lucite	0.191	0.378	4.54	17.6	2.0	3.9	2.6	0.93
PuBe	0.515	0.484	1.37	3.13	0.94	2.3	3.8	0.99
PuBe + 1.27 cm Lucite	0.473	0.412	1.58	3.62	0.87	2.3	3.2	0.84
3 MeV Neutrons from d(D,n)He ³	0.615	0.509	--	1.85	0.83	--	4.0	1.04
Thermal Neutrons from E Pile	0.175	--	6.9	237	--	35	0.11	1.06

(a) Most of the data is $\pm 15\%$ or better(b) ²³⁸U is 20 Fold Depleted

(c) Neptunium-237 Oxide

(d) ²³⁵U is 93% Uranium-235

To reduce the time it takes to scan 1 cm² of area, work is in progress to develop a method that would result in enlarged holes. The method being investigated is similar to the method suggested by Fleisher, Price and Walker.⁽¹⁹⁾ Very thin Lexan plastic is used, through which the etching solution will penetrate completely where a fission fragment has entered. The back of the plastic sheet is coated by an opaque material (such as aluminum) that readily reacts with the sodium hydroxide etching solution. The chemical reaction produces a clear area around the hole much larger than the hole. When the Lexan is now viewed with a strong light behind the opaque layer, spots of light can be seen with very much lower magnification, and a 1 cm² area can be read much more rapidly. The success of this method of etching would significantly reduce the cost of evaluating doses from fission foil neutron dosimeters. An evaluation of dose using the fission foil neutron dosimeter would then cost

much less than evaluation from the NTA film emulsion.

CONCLUSION

For the sources and spectra measured, the equations result in dose evaluations that are slightly higher than the dose calculated from spectra measurements and fluence data. Due to the lack of calibrated intermediate neutron sources, the dose evaluations in this region may be in significant error; but the fission foil neutron dosimeter should overestimate the intermediate neutron dose. Since the uranium foils depress the thermal flux considerably, the dosimeter should be calibrated in a thermal neutron flux under conditions similar to those under which it is to be used. Very thin foils (e.g. 200 μ) could be used to reduce flux depression problems, but the thickness of the film must be greater than the range of a fission fragment in uranium. Freedom from track fading and insignificant beta gamma radiation sensitivity are major

assets of this neutron dosimeter. The potential of the fission foil neutron dosimeter as a personnel dosimeter is very high but has not been realized. Health physicists in the field have known for many years that neutron dosimeters are lacking in accuracy and precision as compared with beta-gamma dosimeters. The fission foil neutron dosimeter should aid in closing this gap.

REFERENCES

- (1) P. B. Price and R. M. Walker. The Use of Mica as a Convenient and Simple Dosimeter for Both Slow and Fast Neutrons, 63-RL-(3253M). General Electric Research Laboratory. February 1963.
- (2) R. M. Walker, P. B. Price, and R. L. Fleischer. "A Versatile, Disposable Dosimeter for Slow and Fast Neutron," Applied Physics Letters, vol. 3, pp. 28-29. July 15, 1963.
- (3) R. L. Fleischer, P. B. Price, and R. M. Walker. "Neutron Flux Measurement by Fission Tracks in Solids," Nuclear Science and Engineering, vol. 22, pp. 153-156. 1965.
- (4) C. M. Unruh, W. V. Baumgartner, L. F. Kocher, L. W. Brackenbush, and G. W. R. Endres. Personnel Neutron Dosimeter Developments, BNWL-SA-537, prepared for presentation to the International Atomic Energy Agency Symposium on Neutron Monitoring for Radiological Protection, Vienna, Austria, August 29-September 2, 1966.
- (5) W. V. Baumgartner, L. W. Brackenbush, C. M. Unruh. A New Neutron and High Energy Particle Dosimeter for Medical Dosimetry Applications, BNWL-SA-619, presented to the International Atomic Energy Agency Symposium on Solid-State and Chemical Radiation Dosimetry in Medicine and Biology, Vienna, Austria, October 3-7, 1966.
- (6) P. R. Prevo, R. E. Dahl and H. H. Yoshikawa. "Thermal and Fast Neutron Detection by Fission-Track Production in Mica," Journal of Applied Physics, vol. 35, pp. 2636-2638. September 1964.
- (7) M. Debeauvois, M. Maurette, J. Mory, and R. Walker. "Registration of Fission Fragment Tracks in Several Substances and Their Use in Neutron Detection," International Journal of Applied Radiation and Isotopes, vol. 15, pp. 289-299. 1964.
- (8) K. Becker. Nuclear Track Registration in Dosimeter Glasses for Neutron Dosimetry in Mixed Radiation Fields, USNRDL-TR-904. U. S. Naval Radiological Defense Laboratory, August 5, 1965.
- (9) R. L. Lehman. Energy Response and Physical Properties of NTA Personnel Neutron Dosimeter Nuclear Track Film, UCRL-9513. Lawrence Radiation Laboratory, January 13, 1961.
- (10) D. J. Hughes and R. B. Schwartz. Neutron Cross-Sections, BNL-352, Brookhaven National Laboratory, July 1955.
- (11) R. J. Howerton. Tabulated Neutron Cross-Sections, UCRL-5226. Lawrence Radiation Laboratory, October 1959.
- (12) Protection Against Neutron Radiation up to 30 Million Electron Volts, Handbook 63. U. S. National Bureau of Standards, Washington, D. C.
- (13) Measurement of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays, Handbook 75. U. S. National Bureau of Standards, Washington, D. C.
- (14) Radiation Quantities and Units (ICRU Report 10a), Handbook 84. U. S. National Bureau of Standards, Washington, D. C.
- (15) Radiobiological Dosimetry (ICRU Report 10e), Handbook 88. U. S. National Bureau of Standards, Washington, D. C.

- (16) Physical Aspects of Irradiation
(ICRU Report 10b), Handbook 85.
U. S. National Bureau of Standards,
Washington, D. C., pp. 47-48,
March 31, 1964.
- (17) G. W. R. Endres. Neutron Spectrum
Measurements at Hanford Work
Locations, HW-SA-3525, General
Electric Co., Richland, Washington
May 1964.
- (18) Reactor Physics Constants, ANL-5800.
Argonne National Laboratory, July
1963.
- (19) R. L. Fleischer, P. B. Price and
R. M. Walker. "Simple Detector
for Neutrons or Heavy Cosmic Ray
Nuclei," Review of Scientific
Instruments, vol. 37, no. 4,
pp. 525-527. 1966.

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