PIN Diode and Neutron Spectrum Measurements at the Army Pulse Radiation Facility

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Abstract

Neutron spectrum measurements using the foil activation technique have been made in two widely varying environments. One is an extremely high neutron-to-gamma field and the other extremely low. These measurements were used to characterize the fields and to evaluate the use of the DN-156 PIN diode for measuring 1 MeV equivalent neutron fluence in silicon ($\Phi 1\text{MeV}(\text{Si})$). The agreement between the $\Phi 1\text{MeV}(\text{Si})$ as measured with diodes and as determined by the spectral measurements was within $\pm 5\%$. A proton recoil neutron spectrum measurement was also made in the low gamma environment.

I. INTRODUCTION

The Army Pulse Radiation Facility (APRF) is a multi-faceted facility operating a Godiva type pulse reactor, housed in a low scatter aluminum silo 30m in diameter and 20m high. The reactor is moveable to several locations and heights. Several well characterized exposure environments are available for experiments.

When testing silicon devices against a nuclear threat, it is essential to consider the difference between the neutron energy spectrum of the threat environment and that of the test environment. This is accounted for by defining a quantity that would have the same damage effect as if all the incident neutrons were 1 MeV in energy. This quantity is defined as the 1 MeV equivalent neutron fluence in silicon ($\Phi 1\text{MeV}(\text{Si})$, Equation 1), where $\Phi(E)$ is the incident neutron spectrum, K_D is the silicon neutron damage function and $\bar{K}_D(1\text{MeV})$ is the ASTM reference silicon damage at 1 MeV [1].

$$\Phi(1\text{MeV}) = \frac{\int_0^{\infty} \Phi(E) K_D(E) dE}{\bar{K}_D(1\text{MeV})} \quad (1)$$

Currently, silicon DN-156 PIN diodes are being used to measure $\Phi 1\text{MeV}(\text{Si})$ directly [2,3]. The purpose of this work is to characterize two neutron environments and to evaluate this technique by comparing it to the results of a foil activation spectrum measurement.

Two neutron spectral measurements were made using

the foil activation technique. Due to the size of the supporting electronic equipment and the limited volume of the device under test (DUT), foil exposures were not made inside the DUT. DN-156 PIN diodes [2,3] and small sulfur pellets were exposed in the DUT to monitor $\Phi 1\text{MeV}(\text{Si})$ during the test. The foil measurements were made in mock-ups of the original item, which were also monitored with DN-156 PIN diodes and sulfur pellets.

II. TEST CONFIGURATIONS

A. 12.7cm Cd-Poly Converter

The first environment was with the DUT directly behind a 12.7cm thick gamma converter made of cadmium-loaded (5% by weight) polyethylene. The converter is 46 cm square. The reactor was placed 2.54 cm in front of the face of the converter and centered on the DUT.

Neutrons are moderated by the polyethylene and interact with the cadmium, producing capture gamma rays. This produces a field with a very low neutron-to-gamma ratio.

Lead and polyethylene shielding materials were used behind the test setup to simulate the shielding used in the actual test.

B. 10.2cm Bismuth shield

In order to create an environment suitable for both activation foils and a proton recoil spectrometer, ROSPEC [4] the mock-up geometry was different from the actual test. A 10.2 cm wall of bismuth bricks was constructed and the detectors placed 50 cm behind it. In the actual test 10.2 cm of bismuth was used but the DUT was directly behind it. Both the foils and the DN-156 PIN diodes were irradiated at the same location.

Bismuth has a very low neutron scatter cross section making it very efficient in transmitting neutrons. It is high Z material (83) making it a very good gamma ray shield. The combination produces a very high neutron-to-gamma field.

III. FOIL MEASUREMENTS

A. Exposures

Twelve to 14 foils were exposed in each environment, covering the full range of neutron energies. Table I shows these reactions and the 5% to 95% energy limits of the foil response. Reactions marked with an * were used in the

indicated configurations. The foils were exposed in sets of 4 or less which required multiple reactor operations. These operations were monitored with sulfur pellets located in two reference positions. DN-156 diodes and sulfurs were also exposed with the foils. The diodes and sulfurs are independent monitors being compared to the results of the foil measurements and are therefore not used as foil sensors.

B. Foil Counting

Gamma lines from all the foils were counted on a high purity germanium detector (HPGe). The detector was calibrated in several fixed, reproducible geometries using a mixed nuclide source traceable to NIST. Each foil was counted twice at distances far enough from the detector to insure that detector dead time and summing corrections were < 1%.

Foil activities were determined as follows [6]:

$$A_o = \frac{C \lambda^2 t_i e^{\lambda t_w} M}{\epsilon P_\gamma F_y A_i (1 - e^{-\lambda t_i}) (1 - e^{-\lambda t_c}) N m} \quad (2)$$

where:

A_o = dps/atom or fissions/atom

C = counts under photo peak

λ = decay constant of product nuclei (s^{-1})

t_i = time of irradiation (s)

t_w = time from end of irradiation to start of count (s)

t_c = time of count (s)

M = atomic mass of target nuclei

ϵ = detector efficiency

P_γ = fraction of γ emission during decay

F_y = fission yield (1 for activation foils)

A_i = isotopic abundance

N = Avogadro's number

m = mass of foil (g)

Fission foil decay correction is complicated by parent daughter decay scheme if ^{140}La line is counted [7].

The resulting activities were used as input into the SANDII spectrum adjustment code [8].

C. SANDII Analysis

SANDII requires 3 inputs; a set of reaction cross sections, a corresponding set of foil activities and an initial input spectrum. The code calculates activities based on these data and compares the calculated and measured activities. If the standard deviation between measured and calculated activities for all the reactions is not within acceptable (user determined) limits the code adjusts the initial spectrum in the areas of poor agreement and makes a new comparison of activities. It continues to iterate in this manner until the preset standard deviation is achieved.

In this work the ENDF/B-V cross section set was

used and initial input spectrum from the SPRIII and ACRR [7] reactors at Sandia National Laboratories were used. These input spectra were used because they represented very similar neutron environments to the ones being measured. Better than 4% standard deviation was achieved with 2 and 7 iterations for the Cd-poly and Bi fields respectively.

IV. DIODE & SULFUR MEASUREMENTS

A. Diodes

The DN-156 PIN diode has several advantages. It is small, fitting inside electronic sub-assemblies easily. It is easy to use. Most importantly it measures $\Phi(1\text{MeV}(\text{Si}))$ directly when properly calibrated. It has been shown to have little or no sensitivity to thermal neutrons or gamma rays [2,3]. The main disadvantage is that they saturate at about 10^{12}n/cm^2 . Although work is being done to extend this range [3], this usually requires a separate low level run to characterize an environment.

APRF diodes are calibrated in a NIST ^{252}Cf field in terms of $\Phi(1\text{MeV})$ to $\pm 9\%$. They were temperature controlled (20°C) and read out 24 hours after exposure so no temperature or fading corrections were needed.

B. Sulfur Pellets

Sulfur pellets are primarily sensitive to neutrons with energies $> 3\text{MeV}$. When sulfur results are used to report the spectrum 3-MeV fluence ($\Phi(>3\text{MeV})$) in a spectrum that differs greatly from a ^{252}Cf spectrum (the calibration spectrum) they are corrected for this spectral difference using the ratio of spectrum averaged cross section ($\bar{\sigma}$) of sulfur($>3\text{MeV}$) in ^{252}Cf to that in the test spectrum [9]. A 3-MeV $\bar{\sigma}$ for the $^{32}\text{S}(\text{n,p})^{32}\text{P}$ reaction can be defined as:

$$\bar{\sigma}_{[3\text{MeV}]} = \frac{\int_0^\infty \Phi(E) \sigma_{32\text{S}}(E) dE}{\int_{3\text{MeV}}^\infty \Phi(E) dE} \quad (3)$$

where $\sigma_{32\text{S}}(E)$ is the $^{32}\text{S}(\text{n,p})^{32}\text{P}$ cross section and $\Phi(E)$ is the neutron spectrum. The denominator of Equation 3 is referred to as the spectrum 3-MeV fluence. The $\bar{\sigma}(\text{Cf})$, calculated from the NIST ^{252}Cf spectrum [10] and the IRDF-90 sulfur cross section [11] is 299mb.

The APRF sulfur system is calibrated in a NIST ^{252}Cf field in terms of $\Phi(>3\text{MeV})_{\text{Cf}}$ to $\pm 3\%$. The corrected $\Phi(>3\text{MeV})$ is accurate to $\pm 10\%$.

C. 1MeV to Sulfur Ratio

In radiation-hardness testing of electronics, neutron fluence is reported in terms of $1\text{MeV}(\text{Si})$ equivalent fluence

TABLE I. REACTIONS USED IN SANDII ANALYSIS

FOIL REACTION	COVERS	LOW ENERGY (MeV)	HIGH ENERGY (MeV)	5" Cd Poly	4" Bi
$^{23}\text{Na}(n,\gamma)^{24}\text{Na}$	None	1.5×10^{-5}	2.1×10^{-1}	*	
$^{23}\text{Na}(n,\gamma)^{24}\text{Na}$	Cd	1.5×10^{-5}	2.1×10^{-1}	*	*
$^{24}\text{Mg}(n,p)^{24}\text{Na}$	Cd	6.5	11.7	*	*
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	Cd	6.4	12.1	*	*
$^{46}\text{Ti}(n,p)^{46}\text{Sc}$	Cd	3.7	9.1	*	*
$^{47}\text{Ti}(n,p)^{47}\text{Sc}$	Cd	1.7	6.8	*	*
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	Cd	5.8	12.3	*	*
$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	Cd	2.1	7.1		*
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	Cd	5.4	11.2		*
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	Cd	1.8	7.0	*	*
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	Cd	4.5×10^{-6}	1.2×10^{-2}	*	*
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	None	4.5×10^{-6}	1.2×10^{-2}	*	*
$^{237}\text{Np}(n,f)^{140}\text{La}$	Cd & ^{10}B	5.0×10^{-1}	4.5	*	*
$^{238}\text{U}(n,f)^{140}\text{La}$	Cd & ^{10}B	1.4	5.9		*
$^{239}\text{Pu}(n,f)^{140}\text{La}$	Cd & ^{10}B	1.4×10^{-2}	3.4	*	*

[1]. Neutron exposures are monitored using sulfur pellets. In order to convert fluence as determined by sulfur activation to $\Phi 1\text{MeV}(\text{Si})$, the ratio of $\Phi 1\text{MeV}(\text{Si})$ to $\Phi(\text{sulfur})$ must be determined in the field that the monitor was exposed in.

There are two ways to determine this ratio. One is to determine the neutron energy spectrum in the test field and take the ratio of $\Phi 1\text{MeV}$ to $\Phi(>3\text{MeV})$. The other is to expose a sulfur pellet along with a calibrated silicon device [2,3,5] in the test field. The APRF uses these monitors to measure the 1MeV/Sulfur ratio directly (Equation 4.)

$$1\text{MeV/Sulfur} = \frac{\Phi 1\text{MeV}_{\text{diode}}}{\Phi(>3\text{MeV})_{\text{sulfur}}} \quad (4)$$

When sulfur pellets are used with the 1MeV/Sulfur ratio to report $\Phi 1\text{MeV}(\text{Si})$ no corrections for differences in $\bar{\sigma}$ are needed. This is because the $\Phi(>3\text{MeV})$ is not determined in an absolute sense but only to relate two reactor irradiations.

The 1MeV/Sulfur ratio is established once. As long as the exposure geometry and neutron environment, as well as the procedure for determining the sulfur activation, remain constant, this ratio can be used in subsequent irradiations to determine $\Phi 1\text{MeV}(\text{Si})$ from the activity of a sulfur monitor.

The stability of the sulfur counting system is $\pm 2\%$ while the diode calibration is $\pm 9\%$ making the uncertainty of the 1MeV/Sulfur ratio $\pm 10\%$

V. ROSPEC MEASUREMENTS

ROSPEC [4] is a self-contained proton recoil neutron spectrometer. Four spherical proportional counters are optimized to cover an energy range from 0.1 MeV to 4.5 MeV. Each detector was irradiated separately 50cm behind 10.7cm of bismuth.

Dead time problems prevented measurements in high background fields close to the reactor. The reactor was run at the lowest reproducible levels (0.1 watt) and results were normalized by reactor power.

VI. RESULTS

A. Spectrum Characteristics

All data reported here has been normalized to a typical reactor pulse of 1.2×10^{17} fissions, which is comparable to 57 kWmin of steady state operation. Several integral parameters are of interest in neutron environments. Table II lists these results. It should be noted that both the

Table II. Spectral Characteristics.

	APRF-FF	CD-POLY	BISMUTH
Φ Total (n/cm ²)	2.77×10^{12}	2.29×10^{12}	1.64×10^{12}
Φ (> 10 keV)	2.75×10^{12}	1.53×10^{12}	1.57×10^{12}
Φ (> 3 MeV)	3.53×10^{11}	2.41×10^{11}	1.09×10^{11}
Φ 1MeV(Si-93)	2.50×10^{12}	1.22×10^{12}	1.30×10^{12}
Φ 1MeV(GaAs)	2.58×10^{12}	1.30×10^{12}	1.37×10^{12}
Φ 1MeV(Si-85)	2.67×10^{12}	1.32×10^{12}	1.35×10^{12}
Φ 1MeV / Φ (>3MeV)	7.08	5.06	11.93
HP(Si-93)	0.91	0.80	0.83
$\bar{\sigma}$ Sulfur _{>3MeV} (b)	0.303	0.296	0.324
Φ 1MeV(Si-93)/cGy(Si, γ)	3.61×10^9	1.02×10^8	1.67×10^{10}

Figure 1. Full Spectrum comparison.

Figure 2. Fast neutron spectrum comparison.

TABLE III. DIODE, SULFUR & FOIL AGREEMENT

		FOIL RESULTS	DIODE & SULFUR	% DIFF
4" BISMUTH	Φ 1MeV(Si-93) n/cm ²	1.30×10^{12}	1.28×10^{12}	1.6
	Φ (> 3MeV) n/cm ² (Cf equivalent)	1.18×10^{11}	1.13×10^{11}	4.4
	1MeV / Sulfur	11.0	12.3	-3.5
5" Cd-Poly	Φ 1MeV(Si-93) n/cm ²	1.22×10^{12}	1.22×10^{12}	-0.5
	Φ (> 3MeV) n/cm ² (Cf equivalent)	2.39×10^{11}	2.37×10^{11}	0.1
	1MeV / Sulfur	5.1	5.2	-1.9

Figure 3. ROSPEC and foil spectra.

old, 1MeV(85), and the new, 1MeV(93) silicon damage functions are reported here. This is for comparison only, the new damage function is used in reporting $\Phi_{1\text{MeV}}(\text{Si})$ [1]. Other useful quantities are the hardness parameter and neutron-to-gamma ratio. The first is the ratio of $\Phi_{1\text{MeV}}(\text{Si}) / \Phi(>10\text{keV})$ which is an indicator of the spectrum shape. The neutron-to-gamma ratio, expressed in terms of $\text{n}\cdot\text{cm}^{-2} / \text{cGy}(\text{Si}, \gamma)$, is useful to know if the DUT maybe sensitive to γ s.

Figures 1 & 2 show the resulting neutron spectra for the fields measured along with a free field calculation [12] for comparison. The full energy spectrum shows a substantial low energy "tail" from scattered neutrons. This is well below the threshold for silicon and has little or no impact on $\Phi_{1\text{MeV}}$. A more useful representation is given in Figure 2, of the energy range from .01 MeV to 20 MeV. Here the differences in spectrum "hardness" can be seen more clearly.

B. Sulfur & Diode

The quantities measured with the sulfur and diode monitors show excellent agreement with full spectrum determinations above. Table III demonstrates this.

The critical parameter is the 1MeV/Sulfur ratio which is used to report $\Phi_{1\text{MeV}}(\text{Si})$ when only a sulfur pellet is used to monitor an exposure. These results are well within the $\pm 10\%$ uncertainty assigned to $\Phi_{1\text{MeV}}(\text{Si})$.

The quantity $\Phi(>3\text{MeV})$ has been corrected to

compare ^{252}Cf equivalent fluence [9], this resulted in an 8% increase in the $\Phi(>3\text{MeV})$ reported by the foils in the bismuth environment and a 1% decrease in the Cd-poly environment.

C. ROSPEC Results

Due to the limited energy range, it was necessary to compare ROSPEC with the foil data from 0.1 MeV to 4.5 MeV. The integral parameter of interest is $\Phi_{1\text{MeV}}(\text{Si})$,

$$\frac{\int_{.1\text{MeV}}^{4.5\text{MeV}} \Phi(E) K_D(E) dE}{\bar{K}_D(1\text{MeV})} \quad (5)$$

Where $\Phi(E)$ is the incident neutron spectrum, $K_D(E)$ is the current Si damage cross section and $\bar{K}_D(1\text{MeV})$ is the ASTM defined reference damage [1]. This differs from the standard definition of $\Phi_{1\text{MeV}}$ only by the limits of integration.

Agreement was within 6%, with ROSPEC reporting $1.21 \times 10^{12} \text{ n/cm}^2$ and foils $1.28 \times 10^{12} \text{ n/cm}^2$. Figure 3 shows a spectrum comparison of the ROSPEC spectrum with the foil

spectrum over the energy range of interest. The discontinuity in the foil spectrum near 1MeV is not understood at this time. It is assumed to be an artifact of the computer code.

VII CONCLUSIONS

DN-156 PIN diodes may be used confidently to characterize a variety of neutron fields in terms of 1MeV(Si) equivalent neutron fluence. This becomes very significant when the DUT is a complex sub-assembly which cannot be subjected to the fluence required for activation foil exposures, or where the exposure volume limits the use of boron covered fission foils.

The APRF has acquired the capability of making neutron spectrum measurements using the activation foil technique. Two important neutron environments have been well characterized for use in radiation-hardness testing. These environments are not limited to electronic testing.

Proton recoil spectroscopy and foil activation techniques have been used successfully in the same radiation environment, providing confirmation of the foil measurements over a critical energy range.

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