UNFOLDING OF NEUTRON SPECTRA FROM GODIVA TYPE CRITICAL ASSEMBLIES

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ABSTRACT

The results from three experiments conducted at the White Sands Missile Range Fast Burst Reactor Facility are the basis for this work. These experiments were designed to measure the 'free-field' neutron leakage spectrum and the neutron spectra from mildly perturbed environments. Using SAND-II, we have taken the experimental data for each experiment and calculated the neutron spectrum utilizing several different trial input spectra. Comparisons are made between the unfolded neutron spectrum for each trial input on the basis of the following parameters: average neutron energy (above 10 KeV), integral fluence (above 10 KeV), spectral index and the hardness parameter, ϕ_{eq}/ϕ.

INTRODUCTION

The unfolding of neutron spectra from foil activation data with a high degree of accuracy has been the subject of many investigations over a period of several years. More recently, this endeavor has evolved the use of 'Unfolding Codes' such as RDMM,[1] SPECTRA,[2] SAND-II[3] and CRYSTAL BALL.[4] Other codes have been written but found to be less satisfactory than those mentioned.

Heimbach[5] has studied in detail the unfolding abilities of SAND-II for a standard set of activation foils commonly in use at the Diamond Ordinance Reactor Facility (DORF). He concludes that, due to the integral nature of the detector responses, the resolution of a SAND-II

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solution spectrum is not expected to be high; but, finds that SAND-II is quite accurate in reproducing the peak maximum corresponding to the peak most probable energy. Kilminster[6] has compared the resultant neutron spectra calculated by SAND-II and SPECTRA and found these two codes to be roughly comparable in their ability to produce a valid solution spectrum from a given set of activation foil data. In addition, he found that the codes were relatively insensitive to error in the measured foil activities.

With these ideas in mind, the work presented in this paper gives a study of the dependence of several parameters, used to characterize a neutron environment, on the choice of trial input spectrum for SAND-II. The parameters chosen for this comparison are (1) average neutron energy above 10 KeV, (2) integral fluence above 10 KeV, (3) spectral index, and (4) hardness parameter, ϕ_{eq}/ϕ.

EXPERIMENTAL

Three experiments were performed on the White Sands Missile Range (WSMR) Fast Burst Reactor (FBR). The first experiment was designed to measure the 'free-field' leakage spectrum (FFLS) 20-inches from the core surface of the FBR. A total of 72 individual activation detectors were exposed to the neutron leakage spectrum of the FBR. These detectors were arranged symmetrically around the reactor core at mid-plane. In the second experiment, the neutron spectrum was measured with the experimenters table (ETS) in place. This table consists of a 4' x 8' x ¼" peg board supported by a tubular metal frame. The reactor core protrudes through a hole in the center of the table. A total of 42 individual activation detectors were mounted midplane to the reactor core. The third experiment involved the measurement of a neutron spectrum that had been perturbed by a ½ inch thick piece of curved aluminum (ALS). The ring on which the activation detectors was mounted was supported by its own tubular frame with the aluminum shield attached in midplane geometry. A total of 44 individual detectors were used. Activity measurements and data analysis procedures are identical to those reported previously.[7,8,9,10]

Harvey et al.[7] have recently concluded that the error involved in the activation data analyzed by previously established techniques[8,9,10] to be within ± 7%; furthermore, it was noted that an activity error of ± 5% or better is possible for those foil reactions where the nuclear data is well known and good counting statistics can be obtained. Similar error analysis for foil activation data have been reported by McElroy et al.[11] and Kellog and Zimmer.[12] Estimates of the overall error for the measured average integral flux was given as ± 10% by McElroy et al.[11] Verbinski[13] reports the probable accuracy in the 1 MeV equivalent (Silicon) neutron fluence and the hardness parameter calculated directly from SAND-II differential spectra to be ± 10% for reactor spectra and ± 5-7% possible with added effort.

DISCUSSION

The average energy, integral fluence and spectral index for each of the three experiments for the various trial inputs used by SAND-II are summarized in Table 1. For the free-field spectrum measurement a total of 13 foil reactions were used, while 11 foil reactions were used for both the experimenters table spectrum measurement and the aluminum shielded spectrum measurement. The average error associated with the foil reaction data was within ± 7%. The 1DF[14] calculated spectrum was expected to provide the best trial input for all three experimental configurations. Comparison with the other three trial input spectra, on the basis of data presented in Table 1, shows the reciprocal energy (RE) trial input to be a poor choice, while the flat (or constant) trial input provides results that compare more favorably to the 1DF results. On the other hand, using Standard Godiva (SG) from the SAND-II library as a trial input gives very good agreement with the 1DF calculation. In any comparison made between SG and 1DF for any of the three experiments an error $\leq$ 3% is found. The peak most probable energy of the solution spectra from the SG and 1DF calculations agree exactly for each experiment. In all three cases, when the 1DF calculated spectrum was used as a trial input, a solution (at the 95% confidence level) was obtained in 6 iterations or less.

Table 1. Spectral Data Derived from Sand-II Calculations

TRIAL INPUT	AVERAGE ENERGY (MeV)		INTEGRAL FLUENCES ABOVE SPECIFIED NEUTRON ENERGY								SI
	>0.01	>0.60	0.01	0.10	0.60	1.0	1.5	3.0	4.5	6.0	
FREE-FIELD SPECTRUM MEASUREMENT											
RE	1.62	2.35	1	0.841	0.662	0.531	0.401	0.178	0.075	0.020	5.62
FLAT	1.58	2.25	1	0.944	0.657	0.498	0.361	0.166	0.074	0.020	6.04
SG	1.56	2.15	1	0.980	0.678	0.510	0.377	0.152	0.055	0.017	6.56
1DF	1.56	2.15	1	0.969	0.679	0.514	0.376	0.154	0.056	0.018	6.51
EXPERIMENTERS TABLE SPECTRUM MEASUREMENT											
RE	1.60	2.26	1	0.853	0.680	0.524	0.382	0.171	0.070	0.018	5.84
FLAT	1.49	2.12	1	0.943	0.656	0.480	0.327	0.145	0.063	0.016	6.91
SG	1.51	2.12	1	0.978	0.660	0.482	0.351	0.148	0.054	0.018	6.75
1DF	1.51	2.12	1	0.966	0.659	0.483	0.347	0.149	0.055	0.019	6.72
ALUMINUM SHIELD SPECTRUM MEASUREMENT											
RE	1.66	2.34	1	0.851	0.680	0.541	0.406	0.175	0.076	0.018	5.43
FLAT	1.58	2.18	1	0.947	0.678	0.508	0.355	0.158	0.068	0.017	6.32
SG	1.60	2.15	1	0.981	0.699	0.529	0.390	0.156	0.056	0.019	6.41
1DF	1.61	2.15	1	0.972	0.700	0.534	0.390	0.158	0.058	0.020	6.34

Concerning the free-field measurement, if one uses accepted values for fission averaged effective cross sections, a spectral index of 6.5 is calculated.[8] This is in extremely good agreement with the spectral index calculated by using the SAND-II results from the SG or 1DF trial inputs. Further, the integral fluence above 10 KeV calculated from fission averaged effective cross sections is within 3% of that calculated by SAND-II. The above results would indicate that if the trial input spectra are a good approximation of the true spectrum then consistent results for average energies, integral fluence values and spectral indices can be obtained. Kilminster[6] has noted "it is hard to conceive of a situation when no knowledge of the incident spectrum is available."

Another method of comparing unfolded neutron spectra is in terms of 1-MeV equivalent fluence, ϕ_{eq}, for silicon and in terms of the hardness parameter ϕ_{eq}/ϕ. The hardness parameter, ϕ_{eq}/ϕ, is defined as the neutron fluence near 1 MeV required to produce the same radiation damage as one unit of neutron fluence of spectral distribution $\phi(E)$.[13] The hardness parameter is calculated by the expression,

$$\phi_{eq}/\phi = \frac{\int_{0.01\ \mathrm{MeV}}^{\infty} \phi(E)D(E)dE}{D(1\ \mathrm{MeV}) \int_{0.01\ \mathrm{MeV}}^{\infty} \phi(E)dE} \quad (1)$$

The 0.01 MeV cutoff simplifies the calculation and introduces less than 1% error in the result since little radiation damage (displacement effects) occurs below this point.[15] The integrals are approximated as follows:

$$\int_{0.01\ \mathrm{MeV}}^{\infty} \phi(E)D(E)dE = \sum_{i=361}^{620} \phi(E_i)D(E_i)\Delta E_i \quad (2)$$

$$\int_{0.01\ \mathrm{MeV}}^{\infty} \phi(E)dE = \sum_{i=361}^{620} \phi(E_i)\Delta E_i \quad (3)$$

and

$$D(1\ \text{MeV}) \equiv \bar{D}(0.85 - 1.15\ \text{MeV}) = 84\ \text{MeV}\cdot\text{mb} \quad (4)$$

The quantity $\phi(E_i)$ is the 620 point differential neutron spectrum calculated by SAND-II.

The last column in Table 2 gives the 'hardness parameter' for each experimental configuration and for each trial input spectrum. Within each experimental configuration, the widest variation observed (7%) is for the RE trial input spectrum, the 'hardness parameter' for all other trial input spectra showing small or insignificant variation. By comparing the 'hardness parameter' and spectral index, it is clear that the 'hardness parameter' is least sensitive to changes in the neutron environment. The 'hardness parameter' of the 1DF trial input is 1.11 and when compared to 1.12 for FFLS, 1.09 for ETS and 1.14 for ALS, very little difference is noted. The spectral index, however, changes from 7.52 to 6.51 for FFLS, 6.72 for ETS and 6.34 for ALS, which is an average change of ~ 15%.

CONCLUSIONS

Provided one uses accurate foil activation data, up to date consistent cross-sections and trial input spectra that are good approximations of what is believed to be the true neutron spectrum; consistent average energies, integral fluences and spectral indices can be calculated.[16] Further, the hardness parameter, ϕ_{eq}/ϕ, can be calculated from SAND-II results for different 'good' trial inputs and found to be consistent not only for these trial inputs but with the hardness parameter calculated from transport calculations. If the user desires to produce from activation foil data average energies, integral fluence values, spectral indices and differential data for calculation of the hardness parameter, SAND-II will provide this data with good accuracy. The error associated with these quantities should not be greater than ± 10% provided care is taken in the measurements.[7,13]

Table 2. Comparison of Spectral Data With Total Fluence and Hardness Parameter

TRIAL INPUT	SI	ϕ	ϕ_{eq}/ϕ
FREE-FIELD SPECTRUM MEASUREMENT			
RE	5.62	9.40×10^{12}	1.05
FLAT	6.04	1.01×10^{13}	1.09
SG	6.56	1.04×10^{13}	1.13
1DF	6.51	1.04×10^{13}	1.12
EXPERIMENTERS TABLE SPECTRUM MEASUREMENT			
RE	6.84	9.01×10^{12}	1.05
FLAT	6.91	1.02×10^{13}	1.06
SG	6.75	1.01×10^{13}	1.10
1DF	6.72	1.01×10^{13}	1.09
ALUMINUM SHIELD SPECTRUM MEASUREMENT			
RE	5.43	7.84×10^{12}	1.07
FLAT	6.32	8.75×10^{12}	1.09
SG	6.41	8.66×10^{12}	1.14
1DF	6.34	8.62×10^{12}	1.14
1DF[a]	7.52	---	1.11

[a]Transport calculation unperturbed by SAND-II.

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