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Benchmarking the Sandia Pulsed Reactor III Cavity Neutron Spectrum for Electronic Parts Calibration and Testing¹

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Abstract

The SPR III bare cavity spectrum and integral parameters have been determined with 24 measured spectrum sensor responses and an independent, detailed, MCNP transport calculation. This environment qualifies as a benchmark field for electronic parts testing.

I. INTRODUCTION

Fast burst reactors are used extensively for determining the responses of electronic parts to neutron-induced displacement damage. In addition, there has been increasingly frequent testing of parts in highly modified environments in attempts either to more closely approximate particular operational environments or to simply make better use of neutron fields that are available. As a consequence of this proliferation of test configurations, there have been instances in which the measured response of an electronic part has differed by large factors (>2) from that predicted by the spectrum assumed to be valid for the test environment. In some instances this can be ascribed to gamma-ray effects. In the rest, the cause must be ascribed to measurement error on the device, incorrect scaling of the radiation field between the test on the part and the spectrum measurement, or to an incorrect spectrum determination. The error caused by the use of an incorrect spectrum is enhanced if only high-threshold monitors such as sulfur or nickel are used with the electronic part to scale the fluence. This is because the fraction of the energy range of the spectrum sampled by the monitor is much smaller than that sampled by the response of the electronic device. The sulfur threshold is about 3 MeV, but the threshold for silicon damage is usually close to 100 keV.

There are two primary incentives for qualifying the SPR III free-field cavity as a reference benchmark field. The first is to provide a well established test environment for users of the facility. The standard benchmark fields at the National Institute for Standards and Technology (NIST) have fluence rates too low and volumes too small for many electronic parts test-

ing requirements. The second is to provide a readily available source that can be used to help characterize the environments for other configurations and at other facilities.

A good measurement of the spectrum with the spectrum-sensor methodology (usually called the foil activation method) requires the use of a sensor set that samples the spectrum adequately over the whole range within which the device of concern to the experimenter is sensitive. The problem is that spectra have frequently been determined from sensor sets that have poor coverage so that the resulting spectrum shape differs considerably from that in the real test environment. For example, the spectrum shape in a TRIGA reactor may resemble a pure fission spectrum above 1 MeV, but be very different at lower energies where the device under test may be sensitive. Furthermore, many laboratories do not have access to fission foils (which provide sensitivity above 10 keV when covered with boron) because of difficulties with licensing and handling. For most spectrum shapes there are few other easily used foils that have response in the 0.01-to 2-MeV range.

Fortunately, silicon sensors have been proven to be very effective in establishing the fluence above 100 keV [1] and can provide the needed response coverage in the absence of fission foils. However, these sensors must be calibrated in a reference field such as in the SPR III cavity. Also, the SPR III central cavity was a baseline field for the experimental verification of the new NJOY- calculated, silicon neutron displacement damage function being incorporated into the revised 1993 ASTM Standard E 722 [2].

The SPR III cavity environment has been characterized in the past [3,4]. However, an improved methodology for developing spectra [5], updated dosimetry reaction cross sections [6], more accurately calibrated dosimetry systems, and expanded counting capabilities at SNL [4] together with experience gained in constructing more than 30 different spectra, have all combined to provide an opportunity to generate the much more realistic spectra needed to satisfy the requirements for electronic parts testing in widely varied environments. In fact, the consistency of the primary activity data, as reflected in

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the quality of the spectrum fit for so many sensors, may serve as a model for how well spectra can be determined by a carefully chosen and carefully evaluated sensor set. In addition, there have been so many users who require specialized radiation configurations that methods have had to be developed to adequately characterize each environment.

This paper describes the characteristics of the SPR III, the modeling of the cavity spectrum, the measurements of the foil activities, the construction of the spectrum with the aid of the SANDII code [7], the final spectrum results, and analyses of the uncertainties.

II. THE FACILITIES

A. The SPR III Reactor

The SPR III is an advanced fast-neutron Godiva-type reactor with a large 16.5-cm central cavity. It was commissioned in 1975. Although it was developed primarily for the radiation testing of electronic parts and systems, it has been used in a very wide variety of research activities. It is positioned in the center of an air-filled shield building called the Kiva. Experiments are conducted not only in the cavity but also outside the core at distances between 0.3 and 3.0 m from the core axis. There are also ports in the shield wall for the fielding of experiments that require well collimated beam geometries. The reactor can be operated in steady-state (up to 10 kW power) or pulsed mode (10 MJ in an 80 μ s FWHM pulse that yields about 5×10^{14} n/cm² in the cavity).

B. The Radiation Metrology Laboratory

The Radiation Metrology Laboratory (RML) [4] is equipped with six separate shielded germanium detectors. Each is calibrated regularly against Amersham International plc gamma line sources. Typically the detectors will yield values for the activity of the same foil that are reproducible to within 1-3%. If detector counts total more than 10^4 , and background counts are low so that statistical uncertainties are small, then the uncertainty of an activity measurement is about 5% for non-fission foils. The uncertainty for fission foils is about 6% because of the added 1% uncertainty of the fast-fission cumulative yield of ¹⁴⁰La.

The RML is also equipped for sulfur dosimetry. Its sensitivity is regularly compared with NIST and the counting facilities at Aberdeen Proving Grounds and at the White Sands Missile Range (WSMR). Thermoluminescent (TLD) gamma-ray dosimeters are also used regularly. There are major efforts being carried on to investigate and evaluate new dosimetry techniques in order to extend the RML's capabilities.

III. CALCULATIONAL MODELS

Radiation transport calculations of the SPR III reactor were performed to:

1. provide an input trial function for least-square-based spectrum determination of the SPR III spectra,
2. provide a basis for the pre-experimental determination of the effect of test articles on the test environment,
3. provide SNL with energy-dependent photon spectra at experiment locations that can be used to improve our interpretation of mixed-field dosimetry,
4. assure a high-fidelity specification of the reactor radiation environment that can be used to support its acceptance as a reference benchmark field,
5. meet the requirement for submitting the SPR III environment to the Cross Section Evaluation Working Group (CSEWG) for inclusion in its set of dosimetry benchmark fields [8].

A. Criticality Modeling

Detailed models of the SPR III reactor have been prepared for use in radiation transport calculations. TWODANT r-z and r- θ geometries [9] and detailed (272 regions and 287 surfaces) MCNP [10] geometries that include the reactor room/Kiva and storage pit [11] have been compared to measured [9, 12] element worths, Δk , and assembly multiplication factors k_{eff} , and found to be in good agreement. Table 1 presents the calculated eigenvalues, k_{eff} , from the MCNP model for various configurations of the SPR III control rods and safety block. The starred configurations correspond to a delayed critical configuration. Table 2 compares the calculated worth of various parts of SPR III with the worths deduced from experimental measurements [12]. The agreement of the calculated eigenvalues and reactivity worths with measurement attests to the fidelity of the reactor modeling.

Table 1: Summary of SPR III MCNP Criticality Calculations

Reactor Configuration			k_{eff}	Rel. Err. (%)
Method	Burst Element	Control Element		
Rod Drop	Up *	6740, 6000, 6740	0.9994	0.06
	Down	6740, 6000, 6740	0.9917	0.07
	Down	5653, 6000, 5653	0.9993	0.06
	Down	5653, 6000, 5653	0.9399	0.07
	Down	9000, 9000, 9000	0.9766	0.06
Asymptotic Period Measurement	Up *	6418, 6418, 6418	0.9993	0.05
	Up	5904, 5904, 5904	1.0047	0.05
	Down	5735, 5735, 5735	0.9997	0.05
	Down	5270, 5270, 5270	1.0052	0.05
Control Element. position 0 = up, 9000 = down				

Table 2: Comparison of the Calculated and Measured Reactivity Worths for Reactor Components

Reactor Configuration	Calculated		Measured	
	$\Delta k(\%)$	Δ	$\Delta k(\%)$	Δ
Burst Element	1.20	0.20	1.114	0.005
Safety Block	9.72	0.21	9.978	0.1
Partially Inserted Control Element	3.57	0.19	3.487	0.019
Δ = relative error in percent				

B. Spectrum Modeling

The detailed MCNP model [11] was used with a ring/point detector in the central cavity and at the 17-in (43.2 cm) leakage location corresponding to the geometries where the activation sensors used in the SANDII spectrum determination were fielded. Calculations were done to determine the energy-dependent neutron spectrum at the central cavity and 17-in leakage locations. Figure 1 compares the MCNP-calculated spectra to the experimentally measured spectra. The differential number spectra shown in the figure are normalized so that the fluence greater than 10 keV, $\Phi_{10\text{keV}}$, integrates to one.

The agreement between the unfolded SANDII spectrum and the MCNP calculation is fairly good. The thermal part of the cavity spectrum was found to be very sensitive to the modeling of the Kiva ceiling and the fission detectors located immediately above the reactor. The thermal tail in the leakage spectrum could be improved by better modeling of the auxiliary equipment in the Kiva.

Several consistent shape differences are seen between the measured and calculated spectra. There is a slight rise in the measured distribution relative to the calculated distribution in the 50-300 keV energy range. This results in a significant depression in the resonance energy region (10 eV - 5 keV), which is emphasized by the logarithmic scale in Figure 1. Uncertainty in the inelastic scattering cross sections used in the radiation transport cross sections for the fuel and support structure may be responsible for this difference.

C. Calculated Sensor Response

The model used in the spectrum calculation was also used to determine calculated foil activities. The 640 energy-group dosimetry cross sections from the SNLRML library [13], with attenuation by the appropriate cover materials, were used as response functions in the MCNP calculation to ensure a high-fidelity comparison with the SANDII best-fit activities. Table 3 compares the C/E (MCNP Calculated/Experimental activation foil) ratios. The calculated activities were scaled to the SANDII-determined neutron fluence for the measured reactor exposures.

Figure 1: Comparison of Measured and Calculated SPR III Spectra

The C/E ratios for the high-threshold-energy sensors are seen to be very good, typically within 5-7% of unity. 25-30% differences are seen for the thermal Au-based sensors. The $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ sensor that determines the SANDII resonance-region spectrum (100 eV-1 keV) shows a 40% disagreement. These sensor response data are very consistent with the spectrum comparison discussed in Section III.B.

D. Agreement Between Experiment and Model

Table 3 shows that the scoring uncertainties in the MCNP calculated sensor activities were very small, typically less than 2%. The energy-dependent fluence had larger uncertainties. This version 4.2(xg) of MCNP includes estimates of the variance-of-the-variance [14]. Column 7 of Table 3 shows that most of the sensor response uncertainty estimates were very reliable, typically passing 8 or more of the 10 tests for good convergence and complete sampling of the underlying probability density function (pdf). It must be noted that several other sources of calculational uncertainty exist besides the statistical scoring. These sources of uncertainty include the transport cross sections, the geometry modeling, and the accuracy of the SPR III geometry and material compositions used to construct the model. Column 10 of Table 3 shows the spectrum-averaged uncertainty in the sensor response due just to the evaluator-specified uncertainty in the dosimetry cross section. Although consistent cross sections were used in the SANDII unfold and in the MCNP calculation, this uncertainty affects the agreement between the experimentally-measured activities and the SANDII calculated activities, which in turn affects the comparison of spectrum shapes in Figure 1. A sensitivity analysis employing adjoint transport techniques is required to further quantify the true calculational uncertainty. The estimated uncertainty of the calculations (10% for high energy, 25% for resonance region, and a factor of two for thermal regions for energy-dependent quantities) is consistent with the observed C/E agreement of the sensor responses and the spectral shape.

Table 3: SPR III Sensor Activities

Sensor Reaction	Foil [®] Cover	Shot	Measured		MCNP Calculated		SAND-II Unfold		$\Delta\sigma_{\text{unc}}$ (%)	95% Energy Response Limits	
			Activity (Bq/nucleus) [§]	$\Delta\sigma_{\text{count}}$	C/E Ratio	$\Delta\sigma_{\text{unc}}$ (%)	Stat. Tests Passed	C/E Ratio	Measured-to-Cal. Dev. (%)	Lower	Upper
1* $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	Cd	8869	6.574E-18	4.5	0.7428	1.16	6/10	1.0269	-2.621	4.750E-6	1.700E+0
2* $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$		8869	7.414E-18	4.5	0.6931	1.12	6/10	0.9766	2.410	8.800E-8	1.600E+0
3* $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	Cd	8843	6.923E-22	2.9	0.5928	1.69	7/10	0.9747	2.568	1.150E-4	1.700E+0
4* $^{63}\text{Cu}(n,\gamma)^{64}\text{Cu}$	Cd	8843	3.302E-18	2.2	0.8776	0.13	9/10	1.0266	-2.585	2.100E-2	2.400E+0
5* $^{115}\text{In}(n,n)^{115m}\text{In}$		8827	6.204E-17	4.7	1.1280	0.14	10/10	0.9766	2.350	1.000E+1	5.900E+0
6* $^{46}\text{Ti}(n,\alpha)^{46}\text{Sc}$	Cd	8843	7.325E-21	3.4	0.9416	0.62	10/10	0.9524	5.009	3.800E+0	9.300E+0
7* $^{46}\text{Ti}(n,p)^{46}\text{Sc}$	Cd	8843	2.882E-19	2.7	1.1590	0.27	10/10	1.0673	-6.314	1.700E+0	7.500E+0
8* $^{46}\text{Ti}(n,p)^{46}\text{Sc}$	Cd	8843	8.684E-21	1.2	0.9456	1.43	8/10	0.9443	5.869	5.900E+0	1.230E+1
9* $^{58}\text{Ni}(n,p)^{58}\text{Co}$	Cd	8827	8.752E-20	3.1	1.0311	0.26	10/10	0.9662	3.462	2.300E+0	7.200E+0
10* $^{54}\text{Fe}(n,p)^{54}\text{Mn}$	Cd	8843	1.400E-20	3.2	1.0893	0.33	8/10	1.0331	-3.197	2.000E+0	7.400E+0
11* $^{56}\text{Fe}(n,p)^{56}\text{Mn}$	Cd	8843	5.408E-19	2.4	0.9791	1.10	8/10	1.0097	-0.956	5.500E+1	1.120E+1
12* $^{64}\text{Zn}(n,p)^{64}\text{Cu}$	Cd	8843	3.882E-18	2.2	1.1090	0.27	8/10	1.0452	-4.323	2.400E+0	7.400E+1
13* $^{24}\text{Mg}(n,p)^{24}\text{Na}$	Cd	8827	1.242E-19	3.0	1.1055	1.48	8/10	1.0648	-6.086	6.500E+0	1.160E+1
14* $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	Cd	8827	6.135E-20	1.9	1.0386	1.63	8/10	0.9940	0.561	6.400E+0	1.200E+1
15* $^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	Cd	8843	1.616E-21	3.4	0.8843	10.38	5/10	1.0016	-0.161	1.270E+0	1.750E+1
16* $^{235}\text{U}(n,f)^{140}\text{La}$	Tcd	8835	1.755E-11	3.0	0.9595	0.08	8/10	0.9872	1.280	6.300E-2	4.100E+0
17* RMLEU	B ₄ C, Tcd	8894	1.500E-11	3.3	0.9857	0.08	8/10	0.9872	1.266	8.000E-2	4.200E+0
18* $^{239}\text{Pu}(n,f)^{140}\text{La}$	Tcd	8835	2.317E-12	3.2	1.1104	0.15	8/10	0.9747	2.624	1.500E+0	6.600E+0
19* RMLDU	B ₄ C, Tcd	8894	2.223E-12	3.2	1.118	0.15	8/10	0.9833	1.718	1.400E+0	6.600E+0
20* $^{239}\text{Pu}(n,f)^{140}\text{La}$	Tcd	8835	2.233E-11	2.7	1.0518	0.08	10/10	1.0377	-3.633	8.800E-2	4.300E+0
21* RMLPU	B ₄ C, Cd	8894	1.912E-11	3.2	1.0959	0.08	10/10	1.0524	-4.979	1.100E-1	4.500E+0
22* $^{237}\text{Np}(n,f)^{140}\text{La}$	Tcd	8835	1.234E-11	2.8	1.1336	0.01	10/10	0.9709	3.039	5.250E-1	5.300E+0
23* $^{237}\text{Np}(n,f)^{140}\text{La}$	B ₄ C, Tcd	8835	1.182E-11	2.8	1.1336	0.01	10/10	0.9690	3.183	5.250E-1	5.300E+0
24* $^{46}\text{Sc}(n,\gamma)^{46}\text{Sc}$	B ₄ C, Tcd	8835	1.192E-20	3.5	0.8163	0.14	9/10	---	---	3.200E-2	1.500E+0
25* $^{46}\text{Sc}(n,\gamma)^{46}\text{Sc}$	Cd	8827	1.372E-20	3.3	0.8149	0.16	9/10	---	---	1.425E-2	1.400E+0
26* $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$	B ₄ C, Tcd	8835	5.963E-20	2.1	0.9551	0.18	7/10	---	---	5.000E-2	2.800E+0
27* $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$	Tcd	8827	7.170E-20	2.1	0.8944	2.65	9/10	---	---	3.400E-2	2.700E+0
28* $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$	B ₄ C, Tcd	8835	4.557E-18	2.7	0.7950	0.13	8/10	---	---	2.700E-2	2.400E+0
29* $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$	Cd	8827	6.618E-18	2.6	0.6383	0.4	6/10	---	---	3.200E-4	2.100E+0
30* $^{55}\text{Fe}(n,\gamma)^{56}\text{Fe}$	Cd	8869	7.974E-21	2.8	1.0100	0.14	10/10	---	---	1.900E-2	2.300E+0
31* $^{27}\text{Al}(n,p)^{27}\text{Mg}$	Cd	8827	2.872E-17	3.0	1.1745	0.51	8/10	---	---	3.500E+0	9.200E+0
32* $^{115}\text{In}(n,\gamma)^{115m}\text{In}$	Cd	8827	4.916E-16	1.3	1.1988	0.95	7/10	---	---	1.425E-6	2.100E+0
33* $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$		8827	7.087E-20	2.1	0.9888	0.32	8/10	---	---	3.200E-8	2.500E+0

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* Assumes the use of the 1993 GLLJCS $^{235}\text{U}(n,f)^{140}\text{La}$ cross section, MAT=1025. This is consistent with use of the SNE-RM cross section library.

§ Fission foil activities are in units of reactions/nucleus

IV. THE MODIFIED SANDII METHOD

The modified SANDII methodology has been described previously [5]. The code uses a trial spectrum and a dosimetry cross section library to calculate activities that are then compared with the activities measured in the test environment. The code then generates a new trial spectrum that provides a reduced standard deviation, S.D., between the measured and calculated activities that is lower than that of the initial or previous run. This process continues until the S.D. falls below a user defined value of say 5%. However, the code needs assistance from the analyst, because it can change the spectrum only where the foil set has significant response. Thus a poor initial trial spectrum with poor sensor coverage will lead to a very distorted and physically unrealistic spectrum. Our approach has been to identify and use a set of sensors that provide such good coverage that the form of the initial trial function becomes almost irrelevant to the final result because the range of solutions that provide matching activities is very limited. For test programs that require a wide range of configurations, it is advantageous to be able to determine spectra without having to have a good trial spectrum a priori. In some cases the details of the material composition of the test package and support structure is not known sufficiently well to permit an adequate calculation of a trial.

Therefore, there are three key factors that are necessary in order to determine a spectrum properly; 1) adequate sensor coverage over the range of energies relevant to the user, 2) accurate and consistent response functions, and 3) accurately measured sensor responses. Consistency here means not only that the sensor set has repeatedly demonstrated that physically meaningful results are obtained with a small calculated/measured deviation for each sensor, but also that each sensor received the same (or properly scaled) fluence and spectrum shape.

The cross section uncertainties have been minimized by using an updated dosimetry cross section library, SNLRML [13], that is primarily based on the recently released ENDF/B-VI [15, 16] and IRDF-90 [17] cross section files. Some cross section selections have been made after discussions with evaluators and after evaluation of our own experiences with consistency in the spectra determination work. The SNLRML cross section library will soon be available through the Oak Ridge National Laboratory (ORNL) Radiation Shielding Information Center (RSIC).

V. RESULTS

A. The Activities

Table 3 lists of the reactions whose activities were measured after exposure in the SPR III cavity. In addition to the normal dosimetry sensors, SNL-specific fission foil compositions were used. These are labeled as RMLEU for enriched

uranium, RMLDU for depleted uranium, and RMLPU for plutonium fission foils. The activities have each been scaled by the power monitor on the reactor to the total energy recorded on the first exposure, reactor operation 8827, and checked for consistency with the ratios of sulfur activities. The reactions with stars (*) next to the reaction number indicate activities that were used in the determination of the final measured spectrum, named SPR3CAV28, plotted in Figure 1. Section V.B explains the criteria for rejecting some of the measured sensor responses.

To ensure equal fluence on each foil, sensors were mounted in two rings 2.5 cm above and below the core vertical centerline at a radius of 11.4 cm. The last two runs were performed at higher yields to provide sufficient activity on some of the weaker foils. The uncertainty introduced by scaling the activities by the yield is <1% because they were run at the same power for different lengths of time. The second run was configured primarily for foils that had to be exposed in boron shields. These had to be separated from foils sensitive to low-energy neutrons that might be shadowed by the boron.

The low-energy portion of the spectrum (<100 keV) constitutes only a small fraction of the fluence, so it was possible to expose fission foils without the boron shield (no danger of overheating). Although these provided additional responses, the shape of the spectrum shifted the range of response to higher energies, making them less independent. This upward shift in range has another effect. Experiments [4] have shown that at high energies the attenuation by our boron covers calculated with SANDII is underestimated by 4 to 5%, because the code uses only exponential attenuation of the boron absorption cross section and ignores the effects of scattering. Therefore, for Table 3 and for the SANDII analysis, the activities of the boron-covered fission foils were increased by 4%.

The uncertainties in the activities are only slightly influenced by counting statistics because they are all counted until about 10^4 counts are recorded. Each foil is counted on at least two different detectors to reduce detector-associated errors. The activities from different, separately calibrated detectors, usually differ by less than 2%. The uncertainties of the sources in the Amersham set used regularly to construct the efficiency factors for each gamma-ray energy vary from 1 to 3%. Table 3 shows the counting-uncertainty of the activities. Additional activity uncertainty components include planchet positioning, calibration curves, reactor yield scaling, fission yield uncertainty, and correction for decay between exposure and reading. When all these terms are considered, an assignment of ~5% uncertainty to all of the activity measurements is justified.

B. The Spectrum

It often goes unnoticed that the best choice of sensor set depends on both the spectrum and the device or object to be tested. In fact, it frequently turns out that some responses must

be removed from the set after the general form of the spectrum has been established. The identification of outliers is easier when many responses are used. This step in judgment is necessary no matter what kind of spectrum "unfold" method is used.

The spectrum shown in Figure 2 resulted from running the SANDII code for 15 iterations with 30 of the response functions for the SPR III central cavity exposures shown in Table 3. The sensor set includes cadmium and cadmium-plus-boron-covered Na, Mn and Sc foils. These foils are normally very useful in environments with large, low-energy tails in the neutron spectra, such as are encountered near pool-type reactors, because their cross sections are very well known near their principal resonances. However, the SPR III spectrum shifts their response regions far upward in energy (as is shown by the energy limits in Table 3) where their cross sections are not as well established. (Although the Cd-covered $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ response limits reaches down to its resonance, it still has only 16% of its response there.) This distortion is not an activity measurement problem. The code tries to alter the spectrum where the foils have high cross sections in an effort to make the activities agree with the measurements. Distortions in the same direction by each foil are very repeatable in the spectra we have examined that have small low-energy tails. It is unreasonable to include reactions in the sensor set that distort the spectrum in a region where it has such a small fraction of its response. Furthermore, since the spectrum is so low in the region of the resonances, the code must shift the spectrum by a large amount in that region in order to change the calculated activity even slightly. Unlike the LSL-M2 least squares spectrum adjustment code [18] which uses the covariance uncertainty matrices, SANDII cannot weight the influence of each reaction at each energy by the uncertainty in the cross section.

There is a shaded band following the spectrum (marked by the circled dots) in Figure 2 which shows the results of a perturbation analysis. This perturbation analysis demonstrates how resistant the solution spectrum is to perturbation of the trial. For this study, the trial was perturbed upward and downward by the half cycle of a sine function in log space with a 30% amplitude at each energy [4]. The code was run 106 times

to see how well the perturbation was reduced at each energy after 15 iterations. This exercise shows the dependence of the solution on the trial spectrum. The primary point here is that above 300 keV there is almost no dependence of the important integral parameter, the 1-MeV silicon equivalent fluence, on the trial function.

For better coverage, it had been our intention to shift the response of the $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$, $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ and $^{45}\text{Sc}(n,\gamma)^{46}\text{Sc}$ reactions upward into the 1-100 keV region by putting them in boron covers, but the shift was too large to be useful for this spectrum. We believe this arrangement would be useful in pool-type reactor environments if fission or silicon damage sensors were not available.

It is interesting to point out that at the $^{23}\text{Na}(n,\gamma)^{24}\text{Na}$ resonance near 3×10^{-3} MeV the code could not correct for the perturbation, but at 1×10^{-4} MeV the $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ reaction pinches the spectrum together very tightly. Thus we are justified in forcing the spectrum through this narrow channel.

C. Integral Parameters

Since the net response of an object exposed to neutron damage is proportional to the integral of its response function over the spectrum, it is ultimately the integral parameters and their uncertainties that are relevant for evaluating the integrity of the characterization of the environment.

The integral parameters listed in Table 4 are useful in testing associated with silicon displacement damage, and are discussed in detail in such ASTM standards as E 720, E 721 and E 722. The parameters of Table 4 and others are defined in section VII. Basically, the SP relates the fluence above 3 MeV, usually measured by sulfur or nickel foils included with the device under test (DUT), to the fluence greater than 10 keV above which silicon devices begin to respond. The HP is a measure of the average silicon damage effectiveness of the neutrons in this spectrum as compared to that of an average 1-MeV neutron.

The perturbation analysis, described in Section V.B., demonstrated that the initial trial function used in the SANDII methodology exerted negligible influence on the spectrum above 100 keV. Therefore, except for Φ_{101} , the uncertainties in the other important integral parameters depend only on the combined uncertainties in the cross sections and in the activity measurements. These are conservatively estimated to be 6% and 5%, respectively. These combine to provide the 8% uncertainty assigned to most of the integral parameters. The uncertainty in the silicon damage function is not relevant because, as detailed in the ASTM E 722-93 standard, it should be treated as an exposure parameter, and it is assumed that everyone doing silicon device tests will use the one contained in the latest ASTM standard. As was pointed out earlier, although the spectra derived with the use of the 30 reactions and the 24 reactions

Figure 2: Effect of Perturbation in the Trial Spectrum

establish the radiation characteristics in other facilities and configurations. Fourth, it can be used to calibrate silicon transistor or diode sensors that can be used elsewhere to verify spectra.

The last reason for establishing a well-characterized SPR III spectrum is more important than it may first seem. A new method has been developed by which a laboratory that has a well-characterized environment can use a simple set of sensors such as transistors, sulfur and perhaps a few other foils along with TLD gamma-ray dosimeters to verify spectra determinations conducted at distant sites [21]. Many of the most useful reactions listed in Table 3 have half-lives too short for practical transportation to a distant counting laboratory. Therefore most of the determinations of the sensor responses for a good spectrum measurement must be made locally.

A full report, in which all the necessary data will be included to document this spectrum determination, is being prepared to qualify the SPR III central cavity as a reference benchmark field, and to meet the CSEWG benchmark field specification requirements [8].

VII. NOMENCLATURE

Φ_{tot}	Total neutron particle fluence in units of n/cm^2 .
$\Phi_{10\text{keV}}$	Fluence greater than 10 keV.
$\Phi_{3\text{MeV}}$	Fluence greater than 3 MeV.
$\Phi_{1\text{MeV}}^{\text{Si}}(93)$	1-MeV(Si) equivalent fluence using ASTM E 722-93 standard.
$\Phi_{1\text{MeV}}^{\text{Si}}(85)$	1-MeV(Si) equivalent fluence using ASTM E 722-85 standard.
SP	Spectrum shape parameter, $\Phi_{10\text{keV}}/\Phi_{3\text{MeV}}$, often referred to as the spectral index (SI) within the radiation testing community.
$\text{HP}_{\text{Si}}(93)$	$\Phi_{1\text{MeV}}^{\text{Si}}(93)/\Phi_{\text{tot}}$, the silicon hardness parameter as defined in the ASTM E 722-93 standard.
$\text{HP}_{10\text{keV}}(85)$	$\Phi_{1\text{MeV}}^{\text{Si}}(85)/\Phi_{10\text{keV}}$, the silicon hardness parameter as traditionally defined by the radiation testing community.
$\langle\sigma\rangle_x$	Spectrum-averaged cross section for reaction x
$\Delta\sigma_{\text{xsec}}$	Uncertainty in spectrum-averaged cross section (%)
$\Delta\sigma_{\text{score}}$	Uncertainty in Monte Carlo statistical scoring (%).

Configuration (Filename)	Shot Date	SP	HP _{10keV(85)}	HP _{Si(93)}	Φ_{Si}^{61} 3MeV (93)	σ_S^{3MeV} (mb)	σ_{Ni}^{3MeV} (mb)	Cross Section Library
SPR-III Bare Cavity (SPR3CAV28-NF)	1992	9.244	0.8973	0.8163	7.557	303.3	505.9	SNLRLM
SPR-III Bare Cavity (BARNOB6)	1986	8.498	0.9111	0.8253	7.022	301.8	497.8	SNLRLM
SPR-III Bare Cavity (BARNOB6)	1986	8.46	0.8890	----	---	328	487	ENDF/B-V
SPR-III 17" Leakage (SCR4)	1988	8.310	0.9249	0.8351	7.039	300.3	502.2	SNLRLM

All spectrum characterization performed with SNL-SAND-II iterative unfold code.
The number of significant digits shown are for reproducibility/traceability and do not imply the level of accuracy

$\Delta\sigma_{\text{count}}$	Uncertainty in counting statistics (%).
$\sigma_{\text{S}}^{3\text{MeV}}$	$\langle\sigma\rangle$ for $^{32}\text{S}(\text{n,p})^{32}\text{P}$ reaction divided by $\Phi_{3\text{MeV}}$.
$\sigma_{\text{Ni}}^{3\text{MeV}}$	$\langle\sigma\rangle$ for $^{58}\text{Ni}(\text{n,p})^{58}\text{Co}$ reaction divided by $\Phi_{3\text{MeV}}$.
dn/dE	Differential neutron number fluence in units of $\text{n}/(\text{cm}^2\text{e-MeV})$, often called $\Phi(\text{E})$.
C/E	Ratio of calculation-to-experiment
Δk	Reactivity worth in dollars.
k_{eff}	Effective multiplication factor of a reactor.
S.D.	Standard deviation.
DUT	Device under test.

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