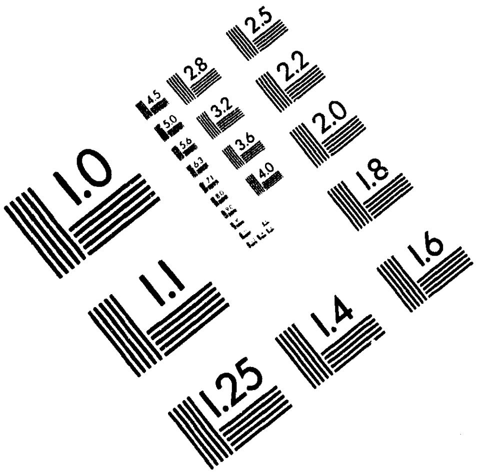

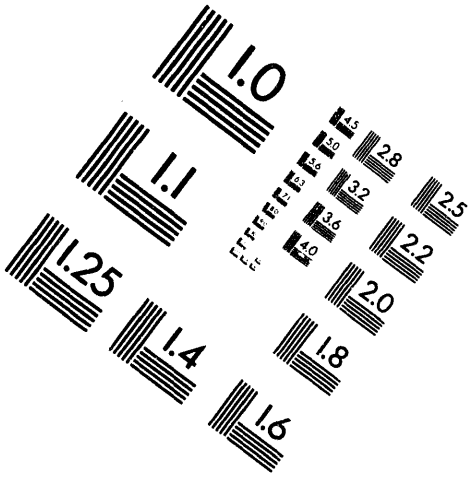

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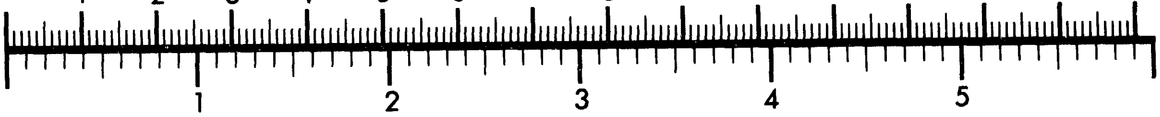

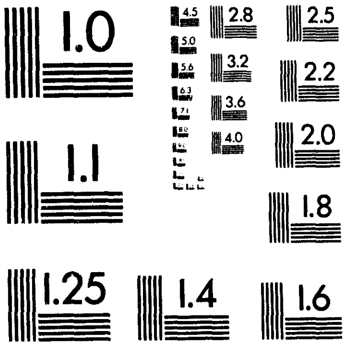

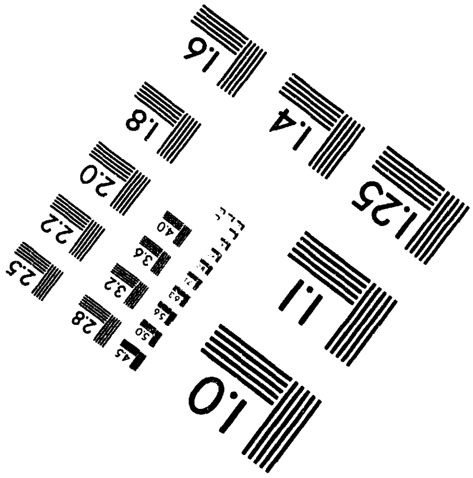

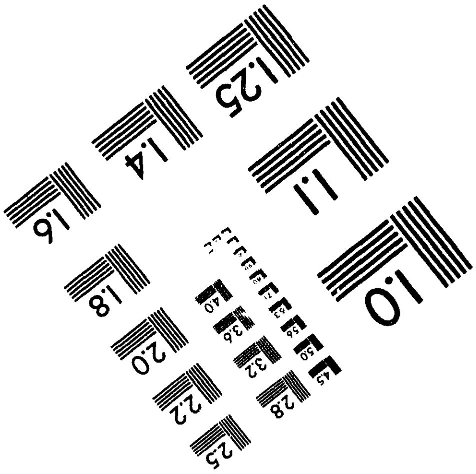

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CHARACTERIZATION OF REACTOR NEUTRON ENVIRONMENTS AT SANDIA NATIONAL LABORATORIES[1]

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ABSTRACT

To assure quality in the testing of electronic parts in neutron radiation environments, Sandia National Laboratories (SNL) has incorporated modern techniques and procedures, developed in the last two decades by the radiation effects community, into all of its experimental programs. Attention to the application of all of these methodologies, experiment designs, nuclear data, procedures and controls to the SNL radiation services has led to the much more accurate and reliable environment characterizations required to correlate the effects observed with the radiation delivered.

I. INTRODUCTION

Work began at SNL around 1971 to improve the characterization methodologies for the reactor environments. Up to that time the neutron fields were evaluated primarily by calculations with transport codes, such as TWOTRAN,[1] coupled with comparisons to experimental data such as fluence profiles, plutonium-sulfur ratios, ionization chamber data, reactivity measurements, and neutron induced-damage ratios. However, without a well determined energy spectrum for each test envronment, the comparisons of test object responses to different environments were unreliable. Furthermore, the prediction of performance in an operational environment could not be achieved unless (1) the test spectrum closedly matched the operational spectrum and (2) the secondary radiation induced effects in the two environments were the same. The advantage of possessing well determined spectra and device response functions is that the necessary damage correlations and predictions can be made.

The proton recoil spectrum measurements made by Powell[2] and the foil-activation measurements (coupled with use of the SANDII unfold code) conducted by Scott[3] yielded the first quality spectrum measurements at SNL, but still lacked sufficient energy coverage and were limited to just a few geometries.

Because the foil-activation plus spectrum-adjustment mode has been chosen for the SNL spectrum determinations, only that mode is discussed here. The more obvious deficiencies and problems associated with the characterization processes circa 1982 were the following:

- A trial spectrum of fair accuracy was required as input for all adjustment codes. Otherwise, the solution could be very nonphysical. This meant that detailed information about the test environment was needed, and that an accurate transport calculation had to be carried out to start the characterization process. Often neither was practical.
- A multitude of environments for different objectives was required by users. This necessitated the development of customized configurations that were often difficult and expensive to model.
- The set of spectrum sensors (usually activation foils) often provided inadequate energy coverage to sufficiently define the spectrum where the device under test was sensitive. At other laboratories (in particular at universities) where fission foils were not available, the coverage was not adequate below 1 MeV, where silicon is sensitive.
- Many dosimetry cross sections were inconsistent with each other, so that it was not possible to construct a spectrum from activation data that did not develop unphysical bumps and dips as it tried to fit the measured activities. If in the fitting process, the sensor response uncertainties were allowed to remain large so that a reasonable looking spectrum could be obtained, the width of the band of acceptable solutions became too large to be very useful for modern test specifications.

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[1]This work was performed at Sandia National Laboratories, which is operated for the U.S. Department of Energy under Contract DE-AC04-94AL85000.

- For electronics, the damage response function of silicon was not sufficiently defined or verified, and displacement damage functions for most other semiconducting materials, such as GaAs did not exist. Thus the correlation of the response of an object with the radiation exposure, by integration of a spectrum and response function, was hampered by additional uncertainty.

There were other problems, common more or less to all the radiation effects laboratories, that had roots more in the way the laboratories operated than in the methodologies used and the nuclear data that was available. Improvements were required in the following additional areas.

- Measurement and documentation procedures
- Continuity of environment characterization over time
- Guiding Standards (particularly the American Society for Testing and Materials (ASTM) in this area)
- Interlaboratory comparisons
- Interactions with users for test design and interpretation of results

In this paper we describe the developments that have been made in this field primarily by personnel at Sandia National Laboratories (SNL), White Sands Missile Range (WSMR), Aberdeen Proving Ground (APG), the National Institute of Standards and Technology (NIST), and John G. Williams now at the Univ. of Arizona. Most of the work and comparisons have been made through ASTM Subcommittee E10.07 on Radiation Dosimetry for Radiation Effects on Materials and Devices and dosimetry intercomparison meetings. The items considered below reflect the adaptation of these advances to our neutron radiation testing programs.

II. CHANGES IN CHARACTERIZATION PROCESSES

The efforts to improve our processes beyond Scott's work commenced about 1980, and are discussed below.

A. Counting Facilities

Major additions to the Radiation Metrology Laboratory[4] (RML) capabilities were begun about 1980 by D. W. Vehar and have continued. The focal point is a set of six shielded germanium gamma-ray detectors that are regularly calibrated against NIST traceable standards. The foil activity data is automatically recorded by a VAX-based computer system coupled to a Canberra analysis system. This array of detectors permits the rapid aquisition of data and the counting of foils in parallel. This meant that the neutron spectrum could be constructed without the need to conduct many reactor runs. Furthermore, each foil is counted on at least two different detector systems. This leads to a considerable reduction in systematic and statistical uncertainty in the foil activities.

B. Spectrum Trial Functions and Adjustments

Although a trial function that is a good approximation to the real spectrum is very valuable, its requirement in the unfold or spectrum adjustment process can lead to serious problems. First, the spectrum adjustment codes may provide a very distorted spectrum if the trial is too far removed from reality. Second, if a high quality trial is needed, it usually means that the analyst must have a good idea of the spectrum before the measurements are made. In principle then, the full material and geometrical configuration must be known in advance to support the radiation transport calculations. Third, in many experimental cases, the user may not know or want to know, in sufficient detail, just what the configuration was.

Therefore a methodology was developed for the application of an outer iteration technique[5] to the SANDII[6] spectrum adjustment code to make it insensitive to the shape of the initial trial function. Reference 5 explains how SANDII, in attempting to alter the spectrum shape to better fit the measured sensor responses, changes the spectrum most strongly where the sensor set has its highest responses. The distortions introduced by the code provide the analyst with clues for construction of a better trial function in the next iteration. The analyst will usually draw a smoothed trial through the energy regions of the last result where the sensors have high response. If the sensor set coverage is sufficient, a few repetitions of this procedure usually leads to approximately the same final spectrum-- no matter what the initial trial. An example of the convergence of solutions from two widely varying trials, a flat (TF), and a falling straight line (TS), is shown in Figure 1.

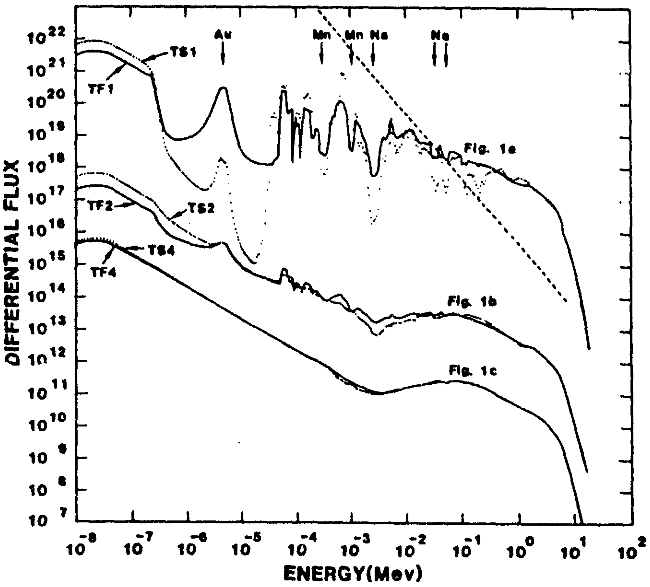

Figure 1. Convergence of Spectra With Different Trials

For each stage, 1a, 1b, and 1c, the solution pairs are displaced vertically to avoid overlap in the figure. For each solution a smooth line was drawn through the result of the previous run to form a trial for the next stage.

The process described above reaches an acceptable solution rapidly and with fewer iterations if the analyst starts with a trial that is representative of the real environment. This methodology is presently the primary vehicle for spectrum determination at SNL.

C. Sensor Coverage

The spectrum cannot be well determined at energies where the sensor set is not responsive. A particularly realistic example is the case when laboratory personel attempt to characterize the environment in a pool-type reactor and do not possess sensors, such as fission foils, sensitive between 10 keV and 1 MeV. If they do not obtain a very good calculation or other estimate of the spectrum to use as a trial function, the damage predicted in a silicon device may be very different from that observed. This is because in pool-type reactors a large fraction of the displacement damage induced may be from neutrons below 1 MeV. Thus it is very important that the spectrum be well determined over the full range of energies to which the test object responds.

A concerted effort has been made to use as many sensors as possible on any spectrum determination, provided that each one has been shown to be consistent with all the other sensors in many other spectrum determinations. This is also a situation where having many detectors in the RML is a great advantage for simultaneous foil counting. Furthermore, the more sensors used, the easier it is to identify erronous data and to obtain a reliable spectrum without having to depend on an accurate trial spectrum. Even more, poor reaction cross sections can be identified and investigated. SNL typically uses between 20 and 30 sensors per spectrum.

D. Interlaboratory Comparisons

Around 1986, SNL, WSMR, APG and others began to hold regular meetings to compare dosimetry methods, calculations, calibrations, and results. What began as comparisons of sulfur based neutron measurements and thermoluminescent detectors (TLD) was quickly extended to other aspects of reactor environment characterization methodologies. Now the routine implementation of the latest nuclear data, the incorporation of newly developed techniques, and the comparison of results have become part of our culture, and integral dosimetry results, such as sulfur fluences, seldom differ by more than 5%. If they do, determined efforts are mounted to resolve the discrepancies.

E. Cross Sections

When dosimetry sets based on the Evaluated Nuclear Data File (ENDF/B-V)[7] became available during the period 1981-84, the outer iteration technique with the SANDII code became much more useful. The fact is that in nature, the real spectrum when folded with all the reaction cross sections must predict the correct activities. When a cross-section compilation is incorrect, the calculated activity will usually not agree with the measured value, and the code will distort the spectrum in trying to make them agree. When many sensors are used in a spectrum determination, it is often obvious when the spectrum is distorted by an incorrect activity. A peak or a valley may appear where there is structure in the cross section of a particular reaction. When the same structure appears in the determination of many independent spectra, the evidence is strong that the cross section, not the measurement, is in error. If the whole cross-section set is of poor quality, the spectra tend to become jumbled (in a similar manner among the different cases), and it is difficult to find a reasonably shaped spectrum to fit the activities.

Two extreme examples turned up in ENDF/B-V, the reactions $^{47}Ti(n,p)^{47}Sc$, and $^{58}Fe(n,\gamma)^{59}Fe$. Attempts to find compatible spectra with these reactions proved fruitless. SNL still cannot use the $^{58}Fe(n,\gamma)$ reaction, but a change in the normalization of the $^{47}Ti(n,p)$ cross section has now made it compatible and useful.[8]

The calculated and measured spectra shown in Figure 2 were determined for the Sandia Pulsed Reactor III (SPR III) central cavity. The latter was constructed with the dosimetry cross sections assembled into a cross-section library, called the SNLRML Dosimetry Library, now available through the Radiation Shielding Information Center, RSIC.[9] Components of this library were derived primarily from ENDF/B-VI[10] and the International Reactor Dosimetry File (IRDF 90).[11] As discussed above, a substantial number of the reactions included in this library have been tested experimentally for compatibility among reactions over many spectra. The shape of the spectrum is very

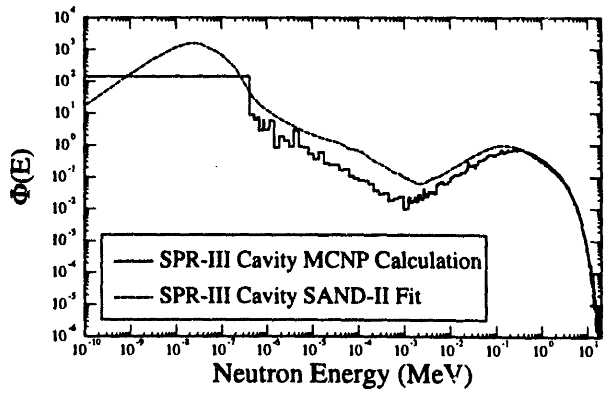

Figure. 2. Calculated and Measured SPR III Cavity Spectra

smooth, and the average standard deviation of the measured and calculated activities is only 3.5%. This spectrum was determined with the help of 24 reactions without the need for any a priori knowledge about the spectrum characteristics. The calculation is discused later.

F. Neutron Displacement Damage

All of these steps to determine a spectrum more accurately are only useful if one can verify that when integrated over important and known response functions, the integral responses that are calculated can be correlated with observed damage. We discuss here the verification of calculated displacement damage functions for bulk silicon and gallium arsenide.

Calculations were commenced in 1985 at SNL[12] and later by J. G. Williams[13] to determine, with the help of the NJOY model,[14] improved displacement damage functions for silicon, gallium arsenide, and other materials used in electronic parts. Afterwards, a considerable effort was mounted at SNL,[15] WSMR,[16] and at Communications Research Centre, Ottawa, Canada to verify the damage functions experimentally. These verifications were accomplished by comparing the ratios of damage generated in bulk silicon, bulk gallium arsenide, 2N2222A silicon bipolar transistors, and GaAs light emitting diodes in a variety of neutron environments.[16,17,18] The resulting damage functions for silicon and gallium arsenide have since been incorporated into ASTM Standard E 722-93.[19]

G. Silicon Devices as Fluence Monitors

The energy dependent silicon displacement damage is a response function very similar to a reaction cross section. Therefore, once it had been verified, it became useful as a fluence monitor. When a transfer calibration is available, it can be used as a spectrum sensor similar to a sulfur foil. Once the devices are calibrated in a well characterized neutron environment, we have found them to be very useful as 1-MeV-equivalent fluence monitors, called Φ_1 monitors,[17,20] and as spectrum sensors[21] to cover the energy range from 100 keV to 1 MeV when fission foils are not available. The fluence, Φ_1, is the fluence of 1 MeV neutrons that would produce the same damage in a silicon device as the fluence delivered by the test spectrum. See reference 19. After a transfer calibration, both 2N2222A transistors and DN-156 diodes[20] have proven to be excellent, direct Φ_1 monitors. For example, the former have been used very inexpensively to map the detailed Φ_1 distribution throughout a missile guidance system.[22] Usually, it is not practical to make a spatial map of varying spectra because a spectrum measurement would have to be made at each location within the experiment.

Just as individual activation foils have responses in different energy regions, and, when incorporated in a set with good coverage, can be used to define a spectrum, silicon also has a response function that can be used for spectrum determinations. It is sensitive from an effective threshold of about 100 keV to a few MeV. Thus, if a laboratory does not have access to fission foils or other sensors sensitive below 1 MeV (a common occurance), a silicon device can provide the needed coverage. Coverage between 100 keV and 1 MeV is particularly important for pool-type reactor environments because of the large 1/E low energy component in their spectra. The transistors have been used successfully as sensors in a number of different spectrum determinations.[22,23]

For a number of reasons, the silicon devices are not of the same quality as activation foils for spectrum determination. They have to be calibrated individually or by batch on a known source; they may respond much more than foils to gamma-ray background; they are usually not useful over as many orders of magnitude in fluence as foils (they may become nonlinear for example), and their responses have not been determined from as fundamental a basis as have cross sections. Their practical advantages, however, are also numerous. They are small and inexpensive, easy to read soon after exposure, and don't perturb the spectrum. Using them just takes a different set of procedures as is explained in a new ASTM standard being developed by ASTM committee E10.07.

H. Transistor Calibrations

Calibration of the transistor sensors by the transfer method requires exposure in a neutron environment whose spectrum is very well known over the range in which silicon is sensitive. For us the SPR III cavity is a prime candidate for this role, because not only is it readily available, but it is also unchanging and generates sufficient fluence for most electronic parts testing. Furthermore, this source was a primary environment used for determining the damage ratios that confirmed the latest silicon damage function. Therefore, a careful repeat measurement of the spectrum was made in 1993 to prepare the data needed to establish the cavity environment as a reference benchmark field.[24] In addition, the core and its surroundings were modeled with the MCNP Monte Carlo neutron and photon transport code.[25] The spectrum is shown in histogram form in Figure 2. The measured and calculated spectra compared very well except for the region around 10 keV (below the silicon threshold) where both techniques have problems (cross sections and geometric modeling of the scattered radiation component). The transistors are calibrated by correlating the observed change in gain with the Φ_1 delivered in the cavity.

I. Environment Verification

The silicon monitors have proven useful in another way. Over the years it has been difficult to compare directly neutron environments that are separated by large distances. The reason is that many of the activation foils that have the best spectrum coverage have relatively short half lives, which hampers the transfer of foil sets between laboratories. This situation is worsened by regulations that inhibit the use of and the transfer of even small quantities of radioative and nuclear materials. However, a small package containing transistors, sulfur dosimeters, and TLD gamma detectors can be very helpful, especially when effects on electronics are being compared.

Participants at SNL, the Univ. of Utah, Penn State, McClellan Air Force Base, WSMR, and APG have exposed packages of the type just described to a variety of reactor environments at their facilities.[23] The object was to compare in each case the damage induced in the transistors, proportional to Φ_1, to that predicted by the spectrum assumed to be valid by the facility personnel for each environment. If they agreed, the comparison constituted a certain degree of confirmation that the environment was correctly characterized for electronic parts testing. At the least, it would confirm the assigned Φ_1.

The results have been mixed. In the cases in which the spectra were already well established with sensor sets that had good coverage (i.e., with fission foils), the agreement in Φ_1 in all cases has been within 5%. These include the fast burst reactor environments at SNL, WSMR, and APG along with pool-type reactor environments at SNL. In the other environments that didn't benefit from the use of fission foils, and as a consequense had poor initial coverage in the 100 keV to 1 MeV range, the initially established spectra did not correctly predict the damage. These spectra were characterized at SNL, using the SANDII code and the activities measured locally at each facility. Obviously the sensor sets were inadequate. To compensate for the coverage deficiency, the transistor measured Φ_1 value was used as a sensor response along with foil activities to establish the spectrum shape. Thus, although this additional response improves the spectrum determination, the independent confirmation of Φ_1 with the transistors is lost.

J. Experiment Design

SNL has put in place a semiformal process for reviewing proposed experiments and exposures to ensure that the needed and optimized irradiation conditions are realized. This first begins with an initial review of the experimental plan by experienced facility operations personnel. They then decide whether a test fidelity specialist should be consulted about any aspect of the test that may require special treatment. The items to be considered vary over a wide range, and might include any or all of the following examples:

- Does a specialized environment need to be fabricated and characterized? Users may need to reduce thermal neutron fluence (to reduce activation) or to attenuate gamma rays.
- Will the experiment materials and configuration distort the radiation field so that it must be characterized with the actual structure in place?
- Are there special safety or operational questions to be answered? For example, are explosives, energy storage devices, or high-pressure gases present? Can polyethylene melt and add reactivity to the core?
- How uniform must the radiations be over what volume in order to meet test specifications?
- What are the best monitors to use to characterize the environment for the application?
- What are all the secondary effects that can influence the experiment? This is an area where the test fidelity specialist (TFS) may have more experience than the user. It is important, therefore, that the TFS be given a full briefing on the object to be tested and the intended performance issues, so that he/she can attempt to provide the best test design and measurement process.

Besides the preliminary communications that are carried out in designing the experiment, there is a formal evaluation of each experiment by the appropriate reactor safety committees. All related safety questions must be answered and taken care of before the experiment can be conducted.

K. Quality, Analysis, and Documentation

As mentioned earlier, all dosimetry systems are checked regularly against NIST-traceable standards. In addition, as often as is feasible, SNL, WSMR, APG, and others compare dosimetry results and share new developments. As part of the SNL services, we also regularly provide analytical support such as transport calculations, spectrum determinations, data analysis, and experiment design. The dosimetry results are provided in formalized reports, and individual attention can be given to particular data that are important to the experiment. Records from past experiments are kept permanently to monitor historical events and to compare past conditions with the present.

L. Code Improvement and Application

The three laboratories frequently mentioned here (SNL, WSMR, and APG) use the SANDII code on a regular basis. SNL has added a number of enhancements to the code to expand its applicability and to enhance the user interface.[26] For example, silicon and gallium arsenide integral parameters are printed out automatically, and the input file has been modified so that transistors can be used as spectrum sensors. The listing and documentation of the enhancements are available from RSIC. SNL also has experience with the least-squares spectrum adjustment code LSL-M2.[27] The expert in the application of that code to electronic parts testing is W. Sallee of WSMR. He has contributed heavily to the LSL discussion as applied to pulsed reactors in ASTM standard E 721[19] on spectrum adjustment codes. The LSL-M2 code requires more input information than does SANDII, but it also provides mathematically defined uncertainties for the generated spectrum.

The MCNP Monte Carlo transport code[25] is used at SNL to calculate the neutron fluence and gamma-ray dose in many of the environments used at the reactors. These are useful for predicting responses of proposed experiments, for providing initial spectrum trial functions, and for estimating fluences in regions that are inaccessable to measurement. As mentioned before, this code was used to calculate the SPR III cavity spectrum shown in Figure 2. Other transport codes such as TWODANT[28] and MORSE[29] are also frequently applied.

M. Standards

There are three principle ASTM standards that deal with neutron displacement effects in electronic devices. As mentioned before, these are E 720, E 721, and E 722.[19] Two others are being developed by ASTM subcommittee E 10.07. One deals with the issues relevant for ensuring test fidelity in electronic parts testing, and the other deals with the use of transistors as monitors and spectrum sensors. Almost all of the issues discussed here and the improvements in the methodologies discussed in this paper are dealt with in these standards and their references. The review and improvement of these documents is an ongoing process, and SNL will continue to contribute to and follow their recommendations.

III. DISCUSSION AND CONCLUSIONS

The radiation environments used to test electronic parts (and for most other purposes) must be well characterized in order for the observed effects to be correlated to the properties of the fields. There were in fact instances in the past when the effects observed differed by as much as a factor of 3 between different laboratories that claimed to have applied the same equivalent fluences to the test object. However, we believe that if the guidelines in the updated ASTM standards mentioned in subsection M are followed, users can be confident that they can reproduce the bulk displacement damage effects in silicon and gallium arsenide devices in different laboratories to within 10%. In order to accomplish this with confidence, all of the features of good characterization practice mentioned must be incorporated into each testing program. The most important element is a dedication to continuous improvement in the handling of all contributing factors.

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