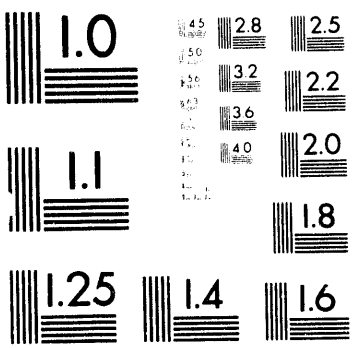
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John (Jake) G. Kelly[1], Patrick J. Griffin[1], Dale C. Raupach[2], Thierry H. Daubenspect[2], John S. Bennion[3], and Dan L. Newell[4]

INTERLABORATORY VERIFICATION OF NEUTRON SPECTRA USED FOR THE TESTING OF ELECTRONIC PARTS[5]

REFERENCE: Kelly, J. G., Griffin, P. J. Raupach, D. C., Daubenspect, T. H., Bennion, J. S., Newell, D. L., **"Interlaboratory Verification of Neutron Spectra Used for the Testing of Electronic Parts,"** Reactor Dosimetry ASTM STP 1228. Harry Farrar IV, E. Parvin Lippincott, and John G. Williams, Eds., American Society for Testing and Materials, Philadelphia, 1994.

ABSTRACT: A methodology has been developed for verifying that a neutron energy spectrum measured for an environment correctly predicts the bulk displacement damage that would be observed in a silicon electronic device. The technique makes use of a package of silicon bipolar transistors (2N2222A), monitor activation foils (such as sulfur pellets), and thermoluminescence detectors (TLDs) that is placed in the test environment. The TLDs and monitors are then used to correct for the gamma-induced damage and to scale the reactor power in the test irradiation to that predicted by the neutron spectrum which is being verified. The damage predicted from the spectrum and the measured damage are then compared. In cases where the sensor set does not have sufficient sensitivity coverage to satisfactorily define the spectrum, the transistors can be used as spectrum sensors to provide sensitivity in the crucial energy region between 0.1 and 2.0 MeV. This results in the loss of the independent verification, but leads in a much higher fidelity spectrum. The technique greatly facilitates inter- and intralaboratory comparisons of effects testing and spectrum determinations.

KEYWORDS: neutrons, displacement damage, neutron spectrum, silicon devices, electronic parts testing, reactors, interlaboratory comparisons, spectrum determination, radiation environment characterization

The testing of electronic parts for sensitivity to permanent neutron-induced displacement damage is carried out in many government, university, and industrial laboratories in a multitude of differing configurations and radiation environments. Despite the fact that the ASTM

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DISCLAIMER

standards have been developed for those who conduct parts testing (primarily in ASTM Standards E-720, E-721, and E-722[1]), observed damage often differs considerably from that predicted by the assumed neutron spectrum.

In response to these inconsistencies and as a result of recent improvements that have been made in the methodology for determining neutron spectra [2,3], new standards for assuring fidelity in electronic parts testing are being developed by committee E 10.07 so that the experimenter can properly account for phenomena that significantly influence his results.

To support the development of these standards, an interlaboratory spectrum verification program has been conducted at Sandia National Laboratories (SNL), Penn State University, the University of Utah, and McClellan AFB. The objective was to demonstrate that SNL can use silicon transistors, sulfur sensors, and thermoluminescence gamma dosimeters (TLDs) to verify that a spectrum derived from a complete set of sensor responses (foil activities) and read locally at each facility, correctly predicts the responses of the electronic parts. In the past it has been very difficult for a potential verifying agency to obtain adequate sensor coverage for environments characterized at facilities not co-located with their dosimetry laboratories. This inadequate coverage is primarily caused by the need to use activation sensors with a long half-lives, and by the special licensing requirements for fission materials that precludes the use of fission foils in many laboratories.

VERIFICATION METHOD

The anticipated procedure for verifying a spectrum for use in silicon electronic parts testing was the following. A set of foils is exposed in the test environment, and the activities are read locally so that any short half-life activities can be determined immediately. For consistency, this usually means that all the foils are read by the same laboratory. This set of measured activities is used in the construction of a neutron spectrum.

If the SANDII spectrum adjustment code [4] is used, a trial spectrum is input to start the process. The code calculates the activities predicted by this trial spectrum (by integrating the trial spectrum multiplied by the reaction cross section over energy) and compares them to the measured values. SANDII then applies an algorithm to generate a new trial function that provides a lower standard deviation, S.D., between the measured and calculated activities. This cycle is repeated until the S.D. falls below a set value, typically ~5%, at which point it declares a solution. From this final spectrum one can calculate the neutron response of any phenomena (whose response function is known) to that environment by integrating over energy that response function times the spectrum. The quantity of interest for this work is the bulk displacement damage to silicon devices such as bipolar transistors. In all of the cases reported here, the spectra were generated at SNL with a modified version of the SANDII methodology [2].

The next step was to expose a package containing calibrated 2N2222A silicon bipolar transistors, sulfur activation monitors and TLD gamma-ray dosimeters in the selected environments at Penn State, the University of Utah and McClellan AFB. These packages were made up and read by SNL at the invitation of the other facilities.

RESULTS

Four very different environments were investigated, but all were in or near pool-type reactors that have a large fraction of the silicon device response at energies between 100 keV and 1 MeV. A requirement for all of these configurations was that the sensor set possess sensitivity in that region. Each test is discussed separately in the following subsections. It became evident that the characterization procedures must be adjusted to fit the peculiarities of each environment. In only one of the tests was there enough sensitivity in the 0.1 to 1.0 MeV region to retain the independence of the verification sensor set data and the activity data used to construct the spectrum. In the other cases, the verification showed significant problems with the initial spectrum determination, and and it became necessary to use the 2N2222A transistors themselves as spectrum sensors in a new baseline spectrum characterization. The measured specific activities that were used in the spectrum determinations are listed in Table 1.

Table 1. Activities

Reactions	Penn State, 2x6 in.		Penn State, 6 in. Pb		U. of Utah		McClellan AFB	
	(bq/nucl.)	%Δ	(bq/nucl.)	%Δ	(bq/nucl.)	%Δ	(bq/nucl.)	%Δ
$^{197}Au(n,\gamma)^{198}Au$	1.144E-15a	-1.25	4.158E-16b	+2.15	7.072E-14a	-2.84	---	---
$^{197}A(n,\gamma)^{198}Au$	1.183E-15	+1.13	4.246E-16	-2.51	1.606E-13	+6.44	---	---
$^{24}Mg(n,p)^{24}Na$	5.130E-20	-8.22	1.240E-20a	-9.19	1.871E-18	-10.1	1.170E-18c	-1.19
$^{54}Fe(n,p)^{54}Mn$	4.857E-21	-5.74	1.465E-21a	+1.84	2.355E-19	+7.80	---	---
$^{58}Ni(n,p)^{58}Ni$	2.983E-20	-0.91	8.611E-21a	-2.20	1.256E-18	-6.65	---	---
$^{27}Al(n,\alpha)^{24}Na$	2.580E-20	-3.38	6.369E-21a	-2.43	1.003E-18	+0.77	5.360E-19c	-2.69
$^{48}Ti(n,p)^{48}Sc$	3.797E-21	+11.5	9.549E-22a	+13.7	1.379E-19	+10.6	---	---
$^{45}Sc(n,\gamma)^{46}Sc$	---	---	9.641E-20a	+0.04	---	---	---	---
$^{45}Sc(n,\gamma)^{46}Sc$	2.928E-19	-1.27	3.307E-19	-0.10	---	---	---	---
$^{64}Zn(n,p)^{64}Cu$	1.459E-18	+0.89	3.905E-19	-3.26	5.500E-17	-10.0	---	---
$^{115}I(n,n')^{115}In$	2.111E-17	-0.076	8.950E-18	+1.22	1.261E-15	-3.51	---	---
$^{235}U(n,f)F$ (RMLEU)	---	---	2.705E-12d*	-0.54	---	---	---	---
$^{239}Pu(n,f)F$	---	---	3.834E-12d*	+3.30	---	---	---	---
$^{237}Np(n,f)F$	---	---	2.022E-12d*	+2.78	---	---	---	---
S.D.	---	4.37	---	4.98	---	6.78	---	3.07
Filename	pn24_si-cu	---	penl16-new-fission	---	ut31	---	mcc12	---

* Units are in reactions/nucleus
a - cover-- Cd 2.587E-3 atoms/barn
b - cover-- Cd 3.540E-3 atoms/barn
c - cover-- Cd 4.71E-3 atoms/barn
d - cover-- Cd 3.26E-3 atoms/barn ^{10}B 0.181 atoms/barn
e - cover-- Cd 4.705E-3 atoms/barn
RMLEU indicates the Radiation Metrology Laboratory's enriched uranium fission foil

Table 1. Activities

Reactions	Penn State, 2x6 in.		Penn State, 6 in. Pb		U. of Utah		McClellan AFB	
	(bq/nucl.)	%Δ	(bq/nucl.)	%Δ	(bq/nucl.)	%Δ	(bq/nucl.)	%Δ
$^{238}U(n,f)F$	---	---	2.897E-13d*	+1.55	---	---	---	---
$^{23}Na(n,\gamma)^{24}Na$	9.972E-19	-0.96	---	---	1.783E-15	-4.00		---
$^{46}Ti(n,p)^{46}Sc$ nat	2.718E-21	+5.79	---	---	---	---	7.340E-20c	+0.63
$^{47}Ti(n,p)^{47}Sc$ nat	1.097E-19	+0.16	---	---	5.897E-18	+11.4	---	---
$^{55}Mn(n,\gamma)^{56}Mn$	2.186E-16	+0.01	---	---	1.336E-14a	+2.88	---	---
$^{90}Zr(n,2n)^{89}Zr$	8.856E-22	-0.32	---	---	3.322E-20	-0.52	---	---
$^{23}Na(n,\gamma)^{23}Na$	---	---	---	---	6.733E-17e	-3.21	3.540E-17c	+1.34
$^{32}S(n,p)^{32}P$	---	---	---	---	---	---	2.689E-18c	-1.06
$^{56}Fe(n,p)^{56}Mn$	---	---	---	---	---	---	5.300E-18c	+5.40
$^{63}Cu(n,\gamma)^{64}Cu$	---	---	---	---	---	---	6.020E-16c	-1.61
$^{nat}Si(n,X)1MEV$	3.160E+12	+0.69	1.732E+12	-6.37	2.252E+14	+0.88	8.947E+13	+4.91
S.D.	---	**4.37**	---	**4.98**	---	**6.78**	---	**3.07**
Filename	**pn24_si-cu**	---	**penl16-new-fission**	---	**ut31**	---	**mcc12**	---

* Units are in reactions/nucleus
a - cover-- Cd 2.587E-3 atoms/barn
b - cover-- Cd 3.540E-3 atoms/barn
c - cover-- Cd 4.71E-3 atoms/barn
d - cover-- Cd 3.26E-3 atoms/barn ^{10}B 0.181 atoms/barn
e - cover-- Cd 4.705E-3 atoms/barn
RMLEU indicates the Radiation Metrology Laboratory's enriched uranium fission foil

In the above table the heading symbol %Δ stands for the percent deviation between the measured activities and that calculated from the experimentally determined spectrum.

Penn State 5.08 x 15.24 cm chamber

This 2 x 6 in.(5.08 x 15.24 cm) chamber is in the water next to the TRIGA core. It is covered with a layer of cadmium to attenuate thermal neutrons, so it was necessary to correct the change in reciprocal gains of these transistors for the effect of the intense cadmium gamma-ray dose. To effect this correction, the form of the transistor response to neutron irradiation developed by Messenger [5,6] must be examined in the form of Eqn. (1)

$$\Delta\left(\frac{1}{h}\right) - \Delta\left(\frac{1}{h}\right)_{\gamma} = K \cdot \Phi_1 \qquad (1)$$

where $\Delta(1/h)=(1/h_f)-(1/h_i)$ and $\Delta(1/h)_\gamma=(1/h_f)_\gamma-(1/h_i)_\gamma$. The $\Delta(1/h)$ is the total change in the reciprocal gain and $\Delta(1/h)_\gamma$ is the change due to gamma-ray damage. In these definitions, h_i is the transistor collector current gain before irradiation, and h_f is the gain after irradiation. The Φ_1 is the 1.0-MeV equivalent neutron fluence and K is the damage constant of this transistor (calibration factor) as measured in the central cavity of the Sandia Pulsed Reactor (SPR III). The manner in which Φ_1 is established for a known spectrum is defined in ASTM Standard E-722.

The magnitude of the gamma response of the transistors, $\Delta(1/h)_\gamma$, was measured by observing the difference in response when exposed in a D_2O tank next to the reactor, with and without a cadmium cover. At the 372.6 Gy absorbed dose to which the transistors were exposed in the 5.08 x 15.24 cm chamber, the transistor reciprocal gain change was $\Delta(1/h)_\gamma$= 0.00716. This constituted about a third of the total response, and had to be subtracted from the measured change of reciprocal gain for each transistor. The value of Φ_1 was then found from Eqn. (1). The Φ_1 was scaled to the value which would have been seen during the spectrum measurement. This was done by multiplying Φ_1 by the calculated sulfur activity that would have been induced by a sulfur foil during the spectrum determination and dividing by the sulfur activity of the foils exposed with the transistors. The sulfur activity for the spectrum run is calculated by folding the spectrum with the sulfur cross section.

Note: It is important that the same sulfur cross section be used in the SANDII spectrum characterization as was used in the sulfur counter calibration.

As in two others of the cases described here, this is the point of departure from the original plan. The SANDII code prints out the energy range within which each foil exhibits 95% of its response to this spectrum. There was poor sensitivity coverage from the sensor set between 0.1 and 1.0 MeV, and the first spectrum derived from the foil set alone did not provide a Φ_1 in very good agreement with the measured value. Subsequently, the measured Φ_1 was added to the SANDII sensor set, and the code was run with a much improved coverage. The resulting spectrum, shown in Figure 1, exhibits an S.D. of 4.5% with a smooth and physically reasonable form. The calculated and measured values of Φ_1, shown in Table 2, are in good agreement, as one would expect, because the code attempts to find a spectrum that agrees with all the sensors. This substitution is equivalent to adding a new foil to the set, and it helps to define the spectrum more tightly. In this case, however, the silicon has a particularly potent influence on the spectrum in the 0.1 - 1.0 MeV range where it is most needed. If fission foils were available, the silicon would not have been necessary as a spectrum sensor. What has been surrendered here, in exchange for an improved spectrum, is the independence of the spectrum characterization and the transistor response . The improved spectrum definition means that the predicted response of many other material (e.g. GaAs) is also improved.

Table 2. Spectrum Parameters

Environment	SI	$HP_{10}(93)$	Φ_{tot}	$\Phi_{10\text{-}keV}$	Φ_1(calc.)	Φ_1(meas.)
Penn State 2x6 in. chamber	6.98	0.851	5.650E+12	3.687E+12	3.138E+12	3.160E+12
Penn State 6 in. dia., Pb	17.96	0.736	3.444E+12	2.512E+12	1.850E+12	1.732E+12
U. of Utah Pb lined cham.	11.69	0.911	7.071E+14	2.448E+14	2.232E+14	2.252E+14
McClellan AFB Test chamber	6.70	0.765	2.274E+14	1.113E+14	8.529+13	8.947E+13

The quantities in the column headings of Table 2 are parameters that characterize the shape and magnitude of the spectrum. SI is the ratio of the neutron fluence above 10 keV, $\Phi_{10\text{-keV}}$, to the fluence above 3.0 MeV, $\Phi_{3\text{-MeV}}$. The term $HP_{10}(93)$ is the 10 keV silicon hardness parameter. It is equal to the integral, from 10 keV to infinity, of the silicon damage function printed in the 1993 ASTM Standard E-722 divided by the 1-MeV reference kerma of 95 MeV•mbarn. These parameters are related by the relation $\Phi_1 = SI \cdot HP_{10}(93) \cdot \Phi_{3\text{-MeV}}$. The fluences are in units of n/cm^2.

Penn State 15.24 cm diameter Lead-Lined Chamber

The activities supplied to SNL by Penn State in this case were measured by Mark Oliver of Aberdeen Proving Ground in the Penn State 6 inch (15.24 cm) diameter cavity lined with 5.08 cm thick lead. This is the only case for which fission foils (^{238}U, ^{237}Np, and ^{239}Pu) were available that show sensitivity in the 0.01 to 2.0 MeV region where they can potentially be in conflict with the transistors in determining the spectrum shape and the Φ_1.

Initially a spectrum was constructed with the activities listed in Table 1 for this geometry with the exception of the ^{235}U fission foil and the silicon transistor. The scaled transistor response was compared to that predicted by the preliminary spectrum and was found to be about 15% lower. For this reason a ^{235}U foil from SNL was exposed at Penn State and counted at SNL to corroborate the Penn State fission foil results. The response of the SNL ^{235}U foil was found to be in good agreement with the other fission foils. Since the spectrum verification with the transistors was still not satisfactory, the trial spectrum was lowered in the 0.1 MeV region and the transistor was added as a sensor to produce the spectrum shown in Figure 2. The spectrum parameters are also shown in Table 2. In this case the measured and calculated values of Φ_1 do not agree as well as in the other cases, because there is still some disagreement between the fission foils and the silicon transistor response.

In all of the cases at SNL in which the fit of the responses of the fission foils have been compared to that of the transistors in the spectrum determinations, the agreement has been better than 3%. The larger differences exhibited in Table 1 reflect a difficulty with the extra step needed to scale the transistor response to the spectrum derived from the activities measured at another facility. A close look at the spectrum shows that the lower transistor response depressed the spectrum slightly above its 0.2 MeV threshold. Below that limit the fission foils push the spectrum up slightly.

One additional observation is that the lead liner lowers the spectrum magnitude above 3.0 MeV so that the spectral index, SI, shown in Table 2 is much higher. The difference is not easily seen in Figure 2. However, this change could cause a serious underestimation of Φ_1 if an experimenter monitored the fluence in his electronic parts test with sulfur foils, and assumed a spectrum appropriate for a chamber witnout lead shielding. This comes about because the determination of the damage in a silicon device is dependent on the product of the $\Phi_{3\text{-Mev}}$, obtained from the sulfur measurement, and SI.

University of Utah Lead Lined Chamber

The University of Utah exposure chamber is a dry box with 5.04 cm thick lead walls to reduce the gamma-ray exposure from the fuel and the water. It is placed in the water beside the TRIGA reactor. The activities measured at the facility and used in the spectrum determination are listed in Table 1.

The first spectrum constructed from the data, after a number of inconsistencies were resolved, looked quite reasonable for a lead-lined chamber. However, the predicted 1.0 MeV silicon damage fluence, Φ_1, was high by a factor of two compared to the measured 2N2222A transistor damage that was scaled by the nickel foil ratios. The output of the SANDII code also showed that for this foil set and spectrum there was almost no sensitivity between 0.3 keV and 1.4 MeV. This huge gap occurred for a combination of reasons. First, fission foils were not available. Second, the lead and water around the chamber left a very large thermal neutron tail in the spectrum so that the response of all the resonance foils, such as gold and manganese were shifted down to the thermal end of the spectrum leaving the gap in the sensitivity coverage of the sensor set. This is an example of how the spectrum in the test environment influences the adequacy of the sensor set. Third, the initial trial function used in the SANDII code was too far from the real spectrum, and the coverage was too poor for the code to pull the trial toward the correct spectrum without using the modified outer iteration SANDII methodology [2].

Subsequently, a set of sensors was sent from SNL to the university for exposure. They were then returned to SNL for reading. The set included cadmium-covered gold, manganese and nickel foils along with bare gold, sulfur and transistor sensors. These tests confirmed the original disagreement between the measured and calculated values of Φ_1, and also showed efficiency errors for the University of Utah counting system of about 1.7. This 1.7 factor was not the cause of the disagreement in Φ_1, but led to scaling errors between sensor sets. The counters were recalibrated and the transistor response was added to the sensor set to help close the sensitivity gap. The spectrum shown in Figure 3 is consistent with both the activities and the transistors. It differs substantially from that normally assumed to be typical for TRIGA environments, mainly because of the very large thermal tail that makes the determination of the spectrum in the 0.1 to 1.0 MeV region, in the absence of fission foils, so difficult. If the test chamber were shielded by a boron layer, it would provide a better environment for the testing of electronic parts, and could be more easily characterized.

McClellan AFB Lead Shielded Chamber

The test chamber at the McClellan AFB TRIGA is also lined with 5.08 cm of lead and is placed next to the core. The characterization of this environment has not yet been completed, and some inconsistencies in the sensor set need to be resolved. For example, when the sulfur and nickel foils were used together in the SANDII code, they could not be made to agree with a spectrum to within 40%. Because these foils are sensitive in the same energy region, the combined deviation between them should be

less than about 3% for any fission type spectrum. In this case the nickel seemed more in disagreement with the others and was left out of the foil set used to construct the spectrum shown in Figure 4. The activities are listed in Table 1. The transistor data from the SNL verification package was also used to help construct the spectrum, and therefore is, by necessity, compatible with the rest of the sensors.

It is important that the discrepancies in the sensor responses be resolved and that better coverage be obtained to characterize this spectrum properly. Another sensor set has been exposed at McClellan AFB and read at SNL. This sensor set should resolve the sulfur-nickel problem, but the present sensor set of only nine responses cannot ensure an adequate characterization. However, since silicon transistors were used, Φ_1 is not likely to change by more than 10%.

SUMMARY AND CONCLUSIONS

The interlaboratory verification experiments have demonstrated the importance of performing a spectrum verification. A good choice for the verification sensor set is one consisting of silicon bipolar transistors, sulfur foils and thermoluminescence dosimeters. In each of the cases studied, this verification process uncovered serious deficiencies in the initial spectrum characterization. Because of these deficiencies, the sensor responses from the verification sensor set were added to those used in the spectrum characterization. Thus the independence of the verification process and the spectrum determination was lost. In the absence of fission foils we recommend that the facility that exposes and reads the sensors include both their own transistors and a foil such as niobium (sensitive in the 10 keV region). The silicon will provide the coverage, and the niobium will supply the mathematically independent response function in that region.

Based on the lessons learned from the attempted spectrum verification at these three reactors, the spectrum verification is likely to be successful only if the following factors are handled properly:

- Foil sets with good energy-sensitivity coverage and well established cross sections are used.
- The respective counting laboratories provide accurately determined activities traceable to NIST.
- The spectrum, consistent with all of the sensors used to construct it, is physically reasonable, relatively smooth, and has a narrow band of acceptable solutions.
- Include in the spectrum sensor set the monitor used with the transistors so that the relative normalization of the counting systems can be compared.

Also, the fielding of the verification sensor set requires that:

- The transistors are calibrated in a well-characterized environment, and after exposure in each test environment are read with proper temperature and annealing corrections.

- In environments in which gamma rays significantly affect the transistor response, TLD data must be used along with separate transistor-gamma-ray-response data to correct for that gamma response.

It can be difficult for an organization to maintain the expertise needed to ensure that the neutron environment characterization is maintained over a long period of time. Cross section and response function libraries are updated. Staffs change, test configurations are modified, and test requirements are altered. Therefore, to ensure fidelity in testing it will be necessary to institutionalize the procedures for that characterization and to find an agency for and a means of confirming, on a periodic basis, that characterization. The sensor package suggested here may serve the latter function.

In those cases where a sensor set with good coverage is not available, transistors can be used to provide coverage in the critical region between 0.1 and 2.0 MeV if neutron displacement damage in electronic parts is the important damage mechanism for the testing. However, the measurement of equivalent damage by the transistors alone is not sufficient to ensure testing fidelity. A high quality and sufficiently independent spectrum determination is also necessary.

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Figure 1. Penn. State 2x6" Chamber Spectrum

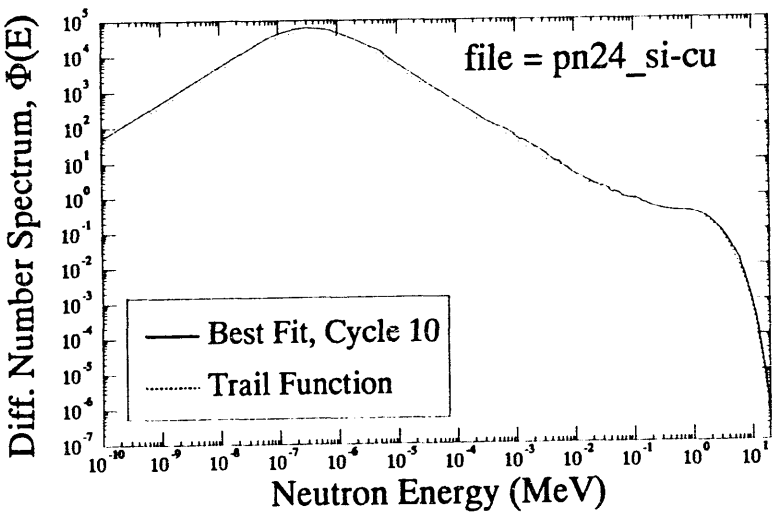


Figure 2. Penn. State 6" Lead-lined Chamber Spectrum

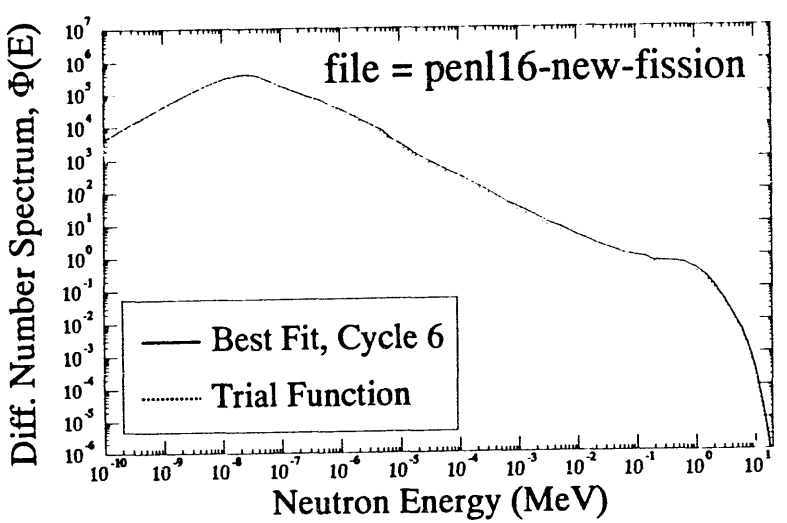


Figure 3. Universlty of Utah Spectrum

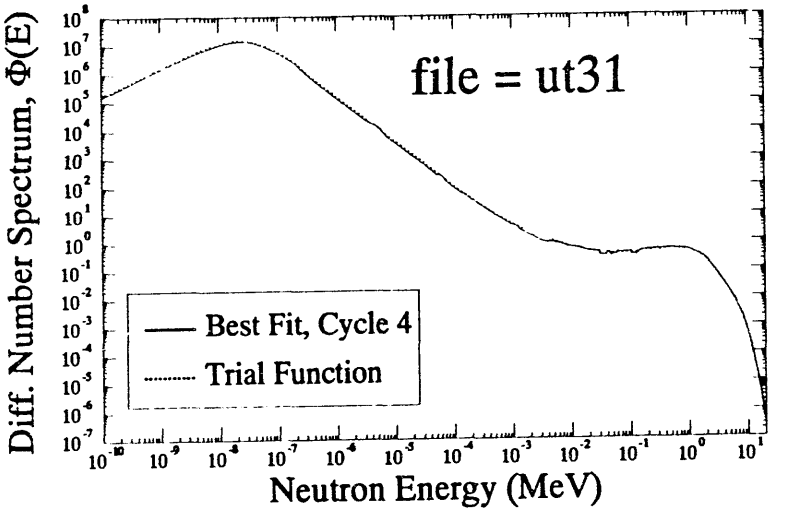
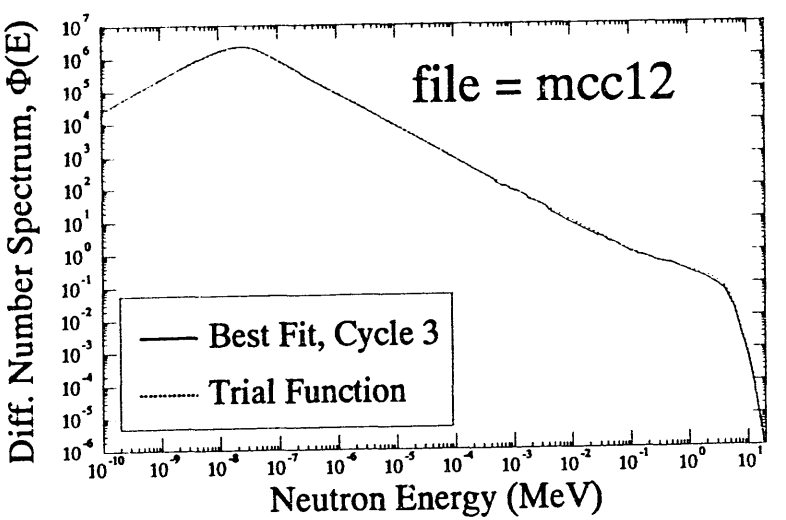


Figure 4. McClellan AFB Spectrum



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