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Characterization of the SPR II Generated Radiation Environments Next to and Within a Guidance System

J. G. Kelly, P. J. Griffin

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CHARACTERIZATION OF THE SPR II GENERATED RADIATION
ENVIRONMENTS NEXT TO AND WITHIN A GUIDANCE SYSTEM

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ABSTRACT

The neutron fluences and spectra and the gamma ray doses inside and in the vicinity of a guidance system exposed to the Sandia Pulsed Reactor II (SPR II) in four configurations have been determined. This project required customization of the environment and the application of new techniques to determine the spectra within the system. The required radiation environment was achieved, and the experimental results clearly demonstrated that the radiation environment inside the system was very different from that seen outside. This example demonstrates very clearly that experimenters must consider the effect the test apparatus may have on the environment inside the system.

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I. INTRODUCTION

A series of experiments was recently carried out in a customized radiation environment next to the Sandia Pulsed Reactor II, (SPR II), to determine the neutron spectrum and the gamma ray dose within and near a guidance system during a series of hardness assurance tests. This report documents the results of those characterization tests. Adequate knowledge about the simulation environment inside the system and determination of the system performance are required in order to predict its response to the operational environment.

The system test geometry was different from that used in the typical electronic parts testing programs in the sense that the mass and material components were expected to modify the radiation environment to the extent that the system response might not be predictable, to an acceptable degree, from free-field data. Since the electronic parts of the system are degraded by the radiation according to the energy response function of the semiconductor materials (usually silicon), the neutron spectrum must be known before the measured and calculated responses can be compared. In most test environments the gamma ray effects are primarily dependent on dose and dose rate, so a detailed knowledge of the spectrum is usually considered unnecessary and too difficult to obtain. (However, contributions by soft gamma rays to dose enhancement effects may have to be considered.)

Obviously, it would be desirable to obtain the spectrum and dose everywhere within the system, but that is impractical. Each spectrum measurement with the foil activation technique requires irradiation of approximately 15 different materials whose activations may take 2 weeks to determine with good counting statistics in a fully equipped counting laboratory. The activity data is then used in a spectrum adjustment methodology.

We have instead exposed a full set of spectrum sensors at one location within the system in each environment to be characterized, and then have mapped the fast neutron profiles throughout the system with sulfur activation monitors and silicon bipolar transistors. TLD gamma dosimeter monitors were also used in the mapping work. Some general features of the mapping results are discussed here and data is included, but any detailed analyses have to be left to those who will be using the radiation field information to understand the effects on the system performance.

A very limited foil set was also placed behind the guidance system to scope significant changes in spectrum shape. These responses can then be compared to those measured when the operating guidance system is tested. The sensor set was very limited because it was competing for counting laboratory time with the set placed inside the IMU.

The details of the procedures to be used in determining neutron spectra with the spectrum sensor technique are contained in appropriate ASTM

standards. The three most important ones are E 720, E 721 and E 722. See Reference 1. These were updated in 1993.

There was an additional complication to the measurement of the spectrum inside the guidance system. The space available for foils was too small for fission foils mounted inside boron covers. The foils ^{235}U , ^{238}U , ^{239}Pu and ^{237}Np provide sensitivity in the energy range 0.2 to 2 MeV which is crucial for determining device degradation in silicon and gallium arsenide semiconductors. Without fission foils most foil sets have little or no response in this region. Therefore we have applied a recently developed technique of using the known response of a silicon 2N2222A bipolar transistor as a spectrum sensor to cover this range. The use of these transistors as spectrum sensors is described in References 2 and 3 and will be the subject of an ASTM standard. The application of this dosimetry technique is discussed in this report.

An additional test was also conducted to investigate the potential of using boron covered resonance reactions to determine the spectrum shape at energies higher than these reactions usually respond when there is a thermal and epithermal low energy tail in the spectrum. This configuration would be useful in situations where room is available for boron covers, but fission foils or silicon transistors are not available to the laboratory conducting the characterization tests.

II. EXPERIMENT DESIGN

The radiation experiment configurations that were characterized are illustrated in Figure 1. The center of the SPR II reactor is 57" above the floor. Its characteristics have been described previously in Reference 4 but until these measurements were made, the radiation environment had not recently been redetermined. Generally, the fast fluence falls off as $1/r^2$ and the fraction of back-scattered neutrons in a $1/E$ tail increases as one approaches the facility shield wall surrounding the reactor.

The guidance system, which in fact was a mockup, modified to accept dosimetry packages throughout, was placed so that sufficient exposure for system tests could be obtained. Its primary components are a 10.5 inch diameter beryllium shell filled with electronic and mechanical parts. For the spectrum measurement a 2" x 2" x 0.75" cavity was reserved for placement of the spectrum sensors. The radial distance where the foils were placed was 22.75 inches from the reactor centerline and was approximately 4.5 inches off the guidance system centerline on the radius toward the reactor. The beryllium had numerous covered ports, and the one between the sensor plane and the reactor was 1/16" thick. However, we believe that much of the fluence that reached the sensors was scattered from the thicker portions of the beryllium shell.

The intention was to characterize four different configurations--free-field without the IMU, free-field but inside the IMU, inside a cadmium loaded polyethylene box (Cd-poly) and inside the IMU, and inside the Cd-poly box without the IMU. The first two were designed to test the effect of the IMU in an environment approximating an exo-atmospheric exposure, and the last two in an endo-atmospheric exposure. The Cd-poly material was placed to scatter neutrons to lower energies and to reduce the fast fluence. The cadmium was included to produce more gamma rays. Estimates suggested that the cadmium would enhance the dose by a factor of three, but the factor achieved was close to five. We have labeled the four cases A, B, C, and D.

For cases A and D without the IMU in place, fission foils inside a boron ball were included in the sensor set because there was sufficient room. This provided an excellent opportunity to see whether the silicon transistors and the fission foils provided the same values for the differential fluence, $\Phi(E)$, in the interval between .2 and 2 MeV where, in their absence, the sensor set would have little response.

As was discussed in the introduction, the determination of the neutron spectrum by the spectrum sensor method (often called the foil activation method) is a major undertaking, and determining the activities of 25 foils in a counting laboratory with six separate detectors takes 2 weeks. Although it would have been desirable to define the spectrum at each point within the system and for many orientations of the IMU, such a task is simply not practical. Therefore, the spectrum was determined for only one

location in each configuration, and mapping over the rest of the volume was carried out to trace the changes in the fast fluence and gamma ray dose relative to those at the position where the spectrum measurements were made.

Figure 1. Geometry for IMV Irradiations at SPR II.

III. NEUTRON SPECTRUM AND FLUENCE MEASUREMENTS

The general procedure used for determining the neutron spectrum is to expose a set of sensors with well-known energy response functions to the environment to be characterized. It is very important that the individual response functions respond to different portions of the spectrum and over the whole energy range (and beyond) where the devices to be tested are affected. (Here one seeks a set of quasi-linearly independent functions that act like the basis functions for construction of the solution spectrum.) The calculated response of a given sensor, j , to a spectrum, $\Phi_t(E)$, is given by

$$R_j = \int \Phi_t(E) \sigma_j(E) dE \quad (1)$$

where $\sigma_j(E)$ is the response function. If the sensor is an activation foil then $\sigma_j(E)$ is the reaction cross section and R_j is proportional to the activity.

The requirement to design a sensor set for good coverage encourages the use of as many of the activation sensors listed in ASTM Standard E 720 as is possible, and, for the cases in this project, to go beyond that to other sensor types such as the silicon transistors.

After the responses of the sensors have been determined, they are input to the SAND II spectrum adjustment code (Reference 5) along with a reasonable trial spectrum, $\Phi_t(E)$. The code then calculates all the responses, R_j , with Equation (1) and compares them with the measured values. An algorithm is invoked to alter the trial in a way that brings the calculated responses into better agreement with the measured responses. This process is iterated until the standard deviation between measured and calculated responses falls below a specified value, generally ~5%, at which time the latest trial spectrum is declared the solution.

The SAND II algorithm does not work perfectly in the absence of a good trial spectrum and an additional methodology can be used to improve the results further (6,7 and ASTM E 721). It involves inspection of the SAND II result to help devise improved trial spectra.

Each spectrum determination is discussed individually below.

Case A. Free-Field Spectrum at 19.5"; Code Name = S2FF11_SNL_SAN.

Run Data

Run: #2295

Date: 7/25/91 at 14:24

Reactor power: 5 kW

Run time: 1535 s

Note: Placement was at 59", 2" above core centerline.

The code name is the name of the computer file for this case. The placement of the sensor set 2" above the reactor fuel centerline was an error, but it should not have had a significant effect on the spectrum shape at the 19.5" distance. The spectrum was measured at 19.5" because that was the closest distance the system could be positioned when, at a later time, the Cd-poly box would be in place. There had been concern that sufficient dose or fluence could not be obtained at larger distances. However, this test showed that the 22.75" distance provided sufficient fluence, and at that distance the fluence was more uniform across the system. All subsequent cases were run at 22.75". The sensors whose responses were determined are listed in Table I. All of these are activation reactions except for those labeled SI1MeV and TLD. The former is the name for the response of the silicon 2N2222A transistors to this fluence in terms of the 1 MeV equivalent neutron fluence, Φ_1 , detected by these devices. An explanation of the evaluation of this response is provided in the next section and in References 2 and 3 for the SAND II spectrum adjustment code (Reference 5). The 1-MeV equivalent damage is to be used as a response on an equal footing with the foil activities. The item "TLD" is a thermoluminescence $\text{CaF}_2\text{:Mn}$ chip that is electron equilibrated with an aluminum cover.

The activities listed are those of the daughter elements at the right side of the listed reaction. They are corrected to that which would exist if measured at the end of the exposure and are further corrected for decay during the run if the correction is significant. The listed activities are the disintegrations per second (Bq) per nucleus of the parent isotope. However, the way the SAND II files are set up, the fission foil responses are listed according to the reactions per nucleus. The F stands for the fission fragment whose activity was read to determine the number of reactions. Discussions of the measurement of activity are contained in ASTM Standard E 720.

Cadmium covers are used to change the energy range of response of the foil. Since the absorption cross section of cadmium is so large below 1 eV, the difference between the activities of a bare and a Cd covered foil is caused by thermal neutrons. The covers used with the fission foils and Na happen to be 4.705×10^{-3} atoms/barn thick and the rest are 2.587×10^{-3} atoms/barn.

A final note to the table: those reactions which were not used in the spectrum determinations are marked with an asterisk. There are a number of reasons for not using a particular reaction in the analysis. Among these are the following: (1) The cross section is not known very well, but the activity was read anyway in hopes that someday an improved cross section will become available and this activity will therefore become useful. (2) The activity was determined with very poor accuracy. This occurs primarily when the activity is so low that the counting statistics are very poor. (3) Somewhere in the measurement process a mistake was made that cannot be traced. However, when a spectrum is being sought, this activity is so far from being compatible with the rest of the sensors that its use will disrupt the evaluated spectrum shape.

Table I
Activities at SPR II Free Field at 19.5"
Case A

<u>Sensor</u>	<u>Activity (Bq/Nucleus)</u>	<u>Cadmium Cover</u>
*27Al(n,p)27Mg	3.252-17	Y
27Al(n, α)24Na	6.883-20	Y
197Au(n, γ)198Au	1.236-16	N
197Au(n, γ)198Au	1.028-16	Y
54Fe(n,p)54Mn	1.749-20	Y
**56Fe(n,p)56Mn	6.942-19	Y
*115In(n, γ)116In	5.171-15	N
*115In(n,n')115In	7.861-17	N
24Mg(n,p)24Na	1.502-19	Y
55Mn(n, γ)56Mn	2.834-17	Y
23Na(n, γ)24Na	6.076-19	N
23Na(n, γ)24Na	1.521-19	Y
58Ni(n,p)58Co	9.908-20	Y
64Zn(n,p)64Cu	4.506-18	Y
*90Zr(n,2n)89Zr	3.715-22	Y
59Co(n, γ)60Co	5.756-21	Y
45Sc(n, γ)46Sc	3.779-20	Y
*46Ti(n,p)46Sc	1.876-20	Y
47Ti(n,p)47Sc	3.418-19	Y
48Ti(n,p)48Sc	1.010-20	Y
32S(n,p)32P	3.100-19	N
	(reactions/nucleus)	
235U(n,f)F	1.616-11	Y+boron
238U(n,f)F	2.520-12	Y+boron
239Pu(n,f)F	2.200-11	Y+boron
237Np(n,f)F	1.366-11	Y+boron
TLD Al cover 0.229 cm	31.35 Grays	N
SI1MeV	1.144+13 1 MeV equivalent (n/cm ²)	N

*Not used in spectrum unfold.

**Not used in the spectrum unfold because this foil was found to have a high level of Mn impurity.

These responses were input to the SAND II code and the procedures were followed that are described in ASTM Standard E 721 and References 6 and 7. The resulting spectrum for this case is shown in Figure 2 and is listed in Appendix XI for 56 points stretched over 11 orders of magnitude in energy. The SAND II spectrum printout actually includes 640 points.

There are a number of features about this spectrum that should be pointed out. The data is close to being the most consistent we have ever seen, and as a result has led to the very smooth spectrum. The large high energy hump is a degraded fission spectrum and the 1/E low energy tail is from down scattering in the reactor materials and in the wall of the shield building. This smooth fit is a very important indicator that the responses were determined correctly, because if a mistake has been made, and an activity is off by even as little as 10% in some cases, the spectrum will exhibit unphysical peaks or bumps where that particular foil has its highest response. In fact, such artificial structure usually identifies the problem activity if the analyst is familiar with the shapes of the response functions of the set.

In this case we took the opportunity to compare the compatibility of the fission foil activities and the silicon transistors because their responses overlap. The spectrum was first determined very well with all the responses except that of the transistors. This result was then used as a trial function in the code with the Si1MeV silicon response added. The measured response for the new ENDF/B-VI silicon displacement damage response function was within 2% of the calculated response for this trial spectrum. This result also demonstrated the important fact that the transistors are not responding significantly to gamma rays. We have demonstrated in this laboratory before that for environments with a Φ_1/γ ratio of greater than 10^{11} n/(cm²·Gy) most of the transistor response in 2N2222A's will be caused by the neutrons. In this case the Φ_1/γ ratio is 3.65×10^{11} n/(cm²·Gy). The reason this is so important is that in case B (inside the IMU in the free field), where the fission foils are not available to fix the spectrum between 0.2 and 2 MeV, a high Φ_1/γ ratio indicates that the transistors can be used without correction for gamma ray dose effects.

Once the spectrum has been determined, the neutron permanent damage response of an object can be predicted provided its response function is known, and Equation (1) is used to calculate that response. (Also, any object whose response function is known can be used as a spectrum sensor as is silicon displacement damage for these measurements.) The spectrum can also be used to calculate parameters that can be used to predict the response to an irradiation in this environment without the need to perform the integrals again. For example, all one needs to do is include with each test package a sulfur pellet monitor. Then the sulfur activity is used to calculate the actual fluence or to calculate the response of any other dosimetry sensor.

A complete discussion of how these parameters are derived and used is beyond the scope of this report. See ASTM E 722 and References 2, 8 and 9. However, for silicon displacement damage an example of the application of this methodology is offered below.

Figure 2. Free Field Spectrum at 19.5".

Suppose a silicon device and a sulfur pellet are exposed to a short pulse of neutrons having the known spectrum, $\Phi(E)$. Calculate the fluence of neutrons above the approximate 3 MeV threshold for the reaction $^{32}\text{S}(n,p)^{32}\text{P}$.

$$\Phi(E > 3 \text{ MeV}) = \frac{A_s}{N\lambda\bar{\sigma}_s} = \Phi_3 \quad (2)$$

where

A_s = sulfur activity at the end of the pulse,

N = number of sulfur atoms in the pellet,

λ = the decay constant for ^{32}P , and

$\bar{\sigma}_s$ = spectrum averaged cross section for sulfur over the spectrum $\Phi(E)$.

$\bar{\sigma}_s$ is defined as

$$\bar{\sigma}_s = \int_0^{\infty} \Phi(E) \sigma_s(E) dE / \int_{3 \text{ MeV}}^{\infty} \Phi(E) dE \quad (3)$$

where $\sigma_s(E)$ is the $^{32}\text{S}(n,p)$ cross section.

Next, calculate the 1 MeV equivalent fluence of this exposure.

$$\Phi_1 = SI \cdot HP \cdot \Phi[E > 3 \text{ MeV}] \quad (4)$$

where SI = the spectral index which is $\int_{10 \text{ keV}}^{\infty} \Phi(E) dE / \int_{3 \text{ MeV}}^{\infty} \Phi(E) dE$

$$HP = \int_{10 \text{ keV}}^{\infty} K_D(E) \Phi(E) dE / [\Phi(E > 3 \text{ MeV}) \cdot SI \cdot D_1]$$

= silicon hardness parameter which is the damage effectiveness of the neutrons of this spectrum compared to that of neutrons near 1 MeV.

$K_D(E)$ = silicon neutron displacement damage function

D_1 = silicon reference, 1-MeV displacement damage value = 95 MeV·mb

From the final spectrum determined by the SANDII Code all of the necessary parameters can be derived. In fact, since the appropriate integrals can be performed within the code, it can be asked to print out the values of SI , HP , $\Phi(E > 3 \text{ MeV})$ and $\bar{\sigma}_s$. For this case $SI = 7.745$, $HP = .856$ and $\bar{\sigma}_s = 298.8 \text{ mb}$. If an experimenter measures an activity of say $A_s/N = 5.0E-19 \text{ Bq/nucleus}$ on a sulfur pellet then from equation (2), $\Phi(E > 3 \text{ MeV}) = 5.0E-19 / (0.2986E-24)(5.614E-7) = 2.97E+12 \text{ n/cm}^2$. The

$\lambda = 5.614\text{E-}7\text{s}^{-1}$ for sulfur in the above equation. Then
 $\Phi_1 = (2.97\text{E}+12)(7.745)(.856) = 1.97 \times 10^{13}\text{n/cm}^2$ from equation (4). Both SI and HP are listed in Table V (p. 30) for each of the four cases discussed in this report. There are two values of HP given for each case--that derived from the old ASTM E 722 (86) silicon damage function, HP_A , and that derived from the ENDF/B-VI cross section set, HP_E . The displacement damage in silicon is then calculated by multiplying Φ_1 by the reference damage caused by a 1 MeV neutron, D_1 .

Note that a large SI means that a large fraction of the fluence above 10 keV is below 3 MeV. (Silicon responds negligibly below 10 keV.) An HP of 0.5 would indicate that the average neutron in this spectrum is only half as damaging as a 1 MeV neutron.

Case B. Spectrum in the IMU Exposed to Free Field at 22.5"; Code Name S2B9_SNL_SAN.

Run Data

A. Run: #2305
Date: 8/15/91 at 11:19
Power: 5 kW
Run time: 1954 s

B. Run: #2307
Date: 8/16/91 at 10:55
Power: 5 kW
Run time: 1954 s

The exposure of the sensors inside the IMU was divided into two runs because of the limited space available, and because for the second run a reduced amount of cadmium cover material could be used to reduce shadowing of bare neutron-low-energy-sensitive sensors. As is shown by the layout drawings of figure 3, the sensors were placed in the 2" x 2" x .75" aluminum box with 0.0625" thick walls. The 2" x 2" face was perpendicular to the line to the core center. The sensors were held in place by two layers of foam. To make efficient use of the beam area, as many as three foils were placed in each location. This increases the opportunity for attenuation in the stack, but that should be negligible for sensors with high threshold energies. Still, to minimize any attenuation, the sensors with the highest thresholds were placed in the front of the stack. A potential problem could exist in the Sc, Mn, Ni stack from shielding, but separate tests did not show significant attenuation. The transistors were silicon bipolar 2N2222A transistors. Their use as sensors is discussed in the next section.

The positioning of the foil set according to our records was consistent with the 22.75" to core center provided by Jose Orozco of Northrop Corp. To monitor the consistency of the fast fluence between the two runs and among the four main sensor positions within the box, a nickel sensor was placed at all locations. These showed no variation between exposures but indicated a possible difference of ~ +5% between the upper left and lower right fluences

(as one looks at Figure 3 he is looking away from the reactor). This difference was not considered sufficient to warrant a correction to the activities based on a fluence profile. However, such a correction could be applied.

The sensor responses are listed in Table II in the same format as in Table I, and the SAND II spectrum results are included in Appendix X2. It is worth looking at Table X2.2, page 59, to observe the 4th and 5th columns in the table which delineate the energy limits between which 95% of the response of each sensor occurs. Without fission foils or the transistors there is the huge gap in response between 0.24 and 1.8 MeV where there is little response by this sensor set to this spectrum. This shows the importance of using the transistors when the fission foils are absent.

We first constructed a spectrum without using the transistor response and then tested the agreement between the measured and calculated response for these transistors for this spectrum. The agreement was within 2%. It is important to note, however, that this agreement must be attributed to the experience of the pilot, not the quality of the data without the transistor response.

The spectrum for this case is shown in Figure 4. There is some additional small scale structure in this solution which reflects some small disagreements between the sensor responses. When sensors disagree, the SAND II code will alter the trial spectrum most rapidly where the response of the disagreeing sensor is largest. That can cause two things to happen. First, bumps or dips will develop where sensors have resonance reaction peaks. Second, if a disagreeing sensor has high response in more than one region, the code will try to alter the spectrum in all high response regions even if the problem is with the spectrum in only one region. With enough sensors, overlap in response can aid in finding the correct alteration in the proper energy region. Nothing can be done about spectrum distortions if the response or response function (activity or cross section) is in serious error, except to leave it out of the analysis.

The most significant feature about this spectrum is that it is very different in shape from that in the free field, Case A. The 1/E low energy tail is relatively so much larger here that the hump at 0.1 MeV is obscured. Notice also how different the values of the parameters in Table V are. If one assumed that the free field spectrum was correct, and monitored the fast fluence inside the IMU with sulfur foils (pellets), the damage in silicon electronic devices would be proportional to SI·HP, the last column in Table V. Thus the actual damage would be $9.10/6.63 = >37\%$ greater than the experimenter who used the sulfur might have thought. The spectrum must be properly characterized in the environment where the susceptible parts are located.

Figure 3. Foil and Sensor Layout.

Figure 4. Spectrum in IMV Exposed to Free Field at 22.75".

Table II
Activities at SPR II Free Field in IMU at 22.75"
Case B

<u>Sensor</u>	<u>Activity (Bq/Nucleus)</u>	<u>Cadmium Cover</u>
*27Al(n,p)27Mg	2.398-17	Y
27Al(n,α)24Na	4.701-20	Y
197Au(n,γ)198Au	4.124-16	Y
197Au(n,γ)198Au	4.648-16	N
54Fe(n,p)54Mn	1.186-20	Y
**56Fe(n,p)56Mn	9.679-19	Y
*115In(n,γ)116In	1.416-15	N
*115In(n,n')115In	5.255-17	N
24Mg(n,p)24Na	8.886-20	Y
55Mn(n,γ)56Mn	2.268-16	Y
23Na(n,γ)24Na	7.569-19	Y
23Na(n,γ)24Na	1.479-18	N
58Ni(n,p)58Co	6.318-20	Y
64Zn(n,p)64Cu	2.777-18	Y
59Co(n,γ)60Co	3.700-20	Y
45Sc(n,γ)46Sc	1.676-19	Y
*46Ti(n,p)46Sc	7.858-21	Y
47Ti(n,p)47Sc	2.205-19	Y
48Ti(n,p)48Sc	6.197-21	Y
32S(n,p)32P	1.922-19	
TLD Al Cover 0.229 cm	2.94+1 Grays	N
Si1MeV	1.043+13 1 MeV equivalent (n/cm ²)	N

*Not used in spectrum unfold.

**Not used in spectrum unfold because this foil was found to have a high level of Mn impurity.

The fact that the transistor sensor response fits so well with the rest of the sensors (the activation foils) is partially explained by the fact that the Φ_1/γ ratio is still a large $3.54 \times 10^{11} \text{ n}/(\text{cm}^2 \cdot \text{Gy})$ which implies that no correction for gamma ray sensitivity of the 2N2222A transistors need be made to justify their use as neutron sensors in this case.

For this case and for Case C, one of the most useful reactions had to be left out. It was the $^{56}\text{Fe}(\text{n},\text{p})^{56}\text{Mn}$ that has a threshold of $\approx 5 \text{ MeV}$. The measured activity was extremely high after this run--by about a factor of five over that expected. We discovered that a new batch of foils had been used, and that they had 100 times more ^{55}Mn impurity in them than they should have. The reaction $^{55}\text{Mn}(\text{n},\gamma)^{56}\text{Mn}$ produces the same radioactive daughter isotope as the $^{56}\text{Fe}(\text{n},\text{p})^{56}\text{Mn}$ reaction but its spectrum averaged cross section is much higher. Thus the iron reaction was swamped by the manganese. Unfortunately, the Case B foils were not read before Case C was conducted so the ^{56}Fe data was lost for both cases.

Case C. Spectrum Inside the Cd-poly Box and in the IMU; Code Name S2CD19_SNL_SAN.

Run Data

- A. Run: #2315
Date: 8/22/91 at 11:23
Power: 5 kW
Run time: 3908 s
- B. Run: #2317
Date: 8/23/91 at 9:48
Power: 5 kW
Run time: 3908 s

This was the most difficult case to analyze because again the fission foils were not available, and for the first time the Φ_1/γ ratio was very low indicating a high probability that the transistor sensors would have been affected by the gamma ray flux. The reason is obviously the influence of the Cd-poly box.

The purpose of the Cd-poly box was to enhance the gamma ray flux by slowing down neutrons to thermal energies in the polyethylene and capturing them in cadmium. The cadmium then emits about 8 MeV of gamma ray energy for each absorption. The Cd-poly box was constructed of layers of cadmium loaded polyethylene, layers of cadmium and layers of polyethylene. The front side was 4" thick, the rear was 2", the sides were 3", the top 4", and the bottom was 3" and included some holes. The large increase in the gamma ray fluence ($\sim \times 5$) and the attenuation of the fast neutrons in the box walls led to a decrease in the Φ_1/γ ratio of almost a factor of 20.

This large decrease in Φ_1/γ ratio to $2.1 \times 10^{10} \text{ n}/(\text{cm}^2 \cdot \text{Gy})$ provided warning that a significant contribution to the transistor response might be

generated by the gamma flux as just mentioned. A second indication came during the initial construction of the spectrum with the SAND II code. A spectrum was developed without the help of the transistor response. When this spectrum was used as a trial function for the code, and the transistor response was added, the response started out ~20% high. Subsequent iterations led to a distorted spectrum.

The next step was to test the transistors for gamma sensitivity so that a correction could be made. The same transistors were exposed to ^{60}Co irradiation at the Sandia Gamma Irradiation Facility (GIF). Although the maximum dose seen by these transistors in Case C was only 172 Gy (1 Gy = 100 rads), they received 500 Gy in the gamma exposure to ensure that enough change in gain occurred so that it could be accurately measured. Indeed a gamma response was determined in the form of the change in the reciprocal of the gain as a function of dose. This was then scaled to the 172 Gy value seen in the reactor exposure, and that value was subtracted from the total change in reciprocal gain measured in that same reactor exposure. An outline of the process by which the response of the transistors is determined when they are used as spectrum sensors is provided in the next section. Tests of the device gamma sensitivity vs. dose need to be made to find the real $\Delta(1/h)$ vs. dose before this correction can be made accurately.

It is appropriate here to point out that if the total response of silicon devices are to be determined, then the contributions of both the gamma rays and the neutrons must be considered. It is only when devices such as the 2N2222A transistors are being used as spectrum sensors that the gamma ray contribution should be subtracted.

The ^{60}Co calibration led to a gamma ray sensitivity of $K_\gamma = 1.6 \times 10^{-5} \text{ Gy}^{-1}$. The Φ_1 in the Table III is that calculated from the change in the reciprocal gain due to neutrons after the gamma ray response was subtracted out. The correction applied was a reduction by 31% from $\Phi_1 = 5.328\text{E}+12 \text{ n/cm}^2$ to $3.683\text{E}+12$. When this corrected equivalent fluence was added to the sensor set, the relatively smooth spectrum shown in Figure 5 was obtained.

There is still a significant uncertainty in the magnitude of the gamma ray correction factor K_γ given above. The experiments to measure this sensitivity were limited in scope and involved some important assumptions. It is not obvious that the change in gain from gamma rays results from exactly the same physical phenomenon as that caused by the neutrons. Is the displacement damage defect structure the same? Are the annealing properties the same? Do ^{60}Co gammas produce the same damage as cadmium capture gamma rays? Their spectra are quite different. Is the gamma ray response linear (as was assumed when the correction factor was scaled)? We know that it is not.

At this point the fact that a relatively smooth and physically reasonable spectrum was obtained with the corrected transistor response is

Table III
Activities at SPR II in Cd-Poly Box and in IMU at 22.75"
Case C

<u>Sensor</u>	<u>Activity (Bq/Nucleus)</u>	<u>Cadmium Cover</u>
* $^{27}\text{Al}(\text{n},\text{p})^{27}\text{Mg}$	1.185-17	Y
$^{27}\text{Al}(\text{n},\alpha)^{24}\text{Na}$	2.981-20	Y
$^{197}\text{Au}(\text{n},\gamma)^{198}\text{Au}$	1.109-15	N
$^{197}\text{Au}(\text{n},\gamma)^{198}\text{Au}$	1.018-15	Y
$^{54}\text{Fe}(\text{n},\text{p})^{54}\text{Mn}$	5.244-21	Y
* $^{115}\text{In}(\text{n},\gamma)^{116}\text{In}$	4.595-14	N
* $^{115}\text{In}(\text{n},\text{n}')^{115}\text{In}$	2.089-17	N
$^{24}\text{Mg}(\text{n},\text{p})^{24}\text{Na}$	5.635-20	Y
$^{55}\text{Mn}(\text{n},\gamma)^{56}\text{Mn}$	2.808-16	Y
$^{23}\text{Na}(\text{n},\gamma)^{24}\text{Na}$	1.136-18	Y
$^{23}\text{Na}(\text{n},\gamma)^{24}\text{Na}$	3.439-18	N
$^{58}\text{Ni}(\text{n},\text{p})^{58}\text{Co}$	2.875-20	Y
$^{64}\text{Zn}(\text{n},\text{p})^{64}\text{Cu}$	1.260-18	Y
$^{59}\text{Co}(\text{n},\gamma)^{60}\text{Co}$	5.591-20	Y
$^{45}\text{Sc}(\text{n},\gamma)^{46}\text{Sc}$	3.271-19	Y
* $^{46}\text{Ti}(\text{n},\text{p})^{46}\text{Sc}$	5.707-21	Y
$^{47}\text{Ti}(\text{n},\text{p})^{47}\text{Sc}$	9.518-20	Y
$^{48}\text{Ti}(\text{n},\text{p})^{48}\text{Sc}$	3.996-21	Y
$^{32}\text{S}(\text{n},\text{p})^{32}\text{P}$	8.486-20	N
TLD Al Cover 0.229 cm	172 Grays	N
SI1 MeV	+3.683+12 1 MeV equivalent (n/cm ²)	N

+Gamma dose corrected.

*Not used in spectrum unfold.

a very strong indicator that the derived spectrum values are correct within the larger uncertainty limits assigned in Table V. The spectrum is shown in Figure 5.

One will notice when examining Table V that the IMU has changed the shape of the spectrum more than the Cd-poly box has.

Case D. Spectrum in the Cd-poly box without the IMU; Code Name S2CDF9_SI_SNL_SAN.

Run Data

Run: #2323
Date: 10/23/91 at 10:23
Power: 5 kW
Run time: 1935 s

This case was run at a later time after preliminary analysis of the earlier runs permitted us to add considerably to the sophistication of the experiment design. Without the IMU in place there was again more room to test additional sensor configurations that could be compared with each other. The fission foils were exposed to compare with the transistor sensors in a low Φ_1/γ environment and replacement low-manganese ^{56}Fe foils were added to the sensor set.

The responses are listed in Table IV and the spectrum constructed without the aid of the three new responses from foils inside a boron ball and without the transistor response is shown in Figure 6. The 2N2222A transistor response was not used here because of its larger uncertainty and because the fission foils ensured adequate spectrum coverage. The boron covered ^{55}Mn , ^{45}Sc and ^{23}Na responses were left out in this first stage so that the spectrum parameters for the various cases could be compared without the additional change in the sensor sets used. The effects of these new response functions are discussed later in this section.

The spectrum in Figure 6 was developed with 18 response functions and is still very smooth. This indicates that there was little conflict among the sensors.

The sensitivity coverage is so satisfactory that the trial function used in the SAND II code can be very poor and the code will still produce essentially the same spectrum parameters. Here the Φ_1/γ ratio is even lower than for Case C, $\sim 0.19 \times 10^{11} \text{ n}/(\text{cm}^2/\text{Gy})$. Table V shows that the spectral index, SI, has dropped to 5.39 although the epithermal tail above the cadmium cutoff is still very large. Hydrogenated materials lower SI and raise a low energy tail if it is not already there.

Figure 5. Spectrum in Cd-Poly Box and in the IMV at 22.75".

Figure 6. Spectrum Inside Cd-Poly Box without IMV at 22.75".

Table IV
Activities at SPR II in Cd-Poly Box, no IMU at 22.75"
Case D

<u>Sensor</u>	<u>Activity (Bq/Nucleus)</u>	<u>Cadmium Cover</u>
* ²⁷ Al(n,p) ²⁷ Mg	9.353-18	Y Not Time Corr.
²⁷ Al(n,α) ²⁴ Na	2.276-20	Y
¹⁹⁷ Au(n,γ) ¹⁹⁸ Au	5.601-16	N
¹⁹⁷ Au(n,γ) ¹⁹⁸ Au	5.533-16	Y
* ⁵⁴ Fe(n,p) ⁵⁴ Mn	3.973-21	Y
⁵⁶ Fe(n,p) ⁵⁶ Mn	1.889-19	Y
* ¹¹⁵ In(n,γ) ¹¹⁶ In	1.726-14	N
* ¹¹⁵ In(n,n') ¹¹⁵ In	1.243-17	N
²⁴ Mg(n,p) ²⁴ Na	4.576-20	Y
⁵⁵ Mn(n,γ) ⁵⁶ Mn	1.189-17	Y
²³ Na(n,γ) ²⁴ Na	4.263-19	Y
²³ Na(n,γ) ²⁴ Na	5.886-19	N
⁵⁸ Ni(n,p) ⁵⁸ Co	2.047-20	Y
⁶⁴ Zn(n,p) ⁶⁴ Cu	1.014-18	Y
⁴⁵ Sc(n,γ) ⁴⁶ Sc	1.415-19	Y
* ⁴⁶ Ti(n,p) ⁴⁶ Sc	2.782-21	Y
⁴⁷ Ti(n,p) ⁴⁷ Sc	6.760-20	Y
⁴⁸ Ti(n,p) ⁴⁸ Sc	3.046-21	Y
³² S(n,p) ³² P	6.049-20	N
* ⁵⁹ Co(n,γ) ⁶⁰ Co	2.716-20	Y
		<u>Cadmium + Boron Cover</u>
* ⁵⁵ Mn(n,γ) ⁵⁶ Mn	4.722-18	Y
* ⁴⁵ Sc(n,γ) ⁴⁶ Si	4.087-21	Y
* ²³ Na(n,γ) ²⁴ Na	2.850-20	Y
(reactions/nucleus)		
²³⁵ U(n,f)F	2.795-12	Y
²³⁸ U(n,f)F	4.662-13	Y
²³⁹ Pu(n,f)F	3.449-12	Y
²³⁷ Np(n,f)F	2.118-12	Y
TLD Al Cover 0.229 cm	114.8 Gy	N
*SI1MeV	+2.184+12 1 MeV equivalent (n/cm ²)	N

+Gamma dose corrected.

Table V
Spectrum Parameters

<u>Environment at SPR II</u>	<u>$\Phi(E>3 \text{ MeV})(n/cm^2)$</u>	<u>SI</u>	<u>HPA</u>	<u>HP_{E6}</u>	<u>T_{run}(sec)</u>	<u>SI•HP_{E6}</u>
A. 19.5" free field	1.785E+12	7.745	0.935	0.856	1535	6.63
B. 22.75" free field in IMU	1.143E+12	15.04	0.650	0.605	1954	9.10
C. 22.75" in Cd-poly in IMU	5.123E+11	11.88	0.650	0.602	3908	7.15
D.a. 22.75" in Cd-Poly no IMU; no Si or boron covered Mn, Sc, Na	3.804E+11	5.390	0.964	0.866	1954	4.67
b. with Si sensor	3.765E+11	5.705	1.009	0.915	1954	5.22
c. with boron covered Mn, Sc, Na	3.792E+11	5.540	0.935	0.840	1954	4.65
E. 35" in free field behind the IMU	7.197E+10	15.51	0.643	0.601	1954	9.32
F. 35" in Cd-Poly Box behind the IMU	4.541E+10	13.86	0.631	0.588	3908	8.15

When the uncorrected transistor response was added to the spectrum, the disagreement was approximately 70%, and the code could not find a spectrum that provided any agreement. The fission foil activities simply would not allow the spectrum to move.

The wonderful opportunity presented itself here to directly compare transistor response predicted from this spectrum with the measured response. (Before, in Case A with a high Φ_1/γ ratio, the agreement was exceptionally good.) This comparison leads to an independently derived correction for the transistor gamma ray response in an environment that is exactly the correct one for the gamma rays--that produced by the capture of neutrons in the Cd-poly box.

The SAND II code can be used in the "activity" mode to predict responses from a given spectrum (without alteration). When a scaled version of this spectrum (normalized to 1 above 10 keV) was folded with each response function in the sensor set, the calculated activities listed in Table VI were generated. The last entry in the table is the predicted transistor response with units in the form of 1 MeV equivalent fluence. When this value is multiplied by the value of the $\Phi(E > 10 \text{ keV}) = 2.050\text{E}+12 \text{ n/cm}^2$ for the actual spectrum, one finds $\Phi_1 = 1.773\text{E}+12 \text{ n/cm}^2$. This compares with $3.251\text{E}+12$ obtained from the transistors when not corrected for the gamma ray effects and $2.184\text{E}+12 \text{ n/cm}^2$ obtained from the transistors after the gamma correction provided by the ^{60}Co calibration. The comparison shows that the neutron response predicted by the comparison with the fission foils is smaller than that predicted by ^{60}Co (the gamma correction is larger).

$$\frac{\Phi_1(\text{ff})}{\Phi_1(^{60}\text{Co})} = \frac{1.773\text{E}+12}{2.184\text{E}+12} = 0.81 \quad (5)$$

This may not be a poor comparison. In Case C where the transistor response was needed to sense the whole spectrum, the Φ_1/γ ratio was larger, and the correction applied to the transistor response was considerably smaller than what would seem necessary here, ~30% compared to ~55%. Thus although a correction based on the fission foil comparison would be larger, we have left the ^{60}Co correction in Case C. The spectrum derived with the silicon response (using the ^{60}Co • gamma correction) is shown in Figure 7. In this case the SI•HP product increased by 12%. Further work on gamma ray sensitivity needs to be carried out before confidence can be placed in either gamma calibration. Obviously a way to apply the fission foil comparison would be to mock up a configuration that reproduces the Case C environment but with just enough room to include the fission foils in the boron ball. That, however, makes the transistors less important for the spectrum determination. It would be more useful if a gamma ray source such as ^{60}Co tied in with TLD measurements could be shown to predict the gamma effects adequately.

Figure 7. Spectrum inside the Cd-Poly Box at 22.75" with ^{60}Co -Gamma Corrected Silicon Response

Table VI
Calculated Responses for Case D Spectrum
(Integral Spectrum Normalized to 1.00E-02 MeV)

activity calculation results					
(normalized to 1.00E-02 mev)					
foil reaction	calculated activity (dps/nucleus)	nominal 5.00 percent activity limits (mev),		actual activity outside limits (percent)	
		lower	upper	lower	upper
s32 (n,p) p32	3.043E-32	2.400E+00	8.000E+00	4.806	4.883
au197(n,g) au198 Cd	2.698E-28	3.800E-06	6.300E-06	4.736	4.908
au197(n,g) au198	2.734E-28	3.400E-06	6.300E-06	5.054	4.923
al27 (n,a) na24 Cd	1.067E-32	6.600E+00	1.230E+01	5.396	4.950
mg24 (n,p) na24 Cd	2.373E-32	6.600E+00	1.190E+01	6.194	4.886
ni58 (n,p) co58 Cd	1.007E-32	2.100E+00	8.000E+00	4.557	5.020
u235 (n,f) la140 B Cd	1.390E-24	1.150E-03	5.200E+00	4.950	4.879
mn55 (n,g) mn56 Cd	5.791E-29	5.750E-07	1.100E-03	4.890	4.594
fe56 (n,p) mn56 Cd	8.973E-32	5.600E+00	1.170E+01	5.358	4.861
ti47 (n,p) sc47 Cd	3.629E-32	1.900E+00	8.100E+00	4.416	5.133
u238 (n,f) la140 B Cd	2.210E-25	1.500E+00	7.500E+00	5.218	4.909
pu239(n,f) la140 B Cd	1.712E-24	3.000E-03	5.400E+00	5.058	5.109
np237(n,f) la140 B Cd	9.806E-25	6.300E-01	6.400E+00	4.874	5.019
ti48 (n,p) sc48 Cd	1.484E-33	6.000E+00	1.260E+01	4.802	4.866
zn64 (n,p) cu64 Cd	4.585E-31	2.600E+00	8.200E+00	4.323	4.915
sc45 (n,g) sc46 Cd	6.774E-32	4.750E-07	3.000E-04	5.519	4.977
na23 (n,g) na24 Cd	2.109E-31	5.500E-07	3.000E-03	4.896	5.562
na23 (n,g) na24	2.887E-31	1.350E-07	3.000E-03	5.112	4.078
si28 (n,x) mev1	8.668E-01	2.400E-01	6.300E+00	5.103	4.851

We intended to pursue another alternative, but support for further work on this project was suspended. A mockup of the Cd-poly environment could be placed in a thermal neutron beam. The thermal neutrons would not cause significant displacement damage in silicon so the transistors would respond primarily to the gamma flux which in this case correctly approximates the gamma environment of the test.

The demonstration that in the Cd-poly box the transistors are significantly affected by the gamma rays shows that the transistors used for mapping in the rest of the IMU must be corrected for the gamma ray sensitivity. The mapping results in the IMU are discussed in Section V.

Review of the ranges of 95% response for scandium, sodium and manganese in Case C showed that most of the response for that spectrum was way down in the thermal energy range. Therefore, their usefulness is reduced in the middle of the spectrum where their resonances are located. The task of defining the spectrum in the middle then depends even more on the fission foils or the transistors. However, there is plenty of reason to fear that a boron ball while cutting off thermal response, might reduce the activity of the foils inside by too much. First, the absorption cross section of boron must be accurately known if it is to predict precisely the attenuation of about an order of magnitude in the fluence to which each sensor is sensitive. Second, the response range of each sensor will be shifted far upward where their cross sections may not be well known. This shift will occur because the boron absorption cross section decreases with energy. Nevertheless, at low energies where the boron absorption cross section totally dominates, an attenuation calculation that ignores scattering may be accurate enough. Therefore the use of boron shields on these materials was worth investigating.

The three sensors, ^{45}Sc , ^{23}Na and ^{55}Mn were placed in a Cd and a boron ball cover, and were placed just above the main set of sensors. A nickel foil was included to normalize the fluence. One can see from Table IV that the manganese activity was reduced by a factor of 25. We have run SAND II with the three extra responses, the ^{45}Sc , ^{23}Na , ^{55}Mn , and the resulting spectrum is shown in Figure 8. The fit, although a little more bumpy, has not changed very much. Even the spectrum parameters have not shifted significantly. In Table V the SI-HP has only shifted by 0.6%.

The most interesting and potentially useful change, however, is the very large shift in the sensitivity ranges of the sensors. Table X4.2 from the SAND II code printout, Appendix X4, shows the upper and lower energy limits of all the sensors including these of the bare and boron covered sensors. The shifts are large enough to almost close the gap left by the absence of both the transistors and the fission foils. Certainly further investigation of this configuration is justified.

Figure 8. Spectrum inside the Cd-Poly Box without the IMU at 22.75" with Boron Covered ⁵⁵Mn, ⁴⁵Sc and ²³Na Sensors.

IV. DETERMINATION OF THE TRANSISTOR RESPONSES

Permanent neutron displacement damage in silicon bipolar transistors is manifested by a reduction in the carrier lifetime and, as a consequence, a reduction of the collector current gain. The phenomena is quantified by the Messenger-Spratt equation (References 10 and 11).

$$\frac{1}{h_{FE\Phi}} - \frac{1}{h_{FE0}} = K_r \Phi_1 \quad (6)$$

where h_{FE0} and $h_{FE\Phi}$ are the current gains before and after exposure to the neutron radiation respectively. This equation says that the change in reciprocal gain $\Delta(1/h) = 1/h_{FE\Phi} - 1/h_{FE0}$ is proportional to the fluence and K_r is the proportionality (or damage) constant. The 1 MeV equivalent fluence is defined earlier in equation (4)

$$\Phi_1 = SI \cdot HP \cdot \int_{3 \text{ MeV}}^{\infty} \phi(E) dE = SI \cdot HP \cdot \Phi_3 \quad (7)$$

One determines K_r by measuring $\Delta(1/h)$ in a standard radiation field for which the spectrum is known. This means the transistors must be calibrated. If the measured quantity, $\Delta(1/h)$, has gamma ray contributions then this contribution must also be measured and subtracted from the total $\Delta(1/h)$, before it can be used in (6). In order to use the transistor as a spectrum sensor, one measures Φ_{1s} and $\Delta(1/h)_s$ in the standard neutron field and $\Delta(1/h)_u$ in the unknown field. The s index stands for quantities of the standard (or reference) field. The u stands for the unknown field. The Φ_{1u} is then found by taking a ratio of equation (6) in the standard field and in the unknown field. That ratio yields equation (8).

$$\Phi_{1u} = \frac{\Delta\left(\frac{1}{h}\right)_u}{\Delta\left(\frac{1}{h}\right)_s} \Phi_{1s} \quad (8)$$

This is the value of the measured response that is included in the input sensor data along with the measured activities. The SAND II code then compares this value with that calculated for the current trial spectrum, Φ_{1t} . This whole process is described in References 2 and 3. Actually one can directly calculate Φ_{1t} by using the current trial spectrum to obtain SI, HP and Φ_{3t} . Since the process of determining the transistor response is so different from that for determining activities, it may seem surprising that this silicon sensor is compatible with activation sensors. However, this process is in fact very general. Any object whose response function is known and whose response can be measured accurately is a potential spectrum sensor.

V. MAPPING OF THE ENVIRONMENT INSIDE THE IMU

The spectrum measurement at one location inside the IMU provided the reference point for the mapping of the radiation throughout the rest of the system. Although it would have been desirable to find the gamma ray dose and the neutron spectrum and fluence everywhere, that option is clearly not practical because of lack of room for sensors, limited time, and limited budget. The next best option is to use a limited set of sensors at each location to indicate relative changes in the three quantities. A silicon transistor can measure the change in silicon damage caused by a change in the environment. For neutrons it is especially useful in the 0.2 to 1 MeV energy region. Sulfur pellets will measure the changes in neutron fluence greater than 3 MeV, and the TLD's will provide the map of the dose. Thus a change in the ratio of the transistor and sulfur responses will provide perhaps the most efficient indicator of spectrum changes relevant for silicon damage with the fewest sensors. Therefore, we proposed the use of these sensors for the mapping in the IMU, and Northrop (Boyce Ahlport and Jose Orozco) carried out the tests.

Their methodology for measuring the transistor responses differed slightly from Sandia's method of using the transistors as sensors for the spectrum determination. The slight differences in results can be readily explained.

The mapping results and the analysis carried out by Northrop are included in a three-volume report #91-24530 entitled, "IMU Mapping Test Report," Reference 12. It contains lists of the responses measured with the sulfur pellets, TLD's and transistors both inside and outside the IMU for all of the reactor runs. For completeness, a copy of Appendix I from that report is included in Appendix VII. The data in that appendix is used to establish the relationships with the neutron spectrum measurements.

The transistors used by both Sandia and Northrop were from the same production lot. If the measurement procedures were identical, the responses to the same environment would be expected to vary by approximately 5% on an individual basis, but they exhibited larger differences than this. The differences in the Sandia and Northrop measurements of the transistor responses are the following.

- A. The Sandia transistors were calibrated in the Sandia Pulsed Reactor III (SPR III) central cavity while Northrop's were calibrated in the 19.5" radius leakage free-field at SPR II. In principal this should not make a difference because the damage constant should only depend on the 1 MeV equivalent fluence. However, in practice there are added uncertainties introduced by the evaluation of the spectrum parameters in the two environments (e.g., different independently determined values of SI and HP are used). This would have introduced an additional uncertainty of a few percent.

- B. The Northrop transistors were used in fluence levels that varied over a wide range. They measured changes in the damage constant as a function of fluence and found that it varied slowly over the fluence range from 10^{12} to 10^{14} n/cm² in the same environment. Their table of the neutron damage constant vs. the free-field fluence is shown in Table VII where $K_r = \Delta(1/h)_A / \Phi_{1A}$. Northrop labels the damage constant as K_n . It is the same quantity as the K_r in this report. The subscript A stands for the Case A environment that was used to calibrate these transistors.

Table VII
Transistor Damage Factor vs. Fluence

Φ_1 (x 10^{12} n/cm ²)	K_n (x 10^{-16} cm ² /n)
1	25.70
3	22.67
10	19.76
30	17.43
100	15.19

The variation of K_n in the table does not cause a problem at this point if one is interested in mapping the change in the damage (which is $\Delta(1/h)$ compared to the change in the $\Phi(E > 3 \text{ MeV}) = \Phi_3$ measured by the sulfur). If we are interested now in the changes in the $\Delta(1/h)/\Phi_3$ ratio with position in a given run, we can multiply all the ratios for that run by a constant and the relative values will still be representative of relative changes in damage and spectrum shape. The authors of the Northrop report have chosen to multiply the ratio by $1/K_n$ where K_n is appropriate for the fluence level determined for the transistors during the calibration run.

$$\frac{\Delta\left(\frac{1}{h}\right)_A}{\Phi_{1A}} = K_n[\Phi_1]$$

The quantity mapped is

$$\frac{\Delta\left(\frac{1}{h}\right) \frac{1}{K_n} \Phi_1(\text{transistors})}{\Phi_3} = \frac{\Phi_1(\text{transistors})}{\Phi_3} = \text{SI} \cdot \text{HP} \quad (9)$$

We see a potential for misinterpretation of the right side of the equation, and it is this last quantity that is used in Northrop's tables at the end of their Appendix I. If the fluence varies in

the IMU then K_n is not really a constant, and their ratio will not be a measure of how the 2N2222A transistor damage, $\Delta(1/h)$, maps. On the other hand, the product $SI \cdot HP$ is generally defined as proportional to the "1 MeV equivalent damage." The variation of this quantity through the IMU provides some measure of the change in shape of the spectrum vs. position. The changes in the magnitude of the spectrum have been suppressed. In addition, if one wishes to see how $\Delta(1/h)$ maps, he can use the mapping data for K_n and Φ_3 to retrieve that information. The main deficiency of Reference 9 is that if the right side is really to represent Φ_1 , as a function of position, Φ_3 must first be used to correct for the changing value of K_n with fluence at each position.

- C. Northrop read their transistor gain changes at a bias of 5 volts, rather than the 10 volt bias used by Sandia. The change in reciprocal gain will tend to be lower for higher bias.
- D. The Sandia transistors were calibrated and read four days after exposure as opposed to one day for the Northrop transistor measurements. Furthermore, the temperature at readout for Northrop was 25.5°C while for Sandia it was about 20°C. These two effects lead to a rise of about 8% in the Sandia value if it is read under the Northrop reading conditions.
- E. Rather than calibrating the transistors in the batch mode as was carried out by Northrop, Sandia calibrated each transistor used in each case. The individual calibration eliminates the error caused by variation within the batch, but this method is more labor intensive. Also, direct temperature-at-readout corrections were applied individually to Sandia's transistors. The batch calibration procedure adds greatly to the random error of the fluence measurements when only one or two transistors are used at each location.
- F. Small errors of between 5% and 10% were inadvertently introduced into the parameters listed in Table V of Northrop Appendix I. This table contained the spectrum parameters used by Northrop to obtain the fluence in their tables. When Sandia determined Φ_1 from the transistors used as spectrum sensors, they used the new and recently verified (Reference 13) ^{28}Si cross section as the response function and the most recent cross sections for the rest of the foils (References 14 and 15). However, the hardness parameter determined from the spectral characterization and reported to Northrop used the older Si damage function listed in ASTM E 722(86), as required by DoD electronics testing specifications. Therefore, we have expanded that table to include the hardness parameters for the two damage functions, $HP_{\text{ASTM}(86)} = HPA$, and HP_{E6} . It is the HP_{E6} that should have been used in the calculation of $SI \cdot HP$.

- G. In the Northrop report, the Φ_1 calculated with the transistors in the Cd-poly box has not taken into account the gamma ray response. A subtraction of the gamma component of the $\Delta(1/h)$ must, of course, be made when these devices are used as spectrum sensors. Such a subtraction should also be carried out for the fluence-ratio tables in the Northrop appendix if they are to represent only neutron fluence ratios. Runs #2309 + 2315 could have their neutron fluence ratios corrected by applying the same factor provided in this report for Case C. The TLD data at each position could be used with the gamma ray sensitivity factor discussed in the last section to predict the gamma contribution to be subtracted out from $\Delta(1/h)$ at each location.

If account is taken of all the factors just mentioned, we are convinced that with further analysis (provided time becomes available) the apparent discrepancies between the Northrop and Sandia reports would be resolved well within the experimental uncertainties. The important observation to be made here is that the Northrop mapping results included here dramatically demonstrate that the spectrum shape is not only influenced by the massive filter structure of the IMU on the large scale, but also on a small scale within the IMU. The changes are enough to cause significant differences in the response of electronic parts as a function of position in the IMU and the external environment.

There is one other correction that should be applied to all of the Northrop tables in which the 3 MeV fluence, Φ_3 , is listed. For those tables the conversion from activity, A, to fluence is calculated in the following manner.

$$\Phi = \frac{A}{\lambda \bar{\sigma}_s}$$

where λ is the decay constant for ^{32}P ($= 5.614\text{E-}7 \text{ s}^{-1}$) and $\bar{\sigma}_s$ is the spectrum averaged cross section of sulfur in that location. The value of $\bar{\sigma}_s$ used in the Northrop tables (except for Appendix F) was 0.299 barns. The correct factor to use would be the local σ_s , but that is only known for one location in the IMU in each of the four cases. It would be appropriate to use the derived values for the four cases. These values are: Case A - 0.291b; Case B - 0.301b; Case C - 0.296b; and Case D - 0.291b. The error induced by using .299 barns is probably in the neighborhood of 3%.

VI. MAPPING OF THE ENVIRONMENT IN THE ABSENCE OF THE IMU

We were asked by Northrop to map the fluence in the region where the IMU was positioned. This was accomplished by assembling on a ball, constructed of three mutually perpendicular cardboard disks, pairs of sulfur pellets and TLD's at 25 locations. The locations on the planes are shown in Figure 9. Position 1 is oriented toward the reactor and position 3 is on the left as one faces away from the reactor. The radiation field should be symmetrical from left to right, and therefore one should average left and right pairs such as 3 and 7, 25 and 22, etc. This will correct for small orientation errors in the positioning of the fixture.

As it has turned out, these maps were not made in exactly the correct configurations. The first map was placed so that the ball would in fact be centered at the same place as the center of the IMU was when the Case A spectrum was determined (19.5" spectrum), but that is not the position finally decided upon for the IMU in the Cd-poly box measurements that this map was supposed to approximate--Case C at 22.75". If the latter distance had been used, a direct comparison with a transport code to each point could be made. For the second map, free field at 22.75", the distance was correct, but problems with the mechanics of SPR II forced us to use SPR III. The radiation field around this reactor is somewhat different. Ideally if time and money permit, these fluence maps will be repeated.

Table VIII shows the average dose, γ , and the 3 MeV fluence, Φ_3 , at each location for the SPR II map at 19.5" in the Cd-Poly box. The center of the fixture was 21" from the reactor core. The spectrum averaged sulfur cross section used was 0.2915 barns and $\lambda = 5.614E-7 \text{ s}^{-1}$. The cross section was derived from the cross section file for sulfur provided in Reference 16. The last column shows the Φ_1/γ ratio in which the Φ_1 is calculated from the $SI \cdot HP_{E6} = 4.64$ appropriate for the Case D spectrum measured in the Cd-poly box. Similarly, Table IX for free field shows the γ , sulfur activity A_S , and Φ_3 at 22.75". The center of the fixture was at about 25" from the reactor core. The spectrum averaged cross section used to convert sulfur activity to Φ_3 was 0.2986 barns and the $SI \cdot HP_{E6}$ was 6.64. Note: the last two columns of this table are not strictly correct because the values used for σ_S and $SI \cdot HP_{E6}$ are appropriate for Case A (free field at 19.5" at SPR II) while these measurements were made at 22.75" outside SPR III in free field. However, we believe that in each map the variation in the doses and the fluences are reasonably representative. Notice one difference, however. In the first map inside the Cd-poly at SPR II, the radiations tended to be larger on the bottom than on the top. In the second case in free field outside SPR III the dose appears to be higher on the top. It is not surprising that the vertical radiation profiles are different for the two reactors.

In the Northrop report, Reference 12, pages F157-160, the dose and sulfur fluences for these two environments without the IMU are plotted against $1/r^2$. The graphs show that the radiations drop as $1/r^2$ from the

Outer radius of fixture is 8.75", inner radius is 5.00"

Figure 9. IMU Mapping Dosimetry Locations.

Table VIII
Sulfur and TLD Map in Cd-Poly Box With Fixture
Centerline at 21" Next to SPR II

Position #	Dose [GY(Si)]	$\sigma_s = 0.2915$ barns		
		Sulfur Activity (dps/gm) x 10^{-5}	Φ_3 (n/cm ²) x 10^{-11}	Φ_1/γ (n/(cm ² ·Gy)) x 10^{11}
1	436.	1.936	1.048	.100
2	210.6	.995	.538	.119
3	98.23	.4934	.267	.126
4	64.32	.3737	.202	.146
5	56.51	.3124	.169	.138
6	62.57	.3622	.196	.145
7	92.90	.4865	.263	.131
8	183.3	.9348	.506	.128
9	192.0	1.102	.596	.144
10	104.9	.5916	.320	.142
11	71.76	.4036	.218	.141
12	96.73	.5646	.306	.146
13	109.6	.6448	.349	.148
14	93.39	.4482	.243	.120
15	64.32	.3386	.183	.132
16	66.42	.3927	.212	.148
17	98.64	.5876	.318	.149
18	217.6	1.162	.629	.134
19	176.9	.7957	.431	.113
20	103.1	.5632	.304	.137
21	112.5	.6637	.359	.148
22	86.56	.4843	.262	.140
23	103.3	.5964	.323	.145
24	99.3	.5715	.309	.145
25	96.02	.4707	.255	.123

Table IX
Sulfur and TLD Map in Free Field With Fixture
Centerline at 25" Next to SPR III

Position #	Dose [Gy(Si)]	$\sigma_S = .2986$ barns		
		Sulfur Activity (dps/gm) x 10^{-5}	Φ_3 (n/cm ²) x 10^{-11}	Φ_1/γ (n/(cm ² ·Gy)) x 10^{11}
1	32.15	3.473	1.835	3.783
2	18.70	2.522	1.332	4.723
3	11.20	1.329	.702	4.156
4	7.980	.8452	.446	3.709
5	6.894	.7251	.383	3.684
6	7.378	.7926	.419	3.762
7	10.31	1.017	.537	3.455
8	18.53	1.910	1.009	3.610
9	21.48	2.274	1.201	3.708
10	12.30	1.387	.733	3.949
11	9.017	.8896	.470	3.455
12	12.13	1.165	.615	3.363
13	13.87	1.367	.722	3.452
14	12.07	1.237	.653	3.589
15	8.088	.8505	.449	3.682
16	7.762	.7911	.418	3.569
17	10.75	1.142	.603	3.720
18	20.07	2.007	1.060	3.396
19	18.59	2.286	1.208	4.307
20	12.93	1.396	.737	3.781
21	12.83	1.331	.703	3.633
22	9.938	1.106	.584	3.898
23	10.76	1.084	.573	3.528
24	12.59	1.214	.641	3.377
25	12.93	1.340	.707	3.629

centerline except for the gamma dose in the Cd-poly box. In that case the main source of gamma rays is the Cd-poly front wall which is between 8 and 12 inches from the core centerline. Those plots show that the dose (beyond 18 inches) and the fluences greater than 3 MeV can be predicted on a $1/r^2$ basis for any point in the horizontal plane. It may, therefore, be unnecessary to repeat the map measurements in the absence of the IMU in order to find the initial reactor spatial radiation distributions for input to transport calculations of the IMU's internal environment.

VII. LIMITED SPECTRUM MEASUREMENTS BEHIND THE IMU

When the tests on an operating IMU are conducted, there will be no room inside for spectrum, fluence or dosimetry measurements. Thus, in order to compare the conditions in the mock-up IMU with those present when the active measurements are made, we placed a limited set of sensors behind the IMU. Our anticipation was that there would not be enough sensors to construct a spectrum, but at least ratios of responses could be compared to identify gross changes in spectrum shape. Indeed the sensors sensitive to high energy neutrons showed a faster dropoff (compared to those inside the IMU for the spectrum determination) than did those sensitive to the lower energy neutrons. The activities measured behind the ball are listed in Table X for the two cases.

The reason for only using a few foils was that these were in competition for counting-laboratory time with the main sensor set used for spectrum determination inside the IMU. However, in these cases there was room behind the IMU for boron covered fission foils. As it turned out, there were enough sensors to construct a reasonable spectrum for each case. We felt that the best way to compare the effects of the IMU between Case C (inside at 22.75") and Case F (behind at about 35") was to use the best trial found for the inside IMU spectrum as the trial (in SAND II) for the behind-the-IMU spectrum in each case. Although the resulting spectra are more bumpy than those found inside, that is a reflection of the trial being in greater initial disagreement with the final spectrum. Since there were fewer sensor responses, the code only changed the shape and magnitude enough to match the measured responses. Thus there was a tendency to maintain the trial function shapes.

The spectra behind the IMU are plotted in Figures 10 and 11. The dashed curves are the trial functions for inside the IMU. Since these spectra are normalized to an integrated fluence of 1.0 n/cm^2 above 10 keV, the plots only show the change in shape. The dashed curves have Φ_3 fluences about 15 times smaller than those inside the IMU. There is only one significant change in the shapes. The fast neutrons have been more rapidly attenuated than the slower neutrons. This may be partly attributed to the fact that the slower neutrons can be more easily scattered around the IMU.

The spectrum parameters have also been listed in Table V and the SAND II printouts are in Appendices V and VI. These spectra are suitable for comparison with those calculated with a transport code which starts with spectra measured without the IMU in place.

Figure 10. Spectrum inside and behind the IMU AT 35".

Figure 11. Spectrum inside and behind the IMU in Cd-Poly Box at 35".

Table X
Activities at SPR II Behind the IMU

Sensor	Free field		Cd-Poly Box	
	Activity (Bq/Nucleus)	Cover ⁺	Activity (Bq/Nucleus)	Cover ⁺
$^{197}\text{Au}(n, \gamma)^{198}\text{Au}$	1.292-16	Y	3.110-16	Y
$^{55}\text{Mn}(n, \gamma)^{56}\text{Mn}$	3.685-17	Y	7.076-17	Y
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	4.035-21	Y	2.474-21	Y
$^{32}\text{S}(n, p)^{32}\text{P}$	1.266-29	N	7.577-21	N
	(Reactions/Nucleus)			
$^{235}\text{U}(n, f)^{\text{F}}$	1.511-12	Y + Boron	9.135-13	Y + Boron
$^{238}\text{U}(n, f)^{\text{F}}$	9.967-14	Y + Boron	6.210-14	Y + Boron
$^{239}\text{Pu}(n, f)^{\text{F}}$	1.760-12	Y + Boron	1.033-12	Y + Boron
$^{237}\text{Np}(n, f)^{\text{F}}$	6.675-13	Y + Boron	3.586-13	Y + Boron

⁺N means no cover, Y means Cd cover

VIII. SUMMARY AND CONCLUSIONS

The measurements designed and carried out to characterize the environments in and around the IMU are representative of the evolutionary development at Sandia of means to better adapt our methodologies to the needs of individual users of our facilities, and to improve the documentation of the results. Improved communications between the testing community and those who provide the radiation services are essential if we are to meet the increasingly demanding and more precisely defined standards for ascertaining the radiation response of electronic parts and for assuring simulation fidelity. Success will come in this regard to the degree that (1) users communicate to the facility what the requirements are on the radiation level and on the spectral characteristics, (2) operators of the facility communicate to experimenters what can be done to customize the environment, the expected influence of the experiment on the environment, the best means to adapt the diagnostics to the experiment and to provide satisfactory values for the characteristic parameters needed.

We and the Northrop experimenters have made a concerted effort to improve this interchange to the point where the proper customized environments have been constructed, characterized and documented so that reasonable correlations between system performance and the radiation fields can be established. We expect the procedures to further improve in the future.

Examples of adaptation of irradiation methodology according to experimental needs are the incorporation of specialized radiation filters, the use of specialized sensors to provide adequate sensitivity coverage when other sensors cannot be used, and mapping with silicon transistors. We feel that adaptation to the needs of the user is a primary responsibility of the facility that provides the radiation services.

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APPENDIX X1 SPECTRUM RESULTS: FREE FIELD AT 19.5"

These appendices are essentially abbreviated printouts of the SAND II spectrum adjustment code for each case. The first table lists the input file which contains the sensors responses and the trial spectrum. The second table compares the measured and calculated responses and the range of energy within which 95% of the response of each sensor resides for this spectrum. The next table contains various spectrum related quantities; some of which are listed in Table V and some of which constitute extra information not needed for this report. The final table contains an abbreviated listing (56 out of 640 energy points) of the differential and integral spectrum values. The spectrum is normalized to an integrated fluence of one neutron above 10 keV.

Table X1.1
Input File: Case A

```

1 CASES
T SAND II INPUT FILE FOR SPR III FOIL SET FOR SHOT 2934
T (MAR. 27, 1984) WITH SPR317 TRIAL SPECTRUM, FREE FIELD.
T
ITERATION    TIME INTEGRATED
19 FOILS
SI1MEV
AU197G      CADMIUM 2.587-3
AU197G
MN55G5      CADMIUM 2.587-3
MG24P       CADMIUM 2.587-3
AL27A       CADMIUM 2.587-3
NI58P       CADMIUM 2.587-3
S32P
NA23G       CADMIUM 4.705-3
NA23G
U235F       BORON 0.101 CADMIUM 2.587-3
U238F       BORON 0.101 CADMIUM 2.587-3
PU239F      BORON 0.101 CADMIUM 2.587-3
NP237F      BORON 0.101 CADMIUM 2.587-3
FE54P       CADMIUM 2.587-3
SC45G       CADMIUM 2.587-3
TI48P       CADMIUM 2.587-3
TI47P       CADMIUM 2.587-3
ZN64P       CADMIUM 2.587-3
ACTS 1.144+13
ACTS 1.028-16 1.236-16 2.834-17 1.502-19
ACTS 6.883-20 9.908-20 3.100-19 1.521-19 6.076-19
ACTS 1.616-11 2.520-12 2.200-11 1.366-11
ACTS 1.749-20 3.779-20 1.010-20 3.418-19
ACTS 4.506-18

```

Table X1.1 (continued)

SPECTRUM TABULAR
 43 POINTS
 ENER 1.00-7 2.00-7
 ENER 3.00-7 5.00-7 7.00-7 1.00-6 2.00-6
 ENER 3.00-6 5.00-6 7.00-6 1.00-5 2.00-5
 ENER 3.00-5 5.00-5 7.00-5 1.00-4 2.00-4
 ENER 3.00-4 5.00-4 7.00-4 1.00-3 2.00-3
 ENER 3.00-3 5.00-3 7.00-3 1.00-2 2.00-2
 ENER 3.00-2 5.00-2 7.00-2 1.00-1 2.00-1
 ENER 3.00-1 5.00-1 7.00-1 1.00-0 1.50-0
 ENER 2.00-0 3.00-0 4.00-0 5.00-0 6.00-0 8.00-0
 FLUX 2.20+4 1.07+4
 FLUX 6.30+3 2.90+3 1.90+3 1.35+3 6.80+2
 FLUX 4.60+2 2.90+2 2.00+2 1.45+2 7.10+1
 FLUX 4.80+1 2.90+1 2.10+1 1.60+1 7.50-0
 FLUX 5.00-0 2.80-0 2.00-0 1.50-0 7.50-1
 FLUX 5.50-1 4.40-1 4.00-1 4.00-1 5.00-1
 FLUX 6.50-1 8.20-1 8.90-1 8.80-1 7.50-1
 FLUX 6.40-1 4.80-1 3.80-1 3.00-1 2.15-1
 FLUX 1.50-1 7.80-2 4.20-2 2.50-2 1.50-2 2.20-3
 LIMIT 50
 DEVIATION 2.00
 DISCARD 3.0
 LOW END THERMAL
 HIGH END FISSION
 NORM 0.010
 PLOT CARDS
 SMOOTH 5

Table X1.2
Measured and Calculated Responses: Case A

STANDARD DEVIATION OF MEASURED-TO-CALCULATED ACTIVITY RATIOS HAS BECOME STABLE (TO WITHIN LESS THAN ONE PERCENT CHANGE PER ITERATION) AT A HIGHER VALUE THAN THE SPECIFIED 2.00 PERCENT.

RESULTS OBTAINED AFTER 7 ITERATIONS

FOIL REACTION	MEASURED ACTIVITY (DPS/NUCLEUS)	CALCULATED ACTIVITY (DPS/NUCLEUS)	NOMINAL 5.00 PERCENT ACTIVITY LIMITS (MEV)		RATIO MEASURED TO CALCULATED ACTIVITIES	DEVIATION OF MEASURED FROM CALCULATED ACTIVITY (PERCENT)
			LOWER	UPPER		
S32 (N,P) P32	3.100E-19	2.992E-19	2.300E+00	7.300E+00	1.036	3.613
AU197 (N,G) AU198 CD	1.028E-18	1.031E-18	4.000E-08	1.800E-02	0.9970	-0.3037
AU197 (N,G) AU198	1.236E-18	1.232E-18	2.400E-08	8.600E-04	1.004	0.3507
AL27 (N,A) NA24 CD	6.883E-20	6.807E-20	6.400E+00	1.220E+01	1.011	1.111
MG24 (N,P) NA24 CD	1.502E-19	1.540E-19	6.500E+00	1.170E+01	0.9752	-2.485
FE54 (N,P) MN54 CD	1.749E-20	1.728E-20	2.300E+00	7.400E+00	1.012	1.196
NI58 (N,P) CO58 CD	9.908E-20	1.000E-19	1.900E+00	7.300E+00	0.9904	-0.9557
U235 (N,F) LA140 B CD	1.616E-11	1.618E-11	6.000E-02	4.500E+00	0.9988	-0.1172
MN55 (N,G) MN56 CD	2.834E-17	2.826E-17	5.500E-07	5.750E-01	1.003	0.2979
TI47 (N,P) SC47 CD	3.418E-19	3.681E-19	1.800E+00	7.300E+00	0.9285	-7.148
U238 (N,F) LA140 B CD	2.520E-12	2.520E-12	1.400E+00	6.600E+00	0.9999	-90.182E-04
PU239 (N,F) LA140 B CD	2.200E-11	2.193E-11	9.200E-02	4.700E+00	1.003	0.2967
NP237 (N,F) LA140 B CD	1.386E-11	1.303E-11	5.750E-01	5.500E+00	1.048	4.843
TI48 (N,P) SC48 CD	1.010E-20	9.941E-21	5.900E+00	1.240E+01	1.016	1.595
ZN64 (N,P) CU64 CD	4.506E-18	4.435E-18	2.600E+00	7.400E+00	1.016	1.594
SC45 (N,G) SC46 CD	3.779E-20	3.810E-20	4.250E-07	9.600E-01	0.9918	-0.8184
NA23 (N,G) NA24 CD	1.521E-19	1.517E-19	6.300E-07	2.000E+00	1.003	0.2741
NA23 (N,G) NA24	6.076E-19	6.079E-19	6.600E-09	4.000E-01	0.9995	-47.660E-03
SI28 (N,X) MEV1	1.144E+13	1.183E+13	2.200E-01	5.500E+00	0.9871	-3.285

STANDARD DEVIATION OF MEASURED ACTIVITIES (PERCENT) 2.521

Table X1.3
Spectrum and Dose Related Quantities: Case A

Response Analysis - Loop = 1 Iteration = 7

Response Function	Dose
Fluence (n/cm**2)	0.1414421E+14
Kerma (rad-Tissue)	31224.98
CP Dose to Elem-57 (rad-Tissue)	35843.02
Dose Eqv. (rem)	368754.7
Dose to Elem-57 from H-1(n,g)H-2 (rad-Tissue)	3482.310
ANSI and NCRP Dose (rem)	384327.3

Spectrum Characterization

Total Fluence (n/cm**2)	1.4144204E+13
Fluence > 10 keV	1.3823119E+13
Fluence > 3 MeV	1.7846244E+12
Avg. Energy (MeV)	1.375078
HP	0.9353362
(ASTM Si Damage Function)	
HP	0.8556793
(ENDF-6 Si Damage Function)	
SI	7.745674
Sulfur Cross Section (mb)	298.7649
(Spectrum Averaged, > 3 MeV)	
Nickel Cross Section (mb)	494.7182
(Spectrum Averaged, > 3 MeV)	

Table X1.4
Case A: Free Field Spectrum at 19.5"
(Normalized to 1 Neutron Above .01 MeV)

E(MeV)	Differential	Integral	E(MeV)	Differential	Integral
1.0E-9	6.509E+3	1.023	1.0E-3	1.631E-0	1.005
2.0E-9	1.250E+4	1.023	2.0E-3	7.616E-1	1.004
3.0E-9	1.813E+4	1.023	3.0E-3	5.414E-1	1.003
5.0E-9	2.767E+4	1.023	5.0E-3	4.539E-1	1.002
7.2E-9	3.650E+4	1.023	7.2E-3	4.007E-1	1.001
1.0E-8	4.516E+4	1.023	1.0E-2	3.894E-1	1.000
2.0E-8	6.016E+4	1.022	2.0E-2	5.121E-1	9.955E-1
3.0E-8	5.999E+4	1.022	3.0E-2	6.636E-1	9.896E-1
5.0E-8	4.452E+4	1.021	5.0E-2	8.300E-1	9.748E-1
7.2E-8	3.087E+4	1.020	7.2E-2	8.947E-1	9.585E-1
1.0E-7	2.227E+4	1.019	1.0E-1	8.844E-1	9.309E-1
2.0E-7	1.077E+4	1.018	2.0E-1	7.312E-1	8.499E-1
3.0E-7	6.065E+3	1.017	3.0E-1	6.328E-1	7.811E-1
5.0E-7	2.785E+3	1.016	5.0E-1	4.888E-1	6.690E-1
7.2E-7	1.784E+3	1.015	7.2E-1	3.976E-1	5.704E-1
1.0E-6	1.305E+3	1.015	1.0E-0	3.160E-1	4.687E-1
2.0E-6	6.595E+2	1.014	1.5E-0	2.180E-1	3.319E-1
3.0E-6	4.474E+2	1.013	2.0E-0	1.471E-1	2.389E-1
5.0E-6	2.988E+2	1.013	3.0E-0	7.743E-2	1.291E-1
7.2E-6	1.896E+2	1.012	4.0E-0	4.189E-2	7.028E-2
1.0E-5	1.401E+2	1.012	5.0E-0	2.471E-2	3.702E-2
2.0E-5	6.878E+1	1.011	6.0E-0	1.503E-2	1.710E-2
3.0E-5	4.624E+1	1.010	7.0E-0	5.561E-3	7.237E-3
5.0E-5	2.838E+1	1.009	8.0E-0	2.315E-3	3.397E-3
7.2E-5	2.052E+1	1.009	9.0E-0	1.158E-3	1.670E-3
1.0E-4	1.593E+1	1.008	1.0E+1	5.675E-4	8.102E-4
2.0E-4	7.790E-0	1.007			
3.0E-4	5.425E-0	1.007			
5.0E-4	2.820E-0	1.006			
7.2E-4	1.995E-0	1.005			

APPENDIX X2
SPECTRUM RESULTS: FREE FIELD IN IMU AT 22.75"

See the Introduction to Appendix X1 for definitions of tables and their quantities.

Table X2.1
Input File: Case B

```

1 CASES
T SAND II INPUT FILE FOR SPR III FOIL SET FOR SHOT 2934
T (MAR. 27, 1984) WITH SPR317 TRIAL SPECTRUM, FREE FIELD.
T
  ITERATION    TIME INTEGRATED
  15 FOILS
  SI1MEV
  AU197G      CADMIUM 2.587-3
  AU197G
  MN55G5      CADMIUM 2.587-3
  MG24P        CADMIUM 2.587-3
  AL27A        CADMIUM 2.587-3
  NI58P        CADMIUM 2.587-3
  S32P
  NA23G        CADMIUM 4.705-3
  NA23G
  FE54P        CADMIUM 2.587-3
  SC45G        CADMIUM 2.587-3
  TI48P        CADMIUM 2.587-3
  TI47P        CADMIUM 2.587-3
  ZN64P        CADMIUM 2.587-3
  ACTS 1.043+13
  ACTS 4.124-18 4.848-18 2.288-18 8.886-20
  ACTS 4.701-20 8.318-20 1.922-19 7.569-19 1.479-18
  ACTS 1.186-20 1.676-19 6.197-21 2.205-19
  ACTS 2.777-18
  SPECTRUM TABULAR
  43 POINTS
  ENER 1.00-7 2.00-7
  ENER 3.00-7 5.00-7 7.00-7 1.00-6 2.00-6
  ENER 3.00-6 5.00-6 7.00-6 1.00-5 2.00-5
  ENER 3.00-5 5.00-5 7.00-5 1.00-4 2.00-4
  ENER 3.00-4 5.00-4 7.00-4 1.00-3 2.00-3
  ENER 3.00-3 5.00-3 7.00-3 1.00-2 2.00-2
  ENER 3.00-2 5.00-2 7.00-2 1.00-1 2.00-1
  ENER 3.00-1 5.00-1 7.00-1 1.00-0 1.50-0
  ENER 2.00-0 3.00-0 4.00-0 5.00-0 6.00-0 8.00-0
  FLUX 2.70+4 1.50+4
  FLUX 1.05+4 7.00+3 5.40+3 4.00+3 2.20+3
  FLUX 1.60+3 1.05+3 8.20+2 6.30+2 3.90+2
  FLUX 2.80+2 1.90+2 1.50+2 1.10+2 7.20+1
  FLUX 5.20+1 3.30+1 2.60+1 1.90+1 1.20+1
  FLUX 9.70-0 7.60-0 6.70-0 5.90-0 4.30-0
  FLUX 3.50-0 2.60-0 2.20-0 1.70-0 1.05-0
  FLUX 8.10-1 5.20-1 3.70-1 2.30-1 1.35-1
  FLUX 9.00-2 4.80-2 2.50-2 1.20-2 6.50-3 1.10-3
  LIMIT 50
  DEVIATION 5.00
  DISCARD 3.0
  LOW END THERMAL
  HIGH END FISSION
  NORM 0.010
  PLOT CARDS
  SMOOTH 5

```

Table X2.2
Measured and Calculated Responses: Case B

SOLUTION HAS BEEN ACHIEVED.
STANDARD DEVIATION OF MEASURED-TO-CALCULATED ACTIVITY RATIOS IS LESS THAN 5.00PERCENT./
SOLUTION RESULTS OBTAINED AFTER 2 ITERATIONS

FOIL REACTION	MEASURED ACTIVITY (DPS/NUCLEUS)	CALCULATED ACTIVITY (DPS/NUCLEUS)	NOMINAL 5.00 PERCENT ACTIVITY LIMITS (MEV)		RATIO MEASURED TO CALCULATED ACTIVITIES	DEVIATION OF MEASURED FROM CALCULATED ACTIVITY (PERCENT)
			LOWER	UPPER		
S32 (N,P) P32	1.922E-19	1.928E-19	2.300E+00	7.300E+00	0.9968	-0.3151
AU197 (N,G) AU198 CD	4.124E-16	4.246E-16	4.250E-06	1.100E-03	0.9713	-2.870
AU197 (N,G) AU198	4.648E-16	4.545E-16	1.350E-07	9.600E-04	1.023	2.260
AL27 (N,A) NA24 CD	4.701E-20	4.293E-20	6.500E+00	1.220E+01	1.095	9.507
MG24 (N,P) NA24 CD	8.886E-20	9.647E-20	6.500E+00	1.180E+01	0.9211	-7.887
FE54 (N,P) MN54 CD	1.186E-20	1.097E-20	2.300E+00	7.400E+00	1.082	8.151
NI58 (N,P) CO58 CD	6.318E-20	6.404E-20	1.900E+00	7.300E+00	0.9865	-1.346
MN55 (N,G) MN56 CD	2.268E-16	2.262E-16	1.150E-06	1.600E-02	1.003	0.2664
TI47 (N,P) SC47 CD	2.205E-19	2.380E-19	1.800E+00	7.300E+00	0.9263	-7.369
TI48 (N,P) SC48 CD	6.197E-21	6.135E-21	5.900E+00	1.240E+01	1.010	1.009
ZN64 (N,P) CU64 CD	2.777E-18	2.828E-18	2.500E+00	7.500E+00	0.9820	-1.800
SC45 (N,G) SC46 CD	1.676E-19	1.602E-19	5.250E-07	1.800E-01	1.046	4.627
NA23 (N,G) NA24 CD	7.569E-19	7.981E-19	8.400E-07	2.400E-01	0.9484	-5.162
NA23 (N,G) NA24	1.479E-18	1.469E-18	1.000E-08	1.150E-01	1.007	0.6843
SI28 (N,X) MEV1	1.043E+13	1.040E+13	1.800E-01	4.800E+00	1.002	0.2448

STANDARD DEVIATION OF MEASURED ACTIVITIES (PERCENT) 4.939

Table X2.3
Spectrum and Dose Related Quantities: Case B

Response Analysis - Loop = 1 Iteration = 2

Response Function	Dose
Fluence (n/cm**2)	0.1970807E+14
Kerma (rad-Tissue)	27581.46
CP Dose to Elem-57 (rad-Tissue)	30201.30
Dose Eqv. (rem)	332587.8
Dose to Elem-57 from H-1(n,g)H-2 (rad-Tissue)	5695.981
ANSI and NCRP Dose (rem)	343578.7

Spectrum Characterization

Total Fluence (n/cm**2)	1.9708098E+13
Fluence > 10 keV	1.7182581E+13
Fluence > 3 MeV	1.1428381E+12
Avg. Energy (MeV)	0.7367926
HP	0.6495145
(ASTM Si Damage Function)	
HP	0.6050978
(ENDF-6 Si Damage Function)	
SI	15.03501
Sulfur Cross Section (mb)	300.6542
(Spectrum Averaged, > 3 MeV)	
Nickel Cross Section (mb)	494.5693
(Spectrum Averaged, > 3 MeV)	

Table X2.4
Case B: Free Field Spectrum in IMU at 22.75"

E(MeV)	Differential	Integral	E(MeV)	Differential	Integral
1.0E-9	7.189E+3	1.147	1.0E-3	1.828E+1	1.072
2.0E-9	1.381E+4	1.147	2.0E-3	1.034E+1	1.058
3.0E-9	2.003E+4	1.147	3.0E-3	8.298	1.049
5.0E-9	3.056E+4	1.147	5.0E-3	7.155	1.033
7.2E-9	4.032E+4	1.147	7.2E-3	6.565	1.018
1.0E-8	4.990E+4	1.147	1.0E-2	6.099	1.000
2.0E-8	6.654E+4	1.146	2.0E-2	4.384	9.486E-1
3.0E-8	6.640E+4	1.145	3.0E-2	3.129	9.090E-1
5.0E-8	4.929E+4	1.144	5.0E-2	2.334	8.523E-1
7.2E-8	3.412E+4	1.143	7.2E-2	2.154	8.023E-1
1.0E-7	2.472E+4	1.142	1.0E-1	1.696	7.478E-1
2.0E-7	1.372E+4	1.141	2.0E-1	9.569E-1	6.251E-1
3.0E-7	9.871E+3	1.139	3.0E-1	7.326E-1	5.403E-1
5.0E-7	6.714E+3	1.138	5.0E-1	4.730E-1	4.209E-1
7.2E-7	5.008E+3	1.136	7.2E-1	3.200E-1	3.329E-1
1.0E-6	3.797E+3	1.135	1.0E-0	1.995E-1	2.585E-1
2.0E-6	2.085E+3	1.132	1.5E-0	1.180E-1	1.780E-1
3.0E-6	1.492E+3	1.131	2.0E-0	8.006E-2	1.277E-1
5.0E-6	9.430E+2	1.128	3.0E-0	4.400E-2	6.651E-1
7.2E-6	7.579E+2	1.126	4.0E-0	2.289E-2	3.351E-2
1.0E-5	5.998E+2	1.124	5.0E-0	1.118E-2	1.682E-2
2.0E-5	3.700E+2	1.120	6.0E-0	6.376E-3	8.101E-3
3.0E-5	2.641E+2	1.116	7.0E-0	2.679E-3	3.691E-3
5.0E-5	1.796E+2	1.112	8.0E-0	1.209E-3	1.777E-3
7.2E-5	1.355E+2	1.109	9.0E-0	6.080E-4	8.733E-4
1.0E-4	1.030E+2	1.105	1.0E+1	2.971E-4	4.223E-4
2.0E-4	6.725E+1	1.097			
3.0E-4	4.998E+1	1.091			
5.0E-4	3.091E+1	1.083			
7.2E-4	2.237E+1	1.077			

APPENDIX X3
SPECTRUM RESULTS: IN Cd-POLY BOX AND IN IMU AT 22.75"

See the introduction to Appendix X1 for definitions of tables and their quantities.

Table X3.1
Input File: Case C

```

1 CASES
T SAND II INPUT FILE FOR SPR III FOIL SET FOR SHOT 2934
T (MAR. 27, 1984) WITH SPR317 TRIAL SPECTRUM, FREE FIELD.
T
ITERATION    TIME INTEGRATED
15 FOILS
SI1MEV
AU197G      CADMIUM 2.587-3
AU197G
MN55G5      CADMIUM 2.587-3
MG24P       CADMIUM 2.587-3
AL27A       CADMIUM 2.587-3
NI58P       CADMIUM 2.587-3
S32P
NA23G       CADMIUM 4.705-3
NA23G
FE54P       CADMIUM 2.587-3
SC45G       CADMIUM 2.587-3
TI48P       CADMIUM 2.587-3
TI47P       CADMIUM 2.587-3
ZN64P       CADMIUM 2.587-3
ACTS 3.683+12
ACTS 1.018-15 1.109-15 2.808-16 5.635-20 2.981-20
ACTS 2.875-20 8.486-20 1.136-18 3.439-18 5.244-21
ACTS 3.271-19 3.996-21 9.518-20 1.260-18
SPECTRUM TABULAR
46 POINTS
ENER 4.00-8 7.00-8 1.00-7 1.50-7 2.00-7
ENER 3.00-7 5.00-7 7.00-7 1.00-6 2.00-6
ENER 3.00-6 5.00-6 7.00-6 1.00-5 2.00-5
ENER 3.00-5 5.00-5 7.00-5 1.00-4 2.00-4
ENER 3.00-4 5.00-4 7.00-4 1.00-3 2.00-3
ENER 3.00-3 5.00-3 7.00-3 1.00-2 2.00-2
ENER 3.00-2 5.00-2 7.00-2 1.00-1 2.00-1
ENER 3.00-1 5.00-1 7.00-1 1.00-0 1.50-0
ENER 2.00-0 3.00-0 4.00-0 5.00-0 6.00-0 8.00-0
FLUX 2.70+5 3.50+5 3.60+5 3.40+5 2.90+5
FLUX 2.20+5 1.15+5 7.00+4 4.20+4 1.60+4
FLUX 1.05+4 6.20+3 4.50+3 3.10+3 1.60+3
FLUX 1.05+3 6.30+2 4.50+2 3.20+2 1.60+2
FLUX 1.20+2 7.20+1 5.30+1 3.90+1 2.30+1
FLUX 1.70+1 1.20+1 9.50-0 7.60-0 4.70-0
FLUX 3.70-0 2.70-0 2.10-0 1.70-0 1.00-0
FLUX 7.10-1 4.20-1 3.10-1 2.00-1 1.25-1
FLUX 8.30-2 4.60-2 2.60-2 1.50-2 9.00-3 2.00-3
LIMIT 50
DEVIATION 4.00
DISCARD 3.0
LOW END E
HIGH END FISSION
NORM 0.010
PLOT CARDS
SMOOTH 5

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Table X3.2
Measured and Calculated Responses: Case C

SOLUTION HAS BEEN ACHIEVED.
STANDARD DEVIATION OF MEASURED-TO-CALCULATED ACTIVITY RATIOS IS LESS THAN 4.00PERCENT./
SOLUTION RESULTS OBTAINED AFTER 7 ITERATIONS

FOIL REACTION	MEASURED ACTIVITY (DPS/NUCLEUS)	CALCULATED ACTIVITY (DPS/NUCLEUS)	NOMINAL 5.00 PERCENT ACTIVITY LIMITS (MEV)		RATIO MEASURED TO CALCULATED ACTIVITIES	DEVIATION OF MEASURED FROM CALCULATED ACTIVITY (PERCENT)
			LOWER	UPPER		
S32 (N,P) P32	8.488E-20	8.484E-20	2.400E+00	7.900E+00	1.000	23.210E-03
AU197 (N,G) AU198 CD	1.018E-15	1.013E-15	3.600E-06	6.000E-05	1.005	0.4718
AU197 (N,G) AU198	1.109E-15	1.116E-15	1.500E-07	5.750E-05	0.9938	-0.6229
AL27 (N,A) NA24 CD	2.981E-20	2.796E-20	6.500E+00	1.230E+01	1.066	6.631
MG24 (N,P) NA24 CD	5.635E-20	6.172E-20	6.600E+00	1.190E+01	0.9130	-8.696
FE54 (N,P) MN54 CD	5.244E-21	4.939E-21	2.400E+00	8.000E+00	1.062	6.179
NI58 (N,P) CO58 CD	2.875E-20	2.825E-20	2.000E+00	7.900E+00	1.018	1.770
MN55 (N,G) MN56 CD	2.808E-18	2.803E-18	4.500E-07	1.150E-03	1.002	0.1772
TI47 (N,P) SC47 CD	9.518E-20	1.026E-19	1.900E+00	8.000E+00	0.9280	-7.199
TI48 (N,P) SC48 CD	3.996E-21	3.904E-21	6.000E+00	1.260E+01	1.024	2.353
ZN64 (N,P) CU64 CD	1.260E-18	1.272E-18	2.600E+00	8.100E+00	0.9907	-0.9345
SC45 (N,G) SC46 CD	3.271E-19	3.323E-19	3.800E-07	8.800E-03	0.9844	-1.557
NA23 (N,G) NA24 CD	1.136E-18	1.125E-18	4.750E-07	4.000E-03	1.010	0.9911
NA23 (N,G) NA24	3.439E-18	3.438E-18	2.800E-08	2.800E-03	1.001	80.466E-03
SI28 (N,X) MEV1	3.683E+12	3.671E+12	1.800E-01	5.600E+00	1.003	0.3317

STANDARD DEVIATION OF MEASURED ACTIVITIES (PERCENT) 3.994

Table X3.3
Spectrum and Dose Related Quantities: Case C

Response Analysis - Loop = 1 Iteration = 7

Response Function	Dose
Fluence (n/cm**2)	0.9438534E+13
Kerma (rad-Tissue)	9853.640
CP Dose to Elem-57 (rad-Tissue)	10907.52
Dose Eqv. (rem)	117821.6
Dose to Elem-57 from H-1(n,g)H-2 (rad-Tissue)	2640.429
ANSI and NCRP Dose (rem)	119843.0

Spectrum Characterization

Total Fluence (n/cm**2)	9.4385377E+12
Fluence > 10 keV	6.0885218E+12
Fluence > 3 MeV	5.1231356E+11
Avg. Energy (MeV)	0.5901202
HP	0.6496077
(ASTM Si Damage Function)	
HP	0.6023297
(ENDF-6 Si Damage Function)	
SI	11.88046
Sulfur Cross Section (mb)	295.1171
(Spectrum Averaged, > 3 MeV)	
Nickel Cross Section (mb)	486.6620
(Spectrum Averaged, > 3 MeV)	

Table X3.4
Case C: Spectrum for IMU in Cd-Poly Box at 22.75"
(Normalized to 1 Neutron Above .01 MeV)

E(MeV)	Differential	Integral	E(MeV)	Differential	Integral
1.0E-9	8.183E+4	1.551	1.0E-3	4.305E+1	1.135
2.0E-9	1.637E+4	1.551	2.0E-3	2.646E+1	1.101
3.0E-9	2.476E+4	1.551	3.0E-3	1.931E+1	1.078
5.0E-9	4.093E+4	1.551	5.0E-3	1.286E+1	1.047
7.2E-9	5.909E+4	1.551	7.2E-3	9.330E-0	1.023
1.0E-8	8.183E+5	1.550	1.0E-2	7.011E-0	1.000
2.0E-8	1.635E+5	1.549	2.0E-2	4.532E-0	9.434E-1
3.0E-8	2.470E+5	1.547	3.0E-2	4.008E-0	9.026E-1
5.0E-8	3.574E+5	1.541	5.0E-2	2.839E-0	8.363E-1
7.2E-8	4.154E+5	1.532	7.2E-2	1.973E-0	7.837E-1
1.0E-7	4.242E+5	1.519	1.0E-1	1.613E-0	7.331E-1
2.0E-7	3.372E+5	1.482	2.0E-1	9.687E-1	6.015E-1
3.0E-7	2.327E+5	1.452	3.0E-1	6.785E-1	5.185E-1
5.0E-7	1.158E+5	1.419	5.0E-1	4.035E-1	4.118E-1
7.2E-7	6.766E+4	1.399	7.2E-1	2.851E-1	3.351E-1
1.0E-6	4.252E+4	1.383	1.0E-0	1.820E-1	2.861E-1
2.0E-6	1.640E+4	1.356	1.5E-0	1.123E-1	1.934E-1
3.0E-6	1.078E+4	1.343	2.0E-0	7.678E-2	1.456E-1
5.0E-6	6.889E+3	1.325	3.0E-0	4.703E-2	8.417E-2
7.2E-6	4.484E+3	1.313	4.0E-0	2.683E-2	4.768E-2
1.0E-5	3.178E+3	1.302	5.0E-0	1.583E-2	2.652E-2
2.0E-5	1.640E+3	1.279	6.0E-0	9.904E-3	1.365E-2
3.0E-5	1.072E+3	1.266	7.0E-0	4.458E-3	6.736E-3
5.0E-5	6.533E+2	1.249	8.0E-0	2.211E-3	3.397E-3
7.2E-5	4.620E+2	1.236	9.0E-0	1.171E-3	1.717E-3
1.0E-4	3.385E+2	1.225	1.0E+1	5.829E-4	8.373E-4
2.0E-4	1.743E+2	1.202			
3.0E-4	1.308E+2	1.185			
5.0E-4	7.635E+1	1.164			
7.2E-4	5.783E+1	1.149			

APPENDIX X4
SPECTRUM RESULTS: IN Cd-POLY BOX WITHOUT IMU AT 22.75"

See the introduction of Appendix X1 for definitions of tables and their quantities.

Table X4.1
Input File: Case D

```

1 CASES
T SAND II INPUT FILE FOR SPR III FOIL SET FOR SHOT 2934
T (MAR. 27, 1984) WITH SPR317 TRIAL SPECTRUM, FREE FIELD.
T
ITERATION    TIME INTEGRATED
21 FOILS
AU197G      CADMIUM 2.587-3
AU197G
MN55G5      CADMIUM 2.587-3
MG24P       CADMIUM 2.587-3
AL27A       CADMIUM 2.587-3
NI58P       CADMIUM 2.587-3
S32P
NA23G       CADMIUM 4.705-3
NA23G
SC45G       CADMIUM 2.587-3
TI48P       CADMIUM 2.587-3
TI47P       CADMIUM 2.587-3
ZN84P       CADMIUM 2.587-3
FE56P       CADMIUM 2.587-3
U235F       BORON 0.101 CADMIUM 4.705-3
U238F       BORON 0.101 CADMIUM 4.705-3
PU239F      BORON 0.101 CADMIUM 4.705-3
NP237F      BORON 0.101 CADMIUM 4.705-3
MN55G5      BORON 0.101 CADMIUM 4.705-3
SC45G       BORON 0.101 CADMIUM 4.705-3
NA23G       BORON 0.101 CADMIUM 4.705-3
ACTS 5.533-16 5.001-16 1.189-16 4.576-20 2.276-20
ACTS 2.047-20 6.049-20 4.263-19 5.886-19
ACTS 1.415-19 3.046-21 6.760-20 1.014-18 1.889-19
ACTS 2.795-12 4.662-13 3.449-12 2.118-12
ACTS 4.722-18 4.087-21 2.850-20
SPECTRUM TABULAR
44 POINTS
ENER 1.00-7 2.00-7
ENER 3.00-7 5.00-7 7.00-7 1.00-6 2.00-6
ENER 3.00-6 5.00-6 7.00-6 1.00-5 2.00-5
ENER 3.00-5 5.00-5 7.00-5 1.00-4 2.00-4
ENER 3.00-4 5.00-4 7.00-4 1.00-3 2.00-3
ENER 3.00-3 5.00-3 7.00-3 1.00-2 2.00-2
ENER 3.00-2 5.00-2 7.00-2 1.00-1 2.00-1
ENER 3.00-1 5.00-1 7.00-1 1.00-0 1.50-0
ENER 2.00-0 3.00-0 4.00-0 5.00-0 6.00-0
ENER 8.00-0 1.00+1
FLUX 4.00+4 6.30+4
FLUX 7.80+4 8.00+4 7.20+4 5.50+4 2.70+4
FLUX 1.80+4 1.08+4 7.20+3 5.20+3 2.60+3
FLUX 1.65+3 9.50+2 6.80+2 4.80+2 2.30+2
FLUX 1.50+2 8.80+1 6.20+1 4.20+1 2.00+1
FLUX 1.25+1 7.60-0 5.70-0 4.20-0 2.30-0
FLUX 1.80-0 1.30-0 1.10-0 8.60-1 5.90-1
FLUX 4.70-1 3.60-1 3.00-1 2.40-1 1.80-1
FLUX 1.40-1 9.40-2 5.80-2 3.40-2 2.00-2
FLUX 5.10-3 1.20-3
LIMIT 50

```

Table X4.1 (continued)
Input File: Case D

DEVIATION 4.00
DISCARD 3.0
LOW END E
HIGH END FISSION
NORM 0.010
PLOT CARDS
SMOOTH 5

Table X4.2
Measured and Calculated Responses: Case D

SOLUTION HAS BEEN ACHIEVED.
STANDARD DEVIATION OF MEASURED-TO-CALCULATED ACTIVITY RATIOS IS LESS THAN 4.00PERCENT./
SOLUTION RESULTS OBTAINED AFTER 8 ITERATIONS

FOIL REACTION	MEASURED ACTIVITY (DPS/NUCLEUS)	CALCULATED ACTIVITY (DPS/NUCLEUS)	NOMINAL 5.00 PERCENT ACTIVITY LIMITS (MEV)		RATIO MEASURED TO CALCULATED ACTIVITIES	DEVIATION OF MEASURED FROM CALCULATED ACTIVITY (PERCENT)
			LOWER	UPPER		
S32 (N,P) P32	6.049E-20	6.218E-20	2.400E+00	8.000E+00	0.9732	-2.679
AU197 (N,G) AU198 CD	5.533E-16	5.534E-16	3.800E-06	6.360E-06	0.9999	-10.765E-03
AU197 (N,G) AU198	5.601E-16	5.610E-16	3.200E-06	6.300E-06	0.9984	-0.1614
AL27 (N,A) NA24 CD	2.278E-20	2.190E-20	6.600E+00	1.230E+01	1.039	3.916
MG24 (N,P) NA24 CD	4.578E-20	4.859E-20	6.600E+00	1.190E+01	0.9418	-5.822
NI58 (N,P) CO58 CD	2.047E-20	2.060E-20	2.100E+00	8.000E+00	0.9939	-0.6095
U235 (N,F) LA140 B CD	2.795E-12	2.948E-12	1.200E-03	5.100E+00	0.9481	-5.190
MN55 (N,G) MN56 CD	1.189E-16	1.214E-16	5.750E-07	1.100E-03	0.9794	-2.064
MN55 (N,G) MN56 B CD	4.722E-18	4.851E-18	3.000E-04	3.800E-01	1.015	1.522
FE56 (N,P) MN56 CD	1.889E-19	1.842E-19	5.600E+00	1.170E+01	1.025	2.547
TI47 (N,P) SC47 CD	6.760E-20	7.418E-20	1.900E+00	8.100E+00	0.9113	-8.871
U238 (N,F) LA140 B CD	4.662E-13	4.516E-13	1.500E+00	7.500E+00	1.032	3.240
PU239 (N,F) LA140 B CD	3.449E-12	3.574E-12	3.400E-03	5.400E+00	0.9651	-3.494
NP237 (N,F) LA140 B CD	2.118E-12	1.999E-12	6.300E-01	6.400E+00	1.059	5.948
TI48 (N,P) SC48 CD	3.048E-21	3.048E-21	6.000E+00	1.260E+01	0.9995	-53.281E-03
ZN64 (N,P) CU64 CD	1.014E-18	9.377E-19	2.600E+00	8.200E+00	1.081	8.139
SC45 (N,G) SC46 CD	1.415E-19	1.418E-19	4.750E-07	4.750E-04	0.9982	-0.1828
SC45 (N,G) SC46 B CD	4.087E-21	3.954E-21	3.200E-03	1.100E+00	1.034	3.357
NA23 (N,G) NA24 CD	4.263E-19	4.212E-19	5.500E-07	3.000E-03	1.012	1.208
NA23 (N,G) NA24	5.886E-19	5.873E-19	1.275E-07	3.000E-03	1.002	0.2291
NA23 (N,G) NA24 B CD	2.850E-20	2.878E-20	1.500E-03	1.900E+00	0.9903	-0.9704

STANDARD DEVIATION OF MEASURED ACTIVITIES (PERCENT) 3.960

Table X4.3
Spectrum and Dose Related Quantities: Case D

Response Analysis - Loop = 1 Iteration = 8

Response Function	Dose
Fluence (n/cm**2)	0.3228540E+13
Kerma (rad-Tissue)	4819.099
CP Dose to Elem-57 (rad-Tissue)	5607.323
Dose Eqv. (rem)	55111.89
Dose to Elem-57 from H-1(n,g)H-2 (rad-Tissue)	920.8719
ANSI and NCRP Dose (rem)	56399.87

Spectrum Characterization

Total Fluence (n/cm**2)	3.2285409E+12
Fluence > 10 keV	2.1006604E+12
Fluence > 3 MeV	3.7919923E+11
Avg. Energy (MeV)	1.047681
HP	0.9349549
(ASTM Si Damage Function)	
HP	0.8403597
(ENDF-6 Si Damage Function)	
SI	5.539728
Sulfur Cross Section (mb)	292.1035
(Spectrum Averaged, > 3 MeV)	
Nickel Cross Section (mb)	479.3481
(Spectrum Averaged, > 3 MeV)	

Table X4.4
Case D: Spectrum for IMU in Cd-Poly Box at 22.75"
(Normalized to 1 Neutron Above .01 MeV)

E(MeV)	Differential	Integral	E(MeV)	Differential	Integral
1.0E-9	4.318E+2	1.539	1.0E-3	4.575E+1	1.092
2.0E-9	8.637E+2	1.539	2.0E-3	1.961E+1	1.062
3.0E-9	1.306E+3	1.539	3.0E-3	1.249E+1	1.046
5.0E-9	2.159E+3	1.539	5.0E-3	7.131E-0	1.027
7.2E-9	3.118E+3	1.539	7.2E-3	5.316E-0	1.013
1.0E-8	4.319E+3	1.539	1.0E-2	3.984E-0	1.000
2.0E-8	8.641E+3	1.539	2.0E-2	2.150E-0	9.709E-1
3.0E-8	1.307E+4	1.539	3.0E-2	1.691E-0	9.518E-1
5.0E-8	2.161E+4	1.539	5.0E-2	1.220E-0	9.230E-1
7.2E-8	3.119E+4	1.538	7.2E-2	9.931E-1	8.985E-1
1.0E-7	4.282E+4	1.537	1.0E-1	7.935E-1	8.732E-1
2.0E-7	6.723E+4	1.531	2.0E-1	5.498E-1	8.072E-1
3.0E-7	8.482E+4	1.524	3.0E-1	4.400E-1	7.575E-1
5.0E-7	8.943E+4	1.506	5.0E-1	3.673E-1	6.776E-1
7.2E-7	7.777E+4	1.488	7.2E-1	3.251E-1	6.007E-1
1.0E-6	6.038E+4	1.468	1.0E-0	2.634E-1	5.166E-1
2.0E-6	2.962E+4	1.426	1.5E-0	2.009E-1	3.989E-1
3.0E-6	1.953E+4	1.401	2.0E-0	1.506E-1	3.092E-1
5.0E-6	1.136E+4	1.371	3.0E-0	9.912E-2	1.855E-1
7.2E-6	7.685E+3	1.350	4.0E-0	5.884E-2	1.069E-1
1.0E-5	5.699E+3	1.338	5.0E-0	3.551E-2	6.013E-2
2.0E-5	2.740E+3	1.291	6.0E-0	2.155E-2	3.154E-3
3.0E-5	1.789E+3	1.268	7.0E-0	1.045E-2	1.584E-2
5.0E-5	1.038E+3	1.241	8.0E-0	5.474E-3	7.879E-3
7.2E-5	7.157E+2	1.221	9.0E-0	2.638E-3	3.888E-3
1.0E-4	5.195E+2	1.204	1.0E+1	1.341E-3	1.908E-3
2.0E-4	2.460E+2	1.168			
3.0E-4	1.702E+2	1.147			
5.0E-4	8.845E+1	1.122			
7.2E-4	5.789E+1	1.106			

APPENDIX X5
SPECTRUM RESULTS: BEHIND THE IMU IN FREE FIELD AT 35"

See the introduction to Appendix X1 for definitions of tables and their quantities.

Table X5.1
Input File: Behind IMU in Case B

```

1 CASES
T SAND II INPUT FILE FOR SPR III FOIL SET FOR SHOT 2934
T (MAR. 27, 1984) WITH SPR317 TRIAL SPECTRUM, FREE FIELD.
T
ITERATION      TIME INTEGRATED
8 FOILS
AU197G      CADMIUM 2.587-3
MN55G5      CADMIUM 2.587-3
NI58P      CADMIUM 2.587-3
S32P
U235F      BORON 0.101 CADMIUM 4.705-3
U238F      BORON 0.101 CADMIUM 4.705-3
PU239F      BORON 0.101 CADMIUM 4.705-3
NP237F      BORON 0.101 CADMIUM 4.705-3
ACTS 1.292-16 3.685-17 4.035-21 1.266-20
ACTS 1.511-12 9.967-14 1.760-12 6.675-13
SPECTRUM TABULAR
43 POINTS
ENER 1.00-7 2.00-7
ENER 3.00-7 5.00-7 7.00-7 1.00-6 2.00-6
ENER 3.00-6 5.00-6 7.00-6 1.00-5 2.00-5
ENER 3.00-5 5.00-5 7.00-5 1.00-4 2.00-4
ENER 3.00-4 5.00-4 7.00-4 1.00-3 2.00-3
ENER 3.00-3 5.00-3 7.00-3 1.00-2 2.00-2
ENER 3.00-2 5.00-2 7.00-2 1.00-1 2.00-1
ENER 3.00-1 5.00-1 7.00-1 1.00-0 1.50-0
ENER 2.00-0 3.00-0 4.00-0 5.00-0 6.00-0 8.00-0
FLUX 2.70+4 1.50+4
FLUX 1.05+4 7.00+3 5.40+3 4.00+3 2.20+3
FLUX 1.60+3 1.05+3 8.20+2 6.30+2 3.90+2
FLUX 2.80+2 1.90+2 1.50+2 1.10+2 7.20+1
FLUX 5.20+1 3.30+1 2.60+1 1.90+1 1.20+1
FLUX 9.70-0 7.60-0 6.70-0 5.90-0 4.30-0
FLUX 3.50-0 2.60-0 2.20-0 1.70-0 1.05-0
FLUX 8.10-1 5.20-1 3.70-1 2.30-1 1.35-1
FLUX 9.00-2 4.80-2 2.50-2 1.20-2 6.50-3 1.10-3
LIMIT 50
DEVIATION 4.00
DISCARD 3.0
LOW END THERMAL
HIGH END FISSION
NORM 0.010
PLOT CARDS
SMOOTH 5

```

Table X5.2
Measured and Calculated Responses: Behind IMU in Case B

SOLUTION HAS BEEN ACHIEVED.
STANDARD DEVIATION OF MEASURED-TO-CALCULATED ACTIVITY RATIOS IS LESS THAN 4.00PERCENT./
SOLUTION RESULTS OBTAINED AFTER 2 ITERATIONS

FOIL REACTION	MEASURED ACTIVITY (DPS/NUCLEUS)	CALCULATED ACTIVITY (DPS/NUCLEUS)	NOMINAL 5.00 PERCENT ACTIVITY LIMITS (MEV)		RATIO MEASURED TO CALCULATED ACTIVITIES	DEVIATION OF MEASURED FROM CALCULATED ACTIVITY (PERCENT)
			LOWER	UPPER		
S32 (N,P) P32	1.268E-20	1.210E-20	2.300E+00	7.000E+00	1.047	4.655
AU197(N,G) AU198 CD	1.292E-16	1.282E-16	4.250E-06	6.300E-05	1.008	0.7667
NI58 (N,P) CO58 CD	4.035E-21	4.004E-21	1.900E+00	7.100E+00	1.008	0.7798
U235 (N,F) LA140 B CD	1.511E-12	1.596E-12	1.425E-03	3.000E+00	0.9469	-5.314
MN55 (N,G) MN56 CD	3.685E-17	3.677E-17	1.000E-06	2.000E-03	1.002	0.2280
U238 (N,F) LA140 B CD	9.987E-14	1.057E-13	1.400E+00	6.300E+00	0.9432	-5.677
PU239(N,F) LA140 B CD	1.760E-12	1.758E-12	3.000E-03	3.500E+00	1.002	0.2397
NP237(N,F) LA140 B CD	6.675E-13	6.398E-13	5.000E-01	4.800E+00	1.043	4.321

STANDARD DEVIATION OF MEASURED ACTIVITIES (PERCENT) 3.820

Table X5.3
Spectrum and Dose Related Quantities: Behind IMU in Case B

```

Response Analysis - Loop =   1 Iteration =   2

Response Function                                     Dose
Fluence (n/cm**2)                                     0.1474531E+13
Kerma (rad-Tissue)                                    1777.142
CP Dose to Elem-57 (rad-Tissue)                       1951.448
Dose Eqv. (rem)                                       21677.39
Dose to Elem-57 from H-1(n,g)H-2 (rad-Tissue)         438.8976
ANSI and NCRP Dose (rem)                             22204.80

```

Spectrum Characterization

```

Total Fluence (n/cm**2)                             1.4745322E+12
Fluence > 10 keV                                     1.1165533E+12
Fluence > 3 MeV                                       7.1967310E+10
Avg. Energy (MeV)                                     0.6259336
HP                                                     0.6434576
      (ASTM Si Damage Function)
HP                                                     0.6009213
      (ENDF-6 Si Damage Function)
SI                                                     15.51473
Sulfur Cross Section (mb)                             299.5485
      (Spectrum Averaged, > 3 MeV)
Nickel Cross Section (mb)                             491.0005
      (Spectrum Averaged, > 3 MeV)

```

Table X5.4
Spectrum Behind the IMU in Free Field at 35"

E(MeV)	Differential	Integral	E(MeV)	Differential	Integral
1.0E-9	2.069E+4	1.321	1.0E-3	4.458E+1	1.104
2.0E-9	3.974E+4	1.321	2.0E-3	2.026E+1	1.077
3.0E-9	5.764E+4	1.321	3.0E-3	1.161E+1	1.059
5.0E-9	8.795E+4	1.320	5.0E-3	9.294	1.039
7.2E-9	1.161E+5	1.320	7.2E-3	8.139	1.020
1.0E-8	1.436E+5	1.320	1.0E-2	6.250	1.000
2.0E-8	1.914E+5	1.318	2.0E-2	4.516	9.471E-1
3.0E-8	1.910E+5	1.316	3.0E-2	3.455	9.070E-1
5.0E-8	1.419E+5	1.313	5.0E-2	2.478	8.484E-1
7.2E-8	9.832E+4	1.310	7.2E-2	2.029	7.981E-1
1.0E-7	7.130E+4	1.308	1.0E-1	1.561	7.472E-1
2.0E-7	3.971E+4	1.302	2.0E-1	9.735E-1	6.235E-1
3.0E-7	2.777E+4	1.299	3.0E-1	7.355E-1	5.374E-1
5.0E-7	1.875E+4	1.294	5.0E-1	4.763E-1	4.175E-1
7.2E-7	1.419E+4	1.291	7.2E-1	3.252E-1	3.283E-1
1.0E-6	1.091E+4	1.287	1.0E-0	2.025E-1	2.529E-1
2.0E-6	6.410E+3	1.279	1.5E-0	1.145E-1	1.722E-1
3.0E-6	5.352E+3	1.273	2.0E-0	7.692E-2	1.238E-1
5.0E-6	4.800E+3	1.262	3.0E-0	4.299E-2	6.445E-2
7.2E-6	2.444E+3	1.254	4.0E-0	2.277E-2	3.189E-2
1.0E-5	1.645E+3	1.249	5.0E-0	1.095E-2	1.530E-2
2.0E-5	9.616E+2	1.236	6.0E-0	5.843E-3	6.912E-3
3.0E-5	6.839E+2	1.228	7.0E-0	2.251E-3	3.012E-3
5.0E-5	4.911E+2	1.216	8.0E-0	9.924E-4	1.426E-3
7.2E-5	7.151E+2	1.210	9.0E-0	4.848E-4	6.919E-4
1.0E-4	3.151E+2	1.192	1.0E+1	2.358E-4	3.337E-4
2.0E-4	1.759E+2	1.167			
3.0E-4	1.262E+2	1.151			
5.0E-4	6.746E+1	1.131			
7.2E-4	5.649E+1	1.116			

APPENDIX X6
SPECTRUM RESULTS: BEHIND THE IMU IN THE Cd-POLY BOX AT 35"

See the introduction to Appendix X1 for definitions of tables and their quantities.

Table X6.1
Input File: Behind the IMU in Case C

```

1 CASES
T SAND II INPUT FILE FOR SPR III FOIL SET FOR SHOT 2934
T (MAR. 27, 1984) WITH SPR317 TRIAL SPECTRUM, FREE FIELD.
T
  ITERATION   TIME INTEGRATED
  8 FOILS
  AU197G      CADMIUM 2.587-3
  MN55G5      CADMIUM 2.587-3
  NI58P       CADMIUM 2.587-3
  S32P
  U235F       BORON 0.101 CADMIUM 4.705-3
  U238F       BORON 0.101 CADMIUM 4.705-3
  PU239F      BORON 0.101 CADMIUM 4.705-3
  NP237F      BORON 0.101 CADMIUM 4.705-3
  ACTS 3.110-16 7.076-17 2.474-21 7.577-21
  ACTS 9.135-13 6.210-14 1.033-12 3.586-13
  SPECTRUM TABULAR
  46 POINTS
  ENER 4.00-8 7.00-8 1.00-7 1.50-7 2.00-7
  ENER 3.00-7 5.00-7 7.00-7 1.00-6 2.00-6
  ENER 3.00-6 5.00-6 7.00-6 1.00-5 2.00-5
  ENER 3.00-5 5.00-5 7.00-5 1.00-4 2.00-4
  ENER 3.00-4 5.00-4 7.00-4 1.00-3 2.00-3
  ENER 3.00-3 5.00-3 7.00-3 1.00-2 2.00-2
  ENER 3.00-2 5.00-2 7.00-2 1.00-1 2.00-1
  ENER 3.00-1 5.00-1 7.00-1 1.00-0 1.50-0
  ENER 2.00-0 3.00-0 4.00-0 5.00-0 6.00-0 8.00-0
  FLUX 2.70+5 3.50+5 3.60+5 3.40+5 2.90+5
  FLUX 2.20+5 1.15+5 7.00+4 4.20+4 1.60+4
  FLUX 1.05+4 6.20+3 4.50+3 3.10+3 1.60+3
  FLUX 1.05+3 6.30+2 4.50+2 3.20+2 1.60+2
  FLUX 1.20+2 7.20+1 5.30+1 3.90+1 2.30+1
  FLUX 1.70+1 1.20+1 9.50-0 7.60-0 4.70-0
  FLUX 3.70-0 2.70-0 2.10-0 1.70-0 1.00-0
  FLUX 7.10-1 4.20-1 3.10-1 2.00-1 1.25-1
  FLUX 8.30-2 4.60-2 2.60-2 1.50-2 9.00-3 2.00-3
  LIMIT 50
  DEVIATION 6.00
  DISCARD 3.0
  LOW END E
  HIGH END FISSION
  NORM 0.010
  PLOT CARDS
  SMOOTH 5

```

Table X6.2
Measured and Calculated Responses Behind the IMU in Case C

SOLUTION HAS BEEN ACHIEVED.
STANDARD DEVIATION OF MEASURED-TO-CALCULATED ACTIVITY RATIOS IS LESS THAN 6.00PERCENT./
SOLUTION RESULTS OBTAINED AFTER 1 ITERATIONS

FOIL REACTION	MEASURED ACTIVITY (DPS/NUCLEUS)	CALCULATED ACTIVITY (DPS/NUCLEUS)	NOMINAL 5.00 PERCENT ACTIVITY LIMITS (MEV)		RATIO MEASURED TO CALCULATED ACTIVITIES	DEVIATION OF MEASURED FROM CALCULATED ACTIVITY (PERCENT)
			LOWER	UPPER		
S32 (N,P) P32	7.577E-21	7.590E-21	2.300E+00	7.700E+00	0.9983	-0.1685
AU197 (N,G) AU198 CD	3.110E-16	2.994E-16	3.800E-06	6.000E-06	1.039	3.872
NI58 (N,P) CO58 CD	2.474E-21	2.537E-21	2.000E+00	7.700E+00	0.9750	-2.497
U235 (N,F) LA140 B CD	9.135E-13	9.760E-13	8.800E-04	3.100E+00	0.9380	-6.403
MN55 (N,G) MN56 CD	7.076E-17	6.819E-17	4.500E-07	1.100E-03	1.038	3.772
U238 (N,F) LA140 B CD	6.210E-14	6.244E-14	1.400E+00	7.000E+00	0.9945	-0.5470
PU239 (N,F) LA140 B CD	1.033E-12	1.032E-12	1.200E-03	3.700E+00	1.001	0.1078
NP237 (N,F) LA140 B CD	3.586E-13	3.520E-13	5.000E-01	5.500E+00	1.019	1.863

STANDARD DEVIATION OF MEASURED ACTIVITIES (PERCENT) 3.386

Table X6.3
Spectrum and Dose Related Quantities: Behind IMU in Case C

Response Analysis - Loop = 1 Iteration = 1

Response Function	Dose
Fluence (n/cm**2)	0.1347324E+13
Kerma (rad-Tissue)	990.2589
CP Dose to Elem-57 (rad-Tissue)	1104.791
Dose Eqv. (rem)	12207.08
Dose to Elem-57 from H-1(n,g)H-2 (rad-Tissue)	370.2944
ANSI and NCRP Dose (rem)	12177.61

Spectrum Characterization

Total Fluence (n/cm**2)	1.3473230E+12
Fluence > 10 keV	6.2953848E+11
Fluence > 3 MeV	4.5407351E+10
Avg. Energy (MeV)	0.3981411
HP	0.6313351
(ASTM Si Damage Function)	
HP	0.5882523
(ENDF-6 Si Damage Function)	
SI	13.86420
Sulfur Cross Section (mb)	297.8732
(Spectrum Averaged, > 3 MeV)	
Nickel Cross Section (mb)	493.1738
(Spectrum Averaged, > 3 MeV)	

Table X6.4
Spectrum Behind the IMU in Cd-Poly Box at 35"

E(MeV)	Differential	Integral	E(MeV)	Differential	Integral
1.0E-9	1.867E+4	2.140	1.0E-3	8.726E+1	1.148
2.0E-9	3.734E+4	2.140	2.0E-3	3.045E+1	1.108
3.0E-9	5.646E+4	2.140	3.0E-3	1.816E+1	1.082
5.0E-9	9.334E+4	2.140	5.0E-3	1.318E+1	1.051
7.2E-9	1.348E+5	2.140	7.2E-3	1.029E+1	1.026
1.0E-8	1.867E+5	2.139	1.0E-2	1.856E-0	1.000
2.0E-8	3.734E+5	2.137	2.0E-2	4.895E-0	9.382E-1
3.0E-8	5.647E+5	2.132	3.0E-2	3.755E-0	8.948E-1
5.0E-8	8.174E+5	2.118	5.0E-2	2.709E-0	8.305E-1
7.2E-8	9.489E+5	2.098	7.2E-2	2.076E-0	7.777E-1
1.0E-7	9.686E+5	2.072	1.0E-1	1.689E-0	7.244E-1
2.0E-7	7.706E+5	1.982	2.0E-1	9.949E-1	5.944E-1
3.0E-7	5.709E+5	1.914	3.0E-1	6.949E-1	5.095E-1
5.0E-7	3.004E+5	1.829	5.0E-1	4.110E-1	4.006E-1
7.2E-7	1.755E+5	1.777	7.2E-1	2.873E-1	3.230E-1
1.0E-6	1.105E+5	1.737	1.0E-0	1.863E-1	2.555E-1
2.0E-6	4.317E+4	1.667	1.5E-0	1.149E-1	1.787E-1
3.0E-6	2.938E+4	1.631	2.0E-0	7.613E-2	1.301E-1
5.0E-6	2.011E+4	1.581	3.0E-0	4.157E-2	7.213E-2
7.2E-6	1.191E+4	1.545	4.0E-0	2.337E-2	3.996E-2
1.0E-5	8.147E+3	1.517	5.0E-0	1.349E-2	2.164E-2
2.0E-5	4.145E+3	1.459	6.0E-0	7.958E-3	1.087E-2
3.0E-5	2.695E+3	1.425	7.0E-0	3.585E-3	5.223E-3
5.0E-5	1.626E+3	1.382	8.0E-0	1.787E-3	2.566E-3
7.2E-5	1.174E+3	1.348	9.0E-0	8.722E-4	1.243E-3
1.0E-4	8.123E+2	1.320	1.0E+1	4.228E-4	5.995E-4
2.0E-4	3.499E+2	1.266			
3.0E-4	3.040E+2	1.233			
5.0E-4	1.040E+2	1.190			
7.2E-4	7.036E+1	1.171			

APPENDIX X7
REPRODUCTION OF NORTHROP "IMU MAPPING TEST REPORT,"
91-24531, APPENDIX I

"IMU Mapping Test Report," 91-24531, Electronics Systems Division,
Northrop Corp., 2301 West 120th St., Hawthorne, California 90251-5032,
December 1991.

APPENDIX I

METHOD FOR USING THE 2N2222 TRANSISTOR AS A NEUTRON DAMAGE SILICON DOSIMETER

SUMMARY: A large number of 2N2222 transistors were used as silicon neutron dosimeters during the IMU-A mapping study at Sandia SPR II reactor (August, 1991) and the initial calibrations have been completed. The temperature coefficients and post neutron anneal characteristics have been determined for a group of fifty parts that were exposed to free field, un-moderated, 1MeV neutron fluences of 1.75, 17.78, 20.09 and 118.8 E+12 N/cm² (using Sandia's FF 3MeV:1MeV conversion factor of 7.2). Transistor gain was measured at a Vce of 5 volts and collector currents of 100 μA, 1 mA, and 10 mA both pre and post neutron irradiation. All gain measurements were temperature corrected and normalized to a 24 hour anneal period before calculation of the incident neutron fluence based upon the 1MeV free field transistor damage constants.

NEUTRON TRANSISTOR TESTS: Pairs of transistors were placed in the appropriate IMU dosimetry bags or located at various free field positions during the SPR II tests. In all cases, the transistor leads were shorted together during exposure. Fifty parts placed in the free field were used to derive the transistor sensitivities and neutron damage constants. A semiconductor parametric analyzer, Hewlett Packard Model 4145A, was used to make all pre and post Beta measurements at collector currents from 3 μA to 100 mA and a Vce potential of 4-5 volts. This data was read by a HP200 computer and stored on disc for post processing. The free field calibration group was used to determine the damage constant Kn at Ic= 100 μA, 1 mA and 10 mA. The damage constant was then used with the IMU dosimetry transistor gain results to calculate neutron fluence. The damage constant Kn is defined below.

$$K_n = \frac{\Delta 1/\beta}{(\text{Fluence})^*} = \frac{\text{Beta}(\text{Post } N)^{-1} - \text{Beta}(\text{Initial})^{-1}}{(1 \text{ MeV Neutron Fluence})^*}$$

BETA TEMPERATURE CHARACTERISTICS: Six control devices were measured at four temperatures between 15 and 45 degrees C. The sensitivities of beta and Vbe to temperature are shown in Figures 1 and 2 for collector currents of 100 μA, 1 mA and 10 mA. Both of these sensitivities decrease in magnitude with increasing current density. The temperature sensitivities were re-checked on a group of nine post neutron devices at 25 and 35 degrees C only. The post neutron group included three devices each at 1.75, 20.1, and 118.8 E + 12 N/cm². The beta and Vbe temperature sensitivities degrade with neutron exposure and are tabulated below.

BETA and Vbe TEMPERATURE SENSITIVITIES

	Ic = 100 μA	Ic = 1.0 mA	Ic = 10 mA
Beta Sensitivities:			
Initial	0.57 +/- .01 %/°C	0.55 +/- .01 %/°C	0.52 +/- .01 %/°C
Post Neutron	0.61 +/- .03 %/°C	0.51 +/- .05 %/°C	0.42 +/- .08 %/°C
Vbe Sensitivities:			
Initial	-2.24 mV/°C	-2.01 mV/°C *	-1.83 mV/°C

* Used to normalize temperature to 25.5 °C or 0.630 Volts, based upon controls.

$$t_c \text{ correct Beta} = \text{Beta} * (1 + \text{Beta Sensitivity} * \Delta T)$$

$$\Delta T (°C) = (0.630 - V_{be}) / -2.01 \text{ mV/°C} \quad \text{is Correction to reach } 25.5 °C$$

Six control parts are measured with each test group. The control's average V_{be} is used to measure room temperature fluctuations. All beta measurements are temperature corrected to a nominal 0.630 volt V_{be} (@ $I_c = 1$ mA; controls) or an ambient temperature of 25.5 C.

POST NEUTRON ANNEAL CHARACTERISTICS: Several groups of parts were measured at post irradiation anneal intervals ranging from two hours to twenty two days. At each interval one set of un-read parts along with all previously read parts would be measured to determine the anneal characteristics and the effect multiple measurements may have. The parameter of interest is the inverse Beta difference (post-pre) or $\Delta 1/\beta$ and it decreases as the post beta measurement increases or anneals. Measuring the post neutron devices multiple times did affect the linear anneal characteristic.

The Betas for each of the fifty characterization parts were corrected for temperature and the group average $\Delta 1/\beta$ values tabulated. These widely dispersed values, ranging between 2 and 100 E-3, were then normalized to the reading taken twenty-four hours after exposure. The normalized $\Delta 1/\beta$ values for a group of four parts, at three collector currents, are shown in Figure 3 plotted against the anneal time. The rate of anneal decreases with both current density and time while the transistor gain improves with time. Combining the current ratios of Figure 3 with the least squared sensitivity of all fifty devices, at $I_c = 1$ mA, yields the following anneal characteristics.

	$I_c = 100 \mu A$	$I_c = 1 \text{ mA}$	$I_c = 10 \text{ mA}$
Anneal Sensitivity =	$\frac{-11.6 \%}{\text{LOG}(\text{hrs}/24)}$	$\frac{-9.4 \%}{\text{LOG}(\text{hrs}/24)}$	$\frac{-9.4 \%}{\text{LOG}(\text{hrs}/24)}$
(+/- 1%)			

$$\Delta 1/\beta \text{ Anneal Correction} = \Delta 1/\beta / (1 + \text{LOG}(\text{hrs}/24) * \text{Anneal Sens.})$$

(Normalized to 24 hours)

NEUTRON DAMAGE CONSTA With each test sample's Beta corrected for temperature changes normalized to one day, and average together, the neutron damage constants were determined. Figure contains the corrected $\Delta 1/\beta$ values plotted against the neutron fluence levels. Each data point shown is a average of 10 to 16 part measurements with standard deviations between 2.5 and 6.1 %. The following least square fluence coefficients and damage constants will be used for the 2N2222 neutron dosimeter.

2N2222 NEUTRON COEFFICIENTS -- SPR II FREE FIELD CALIBRATIONS

I_c	K_n	α
100 μA	7.979 E -14	0.8990
* 1.0 mA	6.030 E -14	0.8858
10.0 mA	4.178 E -14	0.8738

* Calculate incident fluence at this current density.

The fluence levels for the SPR II Ball mapping shots #2301-2315 were calculated based upon the $I_c = 1$ mA Beta and K_n constants. These free field coefficients were also used to calculate fluence for the Cd:P moderated Shots #2309-2315.

2222 NEUTRON DOSIMETERS: The IMU mapping transistors are used in the following manner to calculate incident neutron fluence levels.

Pre Radiation: Measure all parts and controls at room ambient temperature.

Post Neutron: Measure all parts and controls then

1. Determine Temperature offset from control group's V_{be} (nominal 0.630 Volts; $I_c = 1 \text{ mA}$)
2. Correct each Beta for temperature offset.
3. Calculate $\Delta 1/\beta$ value.
4. Correct $\Delta 1/\beta$ for anneal time.
5. $1\text{MeV Neutron Fluence} = [\Delta 1/\beta / K_n]^{1/\alpha}$ (@ $I_c = 1 \text{ mA}$)

where $K_n = 6.030 \text{ E }^{-14}$ and $\alpha = 0.8858$

FIGURE 1. BETA versus TEMPERATURE

FIGURE 2. V_{be} versus TEMPERATURE

FIGURE 3. NORMALIZED $\Delta 1/\beta$ verses ANNEAL TIME

2N2222 Dosimetry Transistor

Sandia SPR II AE00-03 Anneal Times

FIGURE 4. CORRECTED $\Delta I/\beta$ versus NEUTRON FLUENCE

2N2222 Dosimetry Calibration

Ball Test, Sandia SPR II FF (7.2)

$V_{ce}=5V$, $V_{be}=0.63V$, 24hr Anneal, Temp Compensated

Differences in calculating Transistor Silicon Fluence

The usual method of relating transistor beta degradation to 1 MeV fluence, or Damage Equivalent Silicon (DES) uses the accepted $\Delta 1/\beta = K_n \phi^\alpha$, where $\alpha = 1$. This is quite adequate for most cases, particularly when K_n is an approximate value for the transistor geometry. Besides diffusion properties and base width, the damage constant varies with operate temperature, current density, and anneal time since irradiation. Dr. Kelly at Sandia National Laboratories used this linear damage model. As shown in the preceding pages, the transistor $\Delta 1/\beta$ degradation is a little sublinear with fluence. If the calibrating fluence and unknown fluence are fairly equal, this non-linearity is moot. In the ball dosimetry, the fluence was expected to vary an order of magnitude, so the more exact nonlinear algorithm measured for these parts was used.

The 2N2222AJAN transistors used in this mapping experiment for DES dosimeters were chosen and screened with some care. They were all from recent fabrication (same package lot) made by a major supplier. Motorola has been improving their process control with a management initiative to reach zero defects through 6σ process control to the specification parameters. The JAN version was bought to keep die lot consistency which might not occur on plain commercial parts. They were very inexpensive (\$0.30), costing about 1/6 that of TLD crystals. The uniformity of Motorola's current parts made for JAN marketing is excellent. We bought 1500 parts to cover this mapping test series and also the upcoming system test series. All the parts have uniform high gain at the 1 ma test operating current. We characterized them at 1/10th and 10 times the planned test current and found them very tightly grouped, with a standard deviation of about 5%. The small TO-18 metal case was chosen to heat sink the die so negligible heating would shift its parameters during the electrical readout. Also the package is small and will fit in tight spaces. The transistor does not have gold plating on the outside, avoiding neutron activation. A set of sixteen transistors only measured 2 mR/hr at the surface when removed from the SPR reactor, and in a few weeks decayed down to background levels. Only a couple parts had betas 10% under the mean, and these were removed from the dosimetry set.

The damage constants at $1E13$ n/cm² were also quite uniform with a σ of 5%. The dependance of damage constant on current density was found to be the same as has been observed before viz. $K_n \approx I_e^{0.315}$. To minimize self heating, the 1 mA current at only 5 mW self heating was chosen. Dr. Kelly used a ratio technique, determining the damage constant for each transistor in a free field SPR exposure near $1E13$ n/cm², then annealed that transistor for 24 hours at 180C. He measured the parts at about the same anneal delay, and corrected for temperature effects with any shifts in unirradiated control transistors. His average damage constant was $16.85E-16$ cm²/n. Northrop measured the damage constant, corrected to 25.5C and 24 hours post exposure, to be a little higher. If the Northrop sublinear algorithm was expressed as linear with $\alpha = 1$, the damage factors at several neutron fluences would be as shown below. Northrop used the SNL sulfur dosimetry and a 7.2 factor for SI*HP to convert sulfur to 1 MeV Silicon equivalent.

Transistor Damage Factor vs Fluence
 $\alpha = 1$, Linear Algorithm

ϕ 1 MeV x E12	Kn x E-16 cm ² /n
1	25.70
3	22.67
10	19.76
30	17.43
100	15.19

The general effect of the IMU mass, particularly the low atomic number beryllium stable member, would be to soften the neutron spectrum, causing an increased Spectral Index * Hardness Parameter (SI*HP) product. This is discussed in detail, with spectral plots given, in appendix F. Table V, page F-15, shows the free field SI*HP product of 7.24 increases about 33% when the activation foils are moved from a free field into the front facing A2 cavity in the inner ball. This softening is more marked in the cadmium polyethylene moderated spectrum where the SI*HP increases about 50% from 5.16 with no IMU present to 7.82 inside the A2 cavity.

Of interest would be a comparison of the bare reactor sulfur fluence measurements at the 16 dosimetered locations with the ϕ 1 Mev fluence seen by the transistor pair located in the same dosimetry packet. These numbers, with their ratio or measured SI*HP product, are given for the five pulse and one steady SPR exposures, for both the bare and Cd-Poly moderated conditions in I-3 through I-5. To permit easier comparison of all the data in these 12 exposures, the SI*HP ratios are summarized on page I-6.

In general, comparing the SI*HP ratios, they are larger when the fluence is transported through more mass. Note dosimeters #1 in front, and #5 at the rear of the IMU. In the Cd-Poly case, where the average spectral ratio increased 83% going through the IMU. The bare reactor case did not show this change, with only an average 2% increase in the rear spectral ratio compared to the front ratio. Also the absolute values of SI*HP ratios did not closely match those predicted by the SNL analysis. These differences are under study.

TRANSISTOR AND SULFUR FLUENCE DATA, SPECTRAL INDEX (SI) X HARDNESS PARAMETER (HP) DATA

SPR II: FREE FIELD, SHOTS #2301 - #2304

Location	(FF) #2301			(FF) #2302			(FF) #2303			(FF) #2304		
	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s
78. TGG A1	19.15	3.21	5.97	F 20.13	3.08	6.54	9.15	1.60	5.72	13.25	2.13	6.22
83. TGG A2	6.75	1.15	5.87	8.92	1.74	5.13	F 13.29	2.17	6.12	24.51	3.75	6.54
88. TGG A3	R' 3.14	0.45	6.98	16.39	2.39	6.86	4.95	0.96	5.17	F 39.60	5.55	7.14
92. SFIR MT1	6.45	1.28	5.04	R 2.56	0.33	7.69	5.44	0.92	5.91	12.35	2.01	6.14
96. SFIR MT2	11.25	1.68	6.70	8.17	1.27	6.43	R 1.79	0.23	7.85	6.17	1.24	4.98
102. SFIR MT3	F 18.74	3.00	6.25	6.64	1.49	4.46	2.69	0.51	5.26	R 3.23	0.38	8.43
30. EXT. A1	F 20.81	3.74	5.56	F 17.56	3.43	5.12	F 11.85	2.16	5.49			
37. EXT. A2	F 29.74	4.87	6.11	F 27.78	4.57	6.08	F 17.61	3.02	5.83			
43. EXT. A3	R 6.29	1.47	4.28	R 6.33	1.34	4.72	R 3.99	0.94	4.25			
49. EXT. A4	R 3.99	0.79	5.06	R 3.98	1.14	3.49	R 2.78	0.56	4.94			
1. IMU FRONT	36.12	6.20	5.83	36.25	5.92	6.12	23.84	3.80	6.27			
5. IMU REAR	1.20	0.22	5.50	1.44	0.20	7.06	0.88	0.14	6.29			
3. IMU LEFT	11.27	1.78	6.33	9.97	1.76	5.66	5.70	1.33	4.29			
7. IMU RIGHT	6.77	1.43	4.73	7.63	1.32	5.78	4.53	0.85	5.35			
14. IMU TOP	14.95	3.14	4.76	17.30	3.01	5.75	10.72	1.99	5.39			
23. IMU BOTTOM	22.12	3.79	5.84	21.15	3.67	5.76	12.37	2.61	4.74			

TRANSISTOR AND SULFUR FLUENCE DATA, SPECTRAL INDEX (SI) X HARDNESS PARAMETER (HP) DATA

SPR II: FREE FIELD, SHOTS #2305, #2308 and CD:PLY MODERATED, SHOTS #2309, #2310

Location	(FF) #2305 Power			(FF) #2308			(Cd:Ply) #2309			(Cd:Ply) #2310		
	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s
78. TGG A1	52.46	8.18	6.41	R 2.92	0.43	6.84	4.61	0.74	6.21	F 5.25	0.97	5.42
83. TGG A2	F 103.90	12.60	8.25	6.42	1.04	6.17	1.94	0.34	5.72	2.22	0.47	4.72
88. TGG A3	41.27	5.64	7.32	8.27	1.32	6.27	R 1.17	0.19	6.29	4.65	0.82	5.68
92. SFIR MT1	72.82	10.60	6.87	F 34.08	4.89	6.97	1.66	0.31	5.34	R 0.99	0.12	8.11
96. SFIR MT2	R 12.26	1.38	8.88	18.37	2.95	6.23	3.48	0.53	6.60	2.02	0.42	4.83
102. SFIR MT3	22.10	3.09	7.15	11.99	1.78	6.74	F 5.59	1.00	5.59	2.03	0.40	5.02
30. EXT. A1	F 99.28	15.90	6.24				F 4.57	1.07	4.27	F 5.40	1.01	5.35
37. EXT. A2	F 161.80	21.50	7.53				F 6.96	1.32	5.27	F 6.89	1.35	5.10
43. EXT. A3	R 27.21	5.03	5.41				R 1.88	0.38	4.95	R 1.81	0.35	5.16
49. EXT. A4	R 13.57	2.47	5.49				R 1.24	0.22	5.66	R 1.33	0.25	5.32
1. IMU FRONT	230.90	30.50	7.57				11.22	2.16	5.19	9.44	2.05	4.60
5. IMU REAR	6.30	0.84	7.49				0.76	0.09	8.85	0.71	0.08	8.55
3. IMU LEFT	40.57	5.85	6.94				2.48	0.44	5.68	2.31	0.52	4.42
7. IMU RIGHT	36.52	5.59	6.53				2.26	0.51	4.43	2.62	0.53	4.98
14. IMU TOP	78.13	13.50	5.79				4.33	0.89	4.88	4.02	0.95	4.24
23. IMU BOTTOM	107.20	16.50	6.50				5.85	1.19	4.92	5.88	1.15	5.11

TRANSISTOR AND SULFUR FLUENCE DATA, SPECTRAL INDEX (SI) X HARDNESS PARAMETER (HP) DATA

SPR II: CD:PLY MODERATED, SHOTS #2311, #2312, #2314, #2315

Location	(Cd:Ply) #2311			(Cd:Ply) #2312			(Cd:Ply) #2314			(Cd:Ply) #2315 Power		
	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s	2N2222 Fluence 1E+11 ϕ_i	Sulfur Fluence 1E+11 ϕ_s	SI * HP ϕ_i / ϕ_s
78. TGG A1	4.19	0.78	5.39	2.10	0.42	5.06	R 0.41	0.10	4.15	30.68	4.37	7.02
83. TGG A2	F 5.20	0.98	5.30	3.78	0.78	4.85	1.50	0.29	5.26	F 52.38	5.90	8.88
88. TGG A3	2.50	0.45	5.58	F 5.24	1.04	5.04	1.74	0.26	6.77	20.93	2.50	8.37
92. SFIR MT1	2.58	0.40	6.42	2.28	0.42	5.40	F 4.81	0.96	5.02	30.91	4.07	7.59
96. SFIR MT2	R 1.00	0.12	8.40	1.14	0.30	3.75	1.65	0.70	2.37	R 8.68	0.80	10.88
102. SFIR MT3	2.02	0.39	5.15	R 0.75	0.10	7.81	2.61	0.48	5.44	22.19	2.87	7.73
30. EXT. A1	F 5.12	1.08	4.74							F 44.55	6.04	7.38
37. EXT. A2	F 6.62	1.38	4.80							F 70.73	8.43	8.39
43. EXT. A3	R 1.97	0.37	5.28							R 15.67	2.28	6.87
49. EXT. A4	R 1.24	0.22	5.64							R 9.52	1.41	6.75
1. IMU FRONT	9.62	2.07	4.65							106.10	13.20	8.04
5. IMU REAR	0.85	0.08	10.55							6.25	0.49	12.83
3. IMU LEFT	2.44	0.50	4.89							18.51	2.77	6.68
7. IMU RIGHT	2.42	0.45	5.34							24.52	2.99	8.20
14. IMU TOP	3.75	0.86	4.34							47.12	5.28	8.92
23. IMU BOTTOM	5.38	1.09	4.94							58.39	7.21	8.10

SUMMARY OF SPECTRAL INDEX (SI) X HARDNESS PARAMETER (HP) DATA

SPR II: FREE FIELD, SHOTS #2301 - #2308, CD:PLY MODERATED SHOTS #2309 - #2315

	FREE FIELD						Cd:Ply MOD.					
	#2301	#2302	#2303	#2304	#2305 Power	#2308	#2309	#2310	#2311	#2312	#2314	#2315 Power
78. TGG A1	5.97	F 6.54	5.72	6.22	6.41	R 6.84	6.21	F 5.42	5.39	5.06	R 4.15	7.02
83. TGG A2	5.87	5.13	F 6.12	6.54	F 8.25	6.17	5.72	4.72	F 5.30	4.85	5.26	F 8.88
88. TGG A3	R 6.98	6.86	5.17	F 7.14	7.32	6.27	R 6.29	5.68	5.58	F 5.04	6.77	8.37
92. SFIR MT1	5.04	R 7.69	5.91	6.14	6.87	F 6.97	5.34	R 8.11	6.42	5.40	F 5.02	7.59
96. SFIR MT2	6.70	6.43	R 7.85	4.98	R 8.88	6.23	6.60	4.83	R 8.40	3.75	2.37	R 10.88
102. SFIR MT3	F 6.25	4.46	5.26	R 8.43	7.15	6.74	F 5.59	5.02	5.15	R 7.81	5.44	7.73
30. EXT. A1	F 5.56	F 5.12	F 5.49		F 6.24		F 4.27	F 5.35	F 4.74			F 7.38
37. EXT. A2	F 6.11	F 6.08	F 5.83		F 7.53		F 5.27	F 5.10	F 4.80			F 8.39
43. EXT. A3	R 4.28	R 4.72	R 4.25		R 5.41		R 4.95	R 5.16	R 5.28			R 6.87
49. EXT. A4	R 5.06	R 3.49	R 4.94		R 5.49		R 5.66	R 5.32	R 5.64			R 6.75
1. IMU FRONT	5.83	6.12	6.27		7.57		5.19	4.60	4.65			8.04
5. IMU REAR	5.50	7.06	6.29		7.49		8.85	8.55	10.55			12.83
3. IMU LEFT	6.33	5.66	4.29		6.94		5.68	4.42	4.89			6.68
7. IMU RIGHT	4.73	5.78	5.35		6.53		4.43	4.98	5.34			8.20
14. IMU TOP	4.76	5.75	5.39		5.79		4.88	4.24	4.34			8.92
23. IMU BOTTOM	5.84	5.76	4.74		6.50		4.92	5.11	4.94			8.10

F = Forward Cavity R = Rear Cavity

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MS	1105	R. J. Leeper, 1277
MS	1141	T. R. Schmidt, 6502
MS	1142	J. W. Bryson, 6521
MS	1142	D. W. Vehar, 6521
MS	1142	C. V. Holm, 6521
MkS	1142	H. R. Synder, 6521
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