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Determination of Damage Exposure Parameter Values in the PSF Metallurgical Irradiation Experiment

F. W. Stallman

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INTRODUCTION

This report describes the neutron spectral characterization of the metallurgical experiment in the Oak Ridge Research Reactor (ORR) Poolside Facility (PSF) pressure vessel simulation (PVS) configuration (Figs. 1 and 2).

Values for the damage exposure parameters ϕt (ϕt = fluence) > 1.0 MeV, ϕt > 0.1 MeV, and displacements per atom (dpa) were estimated with uncertainties for all locations of metallurgical specimens in the test assembly in the ORR-PSF irradiation experiment. In addition, maps of reaction probabilities were determined for all major threshold dosimetry reactions in order to test consistency of this evaluation with dosimetry measurements which were not included. The fluence maps can be expressed as cosine functions in the axial (z) and lateral (x) direction and by an exponential attenuation perpendicular to the core (y) of the form:

$$P(x,y,z) = P_o \cdot \cos B_x(x-x_o) \cos B_z(z-z_o) e^{-\lambda(y-y_o)} \qquad (1)$$

where P(x,y,z) is the integral response in question (see Table 5). The coordinates are adapted from the system described in the ORR-PSF Blind Test (see Fig. 3). The LSL-M2 adjustment procedure[1] was used followed by cosine fits of the adjusted integral parameters. The method is similar to the one described in NUREG/CR3333;[10] for details see the flow diagram (Fig. 4).

DATA AND PROCEDURES

The spectral fluence calculations by R. E. Maerker and B. A. Worley[2,3] were used as the input spectra for the adjustment procedure. These spectra are obtained as a three-dimensional synthesis of two-dimensional transport calculations. Special attention was paid to the changing core configurations during the two-year irradiation. This calculation contained only evergy groups above 0.1 MeV. The spectrum was extended to the epithermal range (>0.4 eV) using the results of a one-dimensional ANISN calculation of the same configuration fitted smoothly to the three-dimensional calculation. Two more thermal groups were added by extrapolating with a 20°C Maxwellian spectrum. One high-energy group (17.33-18 MeV) was also added extrapolating with a Watt fission spectrum. These extrapolations are needed to obtain correct calculated reaction rates from the ENDF/B-V dosimetry cross-section file, which extends from 10^{-4} eV to 18 MeV.

The calculated spectra with extensions were condensed to 37 energy groups as input for the LSL-M2 adjustment procedure. The energy boundaries are listed in Table 1.

The one-dimensional ANISN calculation was also used to determine the amount of fluence perturbation resulting from a water leak which filled the void box capsule with water instead of gas. The ratios of fluences water/void for 11 energy groups are listed in Table 2. No significant perturbations are found in the capsules for energies above 0.1 MeV. The ANISN calculation for water was used for the input fluences at lower energies.

Variances and covariances for the calulated spectra were based on calculations by R. E. Maerker[4] with some modifications reflecting the different energy-group structures. Simplified and somewhat more conservative variance-covariance data were tried before Maerker's results became available. The resulting damage parameter values differ by less than 2%, indicating that the input variances are not critical.

The dosimetry data were taken from the tables in the Blind Test package, which was distributed February 17, 1984.[2] The "gradient" (GS) dosimetry sets H-1 to H-25, the "backbone" (BB) dosimetry sets HB1 to H10, the HEDL surveillance non-fission sets (HSNF) in SSC1, and the gradient wires along the Charpy specimens were used as input for the LSL procedure (see Fig. 2). No other dosimeters were considered; the remaining dosimetry sensors either duplicated the above data or were widely scattered across the metallurgical capsules, at locations where no spectrum calculations are available. Thus, the additional dosimetry is not likely to improve the results of the adjustment procedure. However, the fluence map obtained from the adjustment procedure can be used to test the remaining dosimetry for consistency.

The H-1 to H-25 capsules each contained a set of non-fission sensors consisting of $^{63}Cu(n,\alpha)^{60}Co$, $^{46}Ti(n,p)^{46}Sc$, $^{58}Ni(n,p)^{58}Co$, $^{54}Fe(n,p)^{54}Mn$, $^{59}Co(n,\gamma)^{60}Co$, $^{58}Fe(n,\gamma)^{59}Fe$, $^{45}Sc(n,\gamma)^{46}Sc$, and $^{109}Ag(n,\gamma)^{110}Ag$. The $^{109}Ag(n,\gamma)$ reaction was excluded because its cross section is not listed in the ENDF/B-V dosimetry file, and three other non-threshold reactions are available. The HB1 to HB10 capsules contained, in addition, the three fission sensors $^{238}U(n,f)$, $^{237}Np(n,f)$, and $^{235}U(n,f)$, with all sensors encapsulated in gadolinium. The count rates published in Ref. 2 for all sensors were converted to reaction probabilities time integrated reaction rates on the basis of the time power history of the irradiation taking into account the difference in core leakage for the different core configurations.[2] Nuclear data were obtained from Ref. 5 and fission yields from Ref. 6. There are slight differences between our evaluation of reaction probabilities and Ref. 2 due to differences in nuclear data, none of them significantly affecting the results of the adjustment procedure. The reaction rate uncertainties were estimated to be 4% for non-fission and 8% for fission reactions (one standard deviation). Averages were calculated whenever more than one reaction was measured at the same location or more than one fission product for the same fission sensor. No photo-fission corrections were made since the measurements and calculations for an identical configuration in the Pool Critical Assembly (PCA) reactor shows negligible effect of photo-fission.[7]

Group cross sections and covariances were obtained from the ENDF/B-V dosimetry file as presented in the IRDF-83 file[8] through the PUFF[9] processing code. The first adjustment runs showed strong inconsistencies which were traced to the $^{238}U(n,f)$ reaction. Its uncertainties were then increased to 500%, resulting in ajustments of the $^{238}U(n,f)$ reaction rates in the order of 30 to 50% in the SSC2 and 0-T positions. [Relative changes are given as the natural logarithm of quotients of the two quantities, e.g., 50% adjustment means $|\ln(x_{adj}/x_{orig.})| = 0.5$; the same definition applies to relative variances.] There were also large differences in reaction probabilities when calculated for the same sensor based on different fission products. These discrepancies can be explained as a consequence of ^{239}Pu "burn-in," that is the production of plutonium by neutron capture of ^{238}U. A detailed investigation of the effects is given in the Appendix. Correction terms can be determined, but the uncertainties in these corrections are very large so that no useful spectral information can be obtained from the $^{238}U(n,f)$ reaction at the SSC2 and 0-T locations.

The LSL-M2 method allows both absolute and relative adjustments. In the latter, only the shape of the calulated spectrum is used with an unrestricted scale factor determined from the differences in magnitude between dosimetry and calculation. Both were tried and no significant difference in the results were found. This means that calculation agrees with the dosimetry equally well in terms of absolute fluences, as in terms of the shape of the fluence spectrum. All results, which are reported here, are based on absolute values of the fluence calculation. Values of Chi-square per degree of freedom are in the order of 0.8, which indicates a good consistency within the input data, and uncertainties that are somewhat on the conservative side. Values of the damage parameters at the center gradient capsules with uncertainties are listed in Table 3. The values of the total and thermal fluences are also included for completeness.

Determination of Gradients

It is possible, in theory, to determine damage parameter values or any other integral responses at any point through a suitable adjustment procedure, such as LSL-M2, even if no dosimeters are located at that position. However, there are practical limitations to the number of spectra and dosimeter measurements which can be processed simultaneously. The direct determination of damage parameters was, therefore, restricted to relatively few points, completing the map through suitable interpolation and extrapolation procedures. Experience has shown that a cosine curve describes fairly accurately the fluences along lines parallel to the core, provided regions of boundary reflection are avoided and the peripheral core loading is sufficiently uniform. It is also reasonable to assume that there is an exponential attenuation of fluences in directions perpendicular to the reactor, at least for sufficiently small distances and not too close to boundaries between different materials.

Experience from this and other experiments with similar configurations (Refs. 10 and 11) have shown that a combined cosine-exponential fit describes accurately the fluence distributions if the interpolation/extrapolation is confined within the boundaries of each metallurgical capsule. A more detailed discussion of the uncertainties is given below.

The first step in the fitting procedure was to fit the $^{54}Fe(n,p)$ reaction probabilities of the gradient wires to a cosine function

$$P(z) = P_C \cos B_z(z-z_0) \quad . \qquad (2)$$

The measurements fit the cosine curve very well, as expected. The residuals are consistent with measuring and positioning errors and appear to be random. A typical example is given in Fig. 5. The two exceptions are the right front of the 1/4T capsule and the right rear of the 1/2T capsule. The data for these two wires are incomplete and appear to be mislabelled since the parallel wire does not show any irregularity. The fitting parameters with standard deviations are listed in Table 4. Fits at the center, which are explained below, are included for comparison.

Ratios of the peak values of parallel gradient wires determine the attenuation of $^{54}Fe(n,p)$ reaction rates along lines perpendicular to the core. There are no significant differences between the left and the right sides but definite changes from capsule to capsule. It was, therefore, assumed that one attenuation coefficient can be applied to all positions within the same capsule but that each capsule has a different coefficient (for experimental confirmation of exponential attenuation, see Ref. 11). The attenuation coefficients for several other integral parameters (damage parameters and threshold reaction rates) were determined by applying the adjustment procedure to positions of the gradient wires and taking the ratios of the adjusted parameter values (see Table 5).

The final lateral (x) and axial (z) cosine fits were made using adjusted values at dosimeter locations along the centerlines, including gradient wires for the x-direction. Typical fits are shown in Figs. 6 and 7. Typical uncertainties for these fits can be found in Table 4 for the center $^{54}Fe(n,p)$ fits. All other fitting parameters, both axial and lateral, have standard deviations of the same size, which are somewhat larger than the standard deviations for the gradient wire fits since there are fewer data points. There are no significant differences in the B_z and z_0 values between center and gradient wire fits within the same capsule, but again, there are significant capsule-to-capsule variations. Thus, one set of fitting parameters can be used within each capsule for a particular integral parameter. Peak values P_0 are also consistent for lateral and axial fits. A complete list of fitting parameters is given in Table 5.

Formula (1) with the parameters from Table 5 provides a complete map of integral parameters, where each set of coefficients is valid within a given metallurgical capsule. Tables 7-11 list the damage parameter values at the crack tips of every metallurgical specimen. These values were calculated for the specimen coordinates in Table 6. Using the values in Tables 7-11, average, maximum, and minimum values are determined for each set of Charpy specimens from the same material and listed in Table 12.

Determination of Uncertainties

The LSL-M2 adjustment procedure provides variances and covariances for all values of adjusted integral parameters. Typical values are found in Table 3. These values are based on the uncertainties for the input data, i.e., transport calculation, dosimetry measurements, and cross sections. For the specimen values in Tables 7-12, however, additional uncertainties are introduced through the use of the fitting-interpolation formula (1). These uncertainties are not the same for all locations but depend on the distance of the specimen from the center. The uncertainties for the attenuation coefficient λ can be calculated directly to be about 3%/cm. Typical uncertainties for the coefficients of the cosine fits are given in Table 4. This translates to additional uncertainties ranging from zero at the center to about 5% at the corners of the capsule. All these uncertainties are in themselves rather uncertain, and a more detailed assignment of uncertainties to individual specimens is, therefore, rather pointless. It suffices to say that none of the estimated standard deviation for damage parameters exceeds 10%. This should be sufficiently accurate for damage correlation studies considering the large variability in metallurgical test results.

CONCLUSIONS

Damage fluences received by the metallurgical specimens in the PSF-PVS experiment can be determined to an accuracy of better than 10%. This is accomplished by combining neutron physics calculations with dosimetry measurement in the multiple spectrum adjustment method LSL-M2. The spatial fluence distribution can be approximated by a cosine-exponential fit which is accurate to better than 5% within each capsule. The same procedure can be used to test the consistency of dosimetry measurements. The accuracy of the spectral characterization is sufficient to establish the PSF-PVS experiment as a benchmark as intended.

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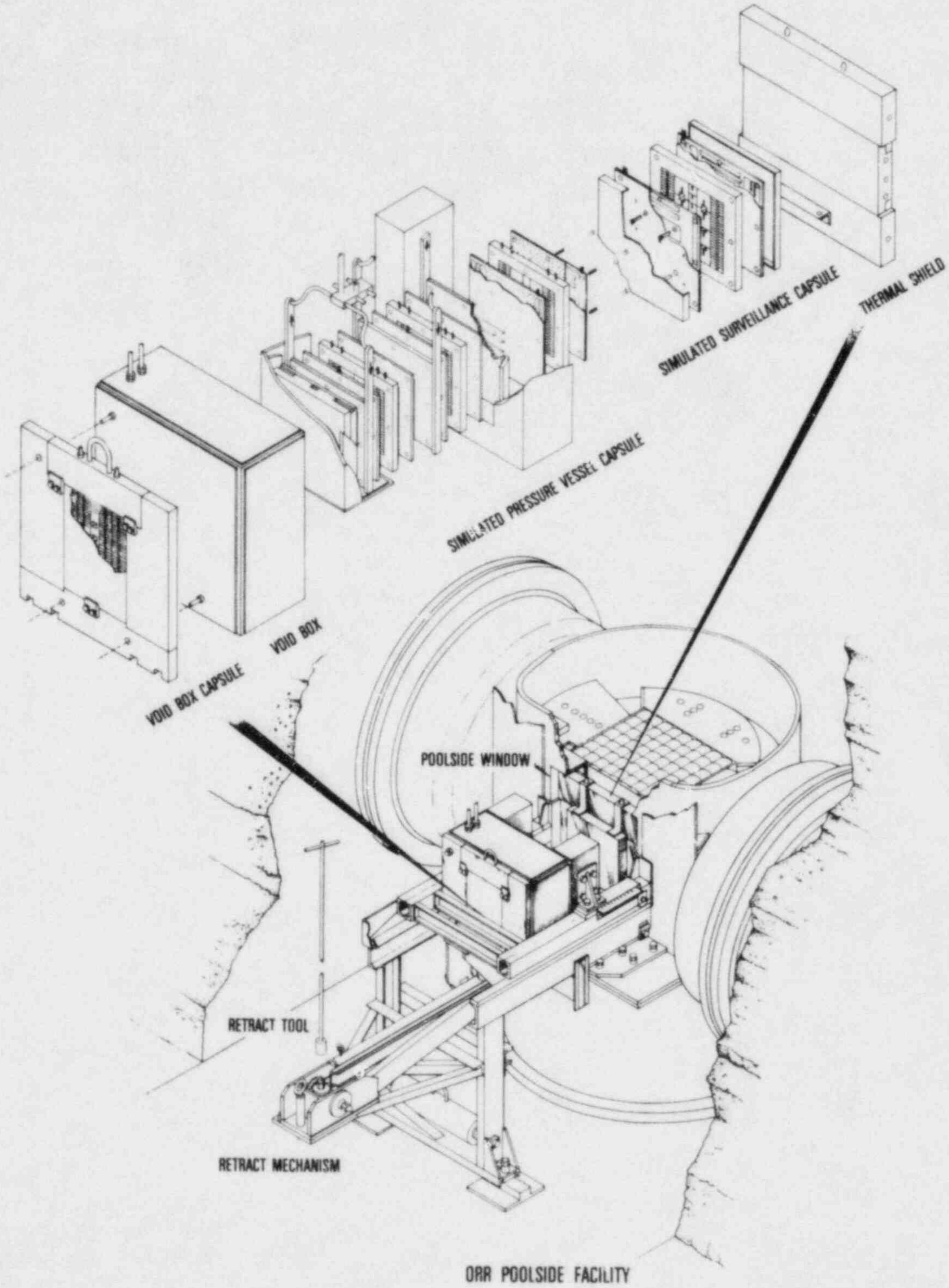

Fig. 1. View of the PSF facility.

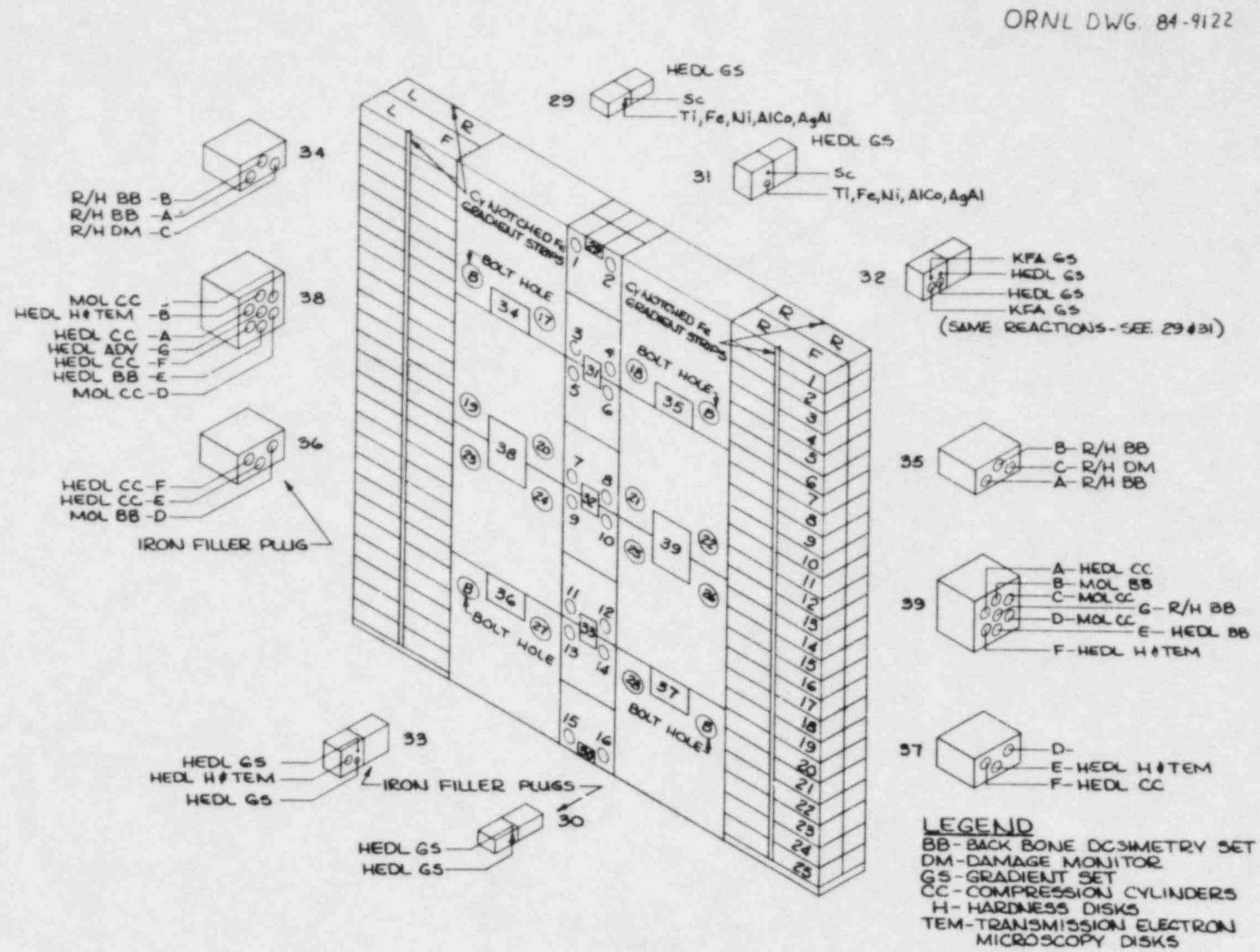

Fig. 2. Illustration of dosimeter and metallurgical specimen locations in the irradiation capsules.

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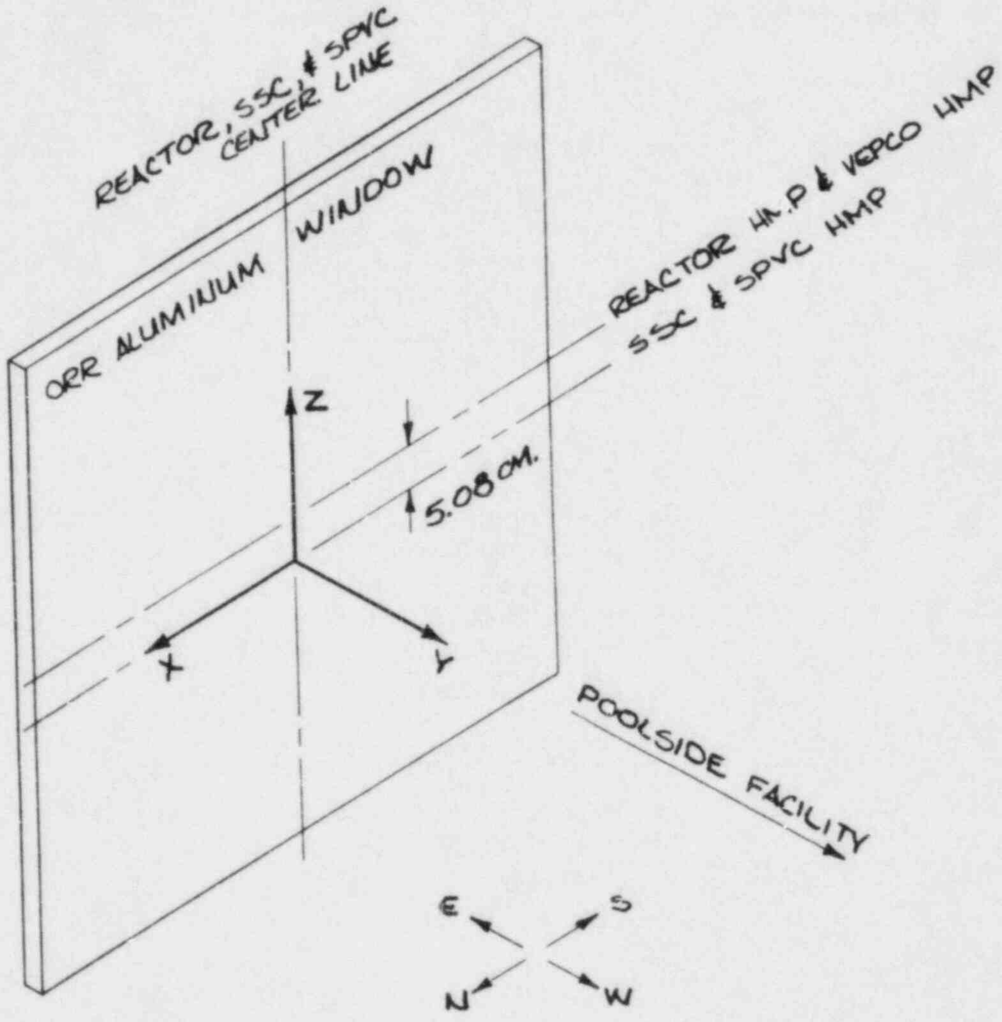

Fig. 3. Coordinate system for the ORR-PSF metallurgical experiment.

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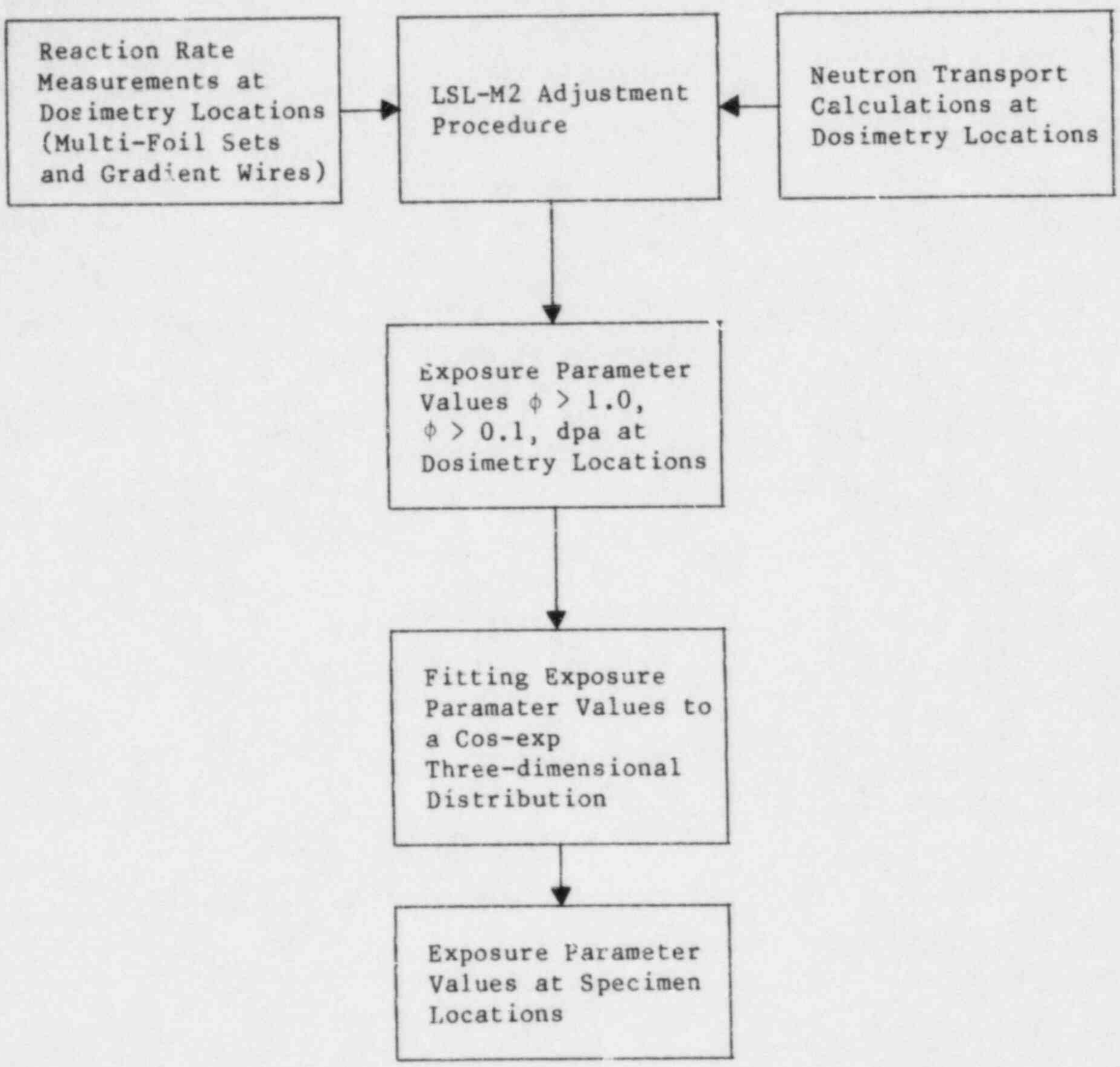

Fig. 4. Methodology for the determination of exposure parameter values and uncertainties.

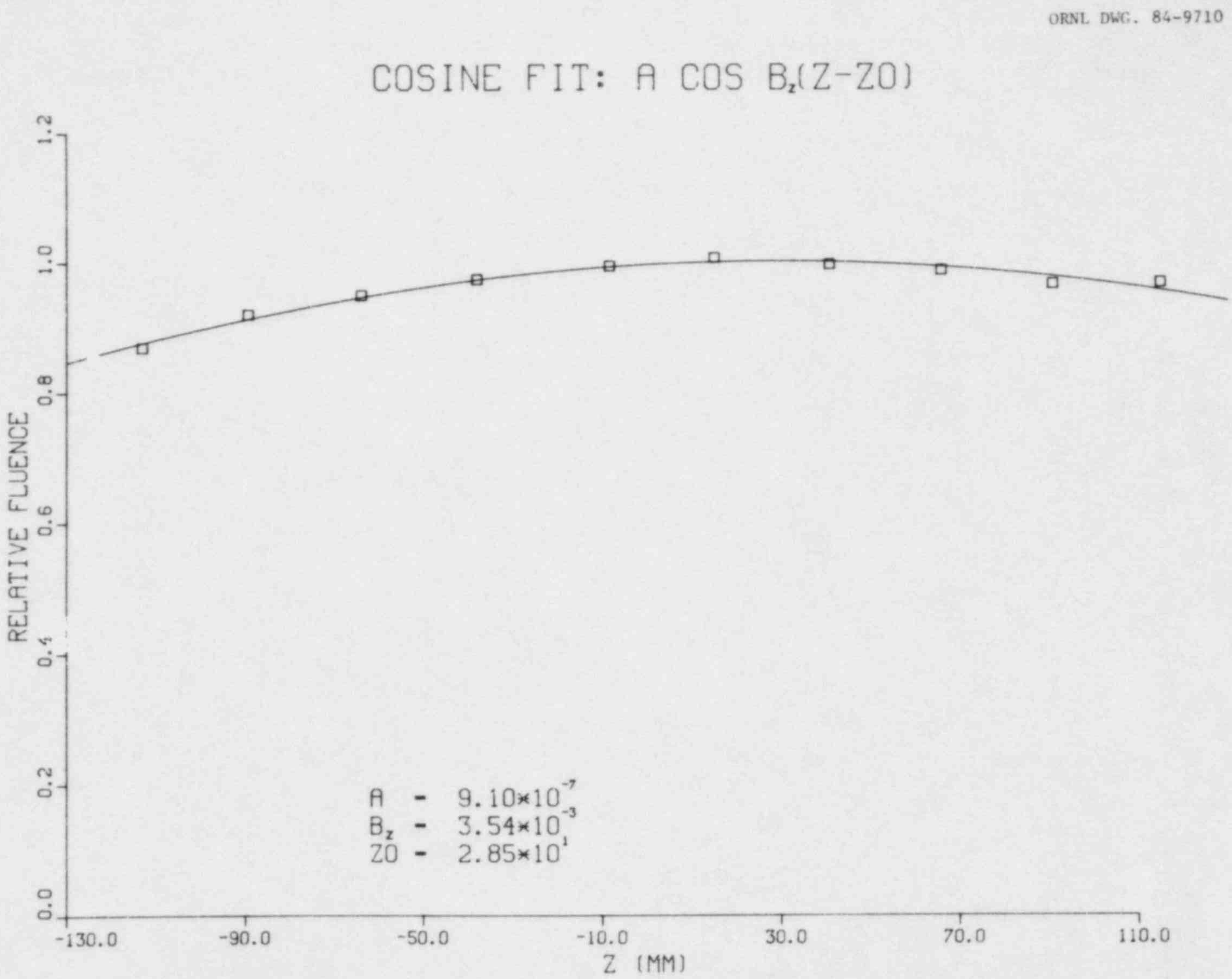

Fig. 5. Cosine fit of the $^{54}Fe(n,p)$ reaction along the gradient wire positioned at the left rear row of Charpy specimens in the 1/4T capsule.

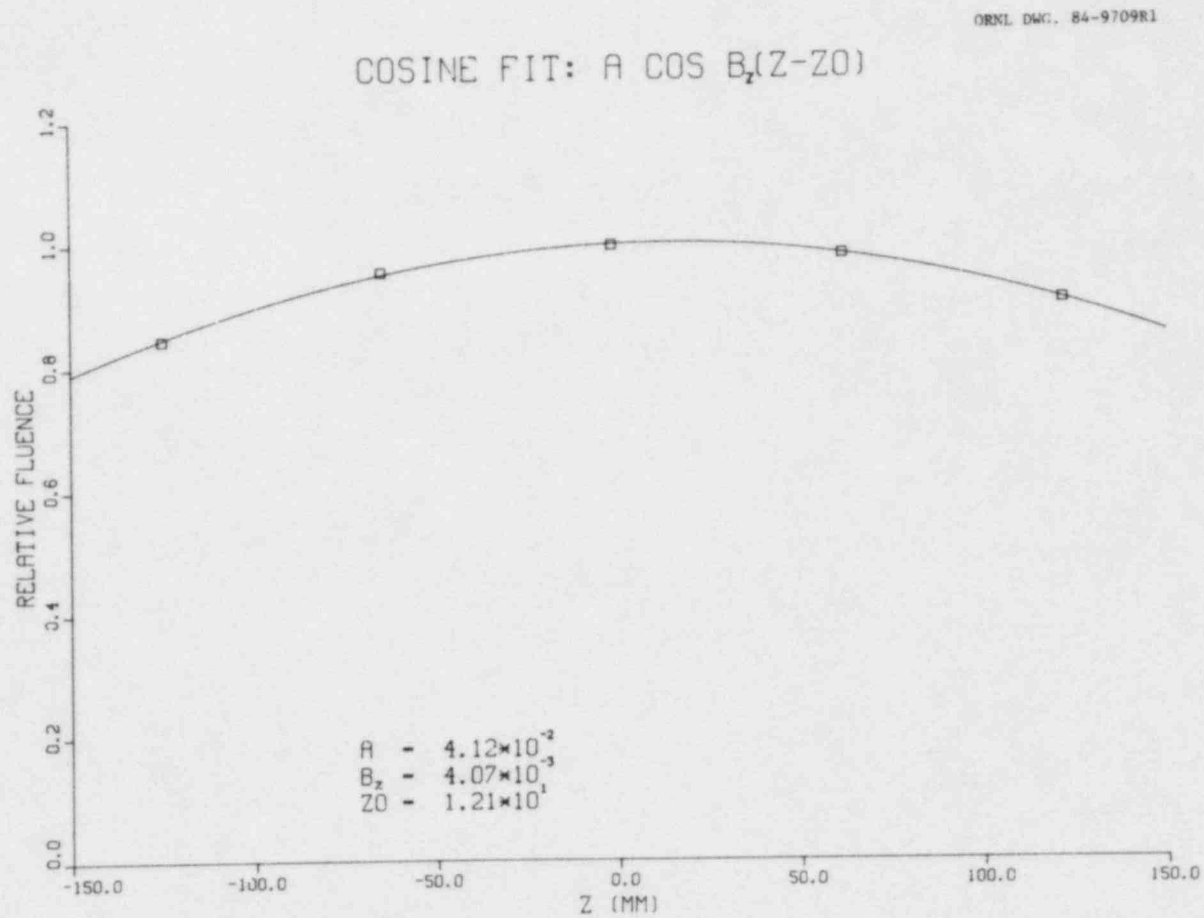

Fig. 6. Cosine fit of dpa determined from the gradient sets H-16 to H-20 at the axial centerline of the 1/4T capsule.

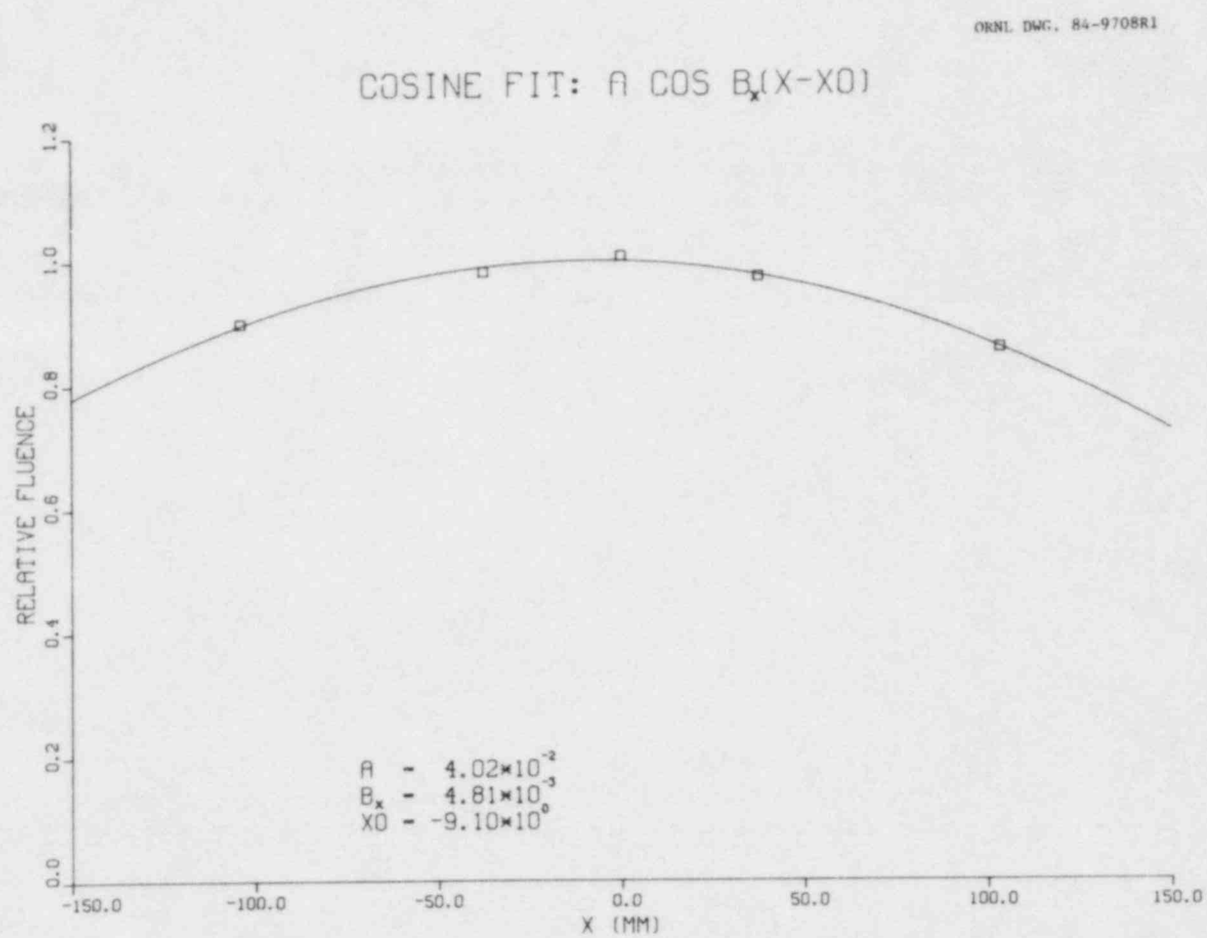

Fig. 7. Cosine fit of dpa in the lateral direction along the centerline of the 1/4T capsule.

Table 1. Energy groups used for the LSL-M2 adjustment procedure in the ORR-PSF metallurgical irradiation experiment

Group no.	Upper energy boundary (eV)
1	1.800 E+7
2	1.733 E+7
3	1.221 E+7
4	1.000 E+7
5	7.408 E+6
6	6.065 E+6
7	4.066 E+6
8	2.725 E+6
9	2.466 E+6
10	2.123 E+6
11	1.827 E+6
12	1.496 E+6
13	1.353 E+6
14	1.003 E+6
15	8.209 E+5
16	6.081 E+5
17	3.020 E+5
18	1.832 E+5
19	9.804 E+4
20	8.652 E+4
21	6.738 E+4
22	4.087 E+4
23	3.431 E+4
24	2.606 E+4
25	2.418 E+4
26	2.188 E+4
27	1.503 E+4
28	1.171 E+4
29	7.102 E+3
30	5.531 E+3
31	3.355 E+3
32	2.612 E+3
33	1.585 E+3
34	1.023 E+2
35	1.068 E+1
36	4.140 E-1
37	1.265 E-1
lowest energy	1.000 E-4

Table 2. Fluence perturbation due to water in the void box

Upper energy (eV)	Fluence ratio water/void					
	SSC	0-T	1/4T	1/2T	3/4T	Void box
1.7333 E+7	1.00	1.00	1.00	1.00	1.00	0.59
8.6071 E+6	1.00	1.00	1.00	1.00	1.00	0.53
4.9659 E+6	1.00	1.00	1.00	1.00	0.99	0.33
2.5924 E+6	1.00	1.00	1.00	1.00	0.98	0.23
2.1225 E+6	1.00	1.00	1.00	1.00	0.97	0.14
1.3534 E+6	1.00	1.00	1.00	0.99	0.95	0.06
7.4274 E+5	1.00	0.98	0.96	0.93	0.86	0.03
2.1280 E+5	1.00	0.97	0.94	0.89	0.80	0.03
6.7379 E+4	1.00	0.96	0.93	0.88	0.80	0.04
2.1875 E+4	1.00	0.97	0.94	0.88	0.79	0.06
3.3546 E+3	1.00	0.99	0.98	0.95	0.93	0.17

Table 3. Fluences and dpa at capsule centers

	ϕ>1.0 MeV 10^{19} n/cm^2*	Std. dev. (%)	ϕ>0.1 MeV 10^{19} n/cm^2	Std. dev. (%)	ϕ<0.4 eV 10^{19} n/cm^2	Std. dev. (%)	ϕ_{total} 10^{19} n/cm^2	Std. dev. (%)	dpa (10^{-2})	Std. dev. (%)
SSC1										
H-4	2.56	5.1%	7.74	5.8%	1.26	7.4%	14.20	5.8%	4.07	4.9%
SSC2										
H-9	5.50	5.1%	16.84	5.8%	2.79	7.4%	30.55	5.5%	8.80	4.9%
0-T										
H-14	4.10	5.1%	12.26	5.8%	6.29	7.6%	27.66	5.8%	6.56	4.9%
1/4T										
H-19	2.21	5.2%	8.98	6.0%	0.84	7.9%	14.75	5.5%	4.13	5.2%
1/2T										
H-24	1.05	5.4%	5.83	6.0%	0.27	8.3%	9.17	5.6%	2.39	5.4%

*10^{19} n/cm^2 is 10^{19} neutrons/cm^2, which was shortened for the table heading.

Table 4. Cosine fit to the gradient wires

	Position	P_0*	B_z (cm^{-1})	Std. dev. (cm^{-1})	z_0 (cm)	Std. dev. (cm)
SSC1	left front	1.80E-6	0.0424	±0.0009	0.43	±0.15
	left rear	1.11E-6	0.0420	±0.0009	1.49	±0.11
	right front	1.84E-6	0.0429	±0.0006	1.13	±0.11
	right rear	1.13E-6	0.0449	±0.0010	1.10	±0.15
	center	1.62E-6	0.0419	±0.0150	1.47	±0.03
0-T	left front	3.08E-6	0.0377	±0.0026	1.29	±0.47
	left rear	2.06E-6	0.0379	±0.0011	1.93	±0.20
	right front	2.94E-6	0.0382	±0.0009	1.53	±0.16
	right rear	1.96E-6	0.0374	±0.0010	1.80	±0.19
	center	2.8[illegible]	0.0363	±0.0084	0.91	±0.02
1/4T	left front	1.39E-6	0.0357	±0.0009	2.87	±0.20
	left rear	9.10E-7	0.0354	±0.0016	2.85	±0.38
	right front	1.31E-6	0.0242	±0.0080	-0.75	±2.40**
	right rear	8.68E-7	0.0339	±0.0016	3.03	±0.38
	center	1.24E-6	0.0331	±0.0144	1.88	±0.04
1/2T	left front	5.47E-7	0.0318	±0.0010	4.34	±0.29
	left rear	3.55E-7	0.0315	±0.0011	4.61	±0.34
	right front	5.21E-7	0.0332	±0.0008	2.93	±0.20
	right rear	3.39E-7	0.0203	±0.0079	1.30	±2.00**
	center	4.78E-7	0.0307	±0.0169	4.27	±0.06

*P_0 = peak value of the reaction probability of the $^{54}Fe(n,p)^{54}Mn$ reaction. Standard deviation is less than 2% in all cases.

**Incomplete and irregular data, possible mislabelling.

Table 5. Fitting parameters for formula (1)

	P_0	B_x (cm^{-1})	x_0 (cm)	B_z (cm^{-1})	z_0 (cm)	λ (cm^{-1})	y_0 (cm)
SSC1							
$\phi t > 1.0$ MeV*	2.500E+19	0.0499	0.41	0.0436	0.97	0.176	13.29
$\phi t > 0.1$ MeV*	7.607E+19	0.0507	0.37	0.0464	0.80	0.134	13.29
dpa	3.995E-02	0.0502	0.38	0.0449	0.90	0.156	13.29
^{237}Np(n,f)	6.679E-05	0.0504	0.38	0.0449	0.89	0.152	13.29
^{93}Nb(n,n')	5.598E-06	0.0497	0.41	0.0437	0.97	0.174	13.29
^{238}U(n,f)	8.763E-06	0.0493	0.41	0.0428	1.04	0.191	13.29
^{58}Ni(n,p)	2.212E-06	0.0471	0.41	0.0417	1.18	0.205	13.29
^{54}Fe(n,p)	1.622E-06	0.0467	0.42	0.0419	1.47	0.20[illegible]	13.29
^{46}Ti(n,p)	2.077E-07	0.0439	0.40	0.0406	1.31	0.209	13.29
^{63}Cu(n,α)	1.091E-08	0.0417	0.38	0.0402	1.38	0.202	13.29
SSC2							
$\phi t > 1.0$ MeV*	5.341E+19	0.0528	-0.95	0.0457	0.03	0.176	13.29
$\phi t > 0.1$ MeV*	1.648E+20	0.0539	-0.88	0.0484	-0.02	0.134	13.29
dpa	8.580E-02	0.0533	-0.91	0.0470	0.02	0.156	13.29
^{237}Np(n,f)	1.437E-04	0.0536	-0.90	0.0470	0.02	0.152	13.29
^{93}Nb(n,n')	1.196E-05	0.0526	-0.94	0.0458	0.03	0.174	13.29
^{238}U(n,f)	1.862E-05	0.0521	-0.97	0.0449	0.06	0.191	13.29
^{58}Ni(n,p)	4.644E-06	0.0497	-1.08	0.0437	0.12	0.205	13.29
^{54}Fe(n,p)	3.407E-06	0.0483	-1.15	0.0415	0.63	0.207	13.29
^{46}Ti(n,p)	4.309E-07	0.0467	-1.24	0.0426	0.20	0.209	13.29
^{63}Cu(n,α)	2.252E-08	0.0449	-1.33	0.0421	0.24	0.202	13.29
O-T							
$\phi t > 1.0$ MeV*	3.924E+19	0.0517	-0.69	0.0395	0.72	0.107	24.05
$\phi t > 0.1$ MeV*	1.214E+20	0.0522	-0.64	0.0432	0.71	0.042	24.05
dpa	6.452E-02	0.0516	-0.67	0.0414	0.71	0.079	24.05
^{237}Np(n,f)	1.055E-04	0.0523	-0.66	0.0416	0.69	0.071	24.05
^{93}Nb(n,n')	8.897E-06	0.0514	-0.69	0.0397	0.73	0.107	24.05
^{238}U(n,f)	1.432E-05	0.0509	-0.72	0.0386	0.76	0.133	24.05
^{58}Ni(n,p)	3.796E-06	0.0488	-0.80	0.0366	0.89	0.169	24.05
^{54}Fe(n,p)	2.805E-06	0.0482	-0.83	0.0363	0.91	0.174	24.05
^{46}Ti(n,p)	3.987E-07	0.0467	-0.92	0.0354	0.97	0.186	24.05
^{63}Cu(n,α)	2.304E-08	0.0458	-0.96	0.0354	0.92	0.183	24.05

Table 5. Continued

	P_0	B_x (cm^{-1})	x_0 (cm)	B_z (cm^{-1})	z_0 (cm)	λ (cm^{-1})	y_0 (cm)
1/4T							
ϕt>1.0 MeV*	2.143E+19	0.0478	-0.96	0.0378	1.30	0.134	28.56
ϕt>0.1 MeV*	8.823E+19	0.0486	-0.86	0.0425	1.14	0.070	28.56
dpa	4.037E-02	0.0481	-0.91	0.0407	1.21	0.097	28.56
^{237}Np(n,f)	6.650E-05	0.0483	-0.92	0.0407	1.16	0.098	28.56
^{93}Nb(n,n')	4.957E-06	0.0478	-0.95	0.0385	1.27	0.127	28.56
^{238}U(n,f)	7.137E-06	0.0479	-0.97	0.0366	1.41	0.153	28.56
^{58}Ni(n,p)	1.697E-06	0.0468	-1.06	0.0336	1.80	0.177	28.56
^{54}Fe(n,p)	1.237E-06	0.0460	-1.10	0.0331	1.88	0.181	28.56
^{46}Ti(n,p)	1.714E-07	0.0462	-1.11	0.0318	2.08	0.187	28.56
^{63}Cu(n,α)	1.018E-08	0.0463	-1.12	0.0321	2.01	0.181	28.56
1/2T							
ϕt>1.0 MeV*	1.016E+19	0.0441	-0.94	0.0349	1.94	0.146	33.70
ϕt>0.1 MeV*	5.727E+19	0.0452	-0.79	0.0413	1.48	0.089	33.70
dpa	2.333E-02	0.0450	-0.83	0.0395	1.59	0.107	33.70
^{237}Np(n,f)	3.773E-05	0.0450	-0.84	0.0393	1.54	0.111	33.70
^{93}Nb(n,n')	2.468E-06	0.0443	-0.91	0.0365	1.80	0.135	33.70
^{238}U(n,f)	3.085E-06	0.0436	-1.00	0.0330	2.20	0.163	33.70
^{58}Ni(n,p)	6.588E-07	0.0423	-1.10	0.0281	3.38	0.183	33.70
^{54}Fe(n,p)	4.777E-07	0.0448	-0.98	0.0307	4.27	0.186	33.70
^{46}Ti(n,p)	6.389E-08	0.0419	-1.20	0.0246	4.74	0.190	33.70
^{63}Cu(n,α)	3.924E-09	0.0428	-1.16	0.0255	4.36	0.182	33.70

*Neutrons/cm^2.

Table 6. Coordinates of the locations of the metallurgical specimens relative to the capsule center (all coordinates in cm)

No.[a]	z	x (left)	x (right)	$(y-y_0)^b$ (front)	$(y-y_0)^b$ (rear)
			Charpy Specimens		
1	12.20	-10.37	+10.37	-1.07	+1.07
2	11.20	-10.37	+10.37	-1.07	+1.07
3	10.20	-10.37	+10.37	-1.07	+1.07
4	9.20	-10.37	+10.37	-1.07	+1.07
5	8.20	-10.37	+10.37	-1.07	+1.07
6	7.19	-10.37	+10.37	-1.07	+1.07
7	6.19	-10.37	+10.37	-1.07	+1.07
8	5.19	-10.37	+10.37	-1.07	+1.07
9	4.19	-10.37	+10.37	-1.07	+1.07
10	3.19	-10.37	+10.37	-1.07	+1.07
11	2.19	-10.37	+10.37	-1.07	+1.07
12	1.19	-10.37	+10.37	-1.07	+1.07
13	0.19	-10.37	+10.37	-1.07	+1.07
14	-0.81	-10.37	+10.37	-1.07	+1.07
15	-1.81	-10.37	+10.37	-1.07	+1.07
16	-2.82	-10.37	+10.37	-1.07	+1.07
17	-3.82	-10.37	+10.37	-1.07	+1.07
18	-4.82	-10.37	+10.37	-1.07	+1.07
19	-5.82	-10.37	+10.37	-1.07	+1.07
20	-6.82	-10.37	+10.37	-1.07	+1.07
21	-7.82	-10.37	+10.37	-1.07	+1.07
22	-8.82	-10.37	+10.37	-1.07	+1.07
23	-9.82	-10.37	+10.37	-1.07	+1.07
24	-10.82	-10.37	+10.37	-1.07	+1.07
25	-11.82	-10.37	+10.37	-1.07	+1.07
			1/2 CT Specimens		
29	11.39	0.0		-0.64	+0.64
31T[c]	8.22	0.0		-0.64	+0.64
31B[c]	4.48	0.0		-0.64	+0.64
32T	1.87	0.0		-0.64	+0.64
32B	-1.87	0.0		-0.64	+0.64
33T	-4.48	0.0		-0.64	+0.64
33B	-8.22	0.0		-0.64	+0.64
30	-11.39	0.0		-0.64	+0.64

Table 6. Continued

No.[c]	z	x (left)	x (right)	$(y-y_o)^b$ (front)	$(y-y_o)^b$ (rear)
			1 CT Specimens		
34	10.05	-4.57		0.0	
38T	3.70	-4.57		0.0	
38B	-3.70	-4.57		0.0	
36	-10.05	-4.57		0.0	
35	10.05		4.57	0.0	
39T	3.70		4.57	0.0	
39B	-3.70		4.57	0.0	
37	-10.05		4.57	0.0	

[a]For numbers of specimens, refer to Fig. 2.

[b]For values of y_o for different capsules, see Table 2.

[c]31T = specimen on top of hole 31.
31B = specimen below hole 31, etc.

Table 7. Damage parameter values at the locations of metallurgical specimens - capsule SSC1

Charpy Specimen

Spec. No.	Fluence >1 MeV 10^{19} n/cm^2*	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm^2	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm^2	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm^2	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})
Left Front				Right Front				Left Rear				Right Rear			
1	2.287	6.483	3.539	1	2.341	6.626	3.617	1	1.570	4.868	2.535	1	1.607	4.975	2.592
2	2.338	6.652	3.624	2	2.393	6.798	3.704	2	1.605	4.995	2.596	2	1.643	5.105	2.654
3	2.384	6.806	3.702	3	2.441	6.956	3.783	3	1.637	5.111	2.652	3	1.675	5.223	2.710
4	2.426	6.946	3.772	4	2.484	7.099	3.855	4	1.666	5.216	2.702	4	1.705	5.331	2.762
5	2.464	7.071	3.834	5	2.522	7.227	3.919	5	1.691	5.310	2.747	5	1.731	5.427	2.807
6	2.497	7.181	3.889	6	2.555	7.339	3.975	6	1.714	5.392	2.786	6	1.754	5.511	2.847
7	2.524	7.275	3.935	7	2.584	7.435	4.022	7	1.733	5.463	2.819	7	1.774	5.583	2.882
8	2.548	7.354	3.974	8	2.608	7.515	4.062	8	1.749	5.522	2.847	8	1.790	5.643	2.910
9	2.566	7.416	4.005	9	2.626	7.579	4.094	9	1.761	5.569	2.869	9	1.803	5.691	2.933
10	2.579	7.463	4.028	10	2.640	7.627	4.117	10	1.770	5.604	2.886	10	1.812	5.727	2.949
11	2.588	7.493	4.042	11	2.649	7.658	4.132	11	1.776	5.627	2.896	11	1.818	5.751	2.960
12	2.591	7.508	4.049	12	2.652	7.673	4.138	12	1.779	5.638	2.901	12	1.821	5.762	2.965
13	2.590	7.506	4.047	13	2.651	7.671	4.137	13	1.778	5.636	2.899	13	1.820	5.760	2.963
14	2.584	7.488	4.037	14	2.644	7.653	4.127	14	1.773	5.623	2.892	14	1.815	5.746	2.956
15	2.572	7.454	4.019	15	2.633	7.618	4.108	15	1.766	5.597	2.879	15	1.807	5.720	2.943
16	2.556	7.404	3.993	16	2.616	7.567	4.081	16	1.755	5.559	2.861	16	1.796	5.682	2.924
17	2.535	7.337	3.959	17	2.595	7.499	4.046	17	1.740	5.510	2.836	17	1.781	5.631	2.899
18	2.509	7.255	3.917	18	2.568	7.415	4.003	18	1.722	5.448	2.806	18	1.763	5.568	2.868
19	2.479	7.158	3.866	19	2.537	7.315	3.952	19	1.701	5.375	2.770	19	1.741	5.493	2.8[illegible]1
20	2.443	7.045	3.808	20	2.501	7.200	3.893	20	1.677	5.290	2.728	20	1.717	5.406	2.789
21	2.403	6.916	3.743	21	2.460	7.069	3.826	21	1.650	5.193	2.681	21	1.689	5.308	2.741
22	2.359	6.773	3.670	22	2.414	6.922	3.751	22	1.619	5.086	2.629	22	1.657	5.198	2.6[illegible]7
23	2.310	6.615	3.589	23	2.364	6.761	3.668	23	1.585	4.967	2.571	23	1.623	5.077	2.628
24	2.256	6.443	3.501	24	2.309	6.585	3.579	24	1.549	4.838	2.508	24	1.585	4.945	2.564
25	2.199	6.257	[illegible].406	25	2.250	6.395	3.482	25	1.509	4.698	2.440	25	1.545	4.802	2.494

1/2 CT Specimen / **1 CT Specimen**

1/2 CT Front				1/2 CT Rear				1 CT Left				1 CT Right			
F23-10R	2.511	7.301	3.930	F23-40R	[illegible].008	6.158	3.224	F23-5R	2.236	6.701	3.550	F23-17R	2.257	6.761	3.582
F23-15R	2.657	7.796	4.174	F23-42R	2.125	6.576	3.424	F23-9R	2.406	7.303	3.842	F23-21R	2.429	7.368	3.876
F23-20R	2.762	8.161	4.353	F23-52R	2.209	6.884	3.571	F23-13R	2.373	7.210	3.790	3PS-12	2.396	7.274	3.824
F23-25R	2.793	8.271	4.406	F23-63R	2.233	6.977	3.614	3PS-11	2.149	6.455	3.414	3PS-14	2.169	6.513	3.444
F23-30R	2.774	8.218	4.376	F23-66R	2.218	6.932	3.590								
3PU-1	2.716	8.034	4.282	3PU-21	2.172	6.776	3.512								
3PU-9	2.574	7.567	4.046	3PU-29	2.058	6.383	3.319								
3PU-13	2.399	6.991	3.755	3PU-33	1.918	5.897	3.080								

*Neutrons per cm^2.

Table 8. Damage parameter values at the locations of metallurgical specimens - capsule SSC2

Spec. No.	Fluence >1 MeV 10^{19} n/cm²*	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})
Charpy Specimen															
Left Front				Right Front				Left Rear				Right Rear			
1	4.812	13.767	7.461	1	4.526	12.973	7.027	1	3.303	10.338	5.345	1	3.107	9.742	5.034
2	4.944	14.199	7.679	2	4.650	13.380	7.232	2	3.393	10.662	5.501	2	3.192	10.047	5.181
3	5.065	14.597	7.879	3	4.764	13.755	7.421	3	3.477	10.961	5.645	3	3.270	10.329	5.317
4	5.176	14.961	8.063	4	4.868	14.099	7.594	4	3.555	11.234	[illegible]	4	3.342	10.586	5.440
5	5.276	15.290	8.228	5	4.962	14.408	7.750	5	3.621	11.481	[illegible]	5	3.406	10.819	5.552
6	5.365	15.583	8.376	6	5.046	14.685	7.889	6	3.682	11.701	6.000	6	3.464	11.027	5.651
7	5.442	15.840	8.505	7	5.119	14.926	8.010	7	3.736	11.894	6.093	7	3.514	11.208	5.738
8	5.509	16.059	8.615	8	5.181	15.133	8.114	8	3.781	12.059	6.171	8	3.557	11.363	5.813
9	5.563	16.241	8.706	9	5.233	15.304	8.199	9	3.819	12.195	6.237	9	3.592	11.492	5.874
10	5.607	16.384	8.777	10	5.274	15.439	8.267	10	3.848	12.303	6.288	10	3.620	11.593	5.922
11	5.638	16.489	8.829	11	5.303	15.538	8.316	11	3.870	12.382	6.325	11	3.640	11.668	5.958
12	5.658	16.556	8.862	12	5.322	15.601	8.347	12	3.883	12.431	6.349	12	3.653	11.715	5.980
13	5.665	16.583	8.875	13	5.329	15.627	8.359	13	3.889	12.452	6.358	13	3.658	11.734	5.988
14	5.661	16.572	8.869	14	5.325	15.616	8.353	14	3.886	12.444	6.353	14	3.655	11.726	5.984
15	5.645	16.521	8.843	15	5.310	15.569	8.328	15	3.875	12.406	6.335	15	3.645	11.690	5.966
16	5.618	16.432	8.797	16	5.284	15.485	8.285	16	3.856	12.339	6.302	16	3.627	11.627	5.936
17	5.578	16.305	8.732	17	5.247	15.365	8.224	17	3.829	12.243	6.255	17	3.601	11.537	5.892
18	5.527	16.139	8.647	18	5.199	15.208	8.144	18	3.794	12.119	6.195	18	3.568	11.420	5.835
19	5.464	15.935	8.544	19	5.140	15.016	8.047	19	3.751	11.966	6.121	19	3.528	11.276	5.765
20	5.390	15.694	8.421	20	5.070	14.789	7.931	20	3.700	11.785	6.033	20	3.480	11.105	5.682
21	5.305	15.416	8.280	21	4.990	14.527	7.798	21	3.641	11.576	5.932	21	3.425	10.908	5.587
22	5.208	15.102	8.120	22	4.899	14.231	7.648	22	3.575	11.340	5.817	22	3.363	10.686	5.479
23	5.101	14.752	7.943	23	4.798	13.902	7.481	23	3.501	11.077	5.690	23	3.293	10.439	5.359
24	4.983	14.368	7.748	24	4.687	13.540	7.297	24	3.420	10.789	5.550	24	3.217	10.167	5.228
25	4.854	13.950	7.536	25	4.566	13.146	7.097	25	3.332	10.475	5.398	25	3.134	9.871	5.084
1/2 CT Specimen								**1 CT Specimen**							
Front				Rear				Left				Right			
F23-7R	5.179	15.258	8.143	F23-38R	4.141	12.871	6.679	F23-2R	4.704	14.274	7.459	F23-24R	4.589	13.958	7.321
F23-17R	5.552	16.518	8.769	F23-46R	4.440	13.933	7.193	F23-6R	5.170	15.394	8.292	F23-28R	5.044	15.519	8.094
F23-19R	5.842	17.499	9.255	F23-54R	4.672	14.761	7.592	F23-20R	5.168	15.899	8.289	3PS-7	5.042	15.524	8.091
F23-27R	5.944	17.849	9.427	F23-58R	4.753	15.056	7.732	3PS-6	4.697	14.289	7.492	3PS-6	4.583	13.952	7.313
F23-29R	5.943	17.852	9.425	F23-62R	4.752	15.058	7.731								
3PU-8	5.839	17.507	9.251	3PU-30	4.669	14.767	7.588								
3PU-16	5.546	16.531	8.762	3PU-32	4.435	13.944	7.187								
3PU-17	5.171	15.276	8.134	3PU-37	4.135	12.886	6.672								

*Neutrons per cm².

Table 9. Damage parameter values at the locations of metallurgical specimens - SPV-capsule O-T

Spec. No.	Fluence >1 MeV 10^{19} n/cm^2*	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm^2	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm^2	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm^2	Fluence >.1 MeV 10^{19} n/cm^2	dpa (ASTM) (10^{-2})
Charpy Specimen															
Left Front				Right Front				Left Rear				Right Rear			
1	3.470	9.756	5.476	1	3.326	9.372	5.256	1	2.760	8.918	4.625	1	2.646	8.567	4.439
2	3.534	9.975	5.588	2	3.387	9.582	5.363	2	2.811	9.119	4.719	2	2.695	8.759	4.530
3	3.593	10.176	5.690	3	3.443	9.775	5.462	3	2.858	9.302	4.806	3	2.739	8.935	4.613
4	3.646	10.357	5.783	4	3.494	9.949	5.551	4	2.900	9.468	4.884	4	2.780	9.095	4.688
5	3.693	10.520	5.866	5	3.540	10.105	5.630	5	2.938	9.616	4.954	5	2.816	9.237	4.755
6	3.734	10.662	5.939	6	3.579	10.242	5.700	6	2.971	9.747	5.016	6	2.847	9.363	4.814
7	3.770	10.785	6.001	7	3.614	10.360	5.760	7	2.999	9.859	5.069	7	2.875	9.470	4.865
8	3.800	10.887	6.054	8	3.642	10.458	5.810	8	3.023	9.952	5.113	8	2.897	9.560	4.907
9	3.824	10.969	6.096	9	3.665	10.537	5.851	9	3.042	10.027	5.148	9	2.916	9.632	4.941
10	3.842	11.031	6.127	10	3.682	10.596	5.881	10	3.056	10.084	5.175	10	2.929	9.686	4.967
11	3.853	11.072	6.148	11	3.693	10.636	5.901	11	3.065	10.121	5.192	11	2.938	9.722	4.984
12	3.859	11.092	6.158	12	3.699	10.655	5.911	12	3.070	10.140	5.201	12	2.943	9.740	4.992
13	3.859	11.092	6.158	13	3.699	10.655	5.910	13	3.070	10.139	5.201	13	2.942	9.740	4.992
14	3.853	11.071	6.147	14	3.693	10.634	5.900	14	3.065	10.120	5.192	14	2.938	9.721	4.983
15	3.841	11.029	6.126	15	3.681	10.594	5.880	15	3.055	10.082	5.174	15	2.928	9.684	4.966
16	3.822	10.966	6.094	16	3.664	10.534	5.849	16	3.041	10.024	5.147	16	2.914	9.630	4.940
17	3.798	10.883	6.052	17	3.640	10.454	5.808	17	3.022	9.949	5.111	17	2.896	9.557	4.906
18	3.768	10.780	5.999	18	3.612	10.355	5.758	18	2.998	9.854	5.067	18	2.873	9.466	4.863
19	3.732	10.656	5.936	19	3.577	10.237	5.697	19	2.969	9.741	5.013	19	2.846	9.357	4.812
20	3.690	10.5[illegible]	5.863	20	3.537	10.099	5.627	20	2.936	9.610	4.951	20	2.814	9.231	4.753
21	3.642	10.350	5.779	21	3.491	9.942	5.547	21	2.898	9.461	4.881	21	2.777	9.088	4.685
22	3.589	10.167	5.686	22	3.440	9.767	5.458	22	2.855	9.294	4.802	22	2.737	8.928	4.609
23	3.530	9.966	5.583	23	3.384	9.573	5.359	23	2.808	9.110	4.715	23	2.692	8.751	4.526
24	3.466	9.746	5.471	24	3.322	9.362	5.251	24	2.757	8.909	4.620	24	2.64[illegible]	8.558	4.435
25	3.396	9.508	5.349	25	3.255	9.133	5.134	25	2.701	8.691	4.517	25	2.589	8.349	4.336

1/2 CT Specimen								1 CT Specimen							
Front				Rear				Left				Right			
F23-1R	[illegible] 830	11.158	6.128	F23-39R	3.343	10.578	5.543	F23-15R	3.587	10.931	5.855	F23-27R	3.526	10.755	5.759
F23-5R	4.015	11.812	6.455	F23-43R	3.504	11.198	5.839	F23-19R	3.819	11.786	6.273	F23-1R	3.754	11.596	6.170
F23-11R	4.151	12.296	6.697	F23-51R	3.624	11.657	6.058	F23-23R	3.787	11.670	6.217	3PS-10	3.722	11.482	6.114
F23-21R	4.193	12.446	6.772	F23-59R	3.660	11.799	6.126	3PS-9	3.503	10.625	5.705	3PS-15	3.443	10.453	5.611
F23-31R	4.175	12.384	6.741	F23-67R	3.645	11.741	6.09[illegible]								
3PU-2	4.109	12.149	6.624	3PU-18	3.587	11.518	5.991								
3PU-10	3.938	11.546	6.322	3PU-14	3.438	10.946	5.719								
3PU-26	3.726	10.797	5.947	3PU-34	3.253	10.236	5.379								

*Neutrons per cm^2.

Table 10. Damage parameter values at the locations of metallurgical specimens - SPV-capsule 1/4 T

Charpy Specimen

Spec. No.	Fluence >1 MeV 10^{19} n/cm²*	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})
Left Front				Right Front				Left Rear				Right Rear			
1	2.041	7.588	3.627	1	1.942	7.246	3.458	1	1.532	6.533	2.948	1	1.458	6.239	[illegible]
2	2.073	7.745	3.695	2	1.973	7.396	3.522	2	1.557	6.669	3.003	2	1.481	5.368	2.863
3	2.102	7.888	3.756	3	2.000	7.533	3.581	3	1.579	6.792	3.053	3	1.502	6.485	2.911
4	2.129	8.017	3.812	4	2.025	7.655	3.634	4	1.598	6.903	3.098	4	1.521	6.591	2.954
5	2.152	8.131	3.861	5	2.048	7.765	3.681	5	1.616	7.001	3.138	5	1.538	6.685	2.992
6	2.172	8.231	3.904	6	2.067	7.860	3.722	6	1.631	7.087	3.173	6	1.552	6.767	3.025
7	2.189	8.315	3.940	7	2.083	7.940	3.756	7	1.644	7.160	3.202	7	1.564	6.837	3.053
8	2.203	8.385	3.970	8	2.096	8.007	3.785	8	1.654	7.220	3.226	8	1.574	6.894	3.076
9	2.214	8.439	3.993	9	2.107	8.059	3.807	9	1.662	7.266	3.245	9	1.582	6.939	3.094
10	2.221	8.479	4.009	10	2.114	8.096	3.823	10	1.668	7.300	3.258	10	1.587	6.97[illegible]	3.107
11	2.226	8.502	4.019	11	2.118	8.119	3.832	11	1.671	7.321	3.266	11	1.590	6.991	3.114
12	2.227	8.511	4.022	12	2.119	8.127	3.8[illegible]5	12	1.672	7.328	3.269	12	1.591	6.997	3.117
13	2.225	8.504	4.019	13	2.117	8.121	3.832	13	1.671	7.322	3.266	13	1.590	6.992	3.114
14	2.220	8.482	4.009	14	2.112	8.099	3.822	14	1.667	7.303	3.258	14	1.586	6.973	3.106
15	2.212	8.444	3.992	15	2.104	8.063	3.806	15	1.661	7.270	3.244	15	1.580	6.942	3.093
16	2.200	8.391	3.969	16	2.094	8.013	3.784	16	1.652	7.225	3.225	16	1.572	6.899	3.075
17	2.186	8.323	3.939	17	2.080	7.948	3.755	17	1.641	7.166	3.201	17	1.562	6.843	3.052
18	2.168	8.240	3.902	18	2.063	7.868	3.720	18	1.628	7.094	3.171	18	1.549	6.774	3.023
19	2.147	8.141	3.859	19	2.043	7.774	3.679	19	1.612	7.010	3.136	19	1.534	6.694	2.990
20	2.123	8.029	3.810	20	2.020	7.667	3.632	20	1.594	6.913	3.096	20	1.517	6.601	2.952
21	2.096	7.901	3.754	21	1.994	7.545	3.579	21	1.574	6.803	3.051	21	1.498	6.496	2.909
22	2.066	7.760	3.692	22	1.966	7.410	3.520	22	1.551	6.681	3.000	22	1.476	6.380	2.861
23	2.033	7.604	3.624	23	1.935	7.261	3.455	23	1.527	6.547	2.945	23	1.453	6.252	2.808
24	1.997	7.434	3.550	24	1.901	7.099	3.384	24	1.500	6.401	2.885	24	1.427	6.112	2.750
25	1.959	7.251	3.470	25	1.864	6.925	3.308	25	1.471	6.244	2.820	25	1.399	5.962	2.688

1/2 CT Specimen								1 CT Specimen							
Front				Rear				Left				Right			
F23-3R	2.163	8.355	3.926	F23-45R	1.825	7.644	3.471	F23-4R	1.997	8.065	3.720	F23-16R	1.956	7.914	3.648
F23-8R	2.252	8.802	4.116	F23-47R	1.899	8.054	3.639	F23-8R	2.102	8.629	3.954	F23-30R	2.060	8.467	3.878
F23-13R	2.314	9.123	4.251	F23-53R	1.952	8.347	3.759	F23-12R	2.074	8.497	3.896	3PS-16	2.032	8.338	3.820
F23-18R	2.330	9.212	4.288	F23-55R	1.966	8.428	3.791	3PS-13	1.920	7.717	3.565	3PT-1	1.881	7.572	3.495
F23-23R	2.314	9.141	4.256	F23-61R	1.952	8.363	3.763								
3PU-3	2.275	8.954	4.175	3PU-27	1.919	8.192	3.691								
3PU-11	2.182	8.497	3.978	3PU-15	1.840	7.774	3.516								
3PU-19	2.068	7.939	3.737	3PU-35	1.744	7.264	3.30[illegible]								

*Neutrons per cm².

Table 11. Damage parameter values at the locations of metallurgical specimens - SPV-capsule 1/2 T

Charpy Specimen

Spec. No.	Fluence >1 MeV 10^{19} n/cm²*	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})	Spec. No.	Fluence >1 MeV 10^{19} n/cm²	Fluence >.1 MeV 10^{19} n/cm²	dpa (ASTM) (10^{-2})
	Left Front				Right Front				Left Rear				Right Rear		
1	1.017	5.166	2.173	1	0.977	4.983	2.092	1	0.745	4.271	1.728	1	0.715	4.119	1.664
2	1.030	5.263	2.209	2	0.989	5.076	2.127	2	0.754	4.351	1.757	2	0.724	4.196	1.692
3	1.042	5.351	2.242	3	1.000	5.161	2.159	3	0.762	4.424	1.784	3	0.732	4.266	1.718
4	1.052	5.429	2.272	4	1.010	5.237	2.188	4	0.770	4.489	1.807	4	0.739	4.329	1.740
5	1.061	5.499	2.298	5	1.018	5.303	2.213	5	0.776	4.546	1.828	5	0.745	4.384	1.760
6	1.068	5.559	2.320	6	1.025	5.361	2.235	6	0.782	4.596	1.846	6	0.750	4.432	1.778
7	1.074	5.609	2.339	7	1.031	5.410	2.253	7	0.786	4.637	1.861	7	0.755	4.473	1.792
8	1.079	5.650	2.354	8	1.036	5.449	2.267	8	0.790	4.671	1.873	8	0.758	4.505	1.804
9	1.083	5.681	2.366	9	1.040	5.480	2.278	9	0.793	4.697	1.882	9	0.761	4.530	1.812
10	1.085	5.703	2.374	10	1.042	5.500	2.286	10	0.794	4.715	1.888	10	0.763	4.547	1.818
11	1.086	5.715	2.378	11	1.043	5.512	2.290	11	0.795	4.725	1.891	11	0.763	4.557	1.822
12	1.086	5.717	2.378	12	1.043	5.514	2.290	12	0.795	4.726	1.892	12	0.763	4.558	1.822
13	1.084	5.709	2.375	13	1.041	5.506	2.287	13	0.794	4.720	1.889	13	0.762	4.552	1.819
14	1.081	5.692	2.368	14	1.038	5.489	2.280	14	0.791	4.705	1.884	14	0.760	4.538	1.814
15	1.077	5.664	2.357	15	1.034	5.463	2.270	15	0.788	4.683	1.875	15	0.757	4.517	1.806
16	1.071	5.628	2.342	16	1.029	5.428	2.256	16	0.784	4.652	1.863	16	0.753	4.487	1.795
17	1.065	5.581	2.324	17	1.022	5.383	2.238	17	0.779	4.614	1.849	17	0.748	4.450	1.781
18	1.056	5.525	2.303	18	1.014	5.329	2.218	18	0.773	4.568	1.832	18	0.742	4.405	1.764
19	1.047	5.460	2.277	19	1.005	5.266	2.193	19	0.766	4.514	1.812	19	0.735	4.353	1.745
20	1.036	5.385	2.248	20	0.995	5.193	2.165	20	0.758	4.452	1.789	20	0.728	4.294	1.723
21	1.024	5.301	2.216	21	0.983	5.112	2.134	21	0.749	4.382	1.763	21	0.719	4.227	1.698
22	1.011	5.208	2.180	22	0.970	5.023	2.100	22	0.740	4.305	1.734	22	0.710	4.152	1.670
23	0.996	5.106	2.141	23	0.956	4.924	2.062	23	0.729	4.221	1.703	23	0.700	4.071	1.640
24	0.980	4.995	2.098	24	0.941	4.817	2.021	24	0.718	4.129	1.669	24	0.689	3.983	1.607
25	0.963	4.876	2.052	25	0.925	4.703	1.976	25	0.705	4.031	1.633	25	0.677	3.888	1.572

	1/2 CT Specimen								1 CT Specimen						
	Front				Rear				Left				Right		
F23-4R	1.054	5.556	2.311	F23-37R	0.875	4.962	2.017	F23-3R	0.963	5.294	2.173	F23-25R	0.947	5.215	2.139
F23-9R	1.087	5.823	2.410	F23-41R	0.903	5.201	2.104	F23-7R	1.001	5.620	2.292	F23-29R	0.984	5.536	2.257
F23-14R	1.109	6.010	2.479	F23-49R	0.922	5.367	2.164	F23-11R	0.984	5.515	2.250	3PT-3	0.967	5.433	2.215
F23-24R	1.114	6.055	2.495	F23-57R	0.925	5.408	2.178	3PT-2	0.916	5.016	2.061	3PT-4	0.901	4.941	2.029
F23-28R	1.104	5.[illegible]98	2.472	F23-65R	0.917	5.357	2.158								
3PU-4	1.086	5.873	2.424	3PU-24	0.902	5.246	2.116								
3PU-12	1.044	5.577	2.310	3PU-31	0.868	4.981	2.017								
3PU-20	0.995	5.220	2.174	3PU-36	0.827	4.662	1.898								

*Neutrons per cm².

Table 12. Average and extreme values of damage parameters for different sets of Charpy specimens

	Fluence > 1.0 MeV (10^{19} n/cm^2)			Fluence > 0.1 MeV (10^{19} n/cm^2)			dpa (10^{-2})		
	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
A302-B Plate									
SSC1	2.51	2.59	2.65	7.25	7.48	7.67	3.92	4.04	4.14
SSC2	5.14	5.41	5.66	15.02	15.82	16.57	8.05	8.47	8.87
0-T	3.58	3.73	3.86	10.24	10.72	11.09	5.70	5.96	6.16
1/4T	2.04	2.15	2.23	7.77	8.21	8.51	3.68	3.88	4.02
1/2T	1.00	1.05	1.09	5.27	5.53	5.72	2.19	2.30	2.38
A533-B Plate									
SSC1	2.20	2.35	2.50	6.26	6.73	7.20	3.41	3.65	3.89
SSC2	4.57	4.97	5.39	13.15	14.41	15.69	7.10	7.75	8.42
0-T	3.25	3.47	3.69	9.13	9.82	10.51	5.13	5.50	5.86
1/4T	1.86	1.99	2.12	6.93	7.47	8.03	3.31	3.56	3.81
1/2T	0.92	0.98	1.04	4.70	5.04	5.38	1.98	2.11	2.25
22NiMoCr37 Forging									
SSC1	1.51	1.64	1.76	4.70	5.14	5.57	2.44	2.66	2.87
SSC2	3.13	3.44	3.79	9.87	10.93	12.12	5.08	5.61	6.19
0-T	2.59	2.80	3.00	8.35	9.12	9.85	4.34	4.71	5.07
1/4T	1.40	1.51	1.63	5.96	6.51	7.09	2.69	2.92	3.17
1/2T	0.68	0.73	0.77	3.89	4.23	4.57	1.57	1.70	1.83
A508-3 Forging									
SSC1	1.74	1.79	1.82	5.51	5.67	5.76	2.84	2.92	2.97
SSC2	3.60	3.72	3.89	11.54	11.92	12.45	5.89	6.09	6.36
0-T	2.90	2.97	3.07	9.56	9.82	10.14	4.91	5.04	5.20
1/4T	1.56	1.61	1.67	6.84	7.06	7.30	3.05	3.15	3.26
1/2T	0.75	0.77	0.79	4.45	4.58	4.72	1.78	1.83	1.89
Submerged Arc Weld (EC)									
SSC1	1.64	1.73	1.80	5.11	5.44	5.69	2.65	2.81	2.93
SSC2	3.27	3.57	3.82	10.33	11.34	12.20	5.32	5.81	6.24
0-T	2.74	2.90	3.04	8.93	9.53	10.03	4.61	4.91	5.15
1/4T	1.50	1.59	1.66	6.49	6.91	7.27	2.91	3.09	3.25
1/2T	0.73	0.76	0.79	4.27	4.50	4.70	1.72	1.81	1.88
Submerged Arc Weld (R)									
SSC1	2.34	2.47	2.58	6.65	7.07	7.44	3.62	3.83	4.02
SSC2	4.65	5.06	5.44	13.38	14.64	15.84	7.23	7.89	8.50
0-T	3.39	3.59	3.77	9.58	10.21	10.78	5.36	5.69	6.00
1/4T	1.97	2.08	2.19	7.40	7.87	8.32	3.52	3.74	3.94
1/2T	0.99	1.03	1.07	5.08	5.33	5.61	2.13	2.23	2.34

APPENDIX:

CALCULATION OF CORRECTIONS FOR ^{239}Pu "BURN-IN" IN THE $^{238}U(n,f)$ FISSION RATE

Neutron fluence determination through measurement of fission products of ^{238}U detectors becomes unreliable for high fluences at low neutron energies due to the production and subsequent fission of ^{239}Pu. The plutonium is produced through disintegration of

$$^{239}U \xrightarrow{23.54\ min} {}^{239}Np \xrightarrow{2.355\ d} {}^{239}Pu$$

of the ^{239}U generated by the $^{238}U(n,\gamma)^{239}U$ reaction. The process can be described by a system of differential equations for the quantities q_x, which are the number of nuclides of isotope x with time t as the independent variable. The parameters of the differential equations are the reaction rates r_x and the decay constants, which govern the transmutation from one nuclide to another. The reaction rates describe the rate of transmutation in a given neutron field

$$r_x = p \int_0^\infty \phi(E)\ \sigma_x(E)dE \qquad (A.1)$$

where p is the power level of the reactor, $\phi(E)$ the fluence rate per unit power at energy E, and $\sigma_x(E)$ the reaction cross section at this energy. Specifically, we define

r_1 = reaction rate $^{238}U(n,f)$F.P.
r_2 = reaction rate $^{238}U(n,\gamma)^{239}U$
r_3 = reaction rate $^{239}Pu(n,f)$F.P. (A.2)

Further, let λ be the decay rate of the given fission product (F.P.) and μ be the rate of transmutation from ^{239}U to ^{239}Pu. To simplify matters, we disregard the conversion to ^{239}Np considering it as instanteneous. We also disregard burnout; the total burnout is not more than 1% for ^{239}Pu fission and much less for all other reactions.

The quantities q_x are defined as follows:

q_1 = amount of ^{238}U
q_2 = amount of ^{239}U (or ^{239}Np)
q_3 = amount of ^{239}Pu
q_4 = amount of fission product (F.P.) . (A.3)

With these definitions and simplifications, we have the following system of differential equations:

$$
\begin{aligned}
\dot{q}_1 &= 0\ (-r_1 q_1 - r_2 q_2) \\
\dot{q}_2 &= -\mu q_2 + r_2 q_1 \\
\dot{q}_3 &= \mu q_2\ (-r_3 q_3) \\
\dot{q}_4 &= -\lambda q_4 + r_1 q_1 + r_3 q_3
\end{aligned}
\qquad \text{(A.4)}
$$

The dot means, as usual, the time derivative; the neglected burnout terms are added in parentheses.

We consider a time interval from t to $t + \Delta t$. The (constant) power level during this interval is p_t, so that $r_x = p_t \rho_x$, with ρ_x the reaction rate per unit power, i.e., the integral in formula (A.1). Thus, $p_t = 0$ during reactor shutdown.

Assuming $q_1(t) = 1$, the solution of the differential equation yields

$$
\begin{aligned}
q_1(t + \Delta t) &= q_1(t) = 1 \ (= \text{constant}) \\
q_2(t + \Delta t) &= q_2(t) e^{-\Delta t} + \rho_2 p_t \Delta t \, \frac{1 - e^{-\mu \Delta t}}{\mu \Delta t} \\
q_3(t + \Delta t) &= q_3(t) + q_2(t)\,(1 - e^{-\mu \Delta t}) + \rho_2 p_t \Delta t \left(1 - \frac{1 - e^{-\mu \Delta t}}{\mu \Delta t}\right) \\
q_4(t + \Delta t) &= q_4(t) e^{-\lambda \Delta t} + \rho_1 p_t \Delta t \, \frac{1 - e^{-\lambda \Delta t}}{\lambda \Delta t} \\
&+ \rho_3 p_t \Delta t \left[q_3(t) \frac{1 - e^{-\lambda \Delta t}}{\lambda \Delta t} + q_2(t) \left(\frac{1 - e^{-\lambda \Delta t}}{\lambda \Delta t} - \frac{e^{-\mu \Delta t} - e^{-\lambda \Delta t}}{(\lambda - \mu) \Delta t} \right) \right. \\
&\left. + \rho_2 p_t \Delta t \left[\frac{e^{-\lambda \Delta t} + \lambda \Delta t - 1}{(\lambda \Delta t)^2} - \frac{1}{\mu \Delta t} \left(\frac{1 - e^{-\lambda \Delta t}}{\lambda \Delta t} - \frac{e^{-\mu \Delta t} - e^{-\lambda \Delta t}}{(\lambda - \mu) \Delta t} \right) \right] \right]
\end{aligned}
\qquad \text{(A.5)}
$$

Repeated application of this formula leads to the determination of the amount of fission product q_4 at the end of an irradiation experiment, $t = t_{end}$, that extends over several periods of reactor operation at different power levels separated by reactor shutdowns.

Starting with $q_2(0) = q_3(0) = q_4(0) = 0$, the final amount at $t = t_{end}$, $q_4(t_{end})$, consists of two independent components, one from the fission of ^{238}U that is proportional to ρ_1, and the other from the fission of ^{239}Pu, proportional to the product $\rho_2 \cdot \rho_3$. Defining the total reaction probability of the reaction as

$$R_x = \rho_x \Sigma p_t \ \Delta t \quad , \qquad \text{(A.6)}$$

we can express the final amount q_4 as

$$q_4(t_{end}) = R_1 C_1 + R_2 R_3 C_2 \qquad \text{(A.7)}$$

where the factors C_1 and C_2 depend only on the power-time history of the irradiation experiment and can be calculated from formula (A.5).

Formula (7) can be written as

$$q_4(t_{end}) = R_1C_1 \left(1 + \frac{R_2R_3}{R_1} \frac{C_2}{C_1}\right) \tag{A.8}$$

so that

$$C_{Pu} = \frac{R_2R_3}{R_1} \frac{C_2}{C_1} \tag{A.9}$$

represents the correction term which must be applied to the fission rate determination based on ^{238}U fission alone. Table A.1 lists the values of R_2R_3/R_1 for different locations estimated from the adjustment procedure, and Table A.2 lists the ratios, C_2/C_1, for the different irradiation histories of SSC1, SSC2, and SPVC and different fission products. Uncertainties for R_2R_3/R_1 are about 22%; the uncertainties for C_2/C_1 are primarily due to fission yield uncertainties in the order of 2-3%. Table A.3 compares the correction terms determined from the differences between measurements of fission products in the ^{238}U detectors and the LSL-M2 estimates of the ^{238}U fission probability with the correction terms calculated from formula (9). The corrections from formula (A.9) do not contain corrections for self-shielding and are, therefore, consistently too large. Inspection of the ratios "(1)/(2)" in Table A.3, for the SSC2 and 0-T positions, suggest a self-shielding factor of about 30%. The remaining discrepancies, including correction terms in the SSC1, 1/4T, and 1/2T positions, are less than 10% relative to the measurements and are in line with the measurement uncertainties of the other fission detectors.

Thus, Pu burn-in explains, at least qualitatively, the ^{238}U fission product measurement, including apparent discrepancies between measurements for different fission products. However, there are large uncertainties connected with the correction terms so that the $^{238}U(n,f)$ detectors are of questionable value for high-fluence applications (epithermal fluence > 10^{19} neutrons/cm^2 per unit lethargy).

Table A.1. Reaction probabilities estimated with LSL-M2

	$^{238}U(n,f)$	$^{238}U(n,\gamma)$	$^{239}Pu(n,f)$	$\frac{^{238}U(n,\gamma)*^{239}Pu(n,f)}{^{238}U(n,f)}$
SSC1				
HB3	8.49 E-6	8.18 E-4	4.64 E-3	0.45
HB4	8.62 E-6	7.97 E-4	4.53 E-3	0.42
SSC2				
HB5	1.84 E-5	1.69 E-3	1.08 E-2	0.99
HB6	1.80 E-5	1.64 E-3	1.04 E-2	0.94
0-T				
HB1	1.42 E-5	1.62 E-3	1.02 E-2	1.16
HB2	1.40 E-5	1.59 E-3	1.00 E-2	1.14
1/4T				
HB7	7.05 E-6	7.10 E-4	4.70 E-3	0.47
HB8	6.97 E-6	6.69 E-4	4.44 E-3	0.43
1/2T				
HB9	3.06 E-6	3.38 E-4	1.94 E-3	0.21
HB10	3.04 E-6	3.42 E-4	1.96 E-3	0.22

Table A.2. Irradiation time-history correction terms for ^{239}Pu burn-in

Fission product	Fission yield			Time-history terms (including fission yield)		
	^{238}U (%)	^{239}Pu (%)	Pu/U	SSC1	SSC2	SPVC
^{95}Zr	5.17	4.72	0.91	0.45	0.52	0.80
^{103}Ru	6.33	6.87	1.09	0.56	0.69	1.00
^{137}Cs	5.97	6.50	1.09	0.48	0.51	0.54
^{140}Ba	5.94	5.29	0.89	0.59	0.72	0.87

Table A.3. Correction terms for Pu burn-in at different locations is the PSF

		Fission product				LSL-M2
		^{95}Zr	^{102}Ru	^{137}Cs	^{140}Ba	estimate
<u>SSC1</u>						
HB3	Measurements*	9.06	9.48	9.34	9.09	8.49
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.067	0.117	0.099	0.071	
	(2) ^{239}Pu burn-in	0.203	0.252	0.216	0.266	
	Ratio (1)/(2)	0.33	0.46	0.46	0.27	
HB4	Measurements*	8.85	9.27	9.16	8.80	8.62
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.027	0.075	0.062	0.021	
	(2) ^{239}Pu burn-in	0.189	0.235	0.202	0.248	
	Ratio (1)/(2)	0.14	0.32	0.31	0.08	
<u>SSC2</u>						
HB5	Measurements*	25.38	28.02	26.33		18.42
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.378	0.521	0.429		
	(2) ^{239}Pu burn-in	0.515	0.683	0.505		
	Ratio (1)/(2)	0.73	0.76	0.85		
HB6	Measurements*	23.56	25.36	24.50		17.96
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.312	0.412	0.364		
	(2) ^{239}Pu burn-in	0.519	0.649	0.479		
	Ratio (1)/(2)	0.62	0.63	0.76		
<u>0-T</u>						
HB1	Measurements*	23.05	26.29	22.13		14.18
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.626	0.854	0.561		
	(2) ^{239}Pu burn-in	0.928	1.160	0.627		
	Ratio (1)/(2)	0.67	0.74	0.89		

Table A.3. Continued

		Fission product				LSL-M2
		^{95}Zr	^{102}Ru	^{137}Cs	^{140}Ba	estimate
HB2	Measurements*	21.77	24.56	20.84		14.03
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.552	0.751	0.485		
	(2) ^{239}Pu burn-in	0.912	1.140	0.616		
	Ratio (1)/(2)	0.61	0.66	0.79		
1/4T						
HB7	Measurements*	8.05	8.77	8.90		7.05
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.142	0.244	0.262		
	(2) ^{239}Pu burn-in	0.376	0.470	0.254		
	Ratio (1)/(2)	0.38	0.52	1.03		
HB8	Measurements*	7.35	8.20	7.77		6.97
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.054	0.176	0.115		
	(2) ^{239}Pu burn-in	0.344	0.430	0.232		
	Ratio (1)/(2)	0.16	0.41	0.50		
1/2T						
HB9	Measurements*	3.23	3.27	3.38		3.06
	Correction terms:					
	(1) Measurements vs. LSL-M2	0.056	0.068	0.104		
	(2) ^{239}Pu burn-in	0.168	1.210	0.113		
	Ratio (1)/(2)	0.33	0.32	0.92		
HB10	Measurements*	3.00	3.24	3.35		3.04
	Correction terms:					
	(1) Measurements vs. LSL-M2	-0.013	0.066	0.102		
	(2) ^{239}Pu burn-in	0.176	1.220	0.119		
	Ratio (1)/(2)	----	0.30	0.86		

*^{238}U fission probability determined from fission product counting but not corrected for Pu burn-in ($*10^{-6}$).

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Values for the damage exposure parameters fluence > 1.0 MeV, fluence > 0.1 MeV, and dpa were determined for all locations of metallurgical specimens in the test assembly of the ORR-PSF irradiation experiment. Determination is based on dosimetry measurements by HEDL and the fluence calculations by R. E. Maerker and B. A. Worley at ORNL. The LSL-M2 adjustment procedure was used. The space dependency of the damage parameter values can be presented as a cosine-exponential function. Uncertainties are between 5 and 10%.

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