ENCLOSURE 3
TO NRC-05-0033

TRANSMITTAL OF THE RPV
NEUTRON FLUX EVALUATION REPORT

GE REPORT, GE-NE-0000-031-6254-R1-NP,
"DTE ENERGY FERMI-2 ENRGY CENTER
NEUTRON FLUX EVALUATION,"
FEBRUARY 2005

NON-PROPRIETARY VERSION

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3901 Castle Hayne Road, Wilmington, North Carolina 28401

GE-NE-0000-0031-6254-R1-NP
DRF 0000-0031-6251
Revision 1
Class I
February 2005

DTE Energy
Fermi-2 Energy Center
Neutron Flux Evaluation

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ACRONYMS AND ABBREVIATIONS

BAF	Bottom of Active Fuel
BOC	Beginning of Cycle
CLTP	Current Licensed Thermal Power
ECP	Engineering Computer Program
ENDF	Evaluated Nuclear Data File
EFPY	Effective Full-Power Year
EOC	End of Cycle
EPU	Extended Power Uprate
GE	General Electric
GE-NE	General Electric Nuclear Energy
IASCC	Irradiation Assisted Stress Corrosion Cracking
ID	Inside Diameter
LTR	Licensing Topical Report
MWt	Megawatt Thermal
NRC	Nuclear Regulatory Commission
OD	Outside Diameter
ORNL	Oak Ridge National Laboratory
RG	Regulatory Guide
RPV	Reactor Pressure Vessel

1.0 INTRODUCTION

1.1 Background

Neutron irradiation of the reactor pressure vessel (RPV) causes reduction in material ductility and creates structural embrittlement at higher operating temperatures. The effect is particularly significant when impurities such as nickel, copper, or phosphorus are present in noticeable levels, as is commonly true for the RPV steel. Therefore determination of neutron fluence level is one of the first steps toward RPV fracture toughness evaluations.

Irradiation by fast neutrons (with energies greater than 1 MeV) can also be a concern with respect to irradiation assisted stress corrosion cracking (IASCC) for reactor internal components such as core shroud, top guide, core plate, etc. Crack growth evaluation for these components also requires adequate determination of neutron fluence level.

Neutron flux, or fluence rate, can be determined through radiochemical analysis of the surveillance flux wire samples; which are made of iron, copper, or nickel, sealed inside a capsule and held in place by a holder near the RPV inside surface. The calculated ratio of surveillance sample flux to the RPV peak flux defines a lead factor. This lead factor can be applied to the sample dosimetry data to determine the RPV peak flux.

Neutron flux can also be determined by solving the Boltzmann neutron transport equation with the discrete ordinates method or Monte Carlo simulation. When appropriate bias is applied to the calculation results, these numerical methods can be used to obtain the best-estimate flux distribution.

1.2 Scope

GE has performed an RPV flux evaluation for the DTE Energy Fermi-2 plant to support a Fermi-2 Extended Power Uprate (EPU). Detailed flux calculations were performed for a representative pre-EPU cycle at the Current Licensed Thermal Power (CLTP) of 3430 MWt and for an EPU core that is representative of future cycles at the target power level of 3952 MWt. The NRC approved GE fluence methodology was used for these flux calculations. In addition, fluence distributions at the Effective-Full-Power Years (EFPY) of interest were evaluated based on the calculated CLTP and EPU flux distributions, in conjunction with the cycle-dependent energy generation data. The objective of this report is to document the flux/fluence evaluation.

2.0 METHODS AND ASSUMPTIONS

2.1 Flux Calculation Methodology

The current GE methodology for neutron flux calculation is documented in a Licensing Topical Report (LTR) NEDC-32983P-A [1], which was approved by the U.S. NRC in the Safety Evaluation Report for referencing in licensing actions [2]. In general, GE's methodology described in the LTR adheres to the guidance in Regulatory Guide 1.190 [3] for neutron flux evaluation.

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The flux calculations are performed with DORTG01V, which is a controlled version of the ORNL DORT computer code in the GE Engineering Computation Program (ECP) library [4]. The NRC has approved the use of DORT as part of the GE methodology [2].

The cross section data used in the DORT calculation are processed with the nuclear cross-section processing package in the GE ECP. The basic cross section data library is the 80-group MATXS6D library, which was based on Version V of the Evaluated Nuclear Data File (ENDF/B-V) and was generated by the Los Alamos National Laboratory. This 80-group library has been revised to include upgraded cross sections from ENDF/B-VI for the important components of BWR neutron flux calculation - oxygen, hydrogen, and individual iron isotopes - to meet the guidelines of Regulatory Guide 1.190, Regulatory Position 1.1.2. [[

]] A P_3 truncation of the Legendre polynomial expansion, which meets Regulatory Position 1.1.2 in RG 1.190, is used to approximate the anisotropy in the differential scattering cross sections. The approach discussed here is consistent with the approved LTR methodology.

2.2 Selection of Representative Pre-EPU Core

It was agreed between GE and DTE Energy that a single representative core would be selected to be the basis for the pre-EPU flux calculations. In order to determine the cycle that would be used, a series of flux calculations were performed for Cycles 1-9 based on the core data retrieved from the GE Engineering Data Bank. The peak RPV ID flux was calculated in each case and used as the basis for selecting the representative pre-EPU cycle.

The results of calculated peak RPV ID fluence for Cycles 1-9 indicate that Cycle 6 is the suitable choice to represent the pre-EPU cycles. Using Cycle 6 as the representative cycle for the pre-EPU cycles would impose a conservatism of about 10% on the pre-EPU fluence.

2.3 Inputs and Assumptions

The operating condition assumed for this analysis is based on the specific core design data of the cycles of interest. Pertinent core data were retrieved and processed from GE's Engineering Data Bank. These data include the three-dimensional descriptions of fuel bundle configuration, initial uranium mass, fuel exposure, and exposure-dependent water density (or void fraction) data.

The RPV and shroud dimensions, jet pump dimensions/configuration, and the configuration and location of surveillance capsule holder are verified data through the Design Input Request (DIR) and DTE Energy response/concurrence. These data are summarized in Table 2-1.

2.3.1 Core Loading

The Cycle 6 core contains 92 bundles of GE6, 47 bundles of GE9, and 625 bundles of GE11. The active fuel length is 150 inches for GE6 and GE9, and 146 inches for GE11. Fuel bundles in the outermost row contain only GE6 fuel. The axial flux shape for the RPV and shroud will be mostly impacted by these peripheral bundles.

The EPU cycle contains a full core load of GE14 fuel. The active fuel length is 150 inches.

2.3.2 (R,θ) Model

Figure 2-1 shows a quadrant of the core and the vessel internal components that are relevant to the flux calculation. [[

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In the angular coordinate θ, the mesh size is ½ degree per mesh interval, except for the two boundary nodes, which is ¼ degree. For a core quadrant, a total of 181 fine meshes are used in the θ-direction. This model is more detailed than the minimum requirement of 40 intervals per octant stipulated in Section 1.3.1 of RG 1.190.

Radial meshes vary in sizes. Sufficient fine mesh steps are provided to simulate the outer boundary profiles of the core. [[

]] The radial mesh size for each region has been selected to conform to the minimum requirements of RG 1.190, Section 1.3.1. [[

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The (r,θ) calculation is performed for the first quadrant of the reactor. The model includes three sets of jet-pump/riser, which are centered at 30°, 60°, and 90°. It also includes the 30° capsule, which is completely shadowed by the jet-pump riser. The azimuthal distribution of RPV flux in the first quadrant is expected to be representative of other quadrants because of the quadrant symmetry in the power distribution. The RPV flux at 0 and 180 degrees is expected to be higher than that at 90 and 270 degrees, due to the absence of jet pumps.

2.3.3 (R,Z) Model

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]] The radial mesh size for each region has been selected to conform to the minimum requirements of RG 1.190, Section 1.3.1. [[

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2.3.4 Material Composition and Coolant Density

Material compositions in each calculation model are treated as homogeneous mixtures. The volume fractions of solid material in each core region are calculated based on specific fuel bundle design data. [[

]], which is NRC approved [5].

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2.3.5 Neutron Source Distribution

Spatial distribution of the neutron source density is simulated based on relative cycle-integrated energy production in conjunction with the fission energy and fission yield data. [[

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Figure 2-3 shows the bundle-dependent relative cycle energy (normalized to the core average) at core midplane elevation (axial node 13) for Cycle 6 and the EPU cycle. These discrete data in the (x,y) plane are processed to form the neutron source distribution in the (r,θ) meshes for the (r,θ) calculation. The source distribution for the (r,z) calculation is generated from a similar process.

2.4 Bias and Uncertainty

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Table 2-1 Design Input Data for Flux Calculation

Parameter	Unit	Data
(A) Surveillance Capsule Basket		
Thickness	inch	0.75
Width	inch	7
Length	inch	9.5
Azimuths	degree	30, 120, 300
Radial Position of Basket Center, from RPV Clad	inch	0.9375
Elevation, Bottom of Basket	inch	283.563
(B) RPV (Beltline Region)		
RPV Base Metal ID	inch	254
RPV Thickness	inch	6.125
RPV Clad Thickness	inch	0.3125
(C) Shroud (Active Fuel Region)		
Shroud ID	inch	203.125
Shroud Thickness	inch	2"
(D) Jet Pump Components		
Recirc. Inlet Nozzles Azimuths	degree	30, 60, 90, 120, 150, 210, 240, 270, 300, 330
Jet Pump Riser Pipe OD	inch	10.71
Jet Pump Riser Pipe ID	inch	10.136
Jet Pump Inlet Mixer OD	inch	8.734
Jet Pump Inlet Mixer ID	inch	8.18
Radial Location of Riser from Core Center	inch	112.28
Radial Offset, Mixer to Riser	inch	0
Distance between Mixers, centerline to centerline	inch	29.5

Table 2-1 Design Input Data for Flux Calculation (Cont.)

Parameter	Unit	Data
(E) Top Guide Beam		
Lower Elevation	inch	364.62
Upper Elevation	inch	380.69
(F) Core Plate		
Elevation of top of core plate support flange	inch	191.12
Upper Elevation	inch	211.31
Thickness	inch	2
(G) Other Core Data		
Thermal Power	MWt	3430 (CLTP) 3952 (EPU)
Elevation of Bottom of Active Fuel (BAF)	inch	216.313
Active Fuel Length	inch	150 (GE6, GE9, GE14) 146 (GE11)

Figure 2-1. Core Layout and Vessel Internal Components

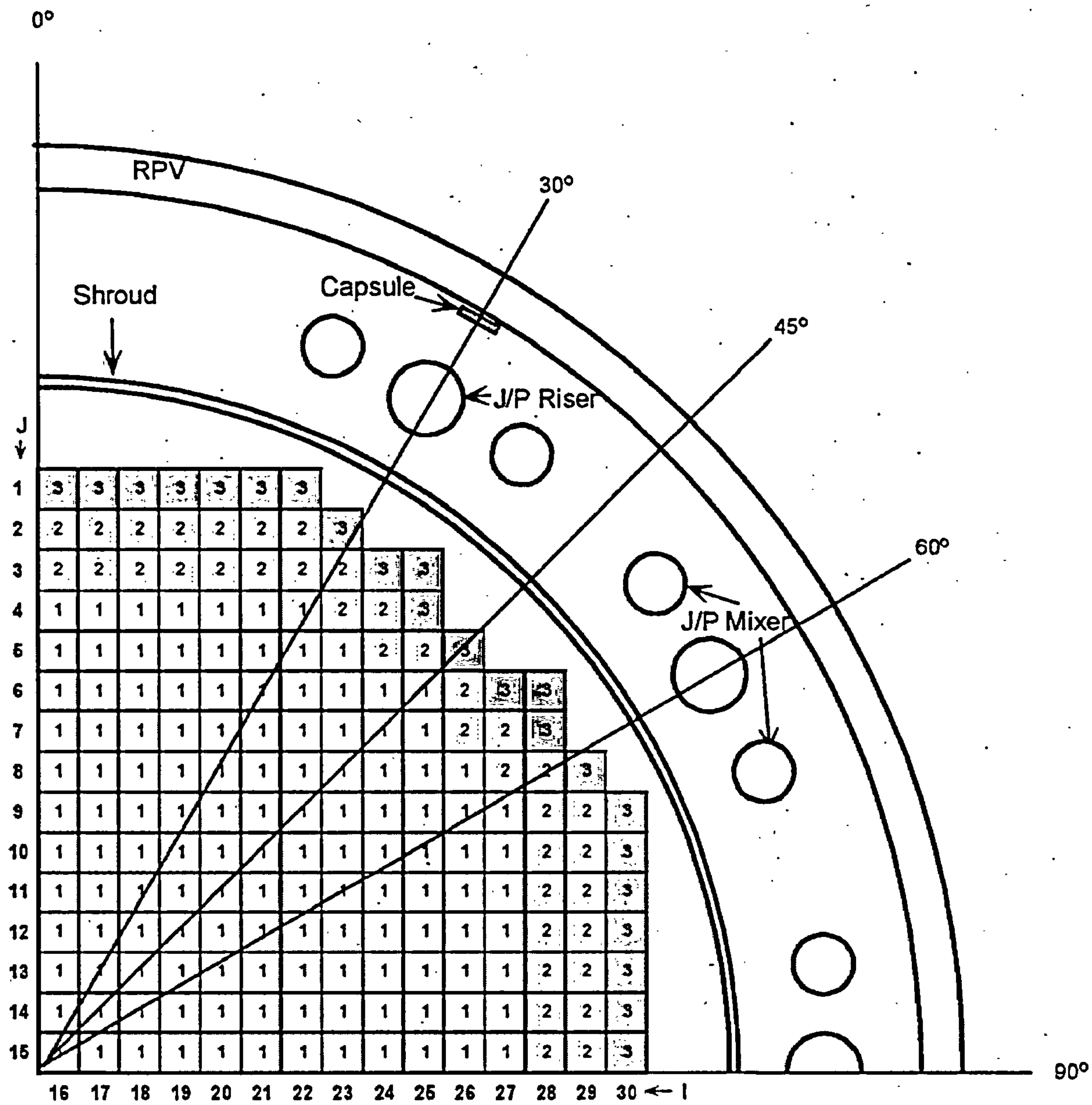

Figure 2-2: Schematic View of (R,Z) Model

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Figure 2-3. Relative Cycle Energy at Core Midplane

EPU Cycle:

J/I	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.603	0.592	0.574	0.566	0.565	0.517	0.406								
2	1.093	1.083	0.929	1.054	0.875	0.923	0.689	0.516							
3	1.334	1.338	1.281	1.327	1.235	1.217	0.913	0.752	0.572	0.367					
4	1.258	1.409	1.491	1.403	1.234	1.313	1.275	1.104	0.780	0.577					
5	1.460	1.564	1.477	1.546	1.427	1.385	1.366	1.057	1.111	0.764	0.607				
6	1.527	1.481	1.583	1.464	1.516	1.498	1.367	1.346	1.191	1.042	0.764	0.577	0.367		
7	1.131	1.528	1.461	1.228	1.235	1.419	1.450	1.043	1.129	1.192	1.112	0.780	0.572		
8	1.166	1.428	1.536	1.332	1.238	1.501	1.396	1.248	1.044	1.347	1.058	1.105	0.752	0.517	
9	1.312	1.530	1.371	1.516	1.428	1.297	1.513	1.397	1.451	1.368	1.368	1.277	0.914	0.691	0.409
10	1.476	1.427	1.520	1.401	1.474	1.504	1.297	1.502	1.422	1.502	1.388	1.315	1.219	0.924	0.518
11	1.141	1.475	1.285	1.092	1.107	1.474	1.429	1.239	1.249	1.520	1.434	1.236	1.237	0.877	0.565
12	1.146	1.403	1.455	1.095	1.091	1.401	1.517	1.334	1.230	1.466	1.550	1.405	1.329	1.056	0.566
13	1.487	1.455	1.299	1.454	1.284	1.519	1.370	1.537	1.462	1.585	1.479	1.493	1.282	0.932	0.575
14	1.409	1.524	1.455	1.403	1.474	1.427	1.530	1.428	1.529	1.482	1.566	1.411	1.340	1.085	0.592
15	1.102	1.409	1.487	1.145	1.140	1.475	1.311	1.166	1.131	1.528	1.461	1.260	1.336	1.094	0.603

Cycle 6:

J/I	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.506	0.511	0.491	0.491	0.465	0.442	0.365								
2	1.035	1.035	0.885	1.012	0.890	0.986	0.837	0.522							
3	1.168	1.193	0.920	1.174	0.876	1.139	0.825	0.959	0.592	0.381					
4	0.973	1.339	1.314	1.320	1.298	1.390	1.251	1.187	1.086	0.625					
5	1.353	1.039	1.441	1.223	1.491	1.414	1.472	1.318	1.205	1.113	0.657				
6	1.135	1.411	1.402	1.478	1.398	1.553	1.409	1.477	1.302	1.299	1.124	0.634	0.391		
7	1.110	1.138	1.430	1.111	1.190	1.415	1.550	1.347	1.000	1.328	1.230	1.104	0.601		
8	1.011	1.349	1.299	1.165	1.139	1.546	1.443	1.286	1.346	1.494	1.340	1.192	0.968	0.515	
9	1.298	1.043	1.310	1.146	1.475	1.436	1.336	1.442	1.564	1.437	1.495	1.264	0.834	0.835	0.367
10	1.062	1.254	1.186	1.357	1.337	1.468	1.467	1.569	1.442	1.585	1.439	1.415	1.176	0.966	0.438
11	0.985	1.188	1.067	0.943	1.045	1.382	1.524	1.180	1.217	1.438	1.524	1.333	0.890	0.871	0.460
12	1.079	1.293	1.202	1.022	0.994	1.458	1.231	1.218	1.156	1.528	1.258	1.329	1.180	0.917	0.481
13	1.411	1.200	1.367	1.335	1.239	1.380	1.520	1.407	1.505	1.457	1.480	1.319	0.833	0.897	0.493
14	1.237	1.472	1.241	1.474	1.401	1.507	1.235	1.477	1.210	1.475	1.070	1.371	1.215	1.053	0.520
15	1.180	1.253	1.468	1.177	1.111	1.205	1.463	1.106	1.176	1.189	1.408	1.004	1.217	1.062	0.527

3.0 FLUX RESULTS

This section documents the flux results from the calculation of the representative pre-EPU core and the EPU core. Per agreement with DTE Energy, a factor of 1.1 has been applied to the calculated EPU flux values to cover any potential non-conservatism owing to the use of the equilibrium cycle core design developed for the EPU project.

3.1 Neutron Flux at RPV Inside Surface

The calculated peak fast flux at the RPV inside surface is shown below:

Parameter	Elevation (Inches above BAF)	Azimuth (°)	Flux (n/cm^2-s)
RPV ID peak flux (>1.0 MeV) – EPU	85.1	64.0	1.01E9
RPV ID peak flux (>1.0 MeV) – CLTP	101.6	26.5	8.73E8

Figure 3-1 shows the azimuthal flux distribution at the peak elevation for the first quadrant of the RPV. The effects of inelastic scattering by steel in the jet-pump components are clearly displayed in Figure 3-1, where the flux depression occurs in regions shadowed by metal components. Fluxes for other quadrants are expected to be similar due to quadrant symmetry of the core loading as well as the arrangement of vessel internal components.

Figure 3-2 shows the axial flux variation at the RPV inside surface. The ratio of peak flux to midplane (75 inches above the BAF) flux is 1.06 for CLTP and 1.01 for EPU. These axial adjustment factors have been incorporated in the calculation of the peak flux.

3.2 Neutron Flux at Surveillance Capsule Location

The calculated fast flux and lead factor at the capsule location is shown below:

Capsule No.	Azimuth (°)	Flux (n/cm^2-s)	Lead Factor
1, 2, and 3 – EPU	30, 120, and 300	1.06E9	1.05
1, 2, and 3 – CLTP	30, 120, and 300	9.11E8	1.04

3.3 Neutron Flux at Shroud Inside Surface

The calculated peak fast flux at the shroud inside surface is shown below:

Parameter	Elevation (Inches above BAF)	Azimuth (°)	Flux (n/cm²-s)
Shroud ID peak flux (>1.0 MeV) – EPU	78.4	65.5	2.78E12
Shroud ID peak flux (>1.0 MeV) – CLTP	109.5	24.5	2.37E12

Figure 3-3 shows the azimuthal flux distribution at the core midplane elevation for the first quadrant of the shroud. Fluxes for other quadrants are expected to be similar due to quadrant symmetry of the core loading.

Figure 3-4 shows the axial flux variation at the shroud inside surface. The ratio of peak flux to midplane (75 inches above the BAF) flux is 1.10 for CLTP and 1.00 for EPU. These axial adjustment factors have been incorporated in the calculation of the peak flux.

3.4 Neutron Flux at Top Guide and Core Plate

The estimated bounding fast fluxes at the top guide and core plate are shown below:

Parameter	Flux (n/cm²-s)
Top Guide bounding flux (>1.0 MeV) – EPU	1.06E13
Top Guide bounding flux (>1.0 MeV) – CLTP	5.81E12
Core Plate bounding flux (>1.0 MeV) – EPU	7.74E11
Core Plate bounding flux (>1.0 MeV) – CLTP	6.32E11

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3.5 Observations

Compared to the CLTP flux, EPU flux increase is approximately 16% at the RPV ID and capsule locations, which is approximately the same as the percent change in power from CLTP to EPU. In the case of the shroud the increase is 17% going from CLTP to EPU. The peak elevation for the shroud and RPV flux distribution shifts towards the core midplane for the EPU, due to the core load of GE14 fuel with part-length rods.

The calculated EPU lead factor of 1.05 is not significantly different from the CLTP lead factor of 1.04. Variation of the lead factor is expected due to change in the axial and azimuthal flux distributions that affect both the capsule flux and the peak RPV flux.

Figure 3-1. Azimuthal Distribution of Fast Neutron Flux at RPV Inside Surface at Peak Elevation

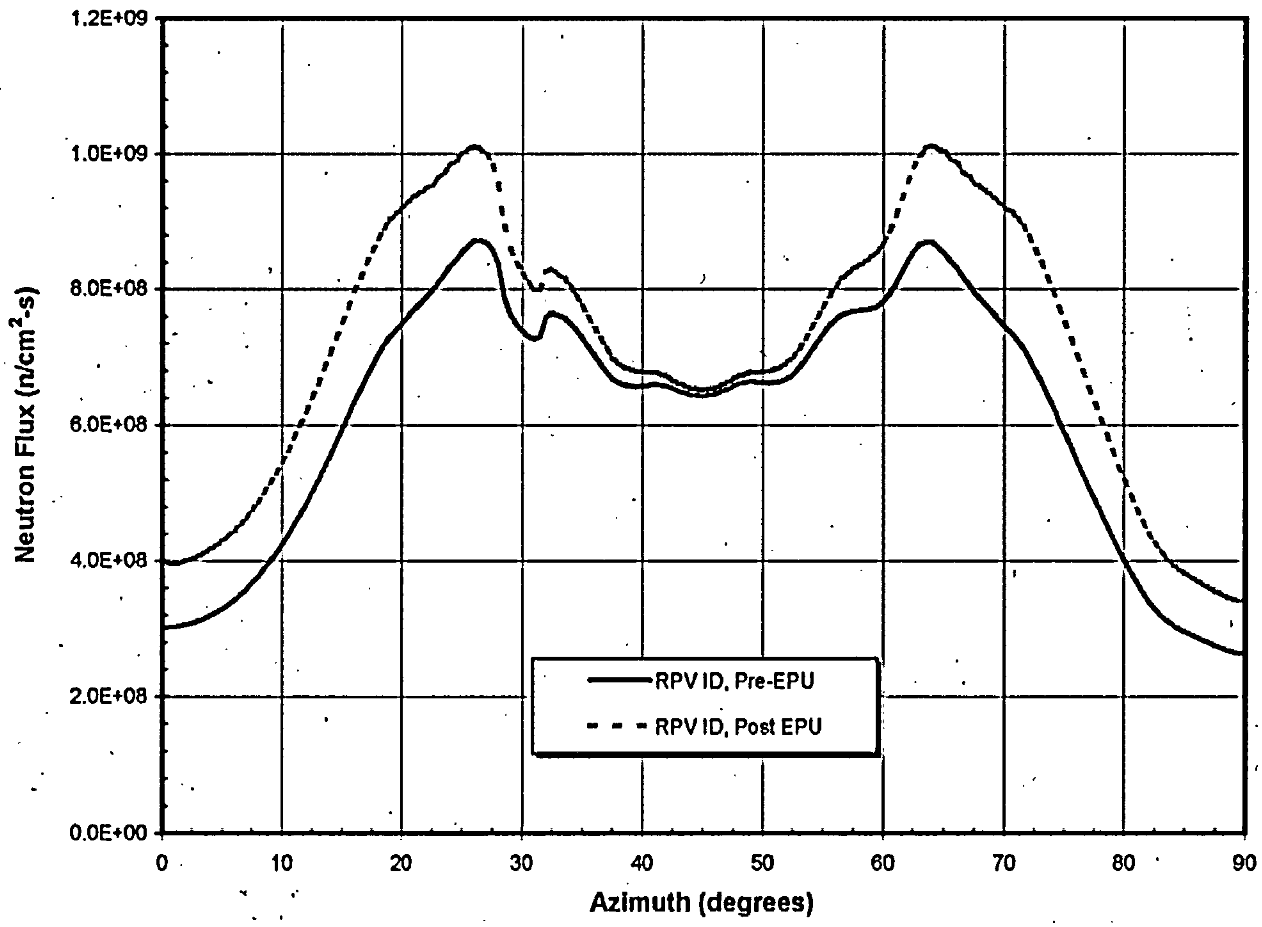


Figure 3-2. Axial Distribution of Relative Fast Neutron Flux at RPV Inside Surface

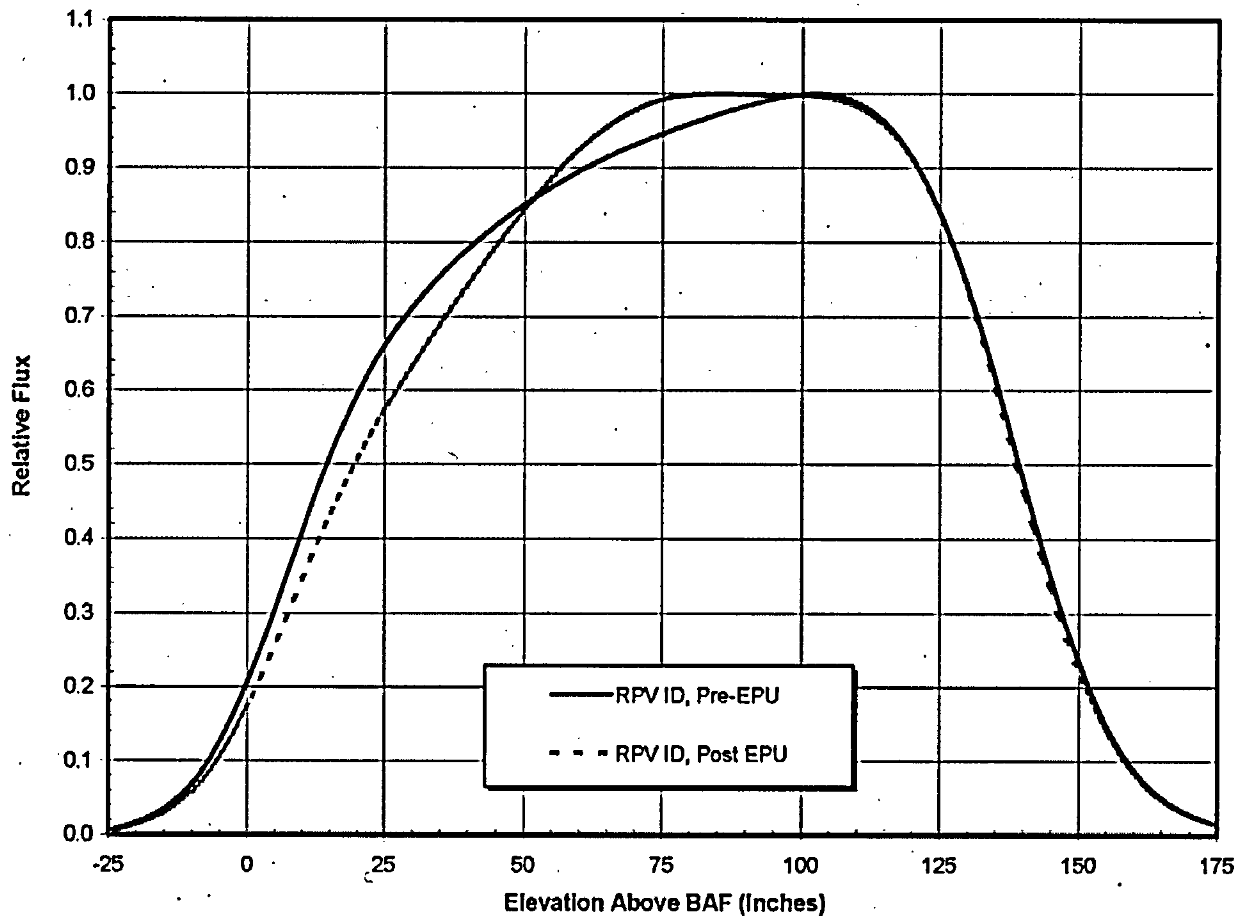


Figure 3-3. Azimuthal Distribution of Fast Neutron Flux at Shroud Inside Surface at Peak Elevation

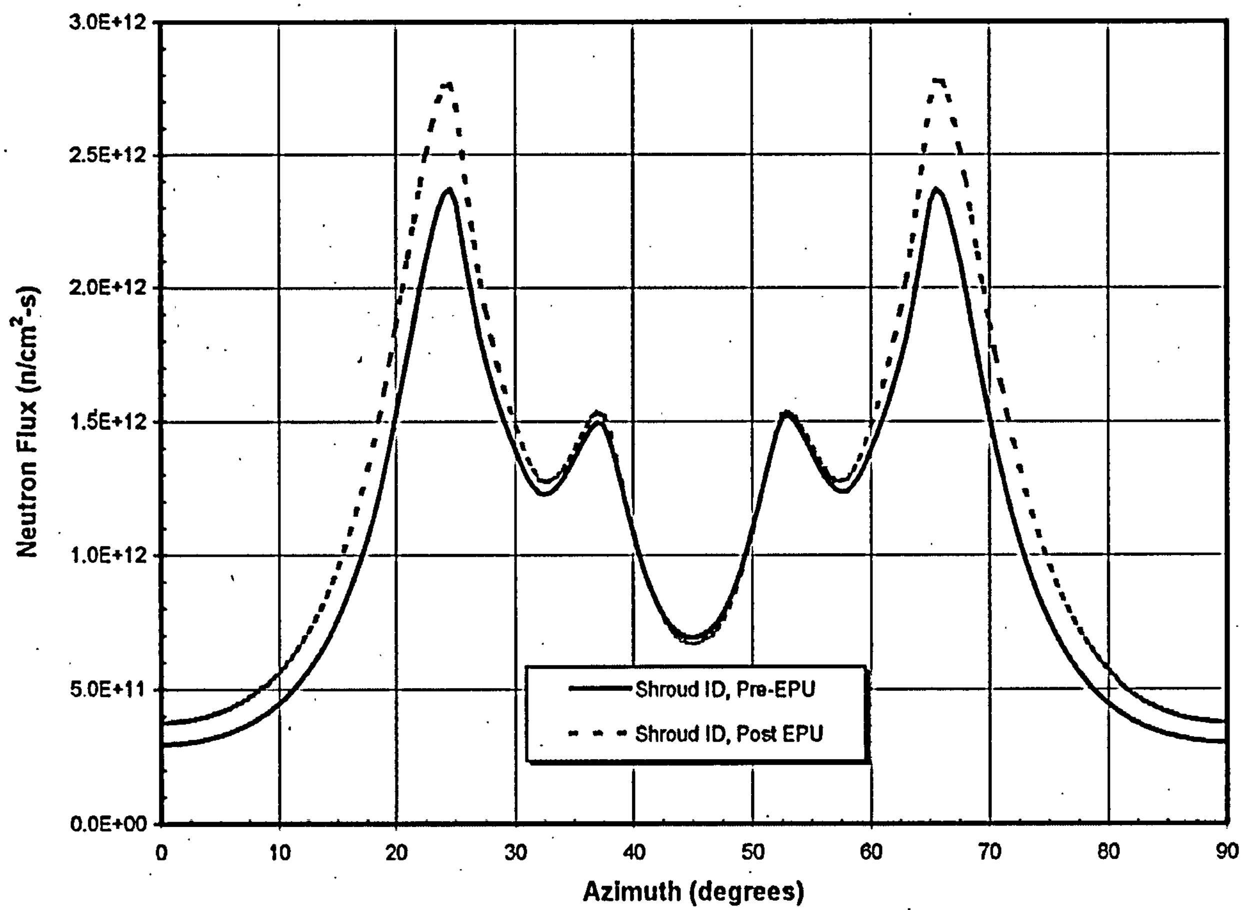
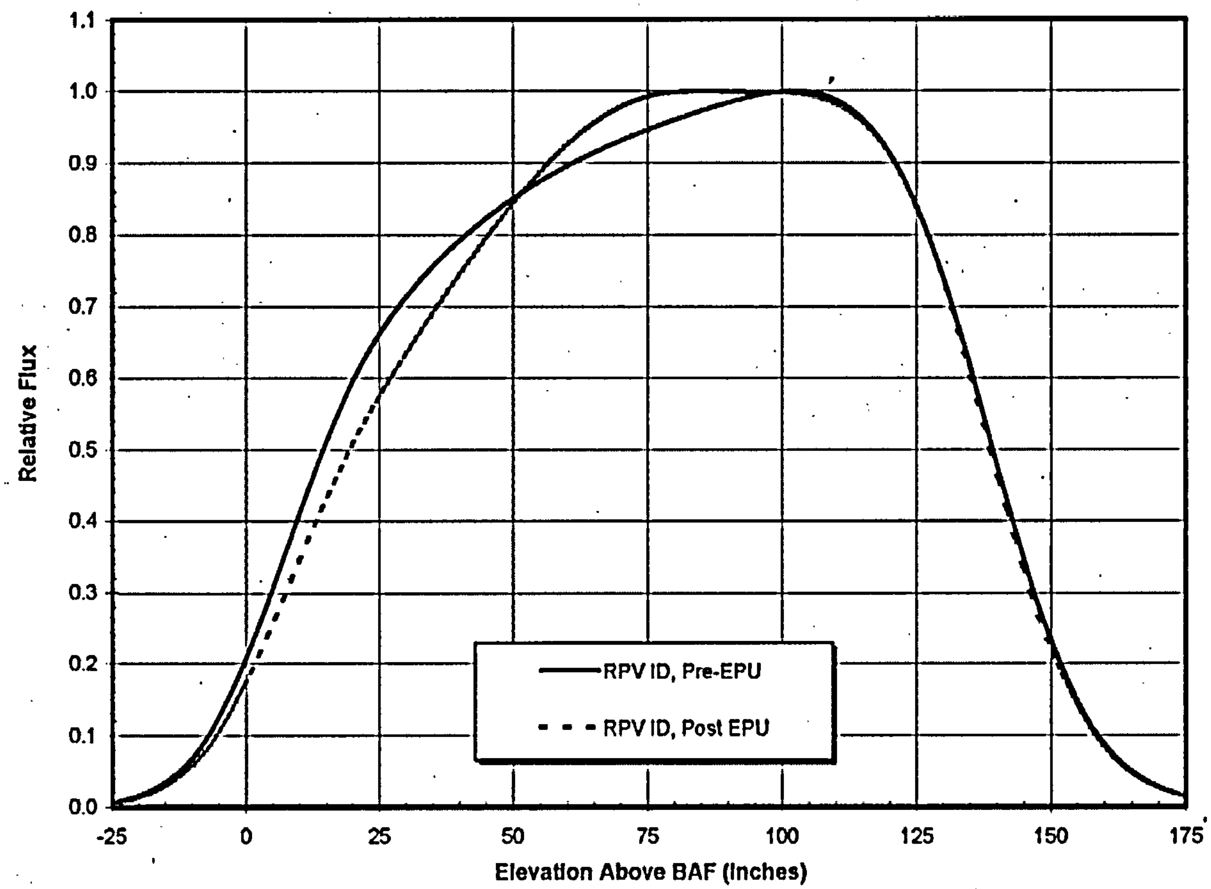


Figure 3-4. Axial Distribution of Relative Fast Neutron Flux at Shroud Inside Surface



4.0 NEUTRON FLUENCE

The flux results reported in this evaluation are used to calculate the fluences for the target EFPY of interest. Based on the cycle power and cycle energy generation data provided by DTE Energy, the total energy generated for Cycles 1-10 is 15,089 GWd. This is equivalent to 12.04 EFPY at the CLTP of 3430 MWt. The flux values at CLTP will be used for this portion of the plant lifetime for the calculation of the fluence. The remainder of the lifetime is conservatively assumed to be operating at the EPU power level.

Using the notation Φ_{CLTP} as the flux at CLTP and Φ_{EPU} as the flux for EPU, fluence can be calculated as

$$\text{32-EFPY Fluence} = (\Phi_{CLTP} * 12.04 + \Phi_{EPU} * 19.96)*(365.25*24*3600)\ n/cm^2.$$
$$\text{24-EFPY Fluence} = (\Phi_{CLTP} * 12.04 + \Phi_{EPU} * 11.96)*(365.25*24*3600)\ n/cm^2.$$

The calculated fluence values are shown below:

Parameter	32-EFPY Fluence (n/cm^2)	24-EFPY Fluence (n/cm^2)
RPV ID peak fluence (>1.0 MeV)	9.68E17	7.13E17
Shroud ID peak fluence (>1.0 MeV)	2.65E21	1.94E21
Top guide bounding fluence (>1.0 MeV)	8.87E21	6.20E21
Core plate bounding fluence (>1.0 MeV)	7.28E20	5.32E20
Girth weld (elevation 28.3125 inches above BAF) peak fluence (>1.0 MeV)	6.23E17	4.66E17

Figure 4-1 shows the axial fluence distribution at the peak azimuth at the RPV inside surface. Two sets of fluence data are presented: at the end of 40 years (32 EFPY) and at intermediate time of 24 EFPY, which will be used for the P-T curve evaluation. Figure 4-2 shows similar data for the shroud inside surface.

Figure 4-1 shows that, at the end of 40-year plant life, the region of fast fluence greater than 1.0E17 n/cm^2 extends from 5.8 inches below and 158.4 inches above BAF elevation. For the 24 EFPY, the region extends from 3.5 inches below and 155.2 inches above BAF elevation.

Figure 4-1. Axial Distribution of Fast Neutron Fluence at RPV Inside Surface at the Peak Azimuth

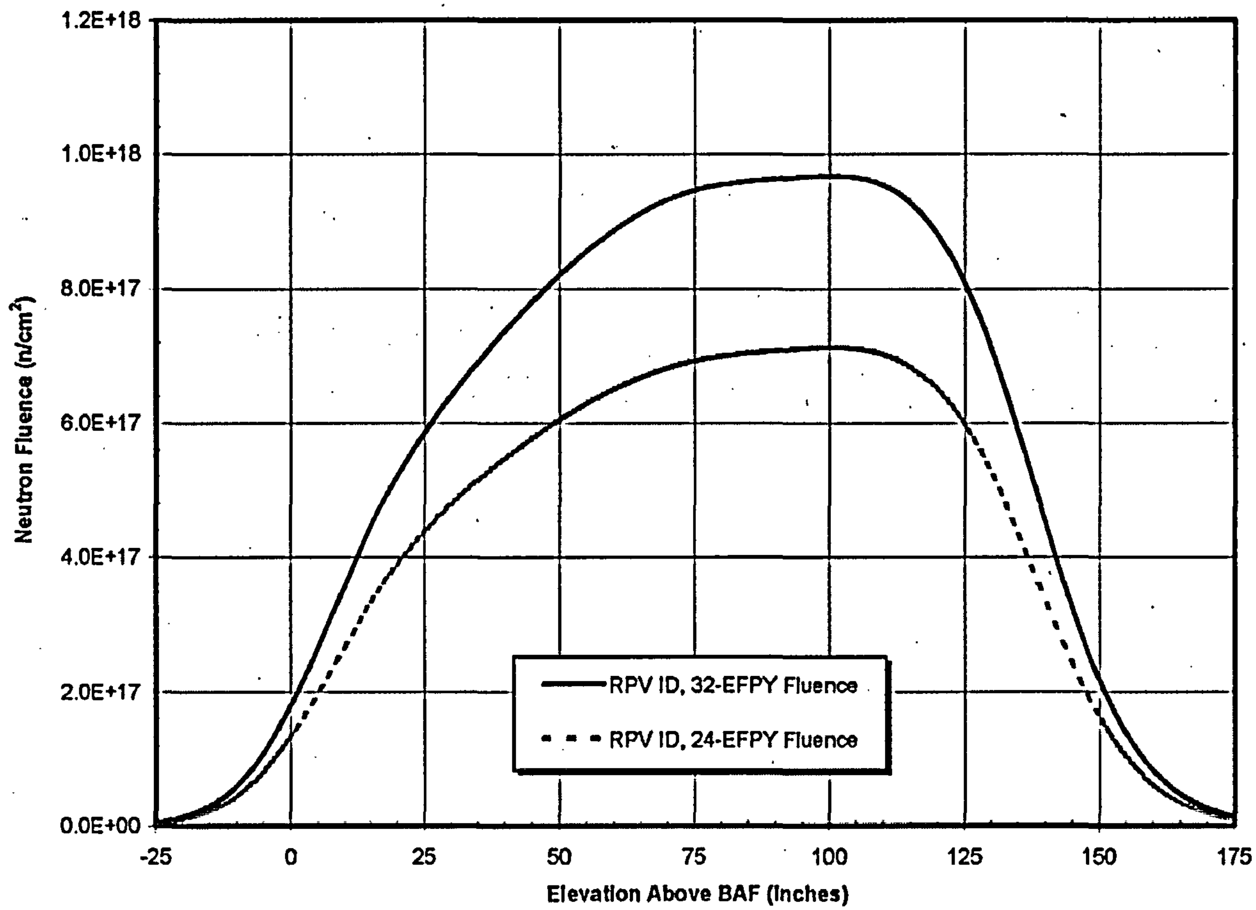
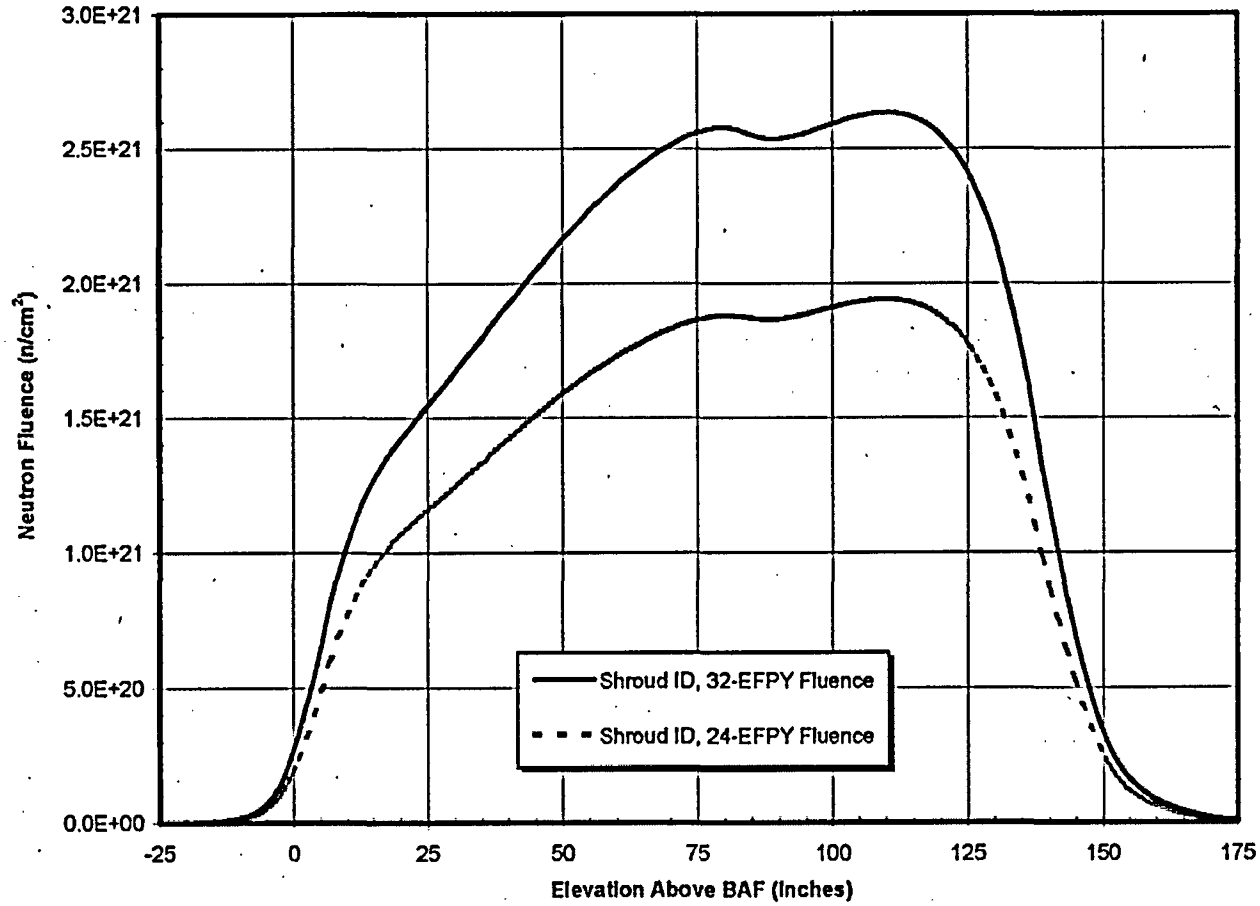


Figure 4-2. Axial Distribution of Fast Neutron Fluence at Shroud Inside Surface at the Peak Azimuth



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