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BENCHMARKING OF PRESSURE VESSEL FLUENCE CALCULATIONS*

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Extended neutron irradiation of certain PWR pressure vessels (PVs) causing significant degradation of vessel material mechanical and structural properties, coupled with the concern that in a PWR transient the pressure vessel may be subjected to pressurized thermal shock,[1] has resulted in a need for accurate and well benchmarked calculations of accumulated pressure vessel fluence. This paper presents results of pressure vessel fluence benchmark calculations and comparisons with measurement data, performed as part of the BNL/NRC Pressure Vessel Embrittlement program.[2-5] The benchmarking effort consisted of calculations of the fast (>1-MeV) neutron fluence for (1) the PV surveillance capsules of two Combustion Engineering reactors (CE-1, a 217-assembly plant, and CE-2, a 133-assembly plant) and a 177-assembly Babcock and Wilcox reactor (B&W-1), (2) flux measurements made in the cavity of a 177-assembly B&W reactor (B&W-2) and (3) the ORNL/PCA benchmark experiment.[6]

The calculations of the neutron transport from the core out to the vessel and cavity were performed with the DOT-3.5 two-dimensional discrete ordinates transport code.[7] The neutron fluence was considered to be separable and the calculations were performed in (r,θ) and (r,z) geometries. The (r,θ) model represented one octant of the core/shield/vessel configuration with reflecting boundary conditions across the rays at 0 and 45 degrees. The axial model represented a vertical plane through the core flats with upper and lower reflectors and vacuum boundary conditions on external surfaces. To

accommodate a fine spatial mesh representation of the source and detector geometries, while satisfying the DOT storage reqirements, the (r,θ) DOT calculations were carried out using a two-step "bootstrap" method. In this method the (r,θ) flux is calculated in two sequential DOT calculations. The flux is first calculated in an inner radial region and the surface flux is determined on an internal radial boundary. This flux is then input as a surface boundary condition to the DOT calculation of the outer radial region.

The neutron transport was calculated in a fixed source mode with an S_8-P_3 angular decomposition using the RSIC DLC-37/EPR (100 group, ENDF/B-IV) cross section library.[8] Region-wise 16-group collapsed macroscopic cross sections were determined using ANSIN.[9] The (r,θ) core neutron source was determined from an assembly-wise exposure distribution using an ENDF/B-IV U-235 Watt fission spectrum and included the effects of spatial source gradients in peripheral fuel assemblies. The DOT (r,z) calculations employed appropriate cycle-averaged axial exposure distributions. Corrections were made to the neutron source for fuel depletion effects.[5]

The CE-1 and CE-2 capsules, mounted on the inside surface of the PV cladding, contained three flux monitor compartments located near the top, middle and bottom of the capsule assembly. Each compartment contained a rectangular carbon steel block in the center of which were embedded bare and cadmium-covered flux monitor wires. The B&W-1 capsules contained neutron flux dosimeters and were mounted on the vessel inner-wall close to the core mid-plane. The B&W-2 cavity detector included both activation and fission foils and was located near the core mid-plane in a spare cavity instrument well.

The measured and calculated (>1-MeV) fluences for the capsule, cavity and ORNL/PCA measurements are compared in Table-1. The calculated CE-1 and B&W-1 capsule fluences are seen to be in good agreement with the measurements while the CE-2 calculation is $\sim$15% low relative to the measured fluence, and just outside the measurement uncertainty. The calculations of both the B&W-2 cavity and ORNL/PCA benchmark experiment are low by $\sim$ 10%. The overall calculation/measurement agreement is considered to be good and indicates that the BNL calculational methodology reproduces the measured (>1-MeV) fluences to within $\sim$15%.

TABLE-1

COMPARISON OF CALCULATED AND MEASURED (>1-MeV) FLUENCES

Measurement	Calculated Fluence [$n/cm^2 \times 10^{18}$]	Measured Fluence [$n/cm^2 \times 10^{18}$]	Calculation-Measurement Differences (%)
CE-1 Capsule	5.8	5.8 ± 0.7	0
CE-2 Capsule	5.1	5.9 ± 0.7	-15
B&W-1 Capsule	.75	.73	+3
B&W-2 Cavity	2.3+	2.6+	-12
ORNL/PCA[6]	.9*	1.0*	-10

+ Flux in units of $10^8 \times n/cm^2$-sec.

* Vessel flux in arbitrary units.

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