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Evaluation of Selected Approximations Used in Pressure Vessel Fluence Calculations*

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In response to concerns over the issue of Pressurized Thermal Shock (PTS),[1] Brookhaven National Laboratory (BNL), under the direction of the USNRC, has developed and benchmarked a methodology for calculating pressure vessel (PV) (>1-MeV) damage fluence. The methodology is based on the DOT-3.5[2] discrete ordinates transport code and has been shown to yield fluence results in good agreement with measurements and results from other calculations.[3,4] This paper describes the basic methodology employed in BNL PV fluence calculations, and the results of a number of studies performed to assess the impact of various special effects on the calculated (>1-MeV) PV fluence. These included the effect of 1) using a spatially uniform source in peripheral assemblies rather than a detailed pin-wise source distribution, 2) neglecting the effects of fuel depletion on the core neutron source, 3) neglecting the radial dependence of the axial fluence shape, and 4) varying the basic nuclear cross-section libraries. In addition, in order to quantify the uncertainties in the calculated fluence, sensitivities to known (or expected) variations in a number of physical parameters were determined.

In the BNL calculations the neutron transport from the core out through the vessel is performed in a "bootstrap" mode with DOT-3.5 in (r,θ) geometry. The energy-dependent neutron source is obtained by combining a core average assembly-wise power distribution with an ENDF/B-IV U-235 group-dependent fission spectrum, χ_g. Conversion from power to neutron source is achieved by using an average value of ν/κ (neutrons/watt). The 16-group, region-dependent P-3 cross-sections are obtained from an ANISN[5] calculation performed with the 100-group DLC-37/EPR (ENDF/B-IV) library.[6] Axial effects are determined by assuming that the vessel axial fluence shape is well approximated by the core average (or peripheral assembly average) axial power distribution.

The effect of neglecting power distribution gradients across peripheral assemblies on the vessel fluence was evaluated by considering pin-wise source distributions in three different core/vessel configurations. Reductions of $\sim$10-20% were observed in the (> 1 -MeV) vessel inner-wall fluence, with the magnitude of the reduction depending on the details of the azimuthal source and the specific reactor geometry. Typically, the fluence reduction at the peak vessel wall location is $\sim$10% and this reduction is included in the BNL calculated fluences.

Fuel depletion effects enter the fluence calculation principally through the energy dependence, χ (E), and the (ν/κ) normalization of the core neutron source. A common assumption made in vessel fluence calculations is that these parameters are characteristic of U-235 thermal fission. With depletion, however, an increasing fraction of the source neutrons results from fissions in the plutonium isotopes. These are characterized by a harder spectrum, χ (E), as well as higher values of ν/κ. Inclusion of this effect becomes increasingly important in the calculation of fluence values associated with low leakage fuel loading patterns where once-burned fuel is loaded into peripheral core locations. DOT calculations were performed at 0,15 and 30 GWD/MTU using exposure dependent sources that accounted for the plutonium build-up in the source energy spectrum and normalization. These calculations indicated increases in the vessel (>1-MeV) fluence of ~12% and 18% at 15 and 30 GWD/MTU, respectively, relative to the zero burn-up results.

The assumption that the vessel axial fluence shape may be approximated by an average axial power distribution implies that the axial flux shape does not vary significantly with radial distance from the core. This assumption was examined in detail by performing DOT calculations in (r,z) and (r) geometries for two different reactor configurations in order to obtain a leakage corrected axial factor ($\phi(r,z)/\phi(r)$). The results of these calculations indicated that while the axial fluence shape does flatten with increasing radius, the degree of flattening is typically less than ~5% at the peak vessel inner-wall location.

The standard BNL fluence methodology is based on the the use of the DLC-37/EPR cross-section library collapsed to 16-groups by region. (The group structure in this collapsed energy representation reproduces the 100-group results to within ~2%.) In order to assess the accuracy of this EPR based library relative to other standard cross-section sets, a number of ANISN calculations were performed for the 1-D ANS LWR benchmark.[7] The vessel inner-wall (>1-MeV) fluence obtained with the 171-group VITAMIN-C[8] library was compared to fluences obtained using the 100-group EPR, 47-group BUGLE-80[9] and 22-group CASK[10] libraries and indicated differences of ~1%, ~2% and ~18%, respectively.

An important part of the qualification effort was the identification of the major contributors to the uncertainty, and the quantification of the magnitude of the overall calculated fluence uncertainty. This involved a large number of ANISN perturbation calculations (for a typical LWR geometry) where dimensions, number densities, microscopic cross-sections, temperatures and source distributions were varied by amounts consistent with expected variations in these parameters. The major sources of uncertainty were 1) the core outer-radius and vessel inner-radius, 2) the water and iron number densities and cross-sections, and 3) the peripheral assembly source distribution and magnitude. The component uncertainties were combined to yield an overall calculated fluence uncertainty of $\sim 20\%$. This compares well with the observed $\lesssim 15\%$ differences between measured and predicted fluences.(3)

The BNL methodology for calculating PV fluence yields accurate results with reasonable computing and manpower expenditures. A number of auxiliary studies have been described here which were performed as part of the development of the calculational methodology and were used to quantify the magnitude of various underlying approximations, and the expected overall fluence uncertainties.

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