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Analysis of the VENUS-3 Experiments

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The results of applying a hybrid superposition-synthesis calculational method to a mockup of a three-dimensional geometry involving a partial length shield assembly at the VENUS-3 facility in Mol, Belgium, are described. Comparisons of transport calculations using the method and many measurements involving nickel, indium, and aluminum dosimeters indicate agreement usually to within measurement uncertainties estimated at around 5%, if effects of inaccuracies in the dosimeter cross sections are minimized and proper orientation of the coordinate system used in the synthesis procedure is observed. These conclusions suggest a solution to the problem of predicting pressure vessel fluence in reactors modified by these partial-length shield assemblies may already exist.

INTRODUCTION AND BACKGROUND

Over the past several years, pressurized thermal shock (PTS) programs have become operational at many reactors in the United States. Since PTS-induced pressure vessel damage is dependent on the accumulated fluence, these programs are mainly concerned with reducing fluence rates incident on critical locations in the pressure vessel (PV) of pressurized water reactors (PWR's). At least two independent methods have been used, and both involve altering the core-source distribution. The first changes the refueling pattern to an in-in-out rotation at the critical azimuths so that twice-burned fuel now appears in the peripheral

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assemblies at those azimuths for which accumulated PV fluences have been the highest. This revised fuel loading scheme typically reduces the core leakage at these azimuths by about a factor of two. For many reactors of moderate age, this reduction is adequate to meet the additional requirements of plant-life extension. A second method is being used in several of the older reactors where fluence-rate reduction factors greater than those afforded by the first method have been deemed necessary. This procedure partially replaces the oxide fuel with metallic rods for those peripheral assemblies again located at the critical orientations. This substitution extends axially over a region that depends on the specific plant design, but covers in particular the most critical weld locations which are subject to PTS phenomena. The reduction in the fluence rates at the critical locations for the latter case is of the order of a factor of ten, and is due principally to the complete removal of the fission source in the critical peripheral assemblies.

One older reactor that has been subjected to both methods of core-leakage reduction has been H.B. Robinson Unit 2, which underwent a revised fuel shuffling scheme for cycle 9 and the introduction of partial-length shield assemblies (PLSA's) consisting of steel rods for cycle 10 and beyond. The analysis of cycle 9 using the LEPRICON procedure appears in the literature and is relatively straightforward(1). However, the use of the PLSA's introduces a geometrical complication that has not existed heretofore in conventional PV transport analysis, and a procedure should first be sought that adequately approximates the results of this three-dimensional transport with calculations involving only the one- and two-dimensional codes already in use.

Accordingly, an agreement was struck between the Nuclear Regulatory Commission (USNRC) and Mol which served the needs of both parties: The USNRC, with the approval of the Electric Power Research Institute, made available LEPRICON software for Mol to use in the dosimetry analysis of their DOEL reactors, while Mol agreed to perform experiments involving a PLSA mockup in their VENUS facility to serve to benchmark the calculational methods. The USNRC, through a contractual agreement with Oak Ridge National Laboratory (ORNL), also agreed to provide the results of an introductory analysis of these measurements.

THE VENUS-3 FACILITY AND THE MEASUREMENTS ANALYZED

The conclusions drawn from a meeting between ORNL and Mol scientists in January 1987 resulted in a design for VENUS-3 in which steel rods were substituted for the fuel over the complete lower half of the pins in the outermost five rows of two diametrically opposite arms of the cross. In Fig. 1 the PLSA modifications

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Fig. 1. Plan view of the VENUS-3 facility showing the location of the nickel dosimeters used in the early run of March 1988 as the white squares and the four black squares in the PLSA.

Fig. 2. Elevation view of the VENUS-3 facility showing the substitution of stainless steel rods for oxide fuel in the lower halves of five peripheral pins.

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are indicated as the left- and right-hand arms. An elevation view of the full arrangement is shown in Fig. 2. The upper half of these assemblies as well as all the remaining pins contain fuel without modification. The core, however, was modified to employ 4% enriched ^{235}U in steel clad pins in the inner zone and 3.3% enriched ^{235}U in zircalloy clad pins in the outer zone. Criticality was achieved by adjusting a different number and arrangement of pyrex rods surrounding the core inner baffle than those in earlier VENUS configurations.

Since the focus of the VENUS-3 experiments is essentially on providing data to test transport methods for calculating ex-core fluence rates, the source description used in the calculations was taken from measurements in order to reduce this potential source of uncertainty as much as possible. The measurements consisted of obtaining a relative pin-by-pin, three-dimensional distribution of the fission source over one-quarter of the core using a gamma-ray scanning technique, and then following up with a normalization factor that would link this relative distribution to the absolute distribution existing during the runs involving the dosimetry exposures. The fuel-pin scans were performed at fine enough spatial intervals that interpolation between measured values was estimated to be accurate to within 5%; the relative individual measurements were estimated to be accurate to within 2%. Absolute measurements of the core fission rates at several locations using four different methods yielded an averaged value of $8.60 \times 10^9 \pm 2.3\%$ (2) as the multiplicative factor for converting the source, arbitrarily normalized in the calculations to 1 fission/s per pin averaged over the core, to the source at full power. Measured reaction rates available for the present analysis involved the $^{58}\text{Ni}(n,p)$, $^{115}\text{In}(n,n')$, and $^{27}\text{Al}(n,\alpha)$ dosimeters at various axial levels and several horizontal locations throughout the configuration. These measurements are believed to have an accuracy of better than 3%. In this paper, explicit comparisons between calculated and measured values will be limited to those locations indicated by the white squares in the core barrel in Fig. 1 for the nickel dosimeters used in the early run of March 1988. This choice covers a large range of locations, starting at 0° behind the PLSA mockup and continuing around to 90° behind the unmodified assembly.

DESCRIPTION OF THE CALCULATIONS

The method chosen for the calculations is a modification of a fluence-rate synthesis procedure often used in more conventional geometry(3,4). By decomposing the usual synthesis prescription into two components, one contribution arising from sources (A) lying above the PLSA region and the other from sources (B) lying within the levels defined by the PLSA region, one can write the

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superposition-synthesis equation as

$$\phi_g(X, Y, Z) = \frac{\phi_g^A(X, Y)\phi_g^A(X, Z)}{\phi_g^A(X)} + \frac{\phi_g^B(X, Y)\phi_g^B(X, Z)}{\phi_g^B(X)}, \quad (1)$$

where X is the principal direction of transport, Y is the transverse direction, and Z is the axial direction. (5)

The sources to be used in the one- and two-dimensional discrete ordinates calculations are

$$S_g^A(X, Y) = \int_{Z_{UL}}^{\infty} S_g(X, Y, Z) dZ, \quad (2) \quad S_g^B(X, Y) = \int_{-\infty}^{Z_{UL}} S_g(X, Y, Z) dZ, \quad (3)$$

$$S_g^A(X, Z) = \int_{-\infty}^{\infty} S_g(X, Y, Z \geq Z_{UL}) dY, \quad (4) \quad S_g^B(X, Z) = \int_{-\infty}^{\infty} S_g(X, Y, Z \leq Z_{UL}) dY, \quad (5)$$

$$S_g^A(X) = \int_{-\infty}^{\infty} dY \int_{Z_{UL}}^{\infty} S_g(X, Y, Z) dZ, \quad (6) \quad S_g^B(X) = \int_{-\infty}^{\infty} dY \int_{-\infty}^{Z_{UL}} S_g(X, Y, Z) dZ, \quad (7)$$

where Z_{UL} is in general the upper level to which the metal rods extend. For VENUS-3, this is the midplane.

The condition that should be met for validity of the method is that the fluence rate due to each component be separable in Y and Z over the spatial region where that component dominates. In the transport geometry using sources defined by Eqs (2) and (6), the core periphery is composed entirely of active pins, while in the geometry defined by Eqs (3) and (7) the outer five rows (in VENUS-3) contain only steel-filled pins.

COMPARISON OF CALCULATED AND MEASURED RESULTS

The measurements and calculations were originally expressed as reaction rates in units of reactions/s per target nucleus at full power. Comparisons are more meaningful when expressed in terms of equivalent fission fluence rates in the present application, however, for they remove some of the dependence of the calculated results on the dosimeter cross sections and of the measured results on reaction-specific parameters such as branching ratios. Thus, these resulting comparisons tend to become better measures of the accuracy of the calculational method itself, which is the primary goal of the VENUS-3 program. These equivalent fission fluence rates are reaction dependent, and are defined for reaction i as

$$\phi_i = \frac{\int_0^{\infty} \phi(E) \sigma_i(E) dE}{\int_0^{\infty} {}^{235}\chi(E) \sigma_i(E) dE}, \quad (8)$$

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where the numerator is the conventional reaction rate and the denominator is the spectrum-averaged reaction cross section in a ^{235}U fission field. For all three reactions analyzed, calculated values of the denominator using the cross-section library adopted for this analysis(6) underestimate the measured values used by Mol by 3 to 5%.(7)

The calculations described so far involve an XY run, an XZ run, and an X run, all for each of the two source components, for a total of six discrete ordinates calculations. It is to be expected, however, that the two measurements in the core barrel at 68° and 89° (or any such similar locations requiring a considerable re-orientation of the coordinate system defined in Eqs (1) through (7) and Fig. 1) may not be well calculated. As pointed out earlier, the significance of the X and Y axes in these equations is in their interpretation as parallel and perpendicular to the principal direction of flow to the detector, respectively. This direction can be approximated in the present geometry for ex-core detectors by a line joining the core center and the detector. For most of the detectors shown in Fig. 1, both in-core and ex-core, the XY coordinate system shown in Fig. 1 is adequate. For detector locations lying at angles greater than 45° with the X-axis, X and Y may be interchanged in Eqs (1) through (7) and the resulting sources resummed. This has no effect on the XY transport calculations if X and Y are now reinterpreted as the old Y and X respectively, and the original XY results are still valid. The XZ and X transport calculations must be redone, however, since their source terms are now different. This results in additional XZ and X runs for each of the two source components. A grand total of ten discrete ordinates calculations were thus made. The reaction rates at 68° and 89° that were calculated using the re-oriented coordinate system provide good reference points for confirming the accuracy of the synthesis procedure in the vicinity of an unmodified assembly, where no consideration of separate source components (i.e., superposition) is necessary.

Some comparisons of the nickel fluence rates in the core barrel are shown in Table 1. Values of C/E at similar locations to those in Table 1 for the indium and aluminum dosimeters are virtually the same, thus extending verification of the method to higher and lower energies. Comparisons at other locations, both in-core and ex-core, some of which are indicated as additional white squares along with a few black squares in Fig. 1, further substantiate the general applicability of the method. The comparisons at most locations agree to within the estimated standard deviation of around 5% which is a composite of all measurement uncertainties.

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Table 1. Some Absolute Comparisons of the Nickel Fluence Rates in the Core Barrel for the March 1988 Run

Z (cm) ^a	Angle ^b	ϕ_r	ϕ_c	ϕ_c/ϕ_r	Angle ^b	ϕ_r	ϕ_c	ϕ_c/ϕ_r
106.5	0 deg	1.70+7 ^c	1.64+7 ^d	0.96	21 deg	1.41+7	1.40+7 ^d	0.99
114.5		2.83+7	2.80+7	0.99		2.39+7	2.37+7	0.99
122.5		4.39+7	4.07+7	0.93		3.56+7	3.46+7	0.97
128.5		5.54+7	5.31+7	0.96		4.54+7	4.48+7	0.99
131.5		6.09+7	5.64+7	0.93		5.03+7	4.80+7	0.95
134.5		6.45+7	6.06+7	0.94		5.41+7	5.24+7	0.97
141.5		6.44+7	6.05+7	0.94		5.35+7	5.16+7	0.96
145.5		5.87+7	5.55+7	0.95		4.78+7	4.67+7	0.98
149.5	45 deg	4.94+7	4.76+7	0.96	68 deg	4.05+7	3.96+7	0.98
153.5		3.76+7	3.62+7	0.96		3.07+7	2.95+7	0.96
106.5		1.75+7	1.77+7 ^e	1.01		3.42+7	3.24+7 ^e	0.95
114.5		2.74+7	2.96+7	1.08		5.72+7	5.50+7	0.96
122.5		3.53+7	3.87+7	1.10		7.09+7	7.00+7	0.99
128.5		3.84+7	4.30+7	1.12		7.51+7	7.51+7	1.00
131.5		3.86+7	4.53+7	1.17		7.68+7	7.53+7	0.98
134.5		3.83+7	4.53+7	1.18		7.50+7	7.40+7	0.99
141.5	89 deg	3.50+7	4.02+7	1.15		6.64+7	6.50+7	0.98
145.5		3.09+7	3.48+7	1.13		5.72+7	5.65+7	0.99
149.5		2.54+7	2.81+7	1.11		4.67+7	4.67+7	1.00
153.5		1.97+7	2.09+7	1.06		3.45+7	3.43+7	0.99
106.5		4.32+7	4.60+7 ^d	1.06	99 deg	4.32+7	4.23+7 ^e	0.98
114.5		7.08+7	7.82+7	1.10		7.08+7	7.00+7	0.99
122.5		8.94+7	1.02+8	1.14		8.94+7	8.85+7	0.99
128.5		9.54+7	1.09+8	1.14		9.54+7	9.46+7	0.99
131.5		9.63+7	1.09+8	1.13		9.63+7	9.55+7	0.99
134.5		9.45+7	1.07+9	1.13		9.45+7	9.26+7	0.98
141.5		8.21+7	9.36+7	1.14		8.21+7	8.14+7	0.99
145.5		7.17+7	8.05+7	1.12		7.17+7	7.14+7	1.00
149.5	10 deg	5.81+7	6.49+7	1.12	25 deg	5.81+7	5.92+7	1.02
153.5		4.32+7	4.78+7	1.11		4.32+7	4.39+7	1.02
114.5		2.48+7	2.44+7 ^d	0.98		2.18+7	2.17+7 ^d	1.00
131.5		5.21+7	4.86+7	0.93		4.35+7	4.25+7	0.98
145.5		5.04+7	4.76+7	0.94		4.09+7	4.07+7	1.00
114.5	33 deg	2.88+7	2.31+7 ^d	0.80	40 deg	2.53+7	2.38+7 ^d	0.94
131.5		4.48+7	4.22+7	0.94		3.76+7	4.34+7	1.15
145.5		3.93+7	3.80+7	0.97		3.06+7	3.62+7	1.18

^aThe pins extend from 105 to 155 cm; the PLSA extends from 105 to 130 cm. See Fig 2.

^bSee Fig. 1.

^cRead as 1.70×10^7 n/cm²·s at full power.

^dBased on orientation of X and Y axes as shown in Fig. 1.

^eBased on orientation of X and Y axes rotated 90 deg counterclockwise to those of Fig. 1.

DISCUSSION OF THE RESULTS AND CONCLUSIONS

Success in the introduction of a source decomposition and superposition technique and combining it with a fluence-rate synthesis procedure is conclusively demonstrated by the axial comparisons at the 0°, 10°, 21°, 25°, 28°, and 33° locations in the core barrel as well as four PLSA locations, the water gap, and all seven locations in the outer baffle. The axial profiles at these locations are influenced by the PLSA and are asymmetric, as contrasted with the nearly perfect symmetry of the profiles

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located well inside the core and in the vicinity of the 68° and 89° core barrel locations. A legitimate conclusion deduced from the comparisons near 0° and 89° is that, at least for VENUS-3, Eqs (1) through (7) are as accurate in the treatment of PLSA-affected regions as earlier equations without source decomposition are in the unaffected ones. It is only at the two locations in the vicinity of 45° in the core barrel that any significant error is incurred with the proposed technique, and presumably this error could be reduced by reorienting the X and Y axes in Eqs (2) through (7) to lie at 45° to the directions shown in Fig. 1, were it really necessary. The error near 45° is still not large, however, being at most 18% (see Table 1). The conclusion that the method provides acceptable accuracy when applied to VENUS-3 does not necessarily imply that comparable accuracies should be realized when applied to PWR's. Differences in geometry between VENUS-3 and H.B. Robinson-2 are still considerable. Nevertheless, the accuracy of the proposed method when applied to VENUS-3 is very encouraging, and suggests that a relatively simple modification to the method, if necessary, could be found for application to PWR's.

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