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Study of the Neutron Flux and Dpa Attenuation in the Reactor Pressure-Vessel Wall

I. Remec

Contract Program or Title:	Embrittlement Data Base and Dosimetry Evaluation Program
Subject of this Document:	Study of the Neutron Flux and Dpa Attenuation in the Reactor Pressure- Vessel Wall
Type of Document:	Letter Report
Author:	I. Remec
Date of Document:	June 1999
Responsible NRC Individual and NRC Office or Division:	C. Fairbanks (301-415-6014) Division of Engineering, U.S. Nuclear Regulatory Commission

**Prepared for the
U.S. Nuclear Regulatory Commission
Washington, DC 20555
under Interagency Agreement DOE 1886-N616-4W
NRC JCN No. W6164**

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Oak Ridge, TN 37831-6363
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LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. Department of Energy
under contract DE-AC05-96OR22464.**

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Manuscript Completed - May 1999

Date Published - June 1999

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ABSTRACT

The study of the neutron flux and dpa attenuation in the reactor pressure vessel (PV) wall presented in this work was performed with state-of-the art methods currently used to determine PV fluxes, the BUGLE-96 cross-section library, and the iron displacement cross sections derived from ENDF/B-VI data.

The calculations showed that the RG 1.99, Rev. 2, extrapolation formula predicts slower—and therefore conservative—attenuation of the neutron flux ($E > 1\text{MeV}$) in the PV wall. More importantly, the calculations gave slower attenuation of the dpa rate in the PV wall than the attenuation predicted by the formula. The slower dpa rate attenuation was observed for all the cases considered, which included two different PWRs, and several configurations obtained by varying the PV wall thickness and thermal shield thickness. For example, for a PV wall thickness of $\sim 24\text{ cm}$, the calculated ratio of the dpa rate at $1/4$ and $3/4$ of the PV wall thickness to the dpa value on the inner PV surface is $\sim 14\%$ and 19% higher, respectively, than predicted by the RG 1.99, Rev. 2, formula.

An investigation into the causes of these relatively large differences was performed through the comparison of a series of calculations with the SAILOR cross section library, based on ENDF/B-IV data, and the BUGLE-96 cross-section library. This approach was used because the dpa rate attenuation in the PV wall, calculated with the SAILOR cross section, P_1 approximation to the angular dependence of scattering cross sections, and dpa cross sections from ASTM standard E 693, comes relatively close (within $\sim 5\%$) to the RG 1.99, Rev. 2, formula prediction. It was found that approximately 40–45% of the differences are caused by the change in cross sections (from SAILOR, P_1 to BUGLE-96, P_1), ~ 35 –40% of the differences are due to the change from P_1 to P_3 , and ~ 15 –20% of the differences are induced by the change from the ENDF/B-IV to the ENDF/B-VI dpa cross sections. Near the PV surfaces the calculated attenuation of the dpa rate also deviates from the simple exponential attenuation used in the RG 1.99, Rev. 2, formula, which contributes to the larger differences, especially near the PV outer surface.

Calculations for various thermal shield thicknesses showed that thicker thermal shield typically results in slower dpa attenuation in the PV wall. However, increasing the thermal shield thickness tends to decrease the dpa rate at the PV inner wall by $\sim 3.5\%$ per 1 cm of the thermal shield thickness increase (1 cm of water replaced by 1 cm of steel). The thickness of the PV wall has a negligible effect on the dpa rate at the PV inner wall; however, the thicker the PV is, the slower is the dpa decrease inside the wall. The effect is small in the region near the PV inner surface but becomes quite important at larger distances from the PV inner wall.

The dpa rate attenuation calculated for the two-loop PWR was found in good agreement with the results for the three-loop PWR with similar PV wall thickness. This agreement indicates that performing a few additional parametric studies with the models used in this study, for different thermal shield, PV, and downcomer thicknesses, may be sufficient to generate the data base for an update of the RG 1.99, Rev. 2, attenuation formula. A more rigorous, but also more time-consuming approach, would require the calculations of the dpa attenuation in the PV wall for several different reactor designs, similar to Guthrie's work, which considered six types of commercial PWRs.

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ACKNOWLEDGMENTS

The author wishes to express his appreciation to the reviewers, J. V. Pace III and R. E. Stoller of the Oak Ridge National Laboratory. Special thanks go to C. H. Shappert for providing the editorial review and to M. R. Whittenbarger for the preparation of this report. The work was performed as a part of the "Embrittlement Data Base and Dosimetry Evaluation Program" (FIN W6164) sponsored by the Nuclear Regulatory Commission and managed by Carolyn Fairbanks of the Nuclear Regulatory Commission.

1. INTRODUCTION

The current methodology for the determination of the fast flux ($E > 1$ MeV) inside the reactor pressure vessel (PV) wall, acceptable to the U.S. Nuclear Regulatory Commission (NRC) is described in Regulatory Guide 1.99, Revision 2 (Ref. 1). The regulatory guide states that "The neutron fluence at any depth in the vessel wall, f (10^{19} n/cm², $E > 1$ MeV), is determined as follows:

$$f = f_{\text{surf}} \times e^{-0.24x} \quad (\text{Eq. 1})$$

where f_{surf} (10^{19} n/cm², $E > 1$ MeV) is the calculated value of the neutron fluence at the inner wetted surface of the vessel at the location of the postulated defect, and x (in inches) is the depth into the vessel wall measured from the vessel inner (wetted) surface. Alternatively, if dpa calculations are made as part of the fluence analysis, the ratio of the dpa at the depth in question to the dpa at the inner surface may be substituted for the exponential attenuation factor in Equation 3." The RG 1.99 Equation 3 is the (Eq. 1) shown above.

The basis for the RG 1.99, Rev. 2, attenuation formula is discussed in Randall's paper (Ref. 2) and can be summarized as follows: Prior to the RG 1.99, Rev. 2, the fast-flux attenuation in the wall was estimated by the formula given in (Eq. 1), but with the coefficient in the exponent of 0.33. This older attenuation formula came from U.S. NRC staff reviews of the surveillance reports. During the preparation of RG 1.99, Rev. 2, it was realized that the changes in neutron spectra with depth of penetration in the wall are significant. To take this into account it was decided to use a "dpa equivalent" (displacements per atom) attenuation formula. To convert the "fluence attenuation" formula to the "dpa attenuation" formula, the calculations reported in Guthrie's paper (Ref. 3) were used. Guthrie and coworkers showed that the dpa attenuation through the vessel wall was less than the attenuation of fast fluence ($E > 1$ MeV) by a factor of ~2.06, which was the average of six calculations (one calculation for each of six different PWR reactors). As explained in Reference 2, to achieve a 2.06-times slower flux attenuation through an 8-in.-thick PV wall, the exponent in the flux attenuation formula was changed from 0.33 to 0.24, which is given in RG 1.99, Rev. 2. (See Eq. 1).*

The transport calculations by Guthrie and coworkers were performed as fixed neutron source calculations with the Westinghouse version of the DOT-3 neutron transport code (Ref. 4), and S_8 angular quadrature. The GAMBIT-1T cross-section library (Ref. 5), based on an early version of ENDF/B evaluated data files, was used. The angular dependence of the scattering cross sections was

*The factor of 2.06, which is the average of the factors calculated for six different reactors, reported in Reference 3, was used with the PV wall thickness of 8 in. However, Reference 3 does not give the thicknesses of the PV wall of the six reactors considered. It is quite possible that calculations for different reactors, from which the average factor 2.06 was derived, were actually done for different PV wall thicknesses. The relatively large spread of the factors reported in Reference 3 (minimum 1.62, maximum 2.23) seems to indicate that different PV thicknesses were used for the different reactor types analyzed.

described with a P_1 approximation. The spectrum of the fission neutron source was the Cranberg fission spectrum.

Since Guthrie's analysis the cross sections were updated several times. A P_3 expansion is routinely used in the transport calculations, and the cross-section libraries typically use a refined energy-group structure (e.g., 8 groups above 1 MeV were used in GAMBIT-1T, compared with 19 groups in BUGLE-96). Given all these changes, it appears necessary to revisit the fast flux and dpa attenuation in the PV wall, which is the purpose of the work presented here. The in-vessel-wall gradients are calculated using (1) the BUGLE-96 multigroup cross-section library (based on ENDF/B-VI), (2) the current methodology of the transport calculations, and (3) the displacement cross sections for iron derived from ENDF/B-VI data. The comparisons with RG 1.99, Rev. 2, attenuation formula are presented. The results from this study will contribute to the data needed for an update of the RG 1.99, Rev. 2, fluence attenuation formula.

2. ANALYSIS AND RESULTS

The calculational method used in this analysis is consistent with state-of-the art methods currently used to determine PV fluxes. The same calculational method has been used, for example, in the analysis of the PCA and HBR-2 benchmarks (Ref. 6 and 7). The neutron transport calculations were performed with the DORT computer code (Ref. 8). The synthesis method, which combines one r - θ , one r - z , and one one-dimensional (1-D) r - calculation to obtain the three-dimensional (3-D) flux distributions, was used throughout the analysis. More about the synthesis method can be found in References 6, 7, and 9. All transport calculations used a P_3 expansion of the scattering cross sections. The only exceptions were the calculations in which the effect of the order of scattering expansion was investigated. All calculations were performed as fixed neutron source calculations. The neutron source spatial distributions were prepared from the core power distributions available from the fuel cycle calculations, which were not part of this study, and were performed with codes used for core design calculations. Two neutron cross-section libraries were used: The BUGLE-96 library represents the currently recommended cross-section library based on ENDF/B-VI (Ref. 10) which was released in 1996. The SAILOR library (Ref. 11) represents older cross-section libraries, based on ENDF/B-IV data. The SAILOR library has been extensively used for PV flux calculations since it was released in 1984. Both cross-section libraries have the same neutron energy group structure of 47 groups (of which 19 groups cover the energy range above 1 MeV), which is of greatest interest in the PV flux calculations. The calculations with the SAILOR library were done to quantify the change in the flux and dpa rate attenuation in the PV wall due to the change in the cross sections.

Most of the calculations were done for the H. B. Robinson-2 (HBR-2), which is a three-loop pressurized-water reactor (PWR) of Westinghouse design, with a reactor thermal power of 2300 MW. The data on reactor core and out-of-core components, geometry, materials, and power distributions were taken from Reference 7. The HBR-2 dimensions, as given in Reference 7, are referred to in this report as the "nominal" dimensions. Starting from the nominal dimensions, the calculations were repeated for different thicknesses of the thermal shield and reactor PV wall, to quantify the effect of these parameters on the attenuation in the PV wall. Each change in geometry required a new set of transport calculations and flux synthesis.

The effect of the change of the thermal shield (TS) thickness is presented in Tables 1–5 and Figures 1–4. Different thermal shield thicknesses were modeled by varying the thermal shield inner radius, and, consequently, the thickness of the water gap between the core barrel and the thermal shield. All other dimensions, in particular the core barrel outer radius, the thermal shield outer radius, and the PV inner radius were the same in all calculations. The flux ($E > 1$ MeV), flux ($E > 0.1$ MeV), and the dpa rate, at the PV inner radius at the azimuthal location where they have maximal values, are listed for different TS thicknesses in Table 1 and are shown in Figure 1. Unless it is specified otherwise, all the irradiation parameters and their attenuation through the PV wall are given for the location at which they reach the maximum value at the PV inner wall. The flux ($E > 1$ MeV) and dpa rate at the PV inner wall decrease monotonously as the TS thickness increases. The flux ($E > 1$ MeV) shows nearly a linear decrease of $\sim 3.5\%$ per centimeter of the TS thickness increase. The decrease in the dpa rate is slower, while the flux ($E > 0.1$ MeV) has a minimum in the range of the TS thickness between 3 to 7 cm. The flux ($E > 1$ MeV) versus the distance from the PV inner (wetted) surface, for different TS thicknesses, is listed in Table 2. The slowest attenuation of the flux ($E > 1$ MeV) through the PV wall is observed for the configuration without the thermal shield (i. e., TS thickness 0 cm). The ratio of the irradiation parameter [e.g., flux ($E > 1$ MeV)], at the given distance from the PV inner (wetted) surface to the value at the PV inner surface, will be referred to as the extrapolation factor. For the TS thickness of 0 cm the flux ($E > 1$ MeV) extrapolation factors at ~ 5 cm and at ~ 15 cm inside the PV wall are $\sim 3\%$ and $\sim 6\%$ higher, respectively, than the values for the TS thickness of ~ 10 cm. As shown in Figure 2, the RG 1.99, Rev. 2, formula predicts slower, therefore conservative, attenuation of the flux ($E > 1$ MeV), than the attenuations obtained from the transport calculations for all the TS thicknesses considered, except for the first few (~ 4 cm) of the PV wall, where the calculated attenuation is slightly slower than the RG 1.99 prediction and gives up to $\sim 4.6\%$ higher extrapolations factors.

The dpa rate attenuation in the PV wall is given in Table 3 for the iron atom displacement cross sections (dpa cross sections) generated from the ENDF/B-VI data, and in Table 4 for the iron-displacement cross sections from the ASTM standard E 693, which were derived from the ENDF/B-IV data (Ref. 12). The dpa cross sections from ASTM E 693 will be referred to in the following as the “ASTM dpa.” The thicker thermal shield typically causes slower dpa rate attenuation in the PV wall. For the TS thickness of ~ 10 cm, the extrapolation factors at ~ 5 cm and at ~ 15 cm from the PV inner wall are $\sim 3.6\%$ and 11.5% higher, respectively, than the extrapolation factors for the configuration without the thermal shield. The dpa rate attenuation curves for different TS thicknesses are compared in Figure 3. The calculated attenuation of the dpa rate is slower than the attenuation predicted by RG 1.99, Rev. 2, for all TS thicknesses considered. For example, for the TS thickness 6.83 cm, the extrapolation factors at ~ 5 cm and 15 cm from the PV inner wall are $\sim 14\%$ and 19% higher than the RG 1.99 formula prediction. The dpa rates calculated with the ENDF/B-VI dpa cross sections are typically slightly higher than the dpa rates calculated with the ASTM dpa cross sections, except at the PV inner surface and in a thin region of the PV close to the inner surface, for the configuration with a thin or no thermal shield. The effect of change from the ASTM to the ENDF/B-VI dpa cross sections will be considered in more detail later. Table 5 gives the attenuation of the flux ($E > 0.1$ MeV) through the PV for different TS thicknesses, and the attenuation curves are shown in Figure 4. Flux ($E > 0.1$ MeV) reaches maximum value within the first few centimeters of the PV wall and then decreases monotonically. In Figure 4 the attenuation curve derived from RG 1.99 is also shown. It predicts much faster attenuation than the calculated curves for the flux ($E > 0.1$ MeV);

however, this comparison must be viewed from the perspective that the RG 1.99 formula is intended to predict the attenuation of the dpa rate and not the flux ($E > 0.1$ MeV).

Next, the effect of PV wall thickness on the flux and dpa rate attenuation in the PV wall was investigated. Different PV wall thicknesses were modeled by changing the PV outer radius, while the inner radius, the thermal shield (6.83 cm thick), and all the rest of the geometry were kept unchanged. Besides the nominal HBR-2 PV thickness of 24.2 cm, the calculations were done for an ~25% thinner and ~25% thicker PV wall. The calculated fluxes ($E > 1$ MeV) are listed in Table 6 and are shown in Figure 5. The PV wall thickness has a negligible effect on the flux ($E > 1$ MeV) on the PV inner surface and throughout most of the PV wall. Only in approximately the last quarter of the PV wall the differences start to show, and the flux ($E > 1$ MeV) in the thinner PV decreases faster towards the PV outer surface than it decreases in the PV with the thicker wall. The results for the dpa rate attenuation are given in Tables 7 and 8 for the ENDF/B-VI and ASTM dpa cross sections, respectively. Figure 6 shows the dpa rate attenuation curves calculated with the ENDF/B-VI dpa cross sections. The dpa rate attenuation is more affected by the PV wall thickness than the flux ($E > 1$ MeV) attenuation. A thicker PV wall results in slower dpa rate attenuation. For example, at ~5 cm from the PV inner surface, the dpa extrapolation factor for the 30-cm-thick PV is ~3.4% higher than the corresponding factor for the PV with an 18.8-cm-thick wall. The differences increase through the PV wall and are in the range of 45%–60% in the vicinity of the PV outer surface. The RG 1.99 attenuation formula predicts faster attenuation than the calculated dpa curves for all three PV thicknesses considered. The only exception is the ~3-cm-thick region near the PV outer surface, for the PV with an 18.75-cm-thick wall, as can be seen in Figure 6. The flux ($E > 0.1$ MeV) attenuation in the PV wall is significantly affected by the PV wall thickness and is illustrated in Figures 7 (Lin-Lin plot) and 8 (Log-Lin plot). The flux ($E > 0.1$ MeV) values and extrapolation factors are listed in Table 9. The dpa rate and flux ($E > 1$ MeV) attenuation curves for different PV wall thicknesses are shown, together with the RG 1.99, Rev. 2, attenuation curve, on Figure 9.

Finally, the impact of the change from the SAILOR (ENDF/B-IV) to the BUGLE-96 cross-section library on the attenuation profiles in the PV were examined. The flux ($E > 1$ MeV) attenuation in the PV, calculated with the two cross-section libraries, was compared in Table 10. The calculations were performed for the nominal HBR-2 geometry. The calculations with the SAILOR library used the ENDF/B-IV fission spectra for ^{235}U and ^{239}Pu , while the BUGLE-96 calculation used the corresponding spectra from ENDF/B-VI data. The BUGLE-96 calculation results in slower flux ($E > 1$ MeV) attenuation. The extrapolation factor for the BUGLE-96 calculation is ~3% higher at ~5 cm from the PV inner wall, and the differences increase towards the PV outer surface, where they reach ~17%. The flux ($E > 1$ MeV) attenuation curves, calculated with SAILOR and BUGLE-96 cross sections, are shown in Figure 10. The dpa rates, calculated with ENDF/B-VI dpa cross sections and fluxes from the SAILOR and BUGLE-96 calculations, are compared in Table 11 and in Figure 11. The differences in the dpa rates, calculated with the two libraries, are similar to the differences observed in flux ($E > 1$ MeV). Again, the BUGLE-96 calculation gives higher extrapolation factors: ~3.7% higher at ~5 cm from the inner PV surface, and ~17% higher near the PV outer surface. Both calculations give considerably slower attenuation of dpa rate than the RG 1.99 formula, except for the region within a few centimeters from the PV outer surface. In most, if not all previous analyses performed with the SAILOR library, the ASTM dpa cross sections were used to determine dpa rates and attenuation in the PV wall. The dpa rates, therefore, were calculated

also with neutron fluxes from the SAILOR calculation and the ASTM dpa cross sections. The comparison of the dpa rate attenuation profile with the one obtained with BUGLE-96 and ENDF/B-VI dpa cross sections is given in Table 12, and in Figure 12. The dpa rate profiles are also compared with the BUGLE-96 flux ($E > 1$ MeV) profile and RG 1.99 attenuation formula. When SAILOR fluxes are combined with ASTM dpa cross sections, the dpa attenuation in the PV wall is slightly faster than the dpa attenuation calculated with the ENDF/B-VI dpa cross sections. The dpa attenuation factor, determined with "BUGLE-96 and ENDF/B-VI dpa cross sections," is $\sim 5.5\%$ higher than the "SAILOR with ASTM dpa cross-sections" attenuation factor at ~ 5 cm from the PV inner wall, and more than 20% higher near the PV outer surface. The dpa attenuation obtained with the "SAILOR with ASTM dpa cross sections" is also slower than the attenuation predicted with RG 1.99 formula throughout the PV wall, except in the region within approximately one quarter of the PV wall thickness from the PV outer wall. The differences between the calculated dpa rate attenuation in the PV wall and RG 1.99 formula are illustrated further in Figure 13, which shows the difference in percent between the extrapolation factors. For the 24.20-cm-thick PV wall, the maximal differences in predicted attenuation between the "BUGLE-96 with ENDF/B-VI dpa cross sections" and RG 1.99 formula is almost 20%, at approximately 15 cm from the PV inner wall; the RG 1.99 formula predicts faster attenuation. Maximal differences between "SAILOR with ASTM dpa cross sections" and RG 1.99 formula are about 8% at ~ 5 cm from the PV inner wall. The differences between dpa attenuation obtained from "BUGLE-96 with ENDF/B-VI dpa cross sections" to the "SAILOR with ASTM dpa cross sections" increase monotonically through the PV wall and exceed 20% near the PV outer surface.

Even though it was expected that the attenuation in the PV wall, calculated with the BUGLE-96 library, would be considerably slower than the attenuation described with the RG 1.99 formula, it is somewhat surprising that the attenuation obtained from "SAILOR with ASTM dpa cross sections" is also considerably slower than the RG 1.99 formula prediction. To investigate these differences, attention is turned to the effect of the approximation used for the description of angular dependence of the scattering cross sections. The transport calculations by Guthrie and coworkers, which furnished data for the RG 1.99, Rev. 2, attenuation formula update, were performed with a P_1 approximation, while all the calculations reported so far in this work used a more accurate P_3 approximation. To quantify the effect of the "P-order" approximation on the flux and dpa rate attenuation in the PV wall, a series of calculations with the P_1 , P_2 , and P_3 expansion of scattering cross sections was performed. All calculations were done for the "nominal" HBR-2 geometry. The results, obtained with the BUGLE-96 library, are given in Table 13 for the flux ($E > 1$ MeV) and in Table 14 for the dpa rate, calculated with ASTM dpa cross sections. The change from P_1 to P_3 results in slower attenuation of the flux ($E > 1$ MeV) and the dpa rate through the PV wall. The flux ($E > 1$ MeV) extrapolation factor, determined with the P_3 approximation, is $\sim 5\%$ higher at ~ 5 cm from the PV inner wall, $\sim 12\%$ higher at ~ 15 cm, and $\sim 17\%$ higher near the PV outer surface. The corresponding effect on the dpa rate attenuation is somewhat smaller: the extrapolation factor is $\sim 3.7\%$ and 6.6% higher at ~ 5 cm, and ~ 15 cm from the PV inner wall, respectively, when P_3 approximation is used instead of the P_1 approximation, and the maximum differences near the PV outer surface are $\sim 8\%$. Figures 14 and 15 show the flux ($E > 1$ MeV) and the dpa rate attenuation in the PV wall, calculated with the BUGLE-96 library and P_1 to P_3 approximations. It can be seen that the effect of the change from P_2 to P_3 is practically negligible; however, the differences in the attenuation curves between the P_1 and P_3 calculations are important. Even the dpa rate attenuation

curve obtained with the P_1 approximation, the BUGLE-96 library, and the ASTM dpa cross sections, shows slower attenuation in the PV wall than predicted by the RG 1.99 formula. The calculations were repeated with the SAILOR library and the P_1 and P_3 approximations. The results are shown, in Figure 16, together with those for the BUGLE-96 library. Detailed comparisons are given in Table 15 and in Figure 17. The calculation with the SAILOR library, P_1 approximation, and the ASTM dpa cross sections gives the fastest dpa rate attenuation in the PV wall and comes close to the RG 1.99, Rev. 2, attenuation formula: maximum differences do not exceed 5% over most of the PV wall thickness. However the "SAILOR, P_1 , ASTM dpa" calculation still gives slower attenuation of the dpa rate than the RG 1.99 formula. The exception is again in the region near the PV surface, where the formula gives slower attenuation. The reason for this is that in the region near the vessel outer surface the flux ($E > 1$ MeV) and the dpa rate decrease faster than in the region closer to the inner wall, because of the effect of the "free" PV outer surface: because of a low density of air in the cavity (compared with the density of PV steel) very few neutrons are scattered back from the cavity into the PV wall. These conditions are reflected in the calculated attenuation curves, but not in the RG 1.99, Rev. 2, formula, which assumes uniform exponential attenuation throughout the PV wall. Besides, as mentioned before (see also Reference 2), the exponent in the RG 1.99, Rev. 2, formula was derived for the PV wall thickness of ~ 20 cm (8-in.), and larger deviations from the actual (calculated) attenuation in the region near PV outer surface, for a PV thicker than ~ 20 cm is not surprising.

The effect of changing from the ASTM dpa cross sections, based on ENDF/B-IV data (Ref. 12) to the new dpa cross sections, derived from the ENDF/B-VI data, is analyzed in Table 16 and in Figure 18. The ENDF/B-VI dpa cross sections result in slightly slower attenuation of the dpa rate through the PV wall. The dpa extrapolation factors obtained with ENDF/B-VI dpa cross sections are $\sim 1.6\%$ and $\sim 4\%$ higher at the ~ 5 cm and ~ 15 cm from the PV inner wall, respectively, than the values obtained with ASTM dpa cross sections. The differences increase monotonically through the PV wall and reach $\sim 4.6\%$ near the PV outer surface.

The contributions to the changes in the dpa attenuation through the PV wall are summarized in Table 17. The dpa extrapolation factor, calculated with the BUGLE-96 library, P_3 approximation, and ENDF/B-VI dpa cross sections is higher than the extrapolation factor obtained with the SAILOR library, P_1 approximation, and ASTM dpa cross sections by $\sim 10\%$ at ~ 5 cm from the PV inner wall, and by $\sim 20\%$ at ~ 15 cm from the PV inner wall. Most of these changes are caused by the changes in the cross sections: the differences in extrapolation factors obtained with SAILOR and BUGLE-96 are 4.2% and 8.9%, at ~ 5 cm and ~ 15 cm from the PV outer wall, when the P_1 approximation for the angular dependence of the scattering cross sections is used. The next biggest contribution comes from the change from the P_1 to P_3 approximation, and hence better description of the anisotropic scattering. This change results in $\sim 3.7\%$ and 6.6% increase in the extrapolation factor, calculated with the BUGLE-96 library. The last contribution is due to the change from ENDF/B-IV dpa cross sections (ASTM, Reference 12) to the new ENDF/B-VI dpa cross sections. This change introduces a modest increase in extrapolation factors of $\sim 1.6\%$ and 3.8% at the ~ 5 cm and ~ 15 cm from the PV inner surface. The difference between the dpa extrapolation factors from the calculation with the "BUGLE-96, P_3 approximation, and ENDF/B-VI dpa cross sections," and the RG 1.99 formula are $\sim 14\%$ and 20% at ~ 5 cm and ~ 15 cm from the PV inner wall. These differences are composed primarily of the contributions discussed above. The differences exceeding these contributions are

most probably caused by the simplifications necessary to describe the dpa attenuation with a simple exponential formula given in RG 1.99, Rev. 2, and by the averaging of results for different power plants, done in the derivation of the formula (see Reference 2).

So far all discussions of the attenuation of the flux and dpa rate through the PV wall were limited to the location of the PV wall, where the flux (and dpa) reached the maximal value on the PV inner surface. However, due to the staircase-shape of the core boundary, the thickness of the water layer between the core baffle and the core barrel varies around the core and causes a variation of neutron flux around the PV circumference. These "azimuthal" variations of the flux ($E > 1$ MeV) and the dpa rate are shown in Figures 19 and 20. The variations are relatively large: the ratio of maximum-to-minimum of the flux ($E > 1$ MeV) and of the dpa rate at the PV inner surface are in the range 2.5–3. Therefore, it appeared of interest to investigate the changes in the attenuation in the PV wall with the azimuthal location as well. In the transport calculation, one octant (i.e., a 45° section) of the reactor horizontal cross section was covered with 74 azimuthal intervals, and the flux and dpa rate attenuation curves were calculated for all the azimuthal intervals. Then, for any depth, "d," from the PV inner surface, the average, maximum, and minimum extrapolation factors were determined. The average value was determined as an arithmetic average over all the azimuthal intervals. The results for the flux ($E > 1$ MeV) and the dpa rate are listed in Tables 18 and 19, respectively, and are illustrated in Figures 21 and 22. The maximum and minimum flux ($E > 1$ MeV) extrapolation factors differ from the average by 2% and 5%, at ~ 5 cm and ~ 15 cm from the PV inner wall. The corresponding differences for the dpa extrapolation factors are slightly larger: $\sim 3\%$ and 8% . The spread of the minimum-to-maximum values for the flux ($E > 1$ MeV) and the dpa rate extrapolation factors increase through the PV wall. However, even the curve for the minimum dpa extrapolation factors indicates slower dpa attenuation than the RG 1.99, Rev. 2, formula, as can be seen from Figure 22. These variations of the extrapolation factors with azimuthal location give an estimation of the uncertainty introduced if only one attenuation formula is used at all azimuthal locations.

The final part of this study consists of an analysis of another power plant, which was a 1876-MW (thermal power) two-loop PWR of Westinghouse design, with a PV inner radius of 167.64 cm, a 17.16-cm-thick PV wall — the PV wall thickness includes 0.32-cm cladding on the inner surface — and a 9.05-cm-thick thermal shield. The same modeling approximations and calculational procedure, as described previously in this report, were used. The transport calculations were performed with the BUGLE-96 and the SAILOR cross-section libraries, with the P_3 approximation for the angular dependence of the scattering cross sections. The flux ($E > 1$ MeV), flux ($E > 0.1$ MeV), and the dpa rate (calculated with ASTM and ENDF/B-VI dpa cross sections) attenuation profiles through the PV wall are listed in Table 20 for the calculations with BUGLE-96 library and in Table 21 for the calculations with the SAILOR library. The absolute values, as well as the extrapolation factors, are given; extrapolation factors, determined from RG 1.99, Rev. 2, formula, are listed for comparison. The flux ($E > 1$ MeV), flux ($E > 0.1$ MeV), dpa (ASTM) rate, and dpa (ENDF/B-VI) attenuation curves in the PV wall are compared with the results obtained for the three-loop plant in the Figures 23–26. For all the irradiation parameters considered, the attenuation curves for the two-loop plant (with a PV wall thickness of 17.16 cm) closely agree with the results for the three-loop plant with a PV thickness of 18.75 cm. Therefore, from the point of view of RG 1.99, Rev. 2, extrapolation formula update, the analysis of the two-loop plant does not contribute any significantly new information.

3. CONCLUSIONS

The attenuation of the dpa rate in the PV wall calculated with the BUGLE-96 cross-section library, P_3 approximation to the angular dependence of the scattering cross sections, and dpa cross sections derived from ENDF/B-VI data is significantly slower than the attenuation predicted by the RG 1.99, Rev. 2, formula. For a PV wall thickness of ~24 cm, the calculated ratio of the dpa rate at 1/4 and 3/4 of the PV wall thickness, to the dpa value on the inner PV surface is ~14%, and 19% higher, respectively, than predicted by the RG 1.99, Rev. 2, formula.

The dpa rate attenuation in the PV wall, calculated with the SAILOR (ENDF/B-VI) cross-section library, P_1 approximation to angular dependence of scattering cross sections, and dpa cross sections from ASTM standard E 693, comes relatively close to the RG 1.99, Rev. 2, formula prediction. The calculation still predicts up to ~5% slower dpa attenuation in the region close to the PV inner wall.

Insight into the causes of the large difference between the dpa attenuation in the PV wall obtained with "BUGLE-96, P_3 , ENDF/B-VI dpa" calculation and the RG 1.99, Rev. 2, formula was obtained from the comparisons of results with the BUGLE-96 and the SAILOR cross-section libraries, the P_1 - P_3 approximations for angular distribution of scattering cross section, and the ASTM and the ENDF/B-VI dpa cross sections. Approximately 40-45% of the difference is caused by the change in cross sections (from SAILOR, P_1 to BUGLE-96, P_1), ~35-40% of the difference is due to the change from P_1 to P_3 , and ~15-20% of the difference is caused by the change from the ENDF/B-IV to the ENDF/B-VI dpa cross sections. Near the PV surfaces the calculated attenuation of the dpa rate also deviates from the simple exponential attenuation used in RG 1.99, Rev. 2, formula, which contributes to the larger differences, especially near the PV outer surface.

Calculations for varied thermal shield thicknesses showed that a thicker thermal shield typically results in slower dpa attenuation in the PV wall. However, increasing the thermal shield thickness tends to decrease the dpa rate at the PV inner wall by ~3.5% per 1 cm of the thermal shield thickness increase (1 cm of water replaced by 1 cm of steel).

The thickness of the PV has a negligible effect on the dpa rate at the PV inner wall; however, the thicker the PV, the slower is the dpa decrease inside the PV wall. The effect is small in the region near the PV inner surface but becomes quite important at larger distances from the PV inner wall.

The dpa rate attenuation curves calculated for the two-loop PWR were found in good agreement with the results for the three-loop PWR with similar PV wall thickness. This agreement indicates that performing a few additional parametric studies with the models used in this study, for different thermal-shield, PV, and downcomer thicknesses, may be sufficient to generate the data base for the update of RG 1.99, Rev. 2, attenuation formula. A more rigorous, but also more time-consuming approach, would require calculations of the dpa attenuation in the PV wall for several different reactor designs, similar to Guthrie's work, which considered six types of commercial PWRs.

4. REFERENCES

1. U.S. Nuclear Regulatory Commission Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," May 1988.
2. P. N. Randall, "Basis for Revision 2 of the U.S. Nuclear Regulatory Commission's Regulatory Guide 1.99," *Radiation Embrittlement of Nuclear Reactor Pressure Vessel Steels: An International Review (Second Volume)*, ASTM STP 909, L. E. Steele, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 149-162.
3. G. L. Guthrie, W. N. McElroy, and S. L. Anderson, "A Preliminary Study of the Use of Fuel Management Techniques for Slowing Pressure Vessel Embrittlement," pp. 111-120 in *Proc. Of the Fourth ASTM-EURATOM Symposium on Reactor Dosimetry*, Gaithersburg, Maryland, March 1982.
4. G. Collier et al., *Second Version of the GAMBIT Code*, WANL-TME-1969, Westinghouse Astronuclear Laboratory, Pittsburgh, November 1969.
5. R. G. Soltesz et al., "Two-Dimensional Discrete Ordinates Transport Technique," *Nuclear Rocket Shielding Methods, Modification, Updating, and Input Data Preparation*, WANL-PR-(LL)034, Vol. 5, Westinghouse Astronuclear Laboratory, Pittsburgh, August 1970.
6. I. Remec and F. B. K. Kam, *Pool Critical Assembly Pressure Vessel Facility Benchmark*, NUREG/CR-6454, ORNL/TM-13205, U.S. Nuclear Regulatory Commission, 1997.
7. I. Remec and F. B. K. Kam, *H. B. Robinson-2 Pressure Vessel Benchmark*, NUREG/CR-6453, ORNL/TM-13204, U.S. Nuclear Regulatory Commission, February 1998.
8. W. A. Rhoades et al., "TORT-DORT Two- and Three-Dimensional Discrete Ordinates Transport, Version 2.8.14," CCC-543, Radiation Shielding Information Center, Oak Ridge National Laboratory, 1994; (DORT version 3.2, dated October 1, 1997, was used.)
9. R. E. Maerker, "LEPRICON Analysis of the Pressure Vessel Surveillance Dosimetry Inserted into H. B. Robinson-2 During Cycle 9," *Nuc. Sci. Eng.* 96:263 (1987).
10. J. E. White et al., "BUGLE-96: Coupled 47 Neutron, 20 Gamma-Ray Group Cross Section Library Derived from ENDF/B-VI for LWR Shielding and Pressure Vessel Dosimetry Applications," RSICC Data Library Collection, DLC-185, Oak Ridge National Laboratory, March 1996.
11. G. L. Simmons et al., "Analysis of the Browns Ferry Unit 3 Irradiation Experiments," EPRI NP-3719 (November 1984), RSICC Data Library Collection, DLC-076/SAILOR; (Sailor, Coupled Self-Shielded, 47-Neutron, 20-Gamma-Ray, P3, Cross-Section Library for Light Water Reactors), Oak Ridge National Laboratory, 1984.

12. E 693 Standard Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacement Per Atom (DPA), E 706(ID), *Annual Book of ASTM Standards*, Sect. 12, Nuclear, Solar, and Geothermal Energy, 1998.

Table 1 Flux ($E > 1$ MeV), flux ($E > 0.1$ MeV), and dpa rate at the PV inner surface, versus the thickness of the thermal shield

Thermal shield thickness	Flux ($E > 0.1$ MeV)		Flux ($E > 1$ MeV)		dpa rate ASTM		dpa rate ENDF/B-VI	
	Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio
cm	$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$			s^{-1}		
0.000	8.82E+10	1.00	4.17E+10	1.00	6.22E-11	1.00	6.14E-11	1.00
3.413	8.16E+10	0.93	3.53E+10	0.85	5.36E-11	0.86	5.31E-11	0.86
6.830	8.05E+10	0.91	3.04E+10	0.73	4.82E-11	0.78	4.80E-11	0.78
10.238	8.63E+10	0.98	2.69E+10	0.65	4.63E-11	0.74	4.64E-11	0.76

Table 2 Flux ($E > 1$ MeV) attenuation in the PV wall, for different thermal shield thicknesses (BUGLE-96 calculations)

		Thermal shield thickness 0 cm		Thermal shield thickness 3.413cm		Thermal shield thickness 6.83cm		Thermal shield thickness 10.238cm	
d^*	r^{**}	Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio
cm	cm	$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$	
0.000	197.49	4.173E+10	1.0000	3.530E+10	1.0000	3.042E+10	1.0000	2.692E+10	1.0000
0.285	197.77	4.147E+10	0.9939	3.502E+10	0.9920	3.014E+10	0.9908	2.663E+10	0.9893
1.474	198.959	3.800E+10	0.9105	3.196E+10	0.9055	2.745E+10	0.9023	2.423E+10	0.9000
3.293	200.778	3.172E+10	0.7601	2.655E+10	0.7522	2.273E+10	0.7472	2.004E+10	0.7443
5.111	202.596	2.545E+10	0.6100	2.121E+10	0.6008	1.811E+10	0.5953	1.593E+10	0.5916
6.930	204.415	2.010E+10	0.4818	1.669E+10	0.4727	1.421E+10	0.4673	1.248E+10	0.4637
8.748	206.233	1.579E+10	0.3783	1.308E+10	0.3704	1.111E+10	0.3653	9.745E+09	0.3620
10.567	208.052	1.235E+10	0.2959	1.020E+10	0.2889	8.657E+09	0.2846	7.583E+09	0.2817
12.385	209.87	9.575E+09	0.2295	7.895E+09	0.2236	6.691E+09	0.2200	5.855E+09	0.2175
14.203	211.688	7.428E+09	0.1780	6.120E+09	0.1734	5.180E+09	0.1703	4.529E+09	0.1682
16.022	213.507	5.719E+09	0.1371	4.703E+09	0.1332	3.977E+09	0.1307	3.475E+09	0.1291
17.840	215.325	4.385E+09	0.1051	3.602E+09	0.1020	3.044E+09	0.1001	2.658E+09	0.0987
19.659	217.144	3.333E+09	0.0799	2.737E+09	0.0775	2.311E+09	0.0760	2.018E+09	0.0750
21.477	218.962	2.487E+09	0.0596	2.040E+09	0.0578	1.721E+09	0.0566	1.501E+09	0.0557
23.296	220.781	1.774E+09	0.0425	1.455E+09	0.0412	1.227E+09	0.0403	1.071E+09	0.0398

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 3 Attenuation of the dpa rate in the PV wall for different thermal shield (TS) thicknesses. Absolute dpa rate values are given as well as the values relative to the dpa rate at the PV inner wall. Neutron fluxes are from the calculations with BUGLE-96. ENDF/B-VI dpa cross sections were used

d*	r**	TS thickness 0 cm		TS thickness 3.413 cm		TS thickness 6.83 cm		TS thickness 10.238 cm		RG 1.99 Rev. 2
		dpa rate	Ratio	dpa rate	Ratio	dpa rate	Ratio	dpa rate	Ratio	
cm	cm	s ⁻¹		s ⁻¹		s ⁻¹		s ⁻¹		
0.000	197.485	6.14E-11	1.0000	5.31E-11	1.0000	4.80E-11	1.0000	4.64E-11	1.0000	1.0000
0.285	197.770	6.13E-11	0.9977	5.30E-11	0.9971	4.79E-11	0.9970	4.62E-11	0.9965	0.9734
1.474	198.959	5.72E-11	0.9318	4.95E-11	0.9313	4.48E-11	0.9338	4.35E-11	0.9372	0.8700
3.293	200.778	4.99E-11	0.8119	4.32E-11	0.8130	3.93E-11	0.8192	3.84E-11	0.8285	0.7326
5.111	202.596	4.24E-11	0.6906	3.68E-11	0.6930	3.37E-11	0.7023	3.32E-11	0.7155	0.6170
6.930	204.415	3.58E-11	0.5834	3.12E-11	0.5871	2.87E-11	0.5983	2.85E-11	0.6143	0.5195
8.748	206.233	3.03E-11	0.4930	2.65E-11	0.4979	2.45E-11	0.5100	2.44E-11	0.5271	0.4375
10.567	208.052	2.56E-11	0.4165	2.24E-11	0.4220	2.09E-11	0.4344	2.09E-11	0.4516	0.3684
12.385	209.870	2.15E-11	0.3506	1.89E-11	0.3563	1.77E-11	0.3685	1.79E-11	0.3851	0.3103
14.203	211.688	1.81E-11	0.2950	1.60E-11	0.3008	1.50E-11	0.3122	1.52E-11	0.3277	0.2613
16.022	213.507	1.51E-11	0.2462	1.34E-11	0.2516	1.26E-11	0.2620	1.28E-11	0.2761	0.2201
17.840	215.325	1.25E-11	0.2037	1.11E-11	0.2086	1.05E-11	0.2178	1.07E-11	0.2301	0.1853
19.659	217.144	1.02E-11	0.1659	9.05E-12	0.1702	8.55E-12	0.1781	8.75E-12	0.1886	0.1561
21.477	218.962	8.04E-12	0.1309	7.14E-12	0.1343	6.75E-12	0.1406	6.91E-12	0.1490	0.1314
23.296	220.781	5.98E-12	0.0973	5.31E-12	0.0998	5.02E-12	0.1045	5.14E-12	0.1108	0.1107

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 4 Attenuation of the dpa rate in the PV wall for different thermal shield (TS) thicknesses. Absolute dpa rate values are given as well as the values relative to the dpa rate at the PV inner wall. Neutron fluxes are from the calculations with BUGLE-96. ASTM dpa cross sections were used

d*	r**	TS thickness 0 cm		TS thickness 3.413cm		TS thickness 6.83cm		TS thickness 10.238 cm		RG 1.99 Rev. 2
		Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio	
cm	cm	s ⁻¹		s ⁻¹		s ⁻¹		s ⁻¹		
0.000	197.485	6.217E-11	1.0000	5.361E-11	1.0000	4.819E-11	1.0000	4.626E-11	1.0000	1.0000
0.285	197.770	6.196E-11	0.9967	5.339E-11	0.9959	4.799E-11	0.9958	4.604E-11	0.9953	0.9734
1.474	198.959	5.766E-11	0.9275	4.969E-11	0.9268	4.477E-11	0.9290	4.313E-11	0.9322	0.8700
3.293	200.778	4.998E-11	0.8039	4.314E-11	0.8047	3.906E-11	0.8105	3.791E-11	0.8195	0.7326
5.111	202.596	4.229E-11	0.6802	3.657E-11	0.6822	3.331E-11	0.6912	3.259E-11	0.7044	0.6170
6.930	204.415	3.554E-11	0.5717	3.083E-11	0.5751	2.825E-11	0.5861	2.785E-11	0.6020	0.5195
8.748	206.233	2.989E-11	0.4808	2.603E-11	0.4855	2.397E-11	0.4974	2.380E-11	0.5145	0.4375
10.567	208.052	2.514E-11	0.4044	2.196E-11	0.4097	2.034E-11	0.4220	2.032E-11	0.4393	0.3684
12.385	209.870	2.108E-11	0.3391	1.847E-11	0.3446	1.719E-11	0.3566	1.728E-11	0.3735	0.3103
14.203	211.688	1.767E-11	0.2842	1.554E-11	0.2899	1.452E-11	0.3012	1.466E-11	0.3170	0.2613
16.022	213.507	1.470E-11	0.2365	1.296E-11	0.2418	1.215E-11	0.2521	1.233E-11	0.2664	0.2201
17.840	215.325	1.213E-11	0.1951	1.072E-11	0.1999	1.008E-11	0.2091	1.025E-11	0.2217	0.1853
19.659	217.144	9.856E-12	0.1585	8.726E-12	0.1628	8.223E-12	0.1706	8.391E-12	0.1814	0.1561
21.477	218.962	7.760E-12	0.1248	6.876E-12	0.1283	6.485E-12	0.1346	6.621E-12	0.1431	0.1314
23.296	220.781	5.764E-12	0.0927	5.107E-12	0.0953	4.818E-12	0.1000	4.919E-12	0.1063	0.1107

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 5 Attenuation of the flux ($E > 0.1$ MeV) through the PV wall for different thermal shield thicknesses (BUGLE-96 calculations)

d*	Thermal shield thickness 0 cm		Thermal shield thickness 3.413 cm		Thermal shield thickness 6.83 cm		Thermal shield thickness 10.238 cm	
	Flux	Ratio	Flux	Ratio	Flux	Ratio	Flux	Ratio
cm	cm ⁻² s ⁻¹		cm ⁻² s ⁻¹		cm ⁻² s ⁻¹		cm ⁻² s ⁻¹	
0.000	8.818E+10	1.0000	8.163E+10	1.0000	8.055E+10	1.0000	8.631E+10	1.0000
0.285	8.993E+10	1.0199	8.310E+10	1.0180	8.188E+10	1.0165	8.761E+10	1.0150
1.474	9.012E+10	1.0221	8.303E+10	1.0173	8.168E+10	1.0141	8.733E+10	1.0118
3.293	8.623E+10	0.9780	7.922E+10	0.9705	7.778E+10	0.9657	8.309E+10	0.9626
5.111	7.964E+10	0.9032	7.298E+10	0.8941	7.156E+10	0.8884	7.635E+10	0.8846
6.930	7.240E+10	0.8211	6.624E+10	0.8115	6.490E+10	0.8058	6.922E+10	0.8019
8.748	6.527E+10	0.7402	5.966E+10	0.7309	5.840E+10	0.7250	6.223E+10	0.7210
10.567	5.838E+10	0.6621	5.332E+10	0.6532	5.215E+10	0.6475	5.554E+10	0.6434
12.385	5.169E+10	0.5862	4.717E+10	0.5778	4.611E+10	0.5725	4.908E+10	0.5686
14.203	4.540E+10	0.5149	4.142E+10	0.5074	4.046E+10	0.5024	4.304E+10	0.4986
16.022	3.931E+10	0.4458	3.584E+10	0.4390	3.499E+10	0.4344	3.719E+10	0.4309
17.840	3.355E+10	0.3805	3.057E+10	0.3745	2.983E+10	0.3704	3.168E+10	0.3670
19.659	2.802E+10	0.3178	2.552E+10	0.3127	2.489E+10	0.3091	2.642E+10	0.3061
21.477	2.252E+10	0.2554	2.049E+10	0.2511	1.997E+10	0.2479	2.116E+10	0.2451
23.296	1.693E+10	0.1920	1.539E+10	0.1886	1.498E+10	0.1860	1.585E+10	0.1836

* d = distance from PV inner (wetted) surface.

**Table 6 Flux ($E > 1$ MeV) attenuation in the PV wall for different wall thicknesses.
(PV inner radius was 197.49 cm in all the cases; calculations with BUGLE-96)**

d*	r**	PV thickness 18.75 cm PV outer radius 216.235		PV thickness 24.20 cm PV outer radius 221.69 cm		PV thickness 30.25cm PV outer radius 227.74 cm		RG 1.99 Rev. 2
		Flux	Ratio	Flux	Ratio	Flux	Ratio	
cm	cm	cm ⁻² s ⁻¹		cm ⁻² s ⁻¹		cm ⁻² s ⁻¹		
0.000	197.49	3.0403E+10	1.0000	3.0420E+10	1.0000	3.04237E+10	1.0000	1.0000
0.285	197.77	3.0123E+10	0.9908	3.0142E+10	0.9908	3.01455E+10	0.9909	0.9734
1.474	198.96	2.7424E+10	0.9020	2.7449E+10	0.9023	2.74540E+10	0.9024	0.8700
3.293	200.78	2.2696E+10	0.7465	2.2731E+10	0.7472	2.27381E+10	0.7474	0.7326
5.111	202.60	1.8061E+10	0.5941	1.8108E+10	0.5953	1.81170E+10	0.5955	0.6170
6.930	204.42	1.4152E+10	0.4655	1.4215E+10	0.4673	1.42272E+10	0.4676	0.5195
8.748	206.23	1.1030E+10	0.3628	1.1113E+10	0.3653	1.11288E+10	0.3658	0.4375
10.567	208.05	8.5473E+09	0.2811	8.6568E+09	0.2846	8.67818E+09	0.2852	0.3684
12.385	209.87	6.5458E+09	0.2153	6.6911E+09	0.2200	6.71955E+09	0.2209	0.3103
14.203	211.69	4.9856E+09	0.1640	5.1802E+09	0.1703	5.21709E+09	0.1715	0.2613
16.022	213.51	3.7056E+09	0.1219	3.9774E+09	0.1307	4.02652E+09	0.1323	0.2201
17.840	215.33	2.6229E+09	0.0863	3.0436E+09	0.1001	3.10774E+09	0.1021	0.1853
19.659	217.14			2.3115E+09	0.0760	2.39520E+09	0.0787	0.1561
21.477	218.96			1.7209E+09	0.0566	1.83834E+09	0.0604	0.1314
23.296	220.78			1.2274E+09	0.0403	1.41107E+09	0.0464	0.1107
24.840	222.33					1.10989E+09	0.0365	
26.272	223.76					8.91255E+08	0.0293	
27.865	225.35					6.83200E+08	0.0225	
29.458	226.94					4.99693E+08	0.0164	

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 7 Dpa rate attenuation in the PV wall for different wall thicknesses. (Calculated with BUGLE-96 cross sections and ENDF/B-VI dpa cross sections)

d*	r**	PV thickness 18.75 cm PV outer radius 216.235cm		PV thickness 24.20 cm PV outer radius 221.69cm		PV thickness 30.25cm PV outer radius 227.74 cm		RG 1.99 Rev. 2
		dpa/s	Ratio	dpa/s	Ratio	dpa/s	Ratio	
cm	cm	s ⁻¹		s ⁻¹		s ⁻¹		
0.00	197.49	4.758E-11	1.0000	4.800E-11	1.0000	4.823E-11	1.0000	1.0000
0.28	197.77	4.739E-11	0.9959	4.786E-11	0.9970	4.811E-11	0.9976	0.9734
1.47	198.96	4.421E-11	0.9291	4.482E-11	0.9338	4.515E-11	0.9363	0.8700
3.29	200.78	3.851E-11	0.8093	3.932E-11	0.8192	3.976E-11	0.8245	0.7326
5.11	202.60	3.269E-11	0.6872	3.371E-11	0.7023	3.426E-11	0.7104	0.6170
6.93	204.42	2.750E-11	0.5779	2.872E-11	0.5983	2.938E-11	0.6093	0.5195
8.75	206.23	2.304E-11	0.4842	2.448E-11	0.5100	2.526E-11	0.5238	0.4375
10.57	208.05	1.917E-11	0.4029	2.085E-11	0.4344	2.176E-11	0.4512	0.3684
12.38	209.87	1.574E-11	0.3309	1.769E-11	0.3685	1.873E-11	0.3884	0.3103
14.20	211.69	1.275E-11	0.2680	1.499E-11	0.3122	1.617E-11	0.3353	0.2613
16.02	213.51	9.977E-12	0.2097	1.258E-11	0.2620	1.393E-11	0.2887	0.2201
17.84	215.33	7.339E-12	0.1543	1.045E-11	0.2178	1.197E-11	0.2483	0.1853
19.66	217.14			8.547E-12	0.1781	1.025E-11	0.2126	0.1561
21.48	218.96			6.749E-12	0.1406	8.706E-12	0.1805	0.1314
23.30	220.78			5.017E-12	0.1045	7.326E-12	0.1519	0.1107
24.84	222.33					6.222E-12	0.1290	
26.27	223.76					5.267E-12	0.1092	
27.86	225.35					4.242E-12	0.0880	
29.46	226.94					3.229E-12	0.0670	

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 8 Dpa rate attenuation in the PV wall for different wall thicknesses. (Calculated with BUGLE-96 cross sections and ASTM dpa cross sections)

d*	r**	PV thickness 18.75 cm PV outer radius 216.235cm		PV thickness 24.20 cm PV outer radius 221.69cm		PV thickness 30.25cm PV outer radius 227.74 cm		RG 1.99 Rev. 2
		dpa/s	Ratio	dpa/s	Ratio	dpa/s	Ratio	
cm	cm	s ⁻¹		s ⁻¹		s ⁻¹		
0.00	197.49	4.779E-11	1.0000	4.819E-11	1.0000	4.841E-11	1.0000	1.0000
0.28	197.77	4.754E-11	0.9948	4.799E-11	0.9958	4.823E-11	0.9964	0.9734
1.47	198.96	4.419E-11	0.9246	4.477E-11	0.9290	4.509E-11	0.9314	0.8700
3.29	200.78	3.829E-11	0.8011	3.906E-11	0.8105	3.948E-11	0.8156	0.7326
5.11	202.60	3.235E-11	0.6768	3.331E-11	0.6912	3.384E-11	0.6990	0.6170
6.93	204.42	2.708E-11	0.5666	2.825E-11	0.5862	2.888E-11	0.5965	0.5195
8.75	206.23	2.260E-11	0.4728	2.397E-11	0.4974	2.471E-11	0.5105	0.4375
10.57	208.05	1.874E-11	0.3920	2.034E-11	0.4221	2.120E-11	0.4380	0.3684
12.38	209.87	1.534E-11	0.3209	1.719E-11	0.3567	1.818E-11	0.3756	0.3103
14.20	211.69	1.239E-11	0.2592	1.452E-11	0.3013	1.565E-11	0.3233	0.2613
16.02	213.51	9.674E-12	0.2024	1.215E-11	0.2521	1.344E-11	0.2776	0.2201
17.84	215.33	7.108E-12	0.1487	1.008E-11	0.2092	1.153E-11	0.2381	0.1853
19.66	217.14			8.223E-12	0.1706	9.852E-12	0.2035	0.1561
21.48	218.96			6.485E-12	0.1346	8.350E-12	0.1725	0.1314
23.30	220.78			4.818E-12	0.1000	7.016E-12	0.1449	0.1107
24.84	222.33					5.953E-12	0.1230	
26.27	223.76					5.035E-12	0.1040	
27.86	225.35					4.053E-12	0.0837	
29.46	226.94					3.084E-12	0.0637	

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

**Table 9 Flux ($E > 0.1$ MeV) attenuation in the PV wall for different wall thicknesses.
PV inner radius was 197.49 cm in all the cases. (Calculations with BUGLE-96)**

d*	r**	PV thickness 18.75 cm PV outer radius 216.235cm		PV thickness 24.20 cm PV outer radius 221.69cm		PV thickness 30.25cm PV outer radius 227.74 cm		RG 1.99 Rev. 2
		Flux ($E > 0.1$ MeV)	Ratio	Flux ($E > 0.1$ MeV)	Ratio	Flux ($E > 0.1$ MeV)	Ratio	
cm	cm	$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$		
0.00	197.49	7.907E+10	1.0000	8.055E+10	1.0000	8.137E+10	1.0000	1.0000
0.28	197.77	8.020E+10	1.0144	8.188E+10	1.0165	8.282E+10	1.0178	0.9734
1.47	198.96	7.946E+10	1.0049	8.168E+10	1.0141	8.293E+10	1.0192	0.8700
3.29	200.78	7.484E+10	0.9466	7.778E+10	0.9657	7.945E+10	0.9764	0.7326
5.11	202.60	6.791E+10	0.8589	7.156E+10	0.8884	7.362E+10	0.9047	0.6170
6.93	204.42	6.054E+10	0.7657	6.490E+10	0.8058	6.738E+10	0.8281	0.5195
8.75	206.23	5.329E+10	0.6740	5.840E+10	0.7250	6.130E+10	0.7534	0.4375
10.57	208.05	4.625E+10	0.5850	5.215E+10	0.6475	5.551E+10	0.6822	0.3684
12.38	209.87	3.938E+10	0.4980	4.611E+10	0.5725	4.995E+10	0.6139	0.3103
14.20	211.69	3.280E+10	0.4149	4.046E+10	0.5024	4.480E+10	0.5506	0.2613
16.02	213.51	2.624E+10	0.3318	3.499E+10	0.4344	3.989E+10	0.4903	0.2201
17.84	215.33	1.957E+10	0.2475	2.983E+10	0.3704	3.531E+10	0.4339	0.1853
19.66	217.14			2.489E+10	0.3091	3.099E+10	0.3808	0.1561
21.48	218.96			1.997E+10	0.2479	2.686E+10	0.3301	0.1314
23.30	220.78			1.498E+10	0.1860	2.300E+10	0.2826	0.1107
24.84	222.33					1.979E+10	0.2433	
26.27	223.76					1.690E+10	0.2077	
27.86	225.35					1.373E+10	0.1688	
29.46	226.94					1.050E+10	0.1290	

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 10 Flux ($E > 1$ MeV) attenuation in the PV wall, calculated with the BUGLE-96 and the SAILOR cross-section libraries. The HBR-2 nominal geometry was used in both calculations. SAILOR calculation used the ENDF/B-IV fission spectra

d*	r**	SAILOR		BUGLE-96		100*(B-A)/A
		Flux	Ratio	Flux	Ratio	
cm	cm	cm ⁻² s ⁻¹	A	cm ⁻² s ⁻¹	B	
0.00	197.49	2.873E+10	1.0000	3.042E+10	1.0000	0.0
0.28	197.77	2.846E+10	0.9908	3.014E+10	0.9908	0.0
1.47	198.96	2.576E+10	0.8968	2.745E+10	0.9023	0.6
3.29	200.78	2.108E+10	0.7339	2.273E+10	0.7472	1.8
5.11	202.60	1.659E+10	0.5773	1.811E+10	0.5953	3.1
6.93	204.42	1.286E+10	0.4478	1.421E+10	0.4673	4.4
8.75	206.23	9.937E+09	0.3459	1.111E+10	0.3653	5.6
10.57	208.05	7.649E+09	0.2662	8.657E+09	0.2846	6.9
12.38	209.87	5.840E+09	0.2033	6.691E+09	0.2200	8.2
14.20	211.69	4.467E+09	0.1555	5.180E+09	0.1703	9.5
16.02	213.51	3.389E+09	0.1180	3.977E+09	0.1307	10.8
17.84	215.33	2.561E+09	0.0892	3.044E+09	0.1001	12.2
19.66	217.14	1.921E+09	0.0669	2.311E+09	0.0760	13.7
21.48	218.96	1.411E+09	0.0491	1.721E+09	0.0566	15.2
23.30	220.78	9.897E+08	0.0345	1.227E+09	0.0403	17.1

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 11 Attenuation of the dpa rate in the PV wall. The ENDF/B-VI dpa cross section was used with BUGLE-96 and SAILOR calculations

d*	r**	SAILOR with ENDF/B-VI dpa		BUGLE-96 with ENDF/B-VI dpa		RG1.99 Rev. 2	100* (A-C)/C	100* (B-C)/C	100* (B-A)/A
		dpa rate	Ratio	dpa rate	Ratio				
cm	cm	s ⁻¹	A	s ⁻¹	B	C	%	%	%
0.00	197.49	4.592E-11	1.0000	4.800E-11	1.0000	1.0000	0.00	0.00	0.00
0.28	197.77	4.560E-11	0.9930	4.786E-11	0.9970	0.9734	2.01	2.42	0.40
1.47	198.96	4.228E-11	0.9207	4.482E-11	0.9338	0.8700	5.82	7.33	1.43
3.29	200.78	3.663E-11	0.7978	3.932E-11	0.8192	0.7326	8.90	11.82	2.68
5.11	202.60	3.110E-11	0.6773	3.371E-11	0.7023	0.6170	9.78	13.82	3.69
6.93	204.42	2.628E-11	0.5723	2.872E-11	0.5983	0.5195	10.16	15.16	4.54
8.75	206.23	2.223E-11	0.4841	2.448E-11	0.5100	0.4375	10.65	16.56	5.34
10.57	208.05	1.879E-11	0.4093	2.085E-11	0.4344	0.3684	11.08	17.91	6.14
12.38	209.87	1.582E-11	0.3444	1.769E-11	0.3685	0.3103	11.00	18.75	6.98
14.20	211.69	1.329E-11	0.2894	1.499E-11	0.3122	0.2613	10.74	19.47	7.89
16.02	213.51	1.105E-11	0.2406	1.258E-11	0.2620	0.2201	9.34	19.06	8.89
17.84	215.33	9.079E-12	0.1977	1.045E-11	0.2178	0.1853	6.69	17.52	10.15
19.66	217.14	7.320E-12	0.1594	8.547E-12	0.1781	0.1561	2.15	14.10	11.69
21.48	218.96	5.681E-12	0.1237	6.749E-12	0.1406	0.1314	-5.86	6.99	13.65
23.30	220.78	4.103E-12	0.0894	5.017E-12	0.1045	0.1107	-19.26	-5.55	16.98

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 12 Flux ($E > 1$ MeV) and dpa rate attenuation in the PV wall. To determine the dpa rates the ENDF/B-VI dpa cross sections were used with BUGLE-96, while ASTM dpa cross sections were used with SAILOR. All calculations are for the HBR-2 geometry

d*	r**	BUGLE-96		SAILOR, ASTM dpa		BUGLE-96, ENDF/B-VI dpa		100* (B-A)/A	RG 1.99 Rev. 2	100* (A-C)/C	100* (B-C)/C
		Flux ($E > 1$ MeV)	Ratio	dpa rate	Ratio	dpa rate	Ratio				
cm	cm	$\text{cm}^{-2}\text{s}^{-1}$		s^{-1}	A	s^{-1}	B	%	C	%	%
0.000	197.49	3.0420E+10	1.0000	4.621E-11	1.0000	4.800E-11	1.0000	0.0	1.0000	0.0	0.0
0.285	197.77	3.0142E+10	0.9908	4.582E-11	0.9916	4.786E-11	0.9970	0.5	0.9734	1.9	2.4
1.474	198.96	2.7449E+10	0.9023	4.229E-11	0.9152	4.482E-11	0.9338	2.0	0.8700	5.2	7.3
3.293	200.78	2.2731E+10	0.7472	3.642E-11	0.7882	3.932E-11	0.8192	3.9	0.7326	7.6	11.8
5.111	202.60	1.8108E+10	0.5953	3.075E-11	0.6655	3.371E-11	0.7023	5.5	0.6170	7.9	13.8
6.930	204.42	1.4215E+10	0.4673	2.586E-11	0.5596	2.872E-11	0.5983	6.9	0.5195	7.7	15.2
8.748	206.23	1.1113E+10	0.3653	2.178E-11	0.4713	2.448E-11	0.5100	8.2	0.4375	7.7	16.6
10.567	208.05	8.6568E+09	0.2846	1.834E-11	0.3968	2.085E-11	0.4344	9.5	0.3684	7.7	17.9
12.385	209.87	6.6911E+09	0.2200	1.538E-11	0.3327	1.769E-11	0.3685	10.7	0.3103	7.2	18.7
14.203	211.69	5.1802E+09	0.1703	1.288E-11	0.2787	1.499E-11	0.3122	12.0	0.2613	6.7	19.5
16.022	213.51	3.9774E+09	0.1307	1.068E-11	0.2311	1.258E-11	0.2620	13.4	0.2201	5.0	19.1
17.840	215.33	3.0436E+09	0.1001	8.758E-12	0.1895	1.045E-11	0.2178	14.9	0.1853	2.3	17.5
19.659	217.14	2.3115E+09	0.0760	7.048E-12	0.1525	8.547E-12	0.1781	16.7	0.1561	-2.3	14.1
21.477	218.96	1.7209E+09	0.0566	5.462E-12	0.1182	6.749E-12	0.1406	19.0	0.1314	-10.1	7.0
23.296	220.78	1.2274E+09	0.0403	3.942E-12	0.0853	5.017E-12	0.1045	22.5	0.1107	-22.9	-5.6

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 13 Flux ($E > 1$ MeV) attenuation in the PV, calculated with the BUGLE-96 cross-section library and the P_1 to P_3 approximations for the anisotropic scattering

d*	P_3		P_2		P_1		RG 1.99 Rev. 2	100* (A-B)/B
	Flux ($E > 1$ MeV)	Ratio	Flux ($E > 1$ MeV)	Ratio	Flux ($E > 1$ MeV)	Ratio		
cm	$\text{cm}^{-2}\text{s}^{-1}$	A	$\text{cm}^{-2}\text{s}^{-1}$		$\text{cm}^{-2}\text{s}^{-1}$	B		
0.00	3.042E+10	1.0000	3.022E+10	1.0000	2.527E+10	1.0000	1.0000	0.00
0.28	3.014E+10	0.9908	2.996E+10	0.9914	2.499E+10	0.9890	0.9734	0.18
1.47	2.745E+10	0.9023	2.733E+10	0.9042	2.255E+10	0.8925	0.8700	1.10
3.29	2.273E+10	0.7472	2.261E+10	0.7482	1.835E+10	0.7261	0.7326	2.91
5.11	1.811E+10	0.5953	1.796E+10	0.5944	1.436E+10	0.5681	0.6170	4.78
6.93	1.421E+10	0.4673	1.406E+10	0.4654	1.111E+10	0.4395	0.5195	6.32
8.75	1.111E+10	0.3653	1.097E+10	0.3629	8.569E+09	0.3391	0.4375	7.73
10.57	8.657E+09	0.2846	8.526E+09	0.2821	6.602E+09	0.2613	0.3684	8.92
12.38	6.691E+09	0.2200	6.576E+09	0.2176	5.044E+09	0.1996	0.3103	10.19
14.20	5.180E+09	0.1703	5.084E+09	0.1682	3.869E+09	0.1531	0.2613	11.23
16.02	3.977E+09	0.1307	3.898E+09	0.1290	2.942E+09	0.1164	0.2201	12.29
17.84	3.044E+09	0.1001	2.979E+09	0.0986	2.230E+09	0.0883	0.1853	13.37
19.66	2.311E+09	0.0760	2.261E+09	0.0748	1.680E+09	0.0665	0.1561	14.30
21.48	1.721E+09	0.0566	1.683E+09	0.0557	1.237E+09	0.0490	0.1314	15.55
23.30	1.227E+09	0.0403	1.200E+09	0.0397	8.707E+08	0.0345	0.1107	17.10

* d = distance from PV inner (wetted) surface.

Table 14 The attenuation of the dpa rate in the PV wall, calculated with the BUGLE-96 cross sections, the P_1 to P_3 approximations for anisotropic scattering, and with the ASTM dpa cross sections

	P_3		P_2		P_1		RG 1.99 Rev. 2	100* (A-B)/B
d^*	dpa/s	Ratio	dpa/s	Ratio	dpa/s	Ratio		
cm	s^{-1}	A	s^{-1}		s^{-1}	B		
0.00	4.819E-11	1.0000	4.786E-11	1.0000	4.002E-11	1.0000	1.0000	0.00
0.28	4.799E-11	0.9958	4.768E-11	0.9963	3.977E-11	0.9937	0.9734	0.21
1.47	4.477E-11	0.9290	4.458E-11	0.9315	3.684E-11	0.9205	0.8700	0.93
3.29	3.906E-11	0.8105	3.890E-11	0.8128	3.170E-11	0.7920	0.7326	2.33
5.11	3.331E-11	0.6912	3.312E-11	0.6919	2.668E-11	0.6666	0.6170	3.70
6.93	2.825E-11	0.5861	2.803E-11	0.5857	2.241E-11	0.5600	0.5195	4.65
8.75	2.397E-11	0.4974	2.376E-11	0.4964	1.889E-11	0.4720	0.4375	5.37
10.57	2.034E-11	0.4220	2.014E-11	0.4208	1.595E-11	0.3987	0.3684	5.85
12.38	1.719E-11	0.3566	1.701E-11	0.3554	1.343E-11	0.3356	0.3103	6.26
14.20	1.452E-11	0.3012	1.436E-11	0.3001	1.132E-11	0.2828	0.2613	6.53
16.02	1.215E-11	0.2521	1.202E-11	0.2511	9.452E-12	0.2362	0.2201	6.75
17.84	1.008E-11	0.2091	9.965E-12	0.2082	7.821E-12	0.1954	0.1853	6.99
19.66	8.223E-12	0.1706	8.132E-12	0.1699	6.372E-12	0.1592	0.1561	7.16
21.48	6.485E-12	0.1346	6.414E-12	0.1340	5.008E-12	0.1251	0.1314	7.52
23.30	4.818E-12	0.1000	4.765E-12	0.0996	3.702E-12	0.0925	0.1107	8.07

* d = distance from PV inner (wetted) surface.

Table 15 Comparison of dpa rate attenuation in the PV wall, calculated with SAILOR library, P_1 approximation, and ASTM dpa cross sections with the dpa rate attenuation obtained with BUGLE-96 library, P_3 approximation, and ENDF/B-VI dpa cross sections. (Comparison with the RG 1.99, Rev. 2, attenuation formula is also given)

d*	SAILOR, P_1 , ASTM dpa		BUGLE-96, P_3 , ENDF/B-VI dpa		RG 1.99 Rev. 2	100* (B-A)/A	100* (A-C)/C	100* (B-C)/C
	dpa rate	Ratio A	dpa rate	Ratio B	C			
cm	s ⁻¹		s ⁻¹					
0.00	3.833E-11	1.0000	4.800E-11	1.0000	1.0000	0.00	0.00	0.00
0.28	3.791E-11	0.9890	4.786E-11	0.9970	0.9734	0.81	1.60	2.42
1.47	3.470E-11	0.9051	4.482E-11	0.9338	0.8700	3.17	4.03	7.33
3.29	2.944E-11	0.7680	3.932E-11	0.8192	0.7326	6.66	4.84	11.82
5.11	2.453E-11	0.6400	3.371E-11	0.7023	0.6170	9.72	3.74	13.82
6.93	2.044E-11	0.5333	2.872E-11	0.5983	0.5195	12.20	2.65	15.16
8.75	1.710E-11	0.4460	2.448E-11	0.5100	0.4375	14.34	1.94	16.56
10.57	1.433E-11	0.3739	2.085E-11	0.4344	0.3684	16.20	1.47	17.91
12.38	1.197E-11	0.3123	1.769E-11	0.3685	0.3103	18.00	0.63	18.75
14.20	1.000E-11	0.2609	1.499E-11	0.3122	0.2613	19.67	-0.17	19.47
16.02	8.275E-12	0.2159	1.258E-11	0.2620	0.2201	21.37	-1.90	19.06
17.84	6.769E-12	0.1766	1.045E-11	0.2178	0.1853	23.34	-4.72	17.52
19.66	5.437E-12	0.1418	8.547E-12	0.1781	0.1561	25.54	-9.12	14.10
21.48	4.198E-12	0.1095	6.749E-12	0.1406	0.1314	28.41	-16.68	6.99
23.30	3.011E-12	0.0786	5.017E-12	0.1045	0.1107	33.06	-29.02	-5.55

* d = distance from PV inner (wetted) surface.

Table 16 Comparison of the dpa rate attenuation in the PV wall, calculated with ENDF/B-VI and ASTM dpa cross sections. Neutron fluxes are from the BUGLE-96 calculation. The HBR-2 "nominal" geometry was used.

d*	r**	dpa rate ASTM		dpa rate ENDF/B-VI		100* (B-A)/A
		Value	Ratio	Value	Ratio	
cm	cm	s ⁻¹	A	s ⁻¹	B	%
0.000	197.485	4.82E-11	1.0000	4.80E-11	1.0000	0.00
0.285	197.770	4.799E-11	0.9958	4.786E-11	0.9970	0.12
1.474	198.959	4.477E-11	0.9290	4.482E-11	0.9338	0.51
3.293	200.778	3.906E-11	0.8105	3.932E-11	0.8192	1.07
5.111	202.596	3.331E-11	0.6912	3.371E-11	0.7023	1.60
6.930	204.415	2.825E-11	0.5861	2.872E-11	0.5983	2.09
8.748	206.233	2.397E-11	0.4974	2.448E-11	0.5100	2.54
10.567	208.052	2.034E-11	0.4220	2.085E-11	0.4344	2.95
12.385	209.870	1.719E-11	0.3566	1.769E-11	0.3685	3.32
14.203	211.688	1.452E-11	0.3012	1.499E-11	0.3122	3.64
16.022	213.507	1.215E-11	0.2521	1.258E-11	0.2620	3.92
17.840	215.325	1.008E-11	0.2091	1.045E-11	0.2178	4.16
19.659	217.144	8.223E-12	0.1706	8.547E-12	0.1781	4.35
21.477	218.962	6.485E-12	0.1346	6.749E-12	0.1406	4.50
23.296	220.781	4.818E-12	0.1000	5.017E-12	0.1045	4.56

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 17 Summary of the changes in dpa attenuation at ~5 cm and 15 cm from the PV inner surface, for a 24.20-cm-thick PV wall

d*	Change in dpa extrapolation factor $\text{dpa}(d)/\text{dpa}(d=0)$ due to change from				Difference in the dpa extrapolation factor calculated with BUGLE-96, P_3 , ENDF/B-VI dpa cross sections and RG 1.99, Rev. 2, extrapolation formula
	Cross-section library from SAILOR, P_1 to BUGLE-96, P_1	BUGLE-96, from P_1 to P_3	dpa cross sections from ENDF/B-IV (ASTM) to ENDF/B-VI	Total change	
cm	%	%	%	%	%
~5	4.2	3.7	1.6	9.8	13.8
~15	8.9	6.6	3.8	19.7	19.5

* d = distance from PV inner (wetted) surface.

Table 18 Flux ($E > 1$ MeV) attenuation in the PV wall. The ratios of the fast flux at a given depth to the fast flux at the PV inner radius are given. The column "average" gives the ratio, at the depth, "d," in the vessel wall, calculated as the arithmetic average over all azimuthal intervals. The columns "maximum" and "minimum" give the maximum and minimum ratio, respectively, over all azimuthal intervals. The deviations (in percent) of the maximum and minimum from the average are also given

d*	Average	Maximum		Minimum		RG 1.99 Rev. 2
	F**(d)/F(d=0)	F(d)/F(d=0)	100*(B-A)/A	F(d)/F(d=0)	100*(C-A)/A	
cm	A	B	%	C	%	
0.00	1.0000	1.0000	0.0	1.0000	0.0	1.0000
0.28	0.9915	1.0043	1.3	0.9837	-0.8	0.9734
1.47	0.9057	0.9218	1.8	0.8868	-2.1	0.8700
3.29	0.7531	0.7664	1.8	0.7419	-1.5	0.7326
5.11	0.6028	0.6163	2.2	0.5924	-1.7	0.6170
6.93	0.4765	0.4888	2.6	0.4647	-2.5	0.5195
8.75	0.3743	0.3850	2.9	0.3635	-2.9	0.4375
10.57	0.2923	0.3022	3.4	0.2815	-3.7	0.3684
12.38	0.2277	0.2356	3.5	0.2187	-4.0	0.3103
14.20	0.1766	0.1837	4.0	0.1670	-5.4	0.2613
16.02	0.1369	0.1421	3.8	0.1303	-4.8	0.2201
17.84	0.1054	0.1100	4.4	0.0975	-7.5	0.1853
19.66	0.0808	0.0848	5.0	0.0756	-6.4	0.1561
21.48	0.0611	0.0644	5.4	0.0560	-8.3	0.1314
23.30	0.0447	0.0480	7.4	0.0400	-10.5	0.1107

* d = distance from PV inner (wetted) surface.

** F = flux.

Table 19 Dpa rate (ASTM) attenuation in the PV wall. The ratios of the dpa rate at a given depth to the dpa rate at the PV inner radius are given. The column "average" gives the ratio, at the given depth, "d," in the vessel wall, calculated as the arithmetic average over all azimuthal intervals. The columns "maximum" and "minimum" give the maximum and minimum ratio over all azimuthal intervals, respectively. The deviations of the maximum and minimum from the average are also given

d*	Average	Maximum		Minimum		RG 1.99 Rev. 2
	dpa(d)/dpa(d=0)	dpa(d)/dpa(d=0)	100*(B-A)/A	dpa(d)/dpa(d=0)	100*(C-A)/A	
cm	A	B	%	C	%	
0.00	1.0000	1.0000	0.0	1.0000	0.0	1.0000
0.28	0.9966	1.0094	1.3	0.9904	-0.6	0.9734
1.47	0.9328	0.9487	1.7	0.9194	-1.4	0.8700
3.29	0.8176	0.8358	2.2	0.8081	-1.2	0.7326
5.11	0.7010	0.7237	3.2	0.6904	-1.5	0.6170
6.93	0.5986	0.6228	4.0	0.5857	-2.2	0.5195
8.75	0.5112	0.5355	4.8	0.4965	-2.9	0.4375
10.57	0.4363	0.4607	5.6	0.4195	-3.9	0.3684
12.38	0.3725	0.3958	6.3	0.3553	-4.6	0.3103
14.20	0.3171	0.3390	6.9	0.2986	-5.8	0.2613
16.02	0.2690	0.2893	7.5	0.2516	-6.5	0.2201
17.84	0.2262	0.2447	8.2	0.2074	-8.3	0.1853
19.66	0.1879	0.2043	8.7	0.1699	-9.6	0.1561
21.48	0.1525	0.1674	9.8	0.1344	-11.9	0.1314
23.30	0.1180	0.1309	10.9	0.0994	-15.8	0.1107

* d = distance from PV inner (wetted) surface.

Table 20 The attenuation of the flux ($E > 1$ MeV), flux ($E > 0.1$ MeV), and dpa rate calculated with the ASTM and ENDF/B-VI dpa cross sections, respectively, inside the PV wall. The calculations were done with the BUGLE-96 library. A two-loop plant of Westinghouse design with a 17.16-cm-thick PV wall was analyzed

d*	r**	ASTM dpa		ENDF/B-VI dpa		Flux ($E > 0.1$ MeV)		Flux ($E > 1$ MeV)		RG 1.99 Rev. 2
		Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio	
cm	cm	s ⁻¹		s ⁻¹		cm ⁻² s ⁻¹		cm ⁻² s ⁻¹		
0.00	167.64	8.596E-11	1.0000	8.570E-11	1.0000	1.480E+11	1.0000	5.174E+10	1.0000	1.0000
0.60	168.24	8.280E-11	0.9632	8.277E-11	0.9658	1.487E+11	1.0044	4.974E+10	0.9613	0.9448
1.80	169.44	7.582E-11	0.8821	7.614E-11	0.8884	1.457E+11	0.9847	4.472E+10	0.8643	0.8433
3.01	170.65	6.850E-11	0.7969	6.905E-11	0.8057	1.392E+11	0.9407	3.907E+10	0.7550	0.7527
4.21	171.85	6.151E-11	0.7156	6.222E-11	0.7261	1.313E+11	0.8871	3.369E+10	0.6511	0.6718
5.41	173.05	5.508E-11	0.6408	5.589E-11	0.6522	1.228E+11	0.8298	2.885E+10	0.5575	0.5996
6.62	174.26	4.922E-11	0.5726	5.009E-11	0.5845	1.142E+11	0.7713	2.458E+10	0.4751	0.5352
7.82	175.46	4.391E-11	0.5108	4.481E-11	0.5229	1.055E+11	0.7132	2.088E+10	0.4036	0.4777
9.02	176.66	3.909E-11	0.4548	3.999E-11	0.4667	9.705E+10	0.6557	1.768E+10	0.3418	0.4264
10.22	177.86	3.470E-11	0.4037	3.558E-11	0.4152	8.870E+10	0.5993	1.493E+10	0.2885	0.3806
11.43	179.07	3.070E-11	0.3571	3.154E-11	0.3680	8.053E+10	0.5441	1.256E+10	0.2428	0.3397
12.63	180.27	2.701E-11	0.3142	2.780E-11	0.3244	7.249E+10	0.4898	1.052E+10	0.2034	0.3032
13.83	181.47	2.357E-11	0.2742	2.430E-11	0.2836	6.453E+10	0.4360	8.765E+09	0.1694	0.2706
15.04	182.68	2.031E-11	0.2363	2.097E-11	0.2447	5.649E+10	0.3817	7.220E+09	0.1395	0.2415
16.24	183.88	1.710E-11	0.1989	1.765E-11	0.2060	4.797E+10	0.3241	5.803E+09	0.1121	0.2156

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Table 21 The attenuation of the flux ($E > 1$ MeV), flux ($E > 0.1$ MeV), and dpa rate calculated with the ASTM and the ENDF/B-VI dpa cross sections, respectively, inside the PV wall. The calculations were done with the SAILOR library. A two-loop plant of Westinghouse design with a 17.16-cm-thick PV wall was analyzed

d*	r**	ASTM dpa		ENDF/B-VI dpa		Flux ($E > 0.1$ MeV)		Flux ($E > 1$ MeV)		RG 1.99
		Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio	
cm	cm	s ⁻¹		s ⁻¹		cm ⁻² s ⁻¹		cm ⁻² s ⁻¹		
0.00	167.64	7.778E-11	1.0000	7.755E-11	1.0000	1.348E+11	1.0000	4.701E+10	1.0000	1.0000
0.60	168.24	7.478E-11	0.9615	7.477E-11	0.9642	1.357E+11	1.0064	4.507E+10	0.9587	0.9448
1.80	169.44	6.820E-11	0.8769	6.852E-11	0.8836	1.331E+11	0.9872	4.023E+10	0.8557	0.8433
3.01	170.65	6.132E-11	0.7884	6.184E-11	0.7975	1.267E+11	0.9401	3.485E+10	0.7413	0.7527
4.21	171.85	5.479E-11	0.7045	5.545E-11	0.7151	1.191E+11	0.8831	2.980E+10	0.6339	0.6718
5.41	173.05	4.882E-11	0.6277	4.956E-11	0.6391	1.109E+11	0.8226	2.530E+10	0.5382	0.5996
6.62	174.26	4.340E-11	0.5580	4.419E-11	0.5698	1.026E+11	0.7611	2.138E+10	0.4549	0.5352
7.82	175.46	3.851E-11	0.4951	3.932E-11	0.5070	9.437E+10	0.7000	1.801E+10	0.3832	0.4777
9.02	176.66	3.408E-11	0.4382	3.489E-11	0.4499	8.625E+10	0.6398	1.513E+10	0.3217	0.4264
10.22	177.86	3.006E-11	0.3866	3.084E-11	0.3977	7.828E+10	0.5806	1.266E+10	0.2693	0.3806
11.43	179.07	2.640E-11	0.3395	2.714E-11	0.3500	7.049E+10	0.5228	1.056E+10	0.2247	0.3397
12.63	180.27	2.304E-11	0.2962	2.373E-11	0.3060	6.284E+10	0.4661	8.770E+09	0.1866	0.3032
13.83	181.47	1.992E-11	0.2561	2.055E-11	0.2650	5.531E+10	0.4102	7.236E+09	0.1539	0.2706
15.04	182.68	1.696E-11	0.2181	1.752E-11	0.2259	4.773E+10	0.3540	5.899E+09	0.1255	0.2415
16.24	183.88	1.403E-11	0.1803	1.449E-11	0.1869	3.962E+10	0.2939	4.680E+09	0.0995	0.2156

* d = distance from PV inner (wetted) surface.

** r = distance from core vertical axis.

Figure 1 Flux ($E > 1 \text{ MeV}$), flux ($E > 0.1 \text{ MeV}$), and dpa rate (ENDF/B-VI dpa) at the PV inner wall as a function of the thermal shield thickness

Figure 2 Flux ($E > 1\text{ MeV}$) attenuation in the PV wall for different thermal shield thicknesses. (Calculations were done with BUGLE-96 library)

Figure 3 Dpa rate attenuation in the PV wall for different thicknesses of the thermal shield (TS). All values are normalized to 1.000 at the PV inner wall (wetted surface). Neutron fluxes are from the calculations with BUGLE-96. ENDF/B-VI dpa cross sections were used

Figure 4 Flux ($E > 0.1 \text{ MeV}$) attenuation in the PV wall for different thermal shield thicknesses. (Calculations were done with the BUGLE-96 library)

Figure 5 Flux ($E > 1\text{ MeV}$) attenuation in the PV wall for different PV wall thicknesses. The curve derived from the RG 1.99, Rev. 2, formula is also shown

Figure 6 Dpa rate attenuation in the PV wall for different PV wall thicknesses. Calculations were done with the BUGLE-96 cross-section library and ENDF/B-VI dpa cross sections. The curve derived from the RG 1.99, Rev. 2, formula is also shown

Figure 7 Flux ($E > 0.1 \text{ MeV}$) attenuation in the PV wall for different PV wall thicknesses. Calculations were done with the BUGLE-96 cross-section library. The curve derived from the RG 1.99, Rev. 2, formula is also shown

Figure 8 Flux ($E > 0.1 \text{ MeV}$) attenuation in the PV wall for different PV wall thicknesses. Calculations were done with the BUGLE-96 cross-section library. The curve derived from the RG 1.99, Rev. 2, formula is also shown

Figure 9 Flux ($E > 1\text{ MeV}$) and dpa rate attenuation in the PV wall for different PV wall thicknesses. Calculations were done with the BUGLE-96 cross-section library and ENDF/B-VI dpa cross sections. The curve derived from the RG 1.99, Rev. 2, formula is also shown

Figure 10 Flux ($E > 1 \text{ MeV}$) attenuation in the PV wall calculated with BUGLE-96 and SAILOR cross-section libraries. SAILOR calculation used ENDF/B-IV fission spectra. The curve derived from the RG 1.99, Rev. 2, formula is also shown

Figure 11 Comparison of dpa rate attenuation in the PV wall. The ENDF/B-VI dpa cross sections were used with both the BUGLE-96 and the SAILOR calculation. The curve derived from the RG 1.99, Rev. 2, attenuation formula is also shown

Figure 12 Flux ($E > 1$ MeV) and dpa rate attenuation in the PV wall calculated with BUGLE-96 and SAILOR cross-section libraries. SAILOR calculation used ENDF/B-IV fission spectra and ASTM dpa cross sections. The ENDF/B-VI dpa cross sections were used with BUGLE-96 calculations. The curve derived from the RG 1.99, Rev. 2 formula is also shown

Figure 13 Comparison of dpa rate attenuation in the PV wall. The BUGLE-96 calculation with ENDF/B-VI dpa cross sections, and the SAILOR calculation with ASTM dpa cross sections are compared between themselves and with the RG 1.99, Rev. 2, attenuation formula

Figure 14 Flux ($E > 1 \text{ MeV}$) attenuation in the PV wall, calculated with BUGLE-96 cross-section library, and the P_1 to P_3 approximations for the anisotropic scattering. Calculations were done for HBR-2 “nominal” dimensions

Figure 15 Dpa rate attenuation in the PV wall, calculated with the BUGLE-96 cross-section library, the P_1 to P_3 approximations for anisotropic scattering, and ASTM dpa cross sections. Calculations were done for HBR-2 “nominal” dimensions

Figure 16 Dpa rate attenuation in the PV wall, calculated with the BUGLE-96 cross-section library, the P_1 to P_3 approximations for anisotropic scattering, and ASTM dpa cross sections. The results from the SAILOR calculation with P_1 and P_3 approximations, ENDF/B-IV fission spectra, and ASTM dpa cross sections are also shown. Calculations were done for HBR-2 “nominal” dimensions

Figure 17 Comparison of the attenuation in the PV wall, as obtained from the BUGLE-96 calculation with P₃ approximation, and ENDF/B-VI dpa cross-sections; and SAILOR calculation with P₁ approximation and ASTM dpa cross sections. The curve derived from RG 1.99, Rev. 2, formula is also given

Figure 18 Comparison of the dpa rate attenuation in the PV wall, calculated with ENDF/B-VI and ASTM dpa cross sections. Neutron fluxes are from the BUGLE-96 calculation. HBR-2 "nominal" geometry was used

Figure 19 Flux ($E > 1\text{ MeV}$) versus azimuthal angle, at the PV inner radius, and at the 1/4 and 3/4 of the PV wall thickness from the PV inner surface. Calculations were done with BUGLE-96 cross-section library for “nominal” HBR-2 geometry

Figure 20 Dpa rate versus azimuthal angle, at the PV inner radius, and at the 1/4 and 3/4 of the PV wall thickness from the PV inner surface. Calculations were done with BUGLE-96 cross-section library and ASTM dpa cross sections, for “nominal” HBR-2 geometry

Figure 21 Flux ($E > 1\text{ MeV}$) attenuation in the PV wall. The curve labeled “average” gives the ratio of the flux at the given depth, “d,” from the inner surface to the flux at the PV inner surface, averaged (arithmetic average) over all the azimuthal intervals. Curves labeled “maximum” and “minimum” give the maximum and minimum ratios over all the azimuthal intervals, respectively

Figure 22 Dpa rate attenuation in the PV wall. The curve labeled “average” gives the ratio of the dpa rate at the given depth, “d,” from the inner surface to the dpa rate at the PV inner surface, averaged (arithmetic average) over all the azimuthal intervals. The curves labeled “maximum” and “minimum” give the maximum and minimum ratios over all the azimuthal intervals, respectively. Dpa rates were obtained from the calculations with BUGLE-96 and ASTM dpa cross sections

Figure 23 Flux ($E > 1$ MeV) attenuation in the PV wall, calculated with BUGLE-96 library, for different PV wall thicknesses. The calculations for the PV thickness of 17.16 cm were done for a two-loop plant. The other curves are those from Figure 5

Figure 24 Flux ($E > 0.1$ MeV) attenuation in the PV wall, calculated with BUGLE-96 library, for different PV wall thicknesses. Calculations for the PV thickness of 17.16 cm were done for a two-loop plant. Other curves are from Figure 8

Dpa rate (ASTM) attenuation in the PV wall

Figure 25 Dpa rate attenuation in the PV wall, calculated with BUGLE-96 library and the ASTM dpa cross sections, for different PV wall thicknesses. Calculations for the PV thickness of 17.16 cm were done for a two-loop plant. Other curves show data from Table 8

Figure 26 Dpa rate attenuation in the PV wall, calculated with BUGLE-96 library and ENDF/B-VI dpa cross sections, for different PV wall thicknesses. Calculations for the PV thickness of 17.16 cm were done for a two-loop plant. Other curves are from Figure 6

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