Shielding Analysis for ITER with Impact of Assembly Gaps and Design Inhomogeneities

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ASSEMBLY GAPS AND DESIGN INHOMOGENEITIES

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ABSTRACT

In the CDA design of ITER, the mechanical design of the blanket/shield/vacuum vessel calls for 2 cm wide assembly gaps between adjacent modules and a wide variation in material arrangement within individual modules. These design requirements weaken the effectiveness of the shield and result in a nonuniform level of radiation damage at the magnets. The detailed material arrangement in the inboard region has been modeled for the 3-D code MCNP with different assembly gap sizes (0-4 cm) to determine the impact on magnet damage. The assembly gaps, which extend radially up to the vacuum vessel, do not result in magnet damage peaking as long as a toroidally continuous vacuum vessel is used between the shield and the magnet. However, the peaking in toroidal damage is more pronounced at the front of the vacuum vessel. A safety factor of 3 used to modify the local 1-D results is adequate to account for 2 cm assembly gaps and uncertainties in modeling and nuclear data. For a 4 cm gap, the safety factor should be 6 for magnet damage and 9 for vacuum vessel damage.

I. INTRODUCTION

In 1987, four parties (USA, J, EC, and USSR) agreed to collaborate on Conceptual Design Activities (CDA) for the International Thermonuclear Experimental Reactor (ITER).[1] A major objective of ITER is to demonstrate the scientific and the technical feasibility of magnetic fusion energy. The CDA phase was completed in December 1991 and work has begun on the Engineering Design Activities (EDA), a six-year phase. At the beginning of the EDA phase, each party has conducted detailed analyses of specific issues related to the completed CDA design. The intent of these analyses is to provide an adequate basis for proceeding to the next phase. The U.S. shielding group has conducted

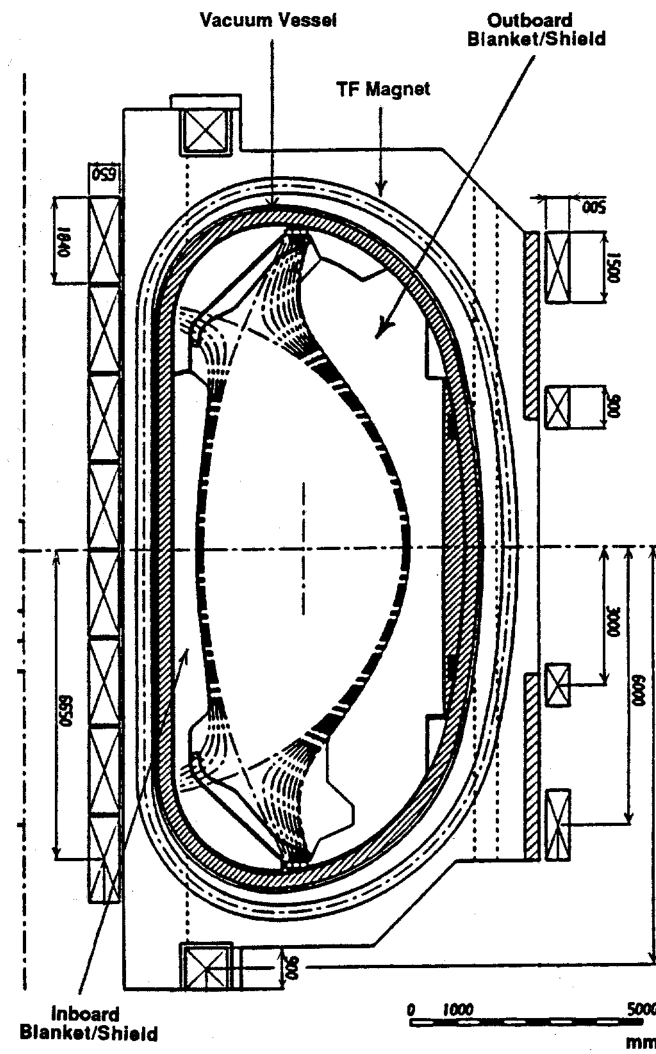

Fig. 1. Vertical cross section of the ITER CDA machine.

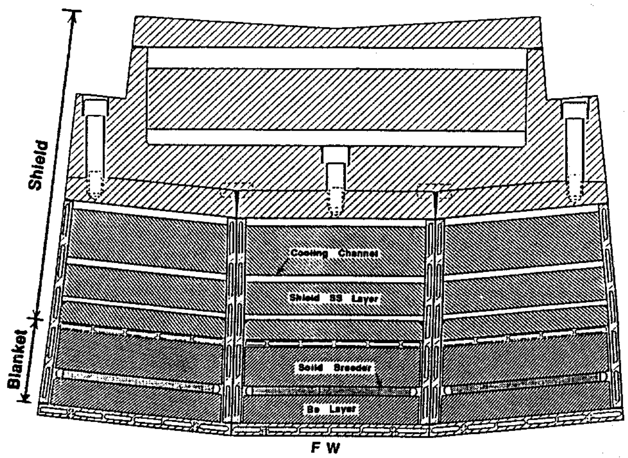

Fig. 2. Inboard blanket and shield design.

research in areas related to magnet shielding with prime emphasis on the impact of the assembly gaps and blanket/shield/vacuum vessel design inhomogeneities on the radiation damage level at the toroidal field (TF) coils. This paper describes the U.S. analyses performed in the frame of the ITER project and presents some recommendations for design modifications during the EDA phase.

ITER is based upon the tokamak concept and could be operating as early as 2005. The ITER CDA is designed to have a fusion power of ~1 GW and will be fueled by deuterium and tritium. Figure 1 shows an elevation view of the machine. The device is significantly larger than any existing fusion experiment. It has a major radius of 6 m. The 16 TF coils are superconducting. The magnetic field is ~5 T at the plasma axis and 11 T at the coils, and the plasma current is 22 MA. The machine operates with pulses of 1000 s flat-top duration, with an aim to demonstrate steady-state operation. The CDA device is scheduled to operate in two phases and achieve a fluence goal of 3 $MW \cdot y/m^2$. The physics phase takes about 6 years and the remainder of the machine's 15 years operating lifetime is devoted to the technology phase, in which integrated nuclear testing is carried out. During the 15 year life, ~3.8 full power years (FPY) of operation are expected.

The superconducting magnets need to be shielded against the 14 MeV neutrons generated by the plasma. About 85 cm thick blanket, shield, and vacuum vessel (V.V.) is required to protect the magnets and attenuate the neutron flux by approximately 4 orders of magnitude. The highest radiation damage in the TF coils occurs at the middle of the inner legs where the shielding space is constrained. The present analyses were performed for the

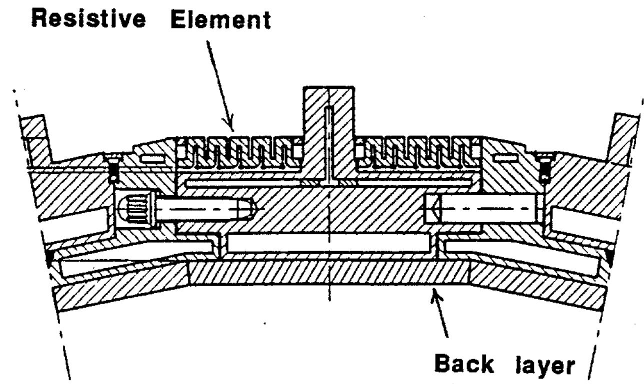

Fig. 3. Detailed mechanical design of the inboard vacuum vessel.

inboard side as it represents the most crucial part of the machine from the shielding viewpoint.

Much of the tritium needed to fuel the machine is regenerated in a breeding blanket located behind the first wall. The blanket is followed by the shield and a 30 cm thick V.V. The inboard blanket and shield are subdivided toroidally into 32 modules separated by 2 cm wide assembly gaps. At the midplane, the radial thicknesses of the inboard blanket and shield are 12 and 38 cm, respectively. The U.S. blanket design developed for ITER is considered in the analysis. It utilizes a water cooled solid breeder (Li_2O) with beryllium multiplier.[2] The shield and V.V. have been optimized by a series of neutronics and thermal hydraulics calculations.[3] They consist of several SS layers spaced by water coolant channels, as shown in Figs. 2 and 3. The back 5 cm thick layer of the V.V. is composed of B_4C and Pb and foreseen to further improve the shielding capability of this component. Parts of the V.V. are occupied by resistive elements that contain a low fraction of steel. Local parts of the magnets, specifically those behind the resistive elements, suffer from high radiation damage. Other hot spots in the magnets result from the thinning of the coil case which is 7 cm thick at the middle of the coil and is toroidally tapered reaching 4 cm at the corners. These toroidal and radial variations in the compositions and dimensions of the blanket, shield, V.V., and coil case along with the presence of the assembly gaps weaken the shielding performance and result in significant damage at the vital components of the reactor.

Proper performance of the TF magnets and reweldability of the V.V. are guaranteed if the radiation limits are met. The most demanding magnet radiation limits are imposed on the insulator dose, nuclear heating, fast neutron fluence (E_n > 0.1 MeV), and atomic displacement in Cu stabilizer. These limits are 5×10^9

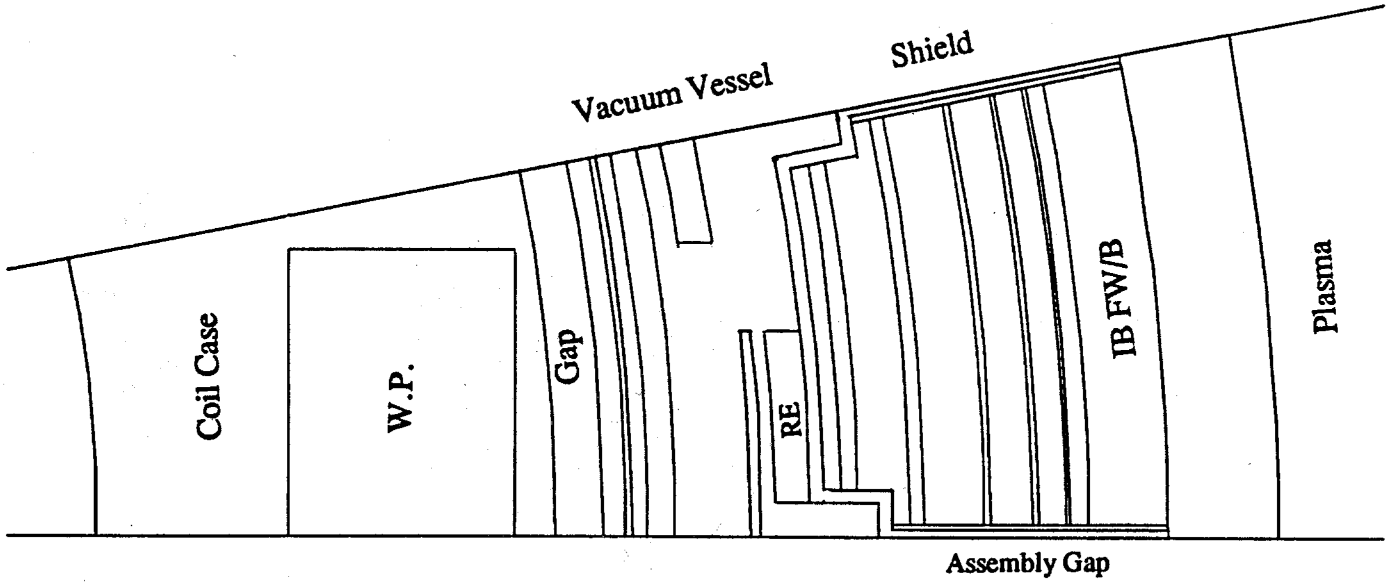

Fig. 4. Inboard region model used in the calculations.

rads, 5 mW/cm^3, 10^{19} n/cm^2, and 6×10^{-3} dpa, respectively. Reweldability of the V.V. is assured if the neutron-induced helium production does not exceed 0.1 appm at the end-of-life. Prior to comparing the results of the shielding analysis to these limits, safety factors are needed to correct the calculated values. Different correction factors are required for the 1-D and 3-D results.[3] The 1-D correction factors account for the presence of the assembly gaps, approximations in modeling, and uncertainties in data. The 3-D correction factors account mainly for the uncertainties in data, assuming that the 3-D model includes the gaps and the design inhomogeneities. The safety factors adopted during the ITER CDA phase were 3 and 1.5 for local responses obtained from the 1-D and 3-D models, respectively.

II. CALCULATIONAL MODEL

The detailed material arrangement in the inboard region of the CDA design has been modeled for the continuous energy, coupled neutron-gamma-ray Monte Carlo code MCNP.[4] The detailed geometrical configuration of the inboard shield, vacuum vessel, and TF coils has been modeled in the calculation. A homogenized region representing the inboard first wall/ blanket is also included in the model. This region is 12 cm thick and consists of 70% Be (0.65 density factor), 12% 316 SS, 9% water, and 9% lithium oxide. The 27 cm thick outboard blanket is included in the model to properly account for the contribution from neutrons and gamma-rays reflected from the outboard region.

The output of the MCNP geometry plotting routine given in Fig. 4 shows a horizontal cross section in the inboard region modeled. Due to symmetry, only 1/32 of the reactor is modeled with surrounding reflecting boundaries. The model includes half a TF coil. The toroidal angle for the model used is 11.25 degrees. The detailed configuration of coolant channels in the shield and vacuum vessel is included along with the gaps at the reflective boundaries. In addition, the low density resistive element region in the vacuum vessel and the lead/boron carbide shield layers at the back of the vacuum vessel are modeled. The thinning of the front coil case as one moves from the middle of the TF coil towards the side of the winding pack is clearly illustrated. The first wall/blanket/shield side walls as well as the assembly gaps between the adjacent inboard first wall/blanket/ shield modules are included in the model. The effect of the assembly gap size on magnet damage peaking is assessed by performing calculations for gap widths of 0, 2, and 4 cm.

Surface flux tallies have been used to determine the radiation effects at the front surfaces of the winding pack, coil case, and vacuum vessel. These surfaces have been segmented toroidally in order to get the detailed toroidal distribution of the radiation effects. Geometry splitting and weight cutoff with Russian Roulette techniques have been used for variance reduction. Sixteen thousand source particles have been sampled in the MCNP calculation yielding statistical uncertainty less than 5% in the calculated radiation effects at any of the surface segments.

III. RESULTS AND OBSERVATIONS

MCNP calculations with different assembly gap sizes (0-4 cm) have been performed to determine the impact on magnet damage peaking. Figures 5, 6, 7, and 8 show the toroidal variation of the fast neutron fluence, copper stabilizer dpa, insulator dose, and nuclear heating, respectively, at the front surface of the winding pack. The results are shown as a function of the toroidal angle from the middle of the TF coil. The results are normalized to the peak inboard neutron wall loading of 0.9 MW/m^2. It is clear from the results that using the detailed material arrangement in the inboard region with assembly gaps, the radiation effects at the winding pack have insignificant toroidal peaking. The toroidal variation of damage in the winding pack is influenced mainly by the thinning of the coil case at the corners of the winding pack as well as the arrangement of the coolant channels and the resistive element in the vacuum vessel. A slight peaking occurs at the corner of the winding pack in the absence of assembly gaps due to the reduced shielding resulting from the thinned coil case. When assembly gaps are included, the peak shifts towards the middle of the coil behind the gap. No significant peaking occurs behind the gap since it does not penetrate all the way to the magnet.

Figure 9 illustrates the toroidal variation of nuclear heating at the front of the coil case. No significant peaking is observed in the absence of assembly gaps. In this case, only a slight peaking in the nuclear heating occurs at the locations behind the regions with large coolant channels. In the cases with assembly gaps, some peaking is observed behind the gaps. The toroidal peaking factor (defined as the ratio of the peak to the average value in toroidal direction) for nuclear heating in the coil case is 1.08 for a 2 cm gap and 1.14 for a 4 cm gap and occurs behind the assembly gap.

On the other hand, toroidally averaged radiation effects in the winding pack and coil case increase by a factor of 1.4 for the 2 cm gap compared to the case without gap due to the removal of shielding material resulting from introducing the gap. This damage increase can be mitigated by increasing the shield thickness by ~3 cm. The 4 cm gap increases magnet damage by a factor of 2.8 compared to the case without the gap. This damage increase can be mitigated by increasing the shield thickness by ~8 cm. Hence, it is concluded from the results that as long as the assembly gaps do not penetrate all the way to the TF coils, their impact on magnet damage is to increase the damage level in the magnet without significant peaking behind them.

During the CDA activities it was suggested that the peak magnet damage results of the one-dimensional and three-dimensional calculations should be modified by safety factors of 3 and 1.5, respectively, to account for uncertainties in nuclear data and modeling.[3] Comparing the one-dimensional results[3] to the three-dimensional results obtained here, confirms that the safety factor of 3 used to modify the local one-dimensional results is adequate to account for the 2 cm assembly gaps and uncertainties in modeling and nuclear data. However, if a 4 cm assembly gap is used, a safety factor of 6 should be considered.

Damage peaking in the vacuum vessel is more pronounced since the assembly gaps penetrate all the way to the front of the vacuum vessel. Figure 10 shows the toroidal variation of the end-of-life helium production at the front surface of the vacuum vessel resistive element. It is clear that while insignificant peaking occurs without assembly gaps, more pronounced peaking is observed with the assembly gaps. The toroidal peaking factor is 1.6 for helium production at the front of the vacuum vessel for a 2 cm gap and increases to 2.3 for a 4 cm gap. As for the magnet radiation effects, the toroidally averaged helium production in the vacuum vessel increases by factors of 1.4 and 2.8 for the 2 cm and 4 cm gaps, respectively, compared to the case without gap due to the removal of shielding material resulting from introducing the gap. Comparing the vacuum vessel helium production one-dimensional results[3] to the three-dimensional results obtained here, indicates that a safety factor of 3 used to modify the local one-dimensional results is adequate to account for the 2 cm assembly gaps and uncertainties in modeling and nuclear data. However, if a 4 cm assembly gap is used, a safety factor of 9 should be used.

IV. SUMMARY

The detailed material arrangement in the inboard region of the CDA design has been modeled for MCNP calculations with different assembly gap sizes (0-4 cm) to determine the impact on magnet damage peaking. Using the detailed material arrangement in the inboard region with assembly gaps, the radiation effects at the winding pack have insignificant toroidal peaking. The toroidal peaking factor in the magnet is small (<1.09). The toroidal variation of damage in the winding pack is influenced mainly by the thinning of the coil case at the corners of the winding pack as well as the arrangement of coolant channels and resistive element in the vacuum vessel.

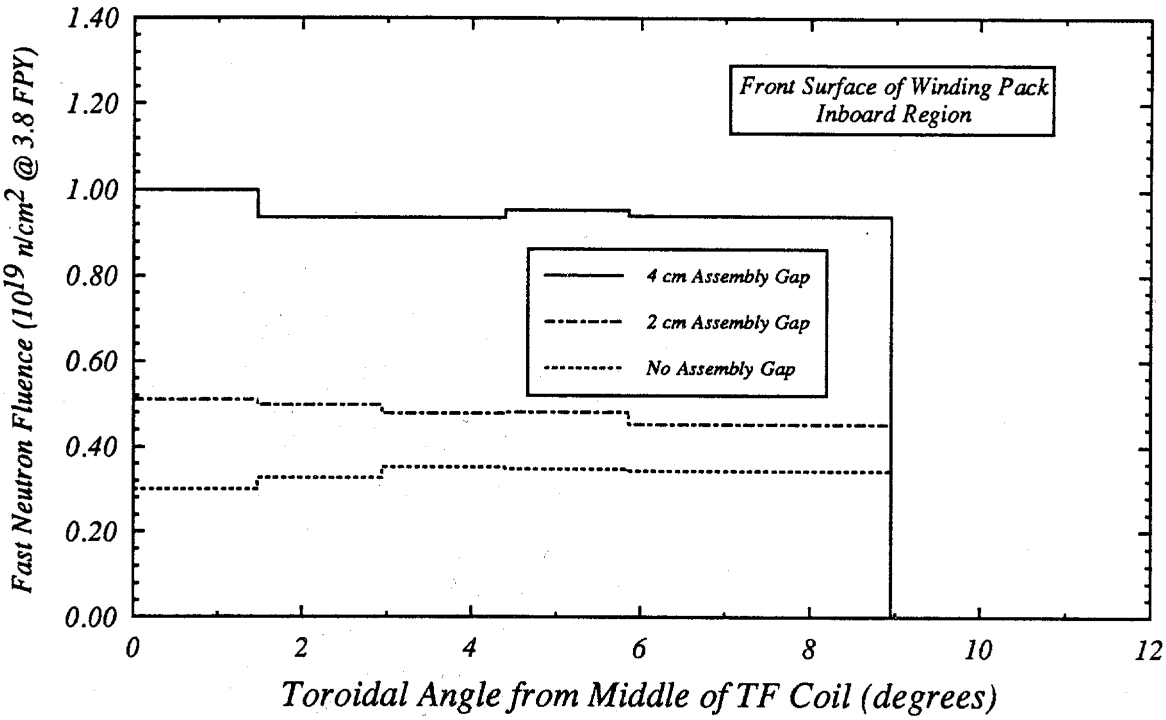

Fig. 5. Toroidal variation of end-of-life fast neutron fluence at the front surface of the winding pack.

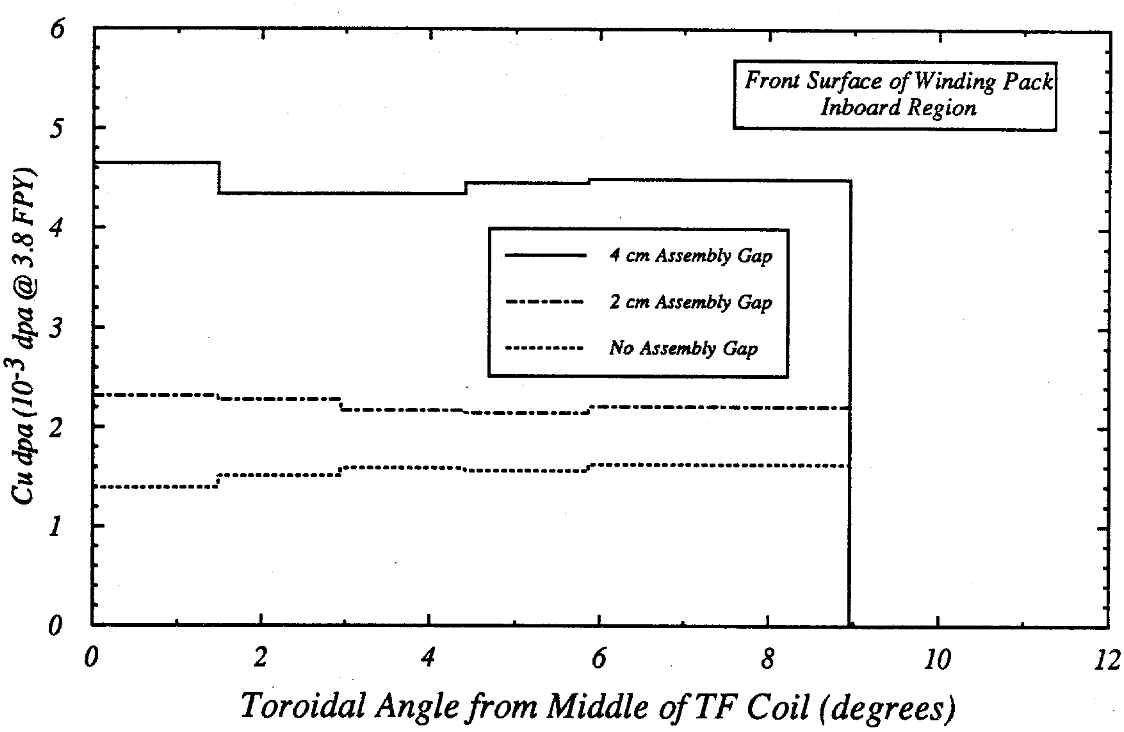

Fig. 6. Toroidal variation of end-of-life copper stabilizer damage at the front surface of the winding pack.

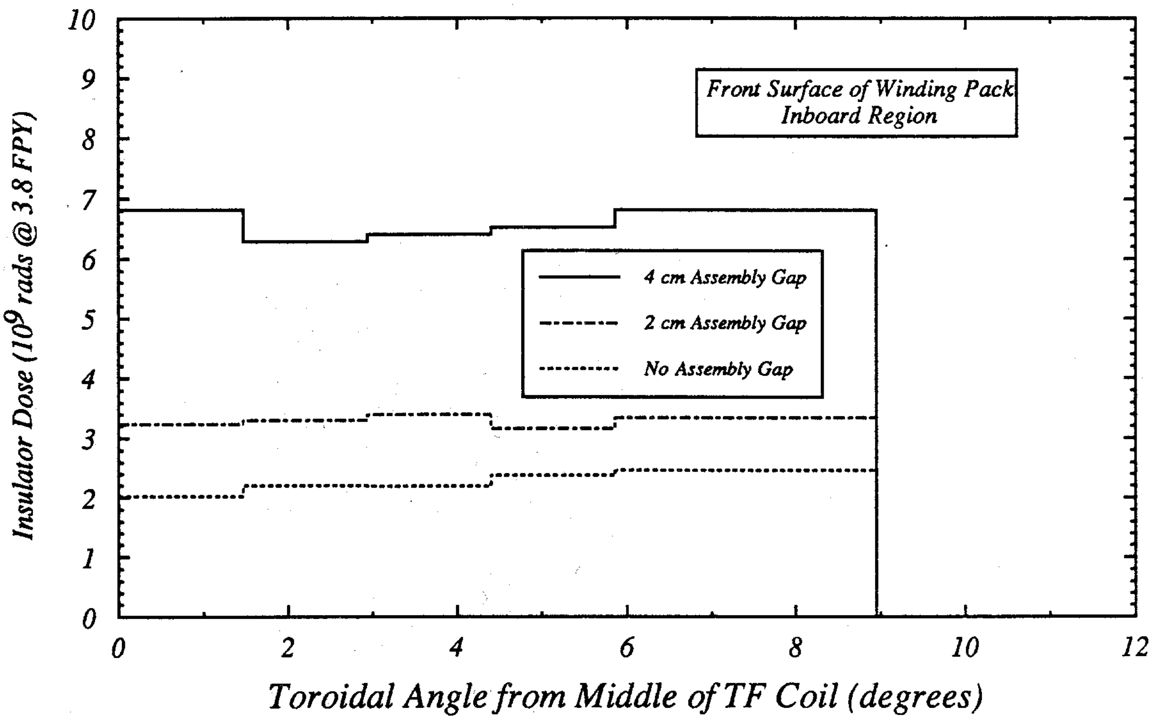

Fig. 7. Toroidal variation of end-of-life insulator dose at the front surface of the winding pack.

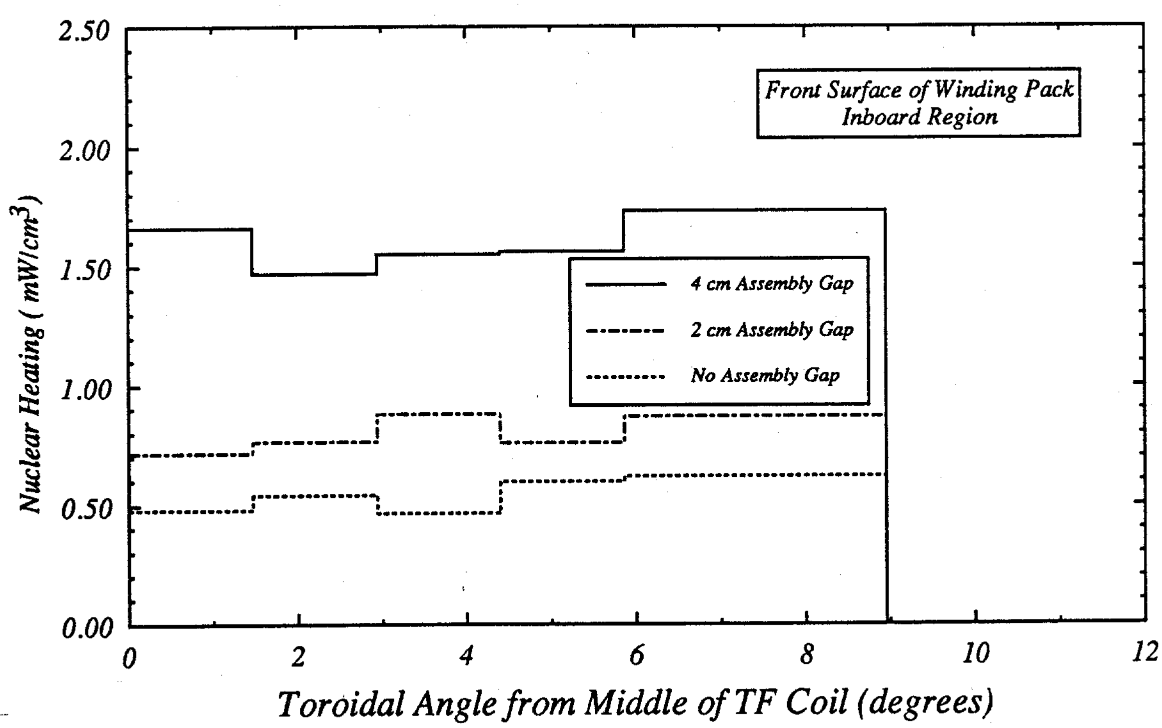

Fig. 8. Toroidal variation of nuclear heating at the front surface of the winding pack.

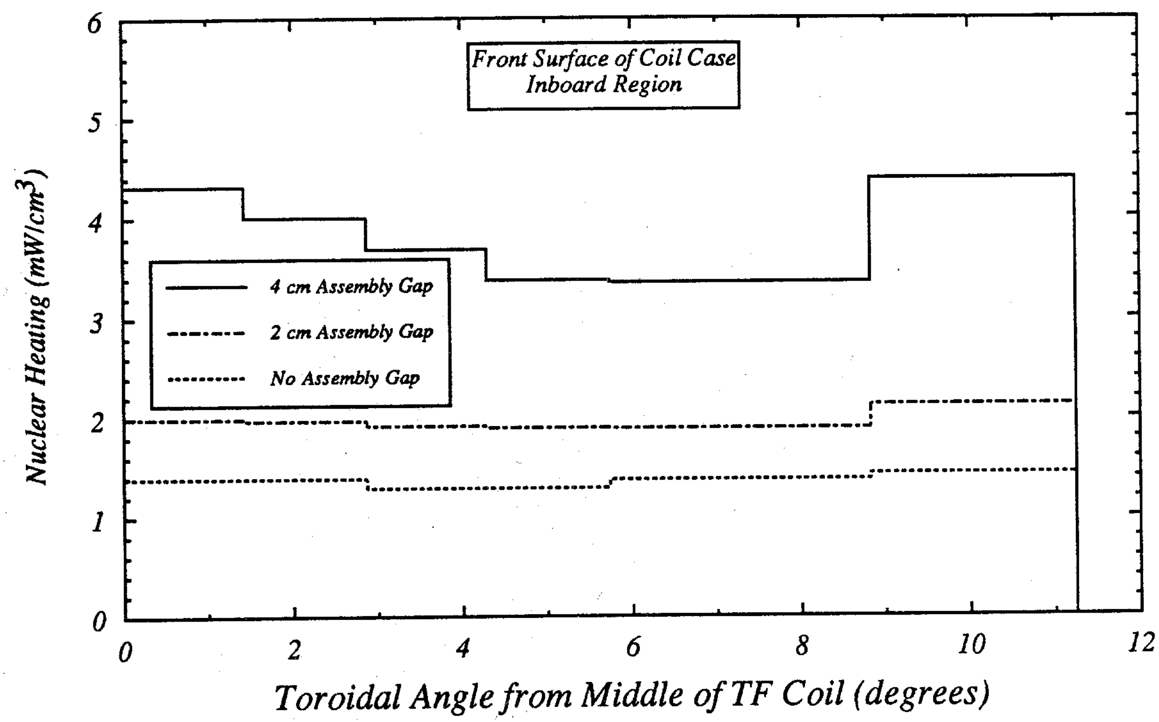

Fig. 9. Toroidal variation of nuclear heating at the front surface of the coil case.

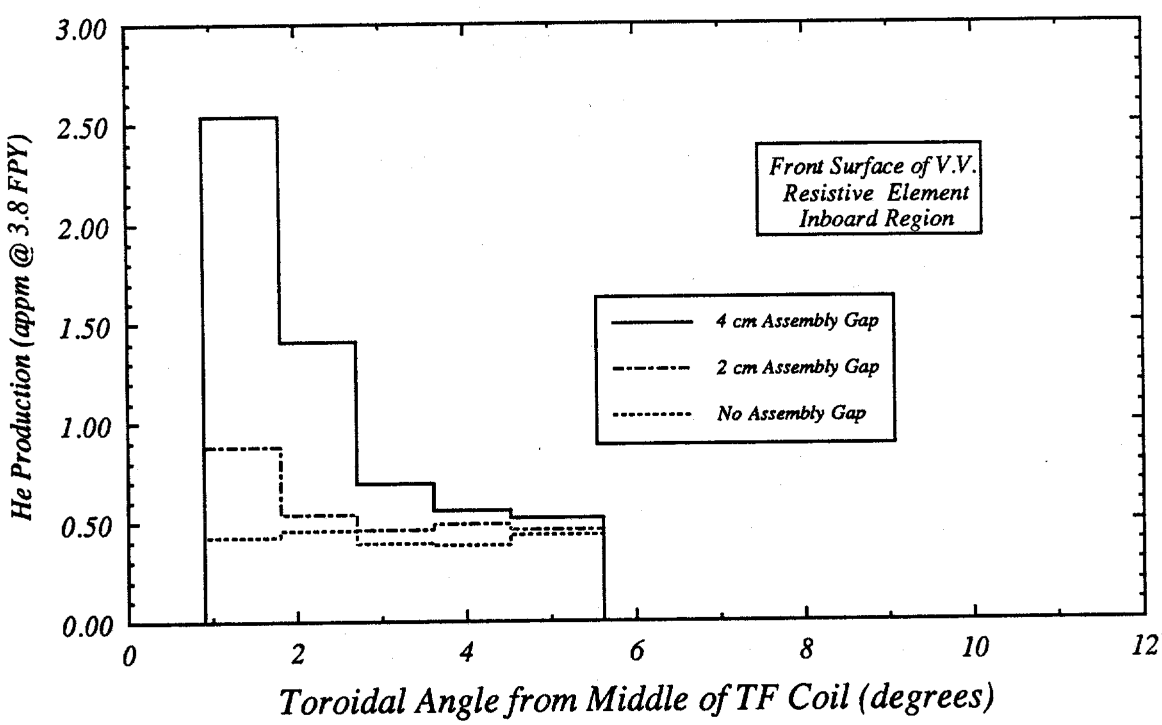

Fig. 10. Toroidal variation of end-of-life helium production at the front surface of the resistive element of the vacuum vessel.

The toroidally averaged radiation effects in the winding pack and coil case increase by a factor of 1.4 for the 2 cm gap compared to the case without a gap due to the removal of shielding material resulting from introducing the gap. Increasing the gap width from 2 to 4 cm results in increasing the toroidally averaged magnet radiation effects by a factor of 2 with no significant peaking. Damage peaking in the vacuum vessel is more pronounced since the assembly gaps penetrate all the way to the front of the vacuum vessel. The toroidal peaking factor is 1.6 for helium production at the front of the vacuum vessel for a 2 cm gap and increases to 2.3 for a 4 cm gap.

It is concluded that the assembly gaps between adjacent shield modules do not result in magnet damage peaking as long as a toroidally continuous vacuum vessel is used between the shield and magnet. However, significant damage peaking results in the vacuum vessel. A safety factor of 3 used to modify the local 1-D results is adequate to account for 2 cm assembly gaps and uncertainties in modeling and nuclear data. For 4 cm gap, the safety factor should be 6 for magnet damage and 9 for vacuum vessel damage.

ACKNOWLEDGMENTS

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