Nuclear Analysis for the INTOR Array of Loops ICRF Launcher Module Design

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NUCLEAR ANALYSIS FOR THE INTOR ARRAY OF LOOPS ICRF LAUNCHER MODULE DESIGN

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ABSTRACT

Nuclear analysis for the array of loops ICRF launcher module design of INTOR is presented. The nuclear radiation environment in the different module components is determined. The fast neutron fluence in the BeO radome is 10^{22} n/cm^2 after one full power year leading to significant microcracking. Activation calculations for SF_6 imply a total activity of 5 x 10^4 Ci at shutdown. Nuclear heating results in a large breakdown rate in SF_6. A 1.6 m thick nuclear shield is needed to allow for hands-on maintenance one day after shutdown behind the launcher module. The results imply that significant design changes are required for the array of loops ICRF launcher module to stand the severe INTOR nuclear environment.

INTRODUCTION

A number of candidate launcher designs were developed for heating the INTOR plasma to ignition using ion cyclotron waves. The concepts considered rely on using a loop antenna structure or a waveguide approach. The ICRF launchers are subject to a severe nuclear environment which impacts the component material selection as well as the choice of the launcher concept to be used. This work is aimed at determining the nuclear environment in the U.S. INTOR baseline launcher design, namely the array of loops with BeO radome.[1]

Four launcher modules (2.4 m x 2.4 m each) are used, each housing 16 element modules in a 4 x 4 array as shown in Fig. 1. A BeO radome brazed to the module frame establishes the vacuum boundary interface with the plasma chamber. Sulfur hexafluoride (SF_6) gas at atmospheric pressure is used behind the radome to enhance the voltage holdoff characteristics of the loop and its transmission line. Each element module consists of the copper loop, the copper ground plane, two 3-3/8" diameter coaxial lines and a nuclear shield made of a box filled with steel balls and flushed with water. The nuclear shield is used to allow for hands-on maintenance 24 hours after shutdown.

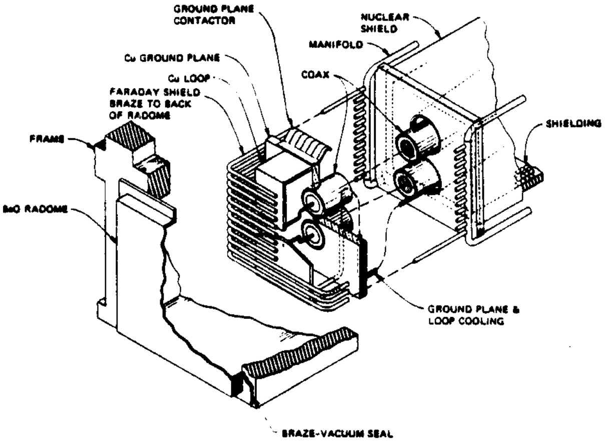

Fig. 1. The ICRF launcher module with configuration of the element module (from Ref. 1).

The three-dimensional neutronics calculations have been performed in two steps. In the first step, the reactor cavity and fusion neutron source were modeled to yield the energy and angular distribution of neutrons and gamma photons incident on the module front surface. In the second step, the detailed geometrical configuration of the element module was modeled and neutron and gamma surface sources were used at the module front surface.

CALCULATIONAL MODEL FOR THE REACTOR CAVITY

The MCNP[2] continuous energy Monte Carlo code with ENDF/B-V cross section data was used. Only 1/16 of the reactor was modeled with albedo reflecting surfaces. The model includes one-fourth of a launcher module. The vertical cross section of the model is given in Fig. 2. The plasma cavity was surrounded by a 0.6 m thick reactor shield to properly account for neutrons and gamma photons reentering the cavity. This shield was assumed to consist of 80 vol% Fe-1422

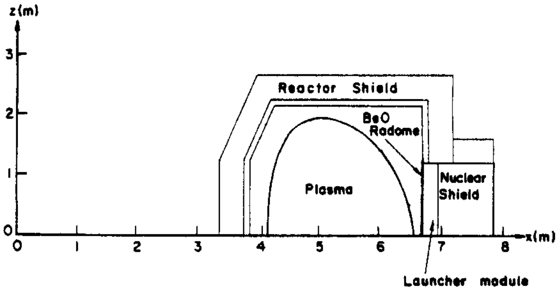

Fig. 2. Vertical cross section of the INTOR cavity model used in the calculations.

and 20 vol% H_2O. The launcher module was divided into three zones. The front zone is 1 cm thick and represents the BeO radome. The second zone is 30 cm thick and consists of 30 vol% 316 SS, 15 vol% Cu, 7 vol% H_2O, 0.26 vol% BeO, and 47.74 vol% SF_6. The third zone is 90 cm thick and consists of 70.6 vol% 316 SS, 0.2 vol% Cu, 0.5 vol% BeO, 27.1 vol% H_2O, and 1.6 vol% SF_6 and represents the nuclear shield, module frame and coaxial lines. Since this model is used only to determine the energy spectrum and angular distribution of neutrons and gamma photons incident on the front surface, using average smeared densities is adequate.

The neutron source was sampled from a D-shaped plasma zone with major radius, minor radius, elongation and triangularity of 5.3 m, 1.2 m, 1.6, and 0.27, respectively. At the midplane the scrapeoff zones are 10 cm and 30 cm thick on the outboard and inboard sides, respectively. The magnetic shift is 15 cm.

A trapping surface was located at the interface between the launcher module and the plasma chamber. At this surface particles entering the module were counted according to energy and angle bins. Twenty thousand histories were used yielding statistical uncertainties less than 2%.

The same geometrical model was used in a separate Monte Carlo run to determine the poloidal variation of the neutron wall loading. In this run, no materials were used in the zones outside the plasma chamber. The uncollided neutrons crossing segmented zones of the plasma chamber boundary were tallied. 5×10^5 histories were used in this calculation yielding less than 1% statistical uncertainties.

The calculated poloidal variation of the neutron wall loading in INTOR is given in Fig. 3. The results are for a fusion power of 620 MW that corresponds to an average wall loading of 1.1 MW/m^2. A peak neutron wall loading of 1.76 MW/m^2 occurs at the reactor midplane on the outboard side. The average wall loading at the module front surface is 1.53 MW/m^2. This significant peaking is attributed to the smaller outboard scrapeoff zone, the outward shift of the peak neutron source in the plasma zone and the fact that the outboard part of the first wall sees more source neutrons than does the inboard part. The front surface of the launcher module at the reactor midplane will be subjected to neutron wall loadings ∼ 60% higher than the average reactor value. Notice that while the average reactor wall loading could be sensitive to the first wall shape, the peak value is independent of the first wall shape provided that the location of the point at which the peak occurs relative to the plasma is unchanged. The MCNP results are in excellent agreement with those obtained using the NEWLIT[3] code.

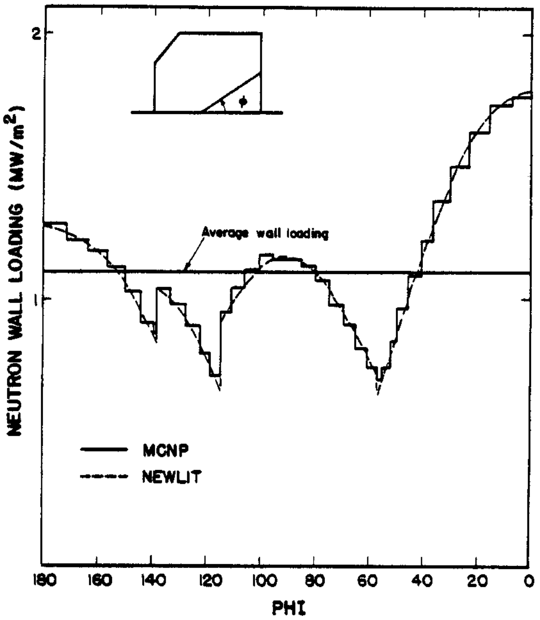

Fig. 3. Poloidal variation of neutron wall loading in INTOR.

NUCLEAR RADIATION INCIDENT ON LAUNCHER MODULE

The energy spectra of neutrons and gamma photons incident on the ICRF module are shown in Fig. 4. The results are for an average neutron wall loading of 1 MW/m^2 at the module front surface. The calculations indicated that for one source neutron generated in the plasma zone, 0.0745 source neutrons impinge directly on the module front surface while a total of 0.151 neutrons (collided and uncollided) are incident on the surface. 0.063 gamma photons produced in the surrounding materials end up impinging on the module front surface. The average neutron and gamma energies are 7.5 and 1.7 MeV, respectively. The angular distributions of neutrons

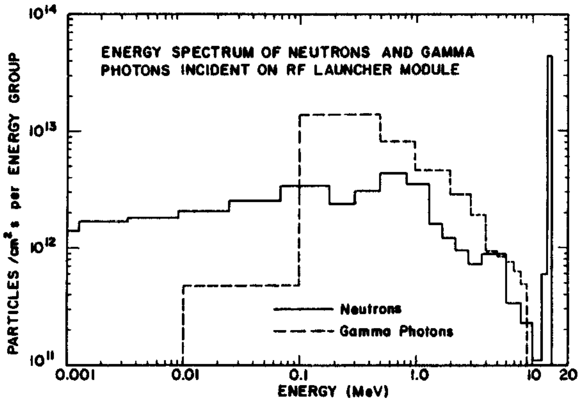

Fig. 4. Energy spectra of neutrons and gamma photons incident on the module surface.

and gamma photons incident on the module front surface are given in Fig. 5. The angle θ is measured from the normal to the surface. The angular distribution peaks at normal incidence.

CALCULATIONAL MODEL FOR THE LAUNCHER ELEMENT MODULE

Because of symmetry, only one-fourth of an element module was modeled for the MCNP calculations with reflecting boundaries. Figures 6 and 7 give different geometrical cross sections in the model showing the different components. Although the model does not account for the blanket and shield adjacent to the launcher module, it gives appropriate representation of the conditions at the central element module where the end effects are insignificant and where the worst radiation environment exists.

The model is an idealization and adaptation of the actual launcher design. The BeO radome was assumed to have a thickness of 1 cm followed by a 0.75 cm thick Faraday shield. The loop was assumed to have a thickness of 1 cm while the ground plane is 2 cm thick. The loop and ground plane coolant zones are 0.75 cm thick. The coaxial line has a central copper tube with inner and outer diameters of 3.12 and 3.34 cm, respectively, and is filled with water. The outer copper tube has inner and outer diameters of 7.68 and 7.94 cm, respectively. The space between the two coaxial conductors is occupied by BeO spacers and SF_6 gas. The coaxial cables go through two right angle bends to reduce radiation streaming to the back of the nuclear shield. A nuclear shield thickness of 90 cm was used in the calculations.

Two separate calculations have been performed. The first one is a coupled neutron-photon calculation with a neutron surface source at the module front surface having the energy

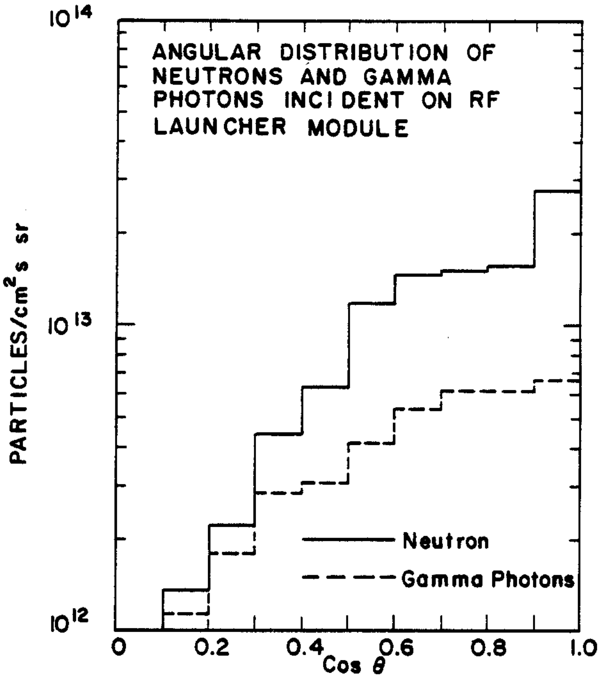

Fig. 5. Angular distributions of neutrons and gamma photons incident on the module surface.

and angular distributions given in Figs. 5 and 6. The second calculation is a photon only calculation in which a photon surface source at the module front surface is sampled from the gamma energy and angular distributions of Figs. 5 and 6. The results of the two calculations were added to get the contribution from both neutron and gamma surface sources. Twenty thousand histories were used together with different variance reduction techniques yielding statistical uncertainties varying from ~ 1% in front zones to ~ 30% at the back of the shield.

NUCLEAR RADIATION PARAMETERS IN RADOME AND BeO SPACERS

Due to its good rf power transparency and thermal conductivity, BeO was proposed for use as the ceramic element module radome that forms the interface with the plasma chamber. We calculated the nuclear radiation environment at the BeO radome as well as some relevant radiation damage parameters. The results, normalized to a unit wall loading, are given in Table I.

For a peak neutron wall loading of 1.76 MW/m^2 at the launcher module, the BeO radome will be subjected to a peak fast neutron fluence of 10^{22} n/cm^2 ($E > 0.1$ MeV) after one year of full operation. The radiation effect of greatest concern in BeO is microcracking that results from the anisotropy of lattice expansion and leads to severe degradation of strength. Since the radome serves as a vacuum boundary, the radiation induced microcracking will limit its

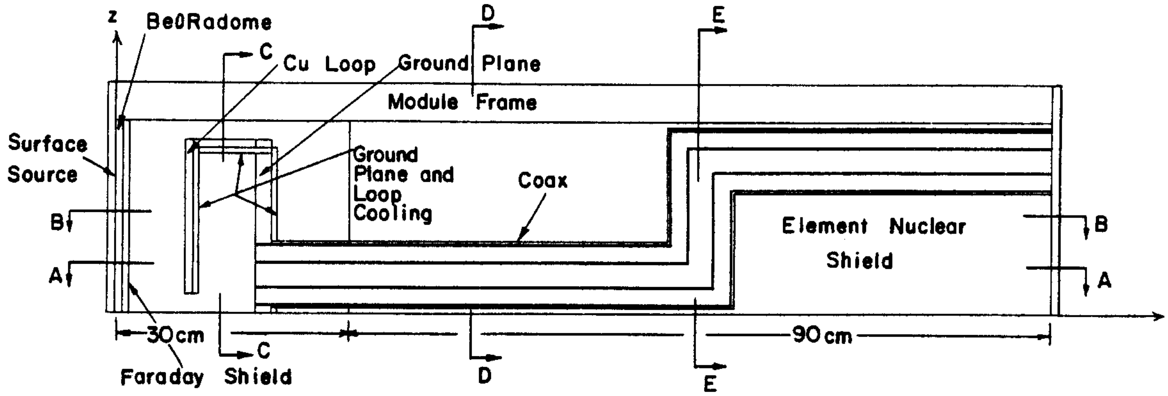

Fig. 6. Vertical cross section of the element module geometrical model used.

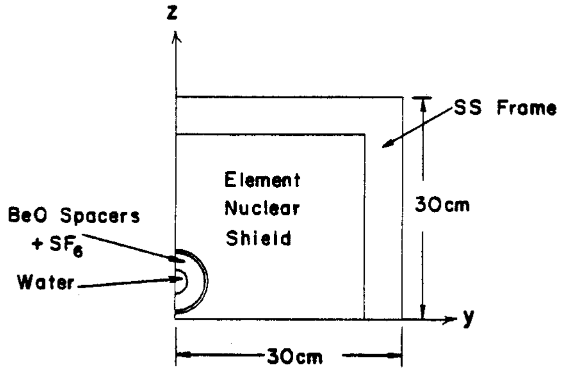

Fig. 7. Section D-D of the geometrical model.

Table I. Nuclear Radiation Parameters in the BeO Radome for 1 MW/m^2 Wall Loading

Neutron flux	2.8×10^{14} $n/cm^2 \cdot s$
Gamma flux	1.53×10^{14} $\gamma/cm^2 \cdot s$
Fast neutron fluence (E > 0.1 MeV) after one full power year (FPY)	5.77×10^{21} n/cm^2
Helium production	431 appm/FPY
Hydrogen production	93 appm/FPY
Tritium production	20 appm/FPY
Power density	8.53 W/cm^3
Absorbed dose rate	8.9×10^{12} rad/FPY

life. Data obtained for samples irradiated in fission reactor neutron environments indicate that the onset of microcracking occurs at fluences of 10^{20}-10^{21} n/cm^2 (E > 0.1 MeV) at temperatures below 300°C.[4] The onset fluence decreases as the temperature decreases. The temperature on the radome surface in the present design is expected to be around 160°C. Considering a fluence limit of 10^{20} n/cm^2, our results indicate that the BeO radome has to be changed every 0.01 FPY. The lower fluence limit was considered to account for lower operating temperatures and the fact that neutrons with a degraded fusion spectrum produce more damage than do the same number of neutrons with a fission spectrum. Use of other candidate ceramics that can tolerate higher neutron fluences such as alumina (Al_2O_3) and spinel ($MgAl_2O_4$) must be thoroughly investigated. Other design changes, such as coating the Faraday shield with BeO or replacing the BeO radome by a BeO window located farther from the plasma, can be considered. BeO is used also as a spacer between the central and return conductors of the coaxial line. The results indicate that the BeO spacers in the front part of the coax will be subjected to high neutron fluences that might result in microcracking after a short time of operation.

NUCLEAR RADIATION ENVIRONMENT AT THE LOOP, GROUND PLANE AND TRANSMISSION LINES

The nuclear radiation environment at the loop, ground plane, and coaxial lines has been determined. In this calculation copper was used. Although other candidate materials can be used, the neutron and gamma fluxes calculated here are not sensitive to the material choice. Table II gives the neutron and gamma fluxes in different zones of the loop, ground plane, and central and return conductors of the coaxial line. The results are normalized to 1 MW/m^2 at the front surface of the module. Degradation of copper conductivity as a result of irradiation is a concern which needs to be assessed using the calculated nuclear environment.

ACTIVATION OF THE SULFUR HEXAFLUORIDE GAS

The level of activity of the SF_6 gas in the launcher module of INTOR has been determined using the DKR code.[5] The code used the neutron spectra obtained from the MCNP Monte Carlo calculation in the different zones of the module. The zone between the BeO radome and the nuclear shield was divided into three segments and the average neutron flux in each segment was used in

Table II. Neutron and Gamma Fluxes in the Loop, Ground Plane and Coaxial Line for 1 MW/m^2

Component	Distance From Front Surface of Module (m)	Neutron Flux (n/cm^2·s)	Gamma Flux (γ/cm^2·s)
Loop			
Front	0.09-0.10	2.61×10^{14}	1.26×10^{14}
Top	0.10-0.18	2.28×10^{14}	1.34×10^{14}
Ground Plane	0.18-0.20	2.19×10^{14}	1.33×10^{14}
Central Conductor in Coax	0.18-0.30	1.76×10^{14}	1.18×10^{13}
	0.30-0.45	1.04×10^{14}	7.61×10^{13}
	0.45-0.60	2.29×10^{13}	2.32×10^{13}
	0.60-0.90	1.69×10^{12}	2.55×10^{17}
	0.90-1.05	2.04×10^{11}	2.20×10^{11}
	1.05-1.20	1.22×10^{10}	7.10×10^{10}
Return Conductor in Coax	0.18-0.30	1.84×10^{14}	1.21×10^{14}
	0.30-0.45	9.67×10^{14}	7.91×10^{13}
	0.45-0.60	2.28×10^{13}	2.41×10^{13}
	0.60-0.90	2.22×10^{12}	2.91×10^{12}
	0.90-1.05	1.88×10^{11}	2.14×10^{11}
	1.05-1.20	2.15×10^{10}	6.80×10^{10}

the DKR calculations. The front segment extends from the radome to the front of the loop. The next segment extends from the loop to the ground plane while the last segment extends from the ground plane to the front surface of the nuclear shield. The flux in a 0.5 cm thick region behind the radome was used in the calculations to determine the peak activation level in the SF_6 gas. An operating time of one full power year at a neutron wall loading of 1 MW/m^2 was used. The specific activities in Ci/cm^3 at shutdown in the three segments as well as the peak are given in Table III.

The results indicate that within three minutes, three of the isotopes (^{16}N, ^{19}O and ^{20}F) will decay away leaving ^{18}F and ^{32}P as the dominant isotopes. From 1 day to 120 days after shutdown, ^{32}P dominates and after 120 days ^{35}S will be the dominant source of activity. The total activity will be down by four orders of magnitude within one year after shutdown. Using the volumes for the segmented zones of SF_6 gas in the module and considering a peak neutron wall loading of 1.76 MW/m^2 we estimated that 893 Ci of SF_6 activity in the element module at the reactor midplane needs to be handled immediately after shutdown. One day after shutdown this activity level will decline to 229 Ci. Using the average launcher module wall loading of 1.53 MW/m^2 we estimated that the total SF_6 activity in the four launcher modules is 5×10^4 Ci after shutdown and 1.3×10^4 Ci one day later.

Table III. Activity (Ci/cm^3) of SF_6 Gas in the Launcher Module for 1 MW-y/m^2 at Shutdown

Zone	Specific Activity (Ci/cm^3)
Peak	3.142×10^{-2}
Segment 1 (1 cm < X < 9 cm)	1.837×10^{-2}
Segment 2 (9 cm < X < 18 cm)	7.042×10^{-3}
Segment 3 (18 cm < X < 30 cm)	2.983×10^{-3}

RADIATION CHEMISTRY OF THE SULFUR HEXAFLUORIDE GAS

The calculated nuclear environment in the SF_6 gas can be used to determine the breakdown rate of SF_6 due to nuclear heating. Although breakdown products do not reduce the dielectric strength, they are extremely reactive. The corrosive nature of the breakdown products is of particular concern in accelerators where the concentration of these products must be kept at low levels by recirculation through purification systems.[6] The average energy deposition rate in the SF_6 gas of the element module at the reactor midplane is 13.84 mW/cm^3. Using the G-factor, defined as the number of breakdown product molecules formed per 100 eV absorbed radiation, one can calculate the breakdown product production rate. No G-factor was measured for SF_6. We assumed that the breakdown of SF_6 by irradiation into $SF_4 + F_2$ is similar to the formation of H_2 by gamma irradiation of ethane which has a G-factor of 6.8.[7] This implies that 5.88×10^{15} breakdown product molecules will be formed per cm^3 per second which represent 0.034% of the original number of SF_6 molecules. This extremely high breakdown product production rate based only on nuclear heating will require continuous recirculation through purification systems.

RADIATION ENVIRONMENT BEHIND THE NUCLEAR SHIELD

Each element of the launcher has a nuclear shield behind it to allow for hands-on maintenance 24 hours after shutdown. Shutdown gamma radiation originates from induced activation in the outer layers of the shield and in unshielded equipment behind the shield. Earlier work on ETF and FED indicated that activation of shield and outlying components will be low enough to result in a general shutdown dose rate of 2.5 mrem/hr one day after shutdown if the neutron flux at the back of the shield is kept at a level of ~ 2×10^6 n/cm^2·s during operation.

Table IV. Nuclear Heat Loads (kW) in One Quarter of the Element Module for 1 MW/m^2

Component	Nuclear Heating (kW)
Radome	5.320
Faraday Shield	3.309
Loop	4.981
Ground Plane	7.761
Loop and Ground Plane Coolant Tubes	2.020
SF_6 Gas	0.112
Coax	1.175
Module Frame	55.040
Nuclear Shield	36.273

The results of the neutronics calculations for the launcher module indicate that the average neutron flux behind a 0.9 m thick shield is 1.81×10^9 n/cm^2·s with a peak value of 1.37×10^{10} n/cm^2·s at the exit of the coax. These values were normalized to a unit wall loading. Given a peak wall loading of 1.76 MW/m^2 we estimated that a total shield thickness of ~ 1.6 m is required to reduce the neutron leakage flux to an acceptable level of ~ 10^6 n/cm^2·s.

NUCLEAR HEAT LOAD IN THE MODULE

Nuclear heating resulting from both neutron and gamma energy deposition was calculated in the different components of the module. The nuclear heat loads in kW are given in Table IV. The results are given for one quarter of the element module (1/64 of the launcher module) and are normalized to unit neutron wall loading. Based on a peak neutron wall loading of 1.76 MW/m^2, a power of 102 kW resulting from nuclear heating should be handled by the loop and ground plane coolant in each element module at the reactor midplane. Only 8 kW of nuclear heat is to be removed by the coolant in the two coaxial lines of the element module. Using the average launcher module wall loading of 1.53 MW/m^2 we calculated the total power from nuclear heating in all four launcher modules to be 45 MW. About 47% of this power comes from nuclear heating in the module frame and 15% from nuclear heating in the nuclear shield.

SUMMARY

Nuclear analysis has been performed for the ICRF launcher module of INTOR consisting of a 4 x 4 array of loops. The poloidal variation of neutron wall loading in INTOR was determined. The launcher modules are subjected to an average neutron wall loading of 1.52 MW/m^2 and a peak value of 1.76 MW/m^2 which is 60% higher than the average reactor value.

The nuclear radiation environment in the different launcher components has been determined. The peak fast neutron (E > 0.1 MeV) fluence in the BeO radome after one year of full operation is 10^{22} n/cm^2 leading to significant microcracking and strength degradation. A total SF_6 activity of 5×10^4 Ci in the four launcher modules needs to be handled after shutdown. One day after shutdown this activity level is reduced by a factor of four. Nuclear heating in SF_6 results in a breakdown rate of 5.9×10^{15} molecules/cm^3·s requiring continuous recirculation through purification systems to remove these corrosive products.

The total nuclear heat load in the four launcher modules amounts to 45 MW. The nuclear heat load to be handled by the loop coolant in one element module is 102 kW. A 1.6 m thick nuclear shield is required to allow for hands-on maintenance behind the module one day after shutdown.

The results obtained in this work imply that significant design changes are required for the array of loops ICRF launcher module to stand the severe INTOR nuclear environment.

ACKNOWLEDGMENTS

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