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Abstract

The 3-D neutronics analysis for the standard ITER divertor cassettes was extended to determine the nuclear parameters at specified locations and address streaming and neutronics issues for the diagnostic cassettes. The nuclear parameters in the attachment keys and coolant pipes for the dome and plasma facing liners of the central diagnostic cassette indicated that the top attachment keys for the outer plasma facing liners have the highest nuclear heating and damage. Rewelding of the coolant pipe connections for the dome block is of particular concern and these connections should be placed farther away from the dome surface. The nuclear parameters in the waveguides and their coolant pipe connections confirmed that rewelding is feasible for these connections. The damage in the VV due to streaming through the viewing slots is much lower than that resulting from streaming through the pumping ducts in the standard cassette and rewelding remains feasible. The increased toroidal gaps between the central diagnostic cassettes and the adjacent cassettes due to cut-outs for X-point viewing increase the total magnet heating by less than 0.1 kW in the 20 TF coils. The increased streaming will be compensated by the added attenuation in the diagnostic equipment and coolant pipes in the ports at the diagnostic cassettes. The nuclear parameters were determined in the candidate materials for the mirror assemblies in the diagnostic cassettes. These are molybdenum, tungsten and copper. Tungsten experiences the lowest damage and is the preferred candidate from the neutronics point of view.

1. INTRODUCTION

Four central diagnostic cassettes are utilized in ITER [1]. They replace the standard divertor cassettes at ports 3, 8, 13, and 18. While the basic structure of the diagnostic cassette body is similar to that of the standard cassette (Fig. 1), the wings and gas boxes are replaced by a full steel structure with thick plasma facing liners (Fig. 2). This provides additional neutron attenuation. On the other hand, the central diagnostic cassette employs viewing slots, mirror assemblies, and cut-outs at ports 3 and 13 for X-point diagnostics that could lead to additional radiation streaming. In addition, waveguide panels are attached to the sides of the cassettes at ports 8 and 18 for microwave diagnostics (Fig. 3). Detailed three-dimensional neutronics calculations have been performed for the standard divertor cassette and nuclear heating and damage profiles were generated [2,3]. The 3-D results of the standard cassette were used along with the geometrical differences in the central diagnostic cassette to determine the nuclear parameters at specified locations and address streaming and neutronics issues associated with the central diagnostic cassette. The impact of the instrumented standard cassettes surrounding the central diagnostic cassettes was taken into account. Conservative assumptions were used in scaling the results from the 3-D results of the standard cassette.

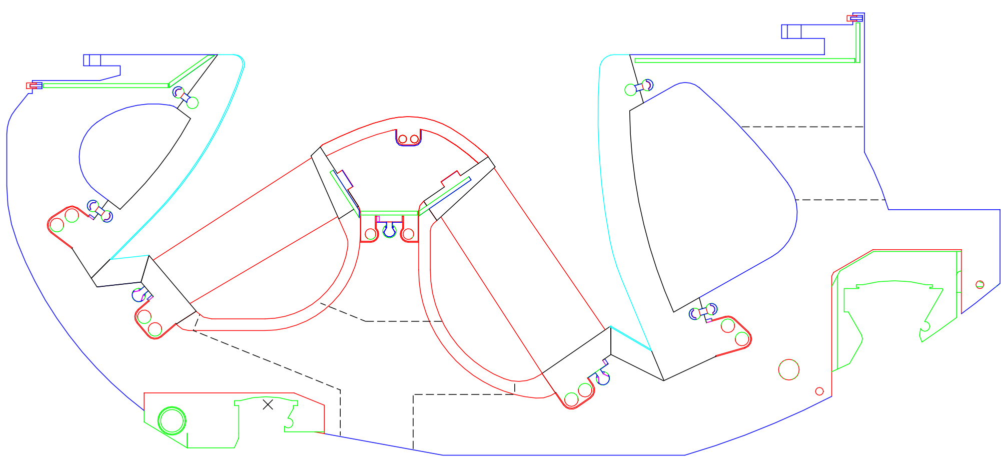

Fig. 1. The standard divertor cassette.

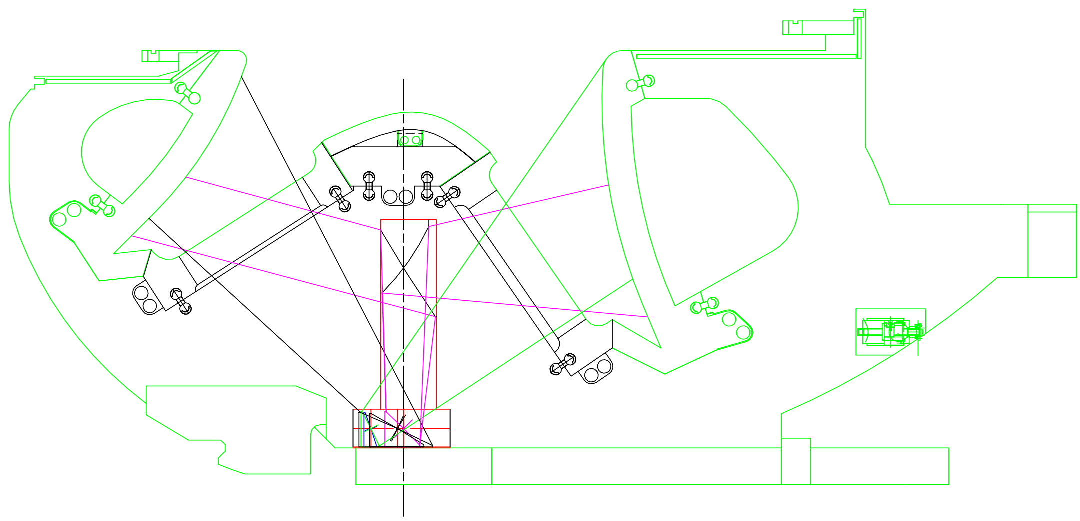

Fig. 2. The central diagnostic cassette showing the viewing slots and mirrors.

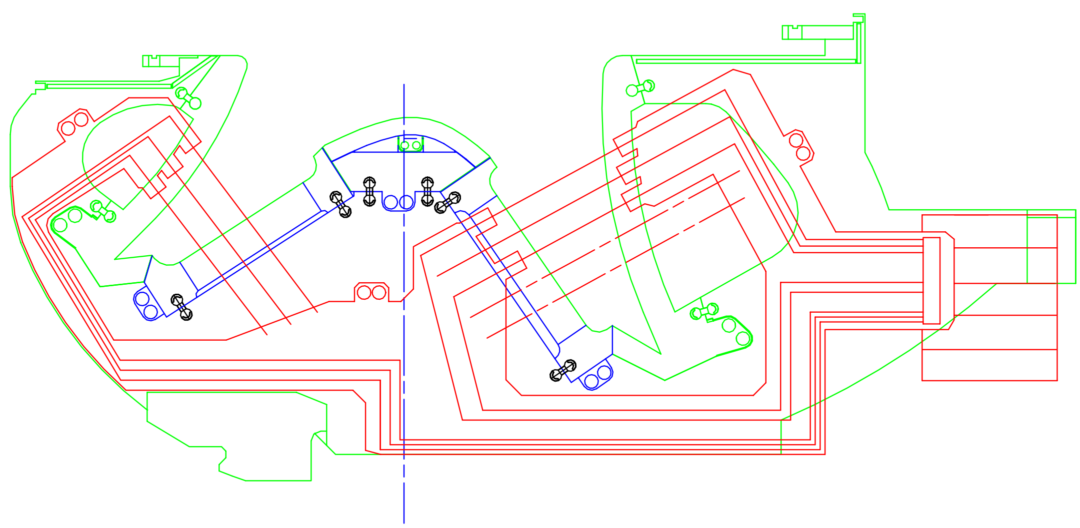

Fig. 3. The central diagnostic cassette showing the waveguide panel.

2. NUCLEAR PARAMETERS IN ATTACHMENTS OF DOME AND LINERS

The plasma facing liners that replace the wings and gas boxes in the central diagnostic cassette are attached mechanically to the cassette body using dumbbell keys from the side. Each of the inner and outer liners is attached using two keys, one at the top and one at the bottom as shown in Fig. 2. The dome block is also attached mechanically to the cassette body with two dumbbell keys.

The central diagnostic cassette is surrounded on both sides by instrumented standard cassettes which have less material in the region adjacent to the plasma facing liners. This includes the wings with more than 75% void fraction and the empty gas boxes shown in Fig. 1. As a result, the nuclear parameters in the bottom attachment keys for the plasma facing liners in the central diagnostic cassette will vary toroidally with the lowest values being at the center of the cassette where more shielding is provided by the thick plasma facing liners. The keys are shielded by the 17.5 cm thick liners. The largest nuclear parameters will be at the sides of the cassette where the impact of the lower material density of adjacent cassettes will be more pronounced. The peak nuclear parameters in the bottom attachment keys at the sides of the central diagnostic cassette were determined using the results of the 3D calculations for the standard cassette taking into account the contribution of neutrons penetrating the plasma facing liner of the central diagnostic cassette with additional effective thickness of about 8 cm.

Regarding the top attachment keys for the plasma facing liners and the attachment keys for the dome block, the impact of the adjacent wings is negligible and the nuclear parameters are toroidally uniform. The nuclear parameters for these keys were determined from the profiles generated for the standard cassette in the dome and central region of the cassette. Table 1 gives the peak nuclear parameters for the attachments. Note that the parameters for the two attachments of the dome block are nearly identical. The atomic displacement and helium production results are given after a full power year (FPY) of operation which corresponds to a fluence of 1 MW-a/m^2. The nuclear parameters at the lower attachment keys for the inner and outer plasma facing liners will be lower by about a factor of two at the toroidal center of the cassette. The top attachment keys for the outer plasma facing liners have the highest nuclear heating and damage.

Table 1. Peak Nuclear Parameters in the Attachment Keys for the Dome and Plasma Facing Liners of the Central Diagnostic Cassette

	Nuclear Heating (W/cm^3)	Atomic Displacement (dpa/FPY)	Helium Production (He appm/FPY)
Dome Body Attachment Keys	0.50	0.09	1.92
Inner Plasma Facing Liner			
Top Key	0.77	0.14	2.95
Bottom Key	0.45	0.08	1.73
Outer Plasma Facing Liner			
Top Key	0.85	0.15	3.26
Bottom Key	0.50	0.09	1.92

3. NUCLEAR PARAMETERS IN COOLING PIPES FOR DOME BLOCK

The dome of the central diagnostic cassette is modified from the standard cassette. While the profile of the dome plasma facing surface is exactly the same as that of the standard cassette, the locations of the water feed/return pipes are different. The dome block is smaller resulting in the coolant pipe connections being located closer to the plasma facing surface of the dome. These coolant pipes are welded to the cassette body. A critical nuclear issue is the feasibility of rewelding the pipes. This depends on the accumulated helium production in the pipes. The results of the 3D calculations for the standard cassette were used, taking into account the different locations for the pipe connections in the central diagnostic cassette. The nuclear heating, atomic displacement rate and helium production rate values are 0.6 W/cm^3, 0.14 dpa/FPY, and 4.65 He appm/FPY, respectively. The damage values correspond to an ITER fluence of 1 $MW\text{-}a/m^2$. Since the limit for rewelding is about 1 He appm, the results imply that rewelding will be possible for these coolant connections if the central diagnostic cassette is used in ITER for a fluence of only about 0.2 $MW\text{-}a/m^2$.

The nuclear parameters were also determined for the coolant pipe connections of the dome plasma facing material. They are exposed to a higher level of radiation because of their proximity to the dome front surface that has a full view of the plasma. The nuclear parameters were determined to be 3.23 W/cm^3, 1.4 dpa/FPY, and 15 He appm/FPY. Rewelding for these pipes is not feasible unless the diagnostic cassette is used for a fluence not exceeding 0.06

MW-a/m^2. For a rewelding limit of 1 He appm and assuming that two identical cassettes will be used at each location with each used for an ITER fluence of 0.5 MW-a/m^2, the He production rate is limited to 0.5 He appm/FPY. For rewelding of the coolant pipe connections of the dome block to be feasible, they have to be moved downward about 7 cm from their present location while remaining at the center of the dome block. For the pipe connections of the dome PFC, the helium production rate is excessive and there is no solution for reweldability other than moving these connections to the same location as that for the dome block, if feasible, and routing the coolant vertically through the dome block to the PFC.

4. PEAK NUCLEAR PARAMETERS IN WAVEGUIDES

Waveguides for microwave diagnostics are incorporated in the central diagnostic cassettes at ports 8 and 18. The waveguide panels are attached to both sides of the central diagnostic cassette. There are 8 diagnostic accesses (3 inboard channels and 5 outboard channels) for each waveguide panel as shown in Fig. 3. The waveguide access points are placed very close to the plasma facing surface. The peak nuclear heating and damage in the waveguide panels occur at these access points. An actively cooled CFC armor brazed to a copper heat sink is provided for protection of the waveguides. Both stainless steel and Cu are employed in the waveguides. Hence the nuclear parameters will be provided for both materials.

Since the waveguide panels are attached to the sides of the central diagnostic cassette, the nuclear parameters will be estimated based on the attenuation in the adjacent standard cassette for which detailed 3D calculations were performed. The waveguides at the inner and outer vertical targets will have similar contributions from the adjacent instrumented standard cassette and the central diagnostic cassette since the vertical targets are identical in both cassettes. On the other hand, the two waveguides at the side of the outer plasma facing liner in the central diagnostic cassette are adjacent to the wings of the instrumented standard cassette with smaller material density. The different contributions to nuclear parameters in these waveguides from the adjacent instrumented standard cassette and the central diagnostic cassette are taken into account. Tables 2 and 3 give the peak nuclear heating, atomic displacement rate and helium production rate in the different waveguides. The damage values are after an ITER fluence of 1 MW-a/m^2. Table 2 gives the results for SS and Table 3 includes the results for Cu. The highest heating and damage occur in the top waveguide adjacent to the outer wings of the instrumented standard cassette. The lowest nuclear parameters are in the inboard waveguides. Although the helium production values are relatively high, this should not be of concern since the assembly/disassembly procedure of the waveguides does not consider the welding/rewelding option and a mechanical attachment is being developed.

Table 2. Peak Nuclear Parameters in SS of the Waveguides

Waveguide Location	Nuclear Heating (W/cm^3)	Atomic Displacement (dpa/FPY)	Helium Production (He appm/FPY)
Inner Vertical Target			
Top	0.58	0.23	2.49
Middle	0.52	0.19	2.18
Bottom	0.50	0.16	2.07
Outer Vertical Target			
Top	1.14	0.61	6.71
Middle	0.86	0.43	4.64
Bottom	0.80	0.35	4.30
Outer Plasma Facing Liner			
Top	1.20	0.78	9.05
Bottom	0.98	0.62	6.02

5. NUCLEAR PARAMETERS IN COOLING PIPES FOR WAVEGUIDE PANELS

The water feed/return pipes for the waveguide panels are welded to the cassette body. These pipe connections are at three locations as shown in Fig. 3. These are in the inner cassette leg, outer cassette leg, and central part of the cassette below the dome. The nuclear parameters at these pipe connections can be determined from the profiles generated from the 3D calculations of the standard cassette. Using these profiles is reasonable for the inner and outer legs which are identical in both the standard and diagnostic cassettes. On the other hand, these profiles yield conservative estimates for the pipe connections in the middle part of the central diagnostic cassette which has more material replacing the wings and gas boxes of the adjacent standard cassette. However, the additional shielding provided in the central diagnostic cassette will have a small impact on reducing the nuclear parameters in these pipe connections since they are at the center of the cassette behind the dome. Hence, the nuclear parameter profiles for the standard cassette were used to estimate the parameters in the pipe connections without correction for the additional shielding. This yields slightly conservative estimates. Table 4 gives the nuclear parameters in the pipe connections for the waveguide panels. The nuclear parameters are the highest for the pipe connections in the central part of the cassette which has the largest view of the plasma. Rewelding appears to be feasible for the connections in the inner and outer legs for a fluence of 1 $MW\text{-}a/m^2$. The conservative helium production for the pipe connections in the central part of the cassette indicates that rewelding is possible if the diagnostic cassette is used in ITER for a fluence less than 0.75 MW-a/m^2. In ITER, it is assumed that two identical cassettes will be used consecutively at each location. Hence, each cassette will be used for an ITER fluence of 0.5 MW-a/m^2 and rewelding will be feasible at these pipe connections for the rewelding limit of 1 He appm.

Table 3. Peak Nuclear Parameters in Cu of the Waveguides

Waveguide Location	Nuclear Heating (W/cm^3)	Atomic Displacement (dpa/FPY)	Helium Production (He appm/FPY)
Inner Vertical Target			
Top	0.64	0.25	1.66
Middle	0.57	0.20	1.45
Bottom	0.55	0.17	1.38
Outer Vertical Target			
Top	1.25	0.65	4.47
Middle	0.95	0.46	3.09
Bottom	0.88	0.37	2.87
Outer Plasma Facing Liner			
Top	1.32	0.84	6.05
Bottom	1.08	0.66	5.40

Table 4. Nuclear Parameters in Coolant Pipe Connections of the Waveguide Panels

Location	Nuclear Heating (W/cm^3)	Atomic Displacement (dpa/FPY)	Helium Production (He appm/FPY)
Inner Leg of Cassette	0.09	0.013	0.70
Outer Leg of Cassette	0.11	0.016	0.76
Central Part of Cassette	0.19	0.033	1.30

6. STREAMING THROUGH THE VIEWING SLOTS

Viewing slots are employed at the toroidal center of the central diagnostic cassette for visible monitoring and imaging of the divertor plasma and target using mirror assemblies. There are two inward and two outward viewing slots with a toroidal width of 8 cm. They are connected to the region below the dome where the mirrors are located. Neutron streaming through these slots is a concern since it can affect the damage in the lower part of the vacuum vessel behind the cassette and impact the feasibility of rewelding. Detailed 3D calculations were performed for the standard cassette with the divertor pumping ducts at the bottom. These ducts have a toroidal width of 17.5 cm and a poloidal width of 37.5 cm. The results showed that the hot spots in the vacuum vessel behind these ducts experience nuclear heating, atomic displacement rate, and helium production rate values of 0.027 W/cm^3, 0.008 dpa/FPY and 0.183 He appm/FPY, respectively. The results implied that rewelding of the vacuum vessel is feasible. The impact of streaming was minimized by inclining the pumping ducts towards the outer and inner divertor legs such that the VV behind them does not see any direct source neutrons. Only secondary neutrons scattered from the divertor cassette components and adjacent blanket modules will contribute to streaming. This is the case also for the viewing slots in the central diagnostic cassette.

Streaming in the case of the diagnostic cassette will be reduced because of the smaller toroidal width (8 cm) of the viewing slots compared to that of the pumping ducts (17.5 cm) in the standard cassette. In addition, the wings and gas boxes in the standard cassette are replaced by a full SS structure with thick plasma facing liners. This results in additional shielding and less streaming. The additional effective shielding thickness around the viewing slots is about 30 cm that results in more than an order of magnitude attenuation. The effect of the adjacent standard cassettes on neutron streaming through the viewing slots is minimal since the slots are at the center of the cassette separated toroidally by at least 30 cm of cassette body material from the adjacent cassettes with wings and gas boxes. Furthermore, attenuation in the mirror assembly results in further reduction of the streaming to the VV. Based on this, it is concluded that the damage in the VV due to streaming through the viewing slots is much lower than that resulting from streaming through the pumping ducts in the standard cassette. Hence, the feasibility of rewelding of the VV behind the slots should not be a concern.

7. SHIELDING IMPACT OF CUT-OUT UNDER THE DIAGNOSTIC CASSETTE

The viewing channel under the central diagnostic cassette is 20 cm high and 18 cm wide in the toroidal direction. The concern is that it might result in higher damage in the VV due to the reduced shielding by the cassette body. However, as discussed above replacing the wings and gas boxes of the standard cassette by full SS structure with thick plasma facing liner results in an increase of about 30 cm in the effective shielding thickness. This more than compensates for the lost shielding in the cut-out for the viewing channel under the diagnostic cassette. Hence, damage in the VV behind the central diagnostic cassette will not be higher than that behind the standard cassette and the feasibility of the VV rewelding should not be a concern.

8. STREAMING THROUGH THE GAPS BETWEEN CASSETTES

The nominal toroidal gap between adjacent divertor cassettes is 1 cm. X-point VUV/ visible spectroscopy and X-point LIDAR/visible spectroscopy are allocated to the central diagnostic cassettes at ports 3 and 13. The viewing access of these diagnostics are made through the gaps between the central cassette and the adjacent one with a cut-out on each side of the outer vertical target and outer leg of the central diagnostic cassette. As a result, the nominal gap of 1 cm is increased to ~2.5 cm at the outboard vertical target and increases to ~12 cm at the back of the upper part of the outboard leg. This can lead to increased streaming into the divertor port and enhanced magnet damage and heating.

Detailed 3D calculations were performed for magnet shielding in the divertor region with the standard cassette geometry including the nominal 1 cm toroidal gap. The peak local magnet damage in the part of the TF coils adjacent to the divertor port was found to be lower than the design limits by at least two orders of magnitude. Although this magnet damage is not solely contributed by streaming through the toroidal gaps, one can conservatively assume that the enhancement in magnet damage is related to the increased gap size. The cut-out in the outer vertical target and outer leg of the central cassette could result in at most a factor of 3 higher local damage in the TF coils adjacent to the divertor ports 3 and 13. This increase is much lower than the design margin. Hence, even with the additional streaming, the peak local magnet damage will remain well below the design limit. In addition, the ports were assumed to be empty in the 3D calculations and the additional shielding provided by the diagnostic equipment and coolant pipes located in the port will certainly reduce the impact of streaming on magnet damage.

The contribution to nuclear heating in the TF coils from the divertor ports was also calculated in the 3D calculation using the standard cassette with the nominal 1 cm toroidal gap. The total heating in the TF coil parts in the divertor region was determined to be 2.1 kW for the 20 TF coils. This is contributed mostly by the parts adjacent to the divertor ports. The larger gap due to the cut-out in the diagnostic cassette can lead to at most a factor of 1.5 higher streaming neutrons into the port. This takes into account the larger gap and the fact that the cut-out is employed only in the upper part of the outer leg of the central cassette. If we conservatively neglect the additional attenuation provided by the diagnostic equipment and coolant pipes located in the port, the nuclear heating in the two halves of TF coils surrounding ports 3 and 13 will increase by a factor of 1.5. The remaining TF coils will not be affected. Hence, the increased gap size results conservatively in only a 5% increase in magnet heating in the divertor region. This corresponds to only 0.1 kW.

To keep an attachment space for the waveguide panels attached to the sides of the central diagnostic cassettes at ports 8 and 18, the toroidal gap between the vertical targets of these cassettes and the adjacent cassettes is increased to 3 cm. However, the gap between adjacent cassette bodies remains with the nominal width of 1 cm. Streaming to the divertor port is determined primarily by the width of the gap between the thicker outer legs. As a result, the impact of the larger gap between the outer vertical targets on magnet damage and heating is negligible particularly when the attenuation by the diagnostic equipment and coolant pipes located in the ports is accounted for.

It is concluded that the increased toroidal gaps between the central diagnostic cassettes and the adjacent cassettes due to cut-outs for X-point viewing and for waveguide attachment results in an increase in the local peak magnet damage of less than a factor of 3. Even with the additional streaming the peak local magnet damage will remain well below the design limit. The increase in total magnet heating is conservatively estimated to be less than 0.1 kW in the 20 TF coils. This is very small compared to the 17 kW design limit on total TF coil nuclear heating in ITER. It should be noted that the increased streaming resulting from the larger gaps might be compensated by the added attenuation in the diagnostic equipment and coolant pipes in the ports at the diagnostic cassettes and the net effect could be a lower magnet damage and heating. Information about the material in the port is needed to quantify this effect.

9. NUCLEAR PARAMETERS IN MIRROR ASSEMBLIES

Mirror assemblies are installed at the toroidal center of the central diagnostic cassette. They are located in the middle part of the cassette. One assembly has toroidal and poloidal widths of 15 and 33 cm, respectively, and is located under the dome as shown in Fig. 2. The other assembly in located at the bottom of the cassette with toroidal and poloidal widths of 20 and 50 cm, respectively. Candidate materials for the mirrors at both locations are molybdenum, tungsten and copper. Molybdenum and tungsten exhibit good optical characteristics and low sputtering yield. On the other hand, copper has large thermal conductivity, so that it is easier to conduct heat to the cassette body. Nuclear heating and damage in the candidate materials will be taken into account in the choice of material for the different mirrors.

The nuclear heating and damage rate were calculated for the mirrors at the two locations below the dome and at the bottom of the cassette. The profiles generated from the 3D calculations with the standard cassette were used to conservatively estimate the values in the mirrors. The results are conservative because less shielding is provided by the wings and empty gas boxes in the standard cassette. The additional effective shielding thickness of about 30 cm in the central diagnostic cassette more than compensates for the streaming through the 8 cm wide viewing slots. The 3D results for the standard cassette were obtained for stainless steel structure. The results were therefore modified to include the differences in damage and heating cross sections for the candidate mirror materials relative to SS. The results are given in Table 5. It is clear that damage and heating values in the top mirror assembly below the dome are about an order of magnitude higher than those in the bottom mirror assembly. Nuclear heating is comparable for the three candidate materials with W being slightly higher. Cu experiences the highest radiation damage (helium production and atomic displacement) among the three candidate materials. On the other hand, W, which has about 20% higher nuclear heating than Mo and Cu will experience the lowest damage. Based on these results it appears that tungsten is the preferred candidate from the neutronics point of view.

Table 5. Nuclear Parameters in the Candidate Mirror Materials

Mirror Assembly Location	Nuclear Heating (W/cm^3)	Atomic Displacement (dpa/FPY)	Helium Production (He appm/FPY)
Top Mirror Assembly			
Mo	0.25	0.021	0.277
W	0.29	0.008	0.013
Cu	0.25	0.043	1.140
Bottom Mirror Assembly			
Mo	0.029	0.0023	0.034
W	0.034	0.0009	0.002
Cu	0.029	0.0048	0.141

10. SUMMARY AND CONCLUSIONS

The 3D results of the standard cassette were used along with the geometrical differences in the central diagnostic cassette to determine the nuclear parameters at specified locations and address streaming and neutronics issues. Conservative assumptions were used in scaling the results from the 3D results of the standard cassette.

The nuclear parameters in the attachment keys and coolant pipes for the dome and plasma facing liners of the central diagnostic cassette have been determined. The top attachment keys for the outer plasma facing liners have the highest nuclear heating and damage with 0.85 W/cm^3 and 3.26 He appm/FPY. Rewelding will be possible for the coolant connections of the dome block if the central diagnostic cassette is used in ITER for a fluence of only 0.2 MW-a/m^2. Rewelding for the coolant pipes for the dome PFC is not feasible unless the diagnostic cassette is used for a fluence not exceeding 0.06 MW-a/m^2. Hence, rewelding of the coolant pipe connections for the dome block should be of particular concern and these connections should be placed farther away from the dome surface.

The nuclear parameters in the waveguides and their coolant pipe connections were determined. The highest heating and damage occur in the top waveguide adjacent to the outer wings of the instrumented standard cassette. The lowest nuclear parameters are in the inboard waveguides. Although the helium production values are relatively high, this should not be of concern since the assembly/disassembly procedure of the waveguides does not consider the welding/rewelding option and a mechanical attachment is being developed. The nuclear parameters are the highest for the pipe connections in the central part of the cassette. Rewelding appears to be feasible for the connections in the inner and outer legs for a fluence of 1 MW-a/m^2. Rewelding is possible for the pipe connections in the central part of the cassette if the diagnostic cassette is used in ITER for a fluence less than 0.75 MW-a/m^2. In ITER, it is assumed that two identical cassettes will be used consecutively, at each location. Hence, each cassette will be used for an ITER fluence of 0.5 MW-a/m^2 and rewelding will be feasible at these pipe connections for the rewelding limit of 1 He appm.

The damage in the VV due to streaming through the viewing slots is much lower than that resulting from streaming through the pumping ducts in the standard cassette. Hence, the feasibility of rewelding of the VV behind the slots should not be a concern. Despite the lost shielding in the cut-out for the viewing channel under the diagnostic cassette, the damage in the VV behind the central diagnostic cassette will not be higher than that behind the standard cassette because of the added shielding in place of the wings and gas boxes.

The increased toroidal gaps between the central diagnostic cassettes and the adjacent cassettes due to cut-outs for X-point viewing and for waveguide attachment results in an increase in the local peak magnet damage of less than a factor of 3. The peak magnet damage will remain well below the design limit. The increase in total magnet heating is conservatively estimated to be less than 0.1 kW in the 20 TF coils which is very small compared to the 17 kW design limit on total TF coil nuclear heating in ITER. It should be noted that the increased streaming resulting from the larger gaps might be compensated by the added attenuation by the diagnostic equipment and coolant pipes in the ports at the diagnostic cassettes and the net effect could be a lower magnet damage and heating. Information about the material in the port is needed to quantify this effect.

The nuclear parameters were determined in the candidate mirror materials. These are molybdenum, tungsten and copper. The damage and heating values in the top mirror assembly are about an order of magnitude higher than those in the bottom mirror assembly. Nuclear heating is comparable for the three candidate materials with W being slightly higher. Cu experiences the highest radiation damage among the three candidate materials. On the other hand, W, which has about 20% higher nuclear heating than Mo and Cu will experience the lowest damage. It appears that tungsten is the preferred candidate from the neutronics point of view.

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