Critical Design Factor for Sector Transport Maintenance in DEMO

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Abstract. This paper mainly focuses on a sector transport maintenance scheme from the aspects of high plant availability. This design study clarifies critical design factors and key engineering issues on the maintenance scheme, that is, (1) how to support an enormous turnover force of the toroidal field (TF) coils in the large open port for sector transport and (2) the transferring mechanism of sector in the vacuum vessel. In addition, maintenance scenario under the high decay heat is proposed for the first time.

1. Introduction

Maintenance is a critical issue for fusion DEMO reactor because the design conditions and requirements for DEMO maintenance scheme are different from. ITER chooses an in-vessel maintenance scheme where small blanket modules are replaced in the vacuum vessel using maintenance vehicles [1]. In the view of plant availability, the replacements of a large number of damaged components like in ITER would not be reasonable. In addition, the remote handling devices need to endure high radiation environment in reactor. Concerning the dose rate of gamma ray under the anticipated operation of ITER, it is evaluated 5 kGy/h. In contrast, the maximum contact dose rate on the outboard blanket surface is estimated to be 300 kGy/h in DEMO (SlimCS case: fusion output of 3GW, 2FPY). In this sense, hot cell maintenance based on sector transport [2,3] or multi-module segment (MMS) for PPCS [4,5,6] seems a promising scheme for DEMO and power reactors. Although various maintenance schemes for DEMO have been proposed, in order to decide a most probable DEMO reactor maintenance scheme, definition of assessment factors for DEMO maintenance is important. The sector transport maintenance scheme has advantages to maintain blanket and divertor without the use of sophisticated remote handling devices including undurable devices (i.e. servomotor) to high radiation in the reactor. The remote handling systems are desired to be able to operate longer than maintenance operation. For example, a servomotor is typically durable bellow about 60MGy. Furthermore, replacement components with high decay heat are transported to the hot cell under a limited cooling system. The maintenance scenario considering handling of decay heat is the new research area has never been studied, and would be one of the critical design issues in DEMO maintenance.

This paper describes critical design factors and key engineering issues on the sector transport maintenance scheme considering three different maintenance schemes based on sector transport. In addition, a feasible maintenance scenario option considering handling of decay heat in sector transport maintenance is proposed.
2. Various sector transport maintenance

Several earlier fusion reactor conceptual design studies employed horizontal maintenance for power core components (INTOR \[7,8\], FED \[9\] and DREAM \[10\]). SlimCS designed in JAEA (2006–2011) adopts the sector transport hot cell maintenance scheme taking into account of 1) compatibility with the sector-wide conducting shell, 2) flexibility for access to core components and 3) high availability \[11-13\]. The sector contained in the segment would include the blanket, shield, manifolds and divertor. In the sector maintenance scheme, the number of cutting/re-welding points of piping is minimized. In addition, use of spare sectors minimizes the time required for the maintenance because the most time-consuming processes such as re-welding and its inspection can be carried out in the hot cell during tokamak operation. Considering enormous electromagnetic forces (turnover force, in particular) induced on sector-scale components upon disruptions, each sector is designed to have a poloidal ring structure without mechanical joints. The sector transport maintenance scheme is broken down by the number of maintenance port and the insert direction into 3 patterns; 1) the sector transport using all horizontal maintenance ports (SAH, as shown in FIG.1.(a)), 2) the sector transport using limited number of vertical maintenance ports (FIG.1.(b)): SLV and 3) the sector transport using limited number of horizontal maintenance ports (FIG.1.(c)): SLH.

2.1. Sector transport using all horizontal maintenance ports (SAH)

The Sector transport using All Horizontal maintenance port (SAH) is conventional sector transport maintenance scheme \[13-14\]. For horizontal sector transport, the cryostat has large horizontal ports and the toroidal field (TF) coils are designed to be larger than those for other maintenance schemes. The sector including blanket modules, divertor, high temperature (HT) shield and low temperature (LT) shield was divided into 30° segments (total 12 segments) in toroidal direction, and the weight of the sectors might be around 720 tons. The blanket is segmented into modules with the size of 1.4–2m (toroidal) × 0.5–0.6m (poloidal), and the shield consists of the assembly of HT shield blocks. Since the HT shield is composed of reduced-activation ferritic martensitic steel (RAFM) \[15\] and water in the PWR condition (290–330 °C, 15 MPa), they need to be high pressure proof. Thus the HT shield blocks are made of cast RAFM blocks with pressure-tight cooling channels made by drilling.
2.2. Sector transport using limited number of vertical maintenance ports (SLV)

In Sector transport using Limited number of Vertical maintenance ports (SLV) [16], the sector including blanket modules, divertor and HT shield was divided into 10° segments (total 36 segments) in toroidal direction, and the weight of the sectors might be around 180 tons. The sector size is determined by the vertical maintenance port size. The sectors are removed and inserted through alternate upper vertical maintenance ports (a total of 6 ports), and are transported in a toroidal direction. The blanket is segmented into modules with the size of 1.3m (toroidal) × 0.6 m (poloidal), and the shield consists of the assembly of HT shield plates. Thus the HT shields are made of cast RAFM plate with pressure-tight cooling channels.

2.3. Sector transport using limited number of horizontal maintenance ports (SLH)

In Sector transport using Limited number of Horizontal maintenance ports (SLH), the sector including blanket modules, divertor and HT shield was divided into 30° segments (total 12 segments) in toroidal direction, and the weight of the sectors might be around 530 tons. The blanket is segmented into modules with the same size of SAH. The sectors are removed and inserted through 4 horizontal ports connected with the corridor, and are transported in a toroidal direction.

3. Critical design issues on sector transport maintenances

3.1. Support against turnover force in TF coils

A critical design issue for previous sector transport maintenance (SAH) is how to support an enormous turnover force of the TF coils [17], in that large open ports required for the SAH do not allow one to set up inter-coil structure adopted in ITER [18]. In the case of SlimCS on SAH, since the height of horizontal maintenance port is 12 m, the maximum TF coil deflection is 1.25 m in the toroidal direction. In order to support the turnover force, a support structure with the use of the tension force of shafts with a diameter of 0.8 m and length of 9 m is studied. Since the support shafts are set at the room temperature and used at a cryogenic temperature, the support structure needs to be flexible to the thermal shrinkage. FIG.2 shows the FEM analysis results by ANSYS with support assembly. The maximum TF coil deflection is 0.12 m in toroidal direction, which is lower than that of horizontal sector transport maintenance. To support the resulting tension force of the shafts, two options are considered. The first option is to support the force by the mezzanine floor of the reactor building as illustrated in FIG.3. In the scheme, the supporting shafts pass through the cryostat and are connected to an insert ring which is prevented from turning by a support ring embedded in the mezzanine floor. The cryostat vacuum is maintained by introducing metal bellows seal the pass-thought. However, the feasibility of such a robust building is still questionable. The second option is to support the force by the cryostat. Although the structural strength of the cryostat is ensured by the reinforcement of the wall and the flanges of the maintenance ports, the feasibility of the option may be determined from the point of view of whether or not a torsion of tritium confinement boundary is acceptable in the safety aspect.

In the case of the limited number of maintenance ports, that is, SLV and SLH, the inter-coil structure against turnover force in TF coils could be adopted like in ITER. FIG.4 shows the inter-coil structures used against turnover force acting on TF coils for (a) sector transport using limited number of vertical maintenance ports (SLV) and (b) sector transport using limited number of horizontal maintenance ports (SLH). The inter-coil structures are panel
configurations, and are combined with bolts and key structures on the center of the TF coils. The inter-coil structures are made of stainless steel and are welded to the TF coil case. The vertical sector transport maintenance scheme has the advantage of the support against turnover force in the TF coils, more than the sector transport using all horizontal maintenance ports (SAH). In the case of SLV, the maximum TF coil deflection calculated by ANSYS is 0.09 m in toroidal direction, which is lower than that of SAH (FIG.5). In this sense, the sector transport scheme can support turnover force of the TF coils by reducing the number of maintenance ports.

3.2. Transport of sector

In the sector transport maintenance scheme, heavy sector (> 100ton) should be transferred in high radiation environment. The key design factor is the feasibility of the sector transferring mechanism considering the radiation resistance. For the SAH maintenance, the sectors are transported in single direction (R direction) with a wheeled plat-form, which is inserted under the sector for maintenance. The driving source of sector transport could be arranged in behind the gamma shield. Therefore, the sector transport for the SAH would be technically possible.
On the other hands, the limited number of maintenance ports, that is, the SLV and SLH maintenance schemes require the two direction transferring mechanism of sector in the vacuum vessel. This is key engineering issue on these maintenance schemes in view of high radiation environment. In the case of the SLV maintenance scheme, the 10° sector requires that the center of mass of the sector is lower than the slide rail to avoid turning over as shown in FIG.6. FIG.7 shows the sector transport in a toroidal direction using a movable carriage. The hanging sector is laid out on the sliding table with a movable carriage. When the sectors are transported in the toroidal direction, the weight of the sector is supported on the outer equatorial plane and an upper point. The two slide rails have movable carriages, which have bearings, wheels and three jacks. Therefore, the sectors can slide using a relatively, small amount of power.

FIG. 6. Inter-coil structures in (a) SLH and (b) SLH.

FIG. 7. Sector transport in the toroidal direction by movable carriage.

In the case of the SLH maintenance scheme, the sector size is 30° segments (total 12 segments) in toroidal direction. Therefore, the sector is transferred with the wheeled plat-form illustrated in FIG.8, which is inserted under the sector for maintenance. The wheeled plat-form has 54 roller bearing wheels (maximum load rating of 40 ton/wheel). When the sectors are transported in the toroidal direction, the wheel is turned by the external power supply. The transferring mechanism of sector in the toroidal direction is a rack-and pinion method and back-up of that is a chain method. The driving source of sector transport could be arranged in behind the gamma shield.

FIG. 8. Conceptual view of the wheeled plat-form for the SLH maintenance scheme.
3.3. Comparison between the three sector transport maintenance schemes

TABLE 1 shows a comparison of sector transport using all horizontal maintenance ports (SAH) and the sector transport using limited number of vertical maintenance ports (SLV) and the sector transport using limited number of horizontal maintenance ports (SLH) maintenance scheme. The SAH maintenance adopts a simpler and faster approach in removing fewer large sectors. Therefore, in the viewpoint of hardware required for sector transport, a technology jump from the present seems smaller than SLV and LHT. However, the SAH has a critical design issue of how to support an enormous turnover force of the TF coils. By limiting the number of maintenance ports, the sector transport scheme can setup the inter-coil structure and support turnover force of the TF coils. On the whole, the SLH has the advantage as follows; i) the number of sector is less than SLV, ii) the inter-coil structures could be adopted. In these assessment factors, the sector transport using limited number of horizontal maintenance ports (SLH) maintenance scheme is a more realistic maintenance scheme, and the key engineering issue is the transferring mechanism of sector in the vacuum vessel. Of course, it is necessary to continue such a careful assessment for any other possible maintenance schemes.

<table>
<thead>
<tr>
<th></th>
<th>SAH</th>
<th>SLV</th>
<th>SLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance port</td>
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<td>Limited</td>
<td></td>
</tr>
<tr>
<td>Pull direction</td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Number of sector</td>
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<td>36</td>
<td>12</td>
</tr>
<tr>
<td>Weight of sector</td>
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<td>~200 ton</td>
<td>~500 ton</td>
</tr>
<tr>
<td>Support against T-O force in TF coil</td>
<td>Supported by building or cryostat</td>
<td>Inter-coil structure</td>
<td>Inter-coil structure</td>
</tr>
<tr>
<td>Sector transport</td>
<td>One direction</td>
<td>Two directions</td>
<td>Two directions</td>
</tr>
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4. Maintenance scenario considering handling of decay heat

During the maintenance, all coolant needs to be tentatively removed. Then, how to remove the decay heat during the period is a critical issue to be resolved. In the maintenance scenario, the key assessment factors are the following; (1) cooling system for keeping reactor components at its operation temperature of 550°C under decay heat, (2) tritium removal from reactor components. For the reactor with the fusion power of 3 GW, the total decay heat was as high as 52 MW immediately after the shutdown and 3.1 MW one month later [19]. Although the cool down time defined as the time from the shutdown to the start of maintenance scheme should be short for plant availability, the handling of decay heat should be considered, too. Therefore, the key design factors are the cool down time in reactor and the cooling method in maintenance scheme for keeping components under operation temperature. FIG.9 shows the temperature evolution of outboard blanket, inboard blankets and divertor calculated by one-dimensional heat conduction analysis. The cool down time is one month in which the sector is kept at 40°C. If the transport time of sector exceeds about 40 hours, the temperature of outboard blanket would exceed the maximum allowable temperature of F82H (550°C). This result shows that the sector should be transported to hot cell within 40 hours in the case the cool down time is one month. In the horizontal sector transport maintenance, the maintenance time including removal of cooling piping, drain of cooling water and sector
transport to hot cell is about 32 hours. Furthermore, the tritium release in the sector transport can be suppressed because the components temperature drops by forced-air cooling system.

5. Summary

This paper mainly focuses on a sector transport maintenance scheme from the aspects of high plant availability. The sector transport maintenance scheme has advantages to be short maintenance time and to maintain blanket and divertor without the use of sophisticated remote handling devices including undurable devices to radiation in the reactor. In this study, considering three different maintenance schemes based on (1) the number of maintenance port and (2) the insert direction, the critical design factors and key engineering issues on the sector transport maintenance scheme are clarified. This design study clarifies critical design factors and key engineering issues on the maintenance scheme, that is, (1) how to support an enormous turnover force of the toroidal field (TF) coils in the large open port for sector transport and (2) the transferring mechanism of sector in the vacuum vessel. In these assessment factors, the sector transport using limited number of horizontal maintenance ports (SLH) maintenance scheme is a more realistic maintenance scheme.

In addition, maintenance scenario under the high decay heat is proposed for the first time. In the maintenance scenario, the key assessment factors are the following; (1) cooling system for keeping reactor components at its operation temperature of 550°C under decay heat and (2) tritium removal from reactor components. The key design factors are the cool down time in reactor and the cooling method in maintenance scheme for keeping components under operation temperature. Based on one-dimensional heat conduction analysis, if the transport time of sector exceeds about 40 hours, the temperature of outboard blanket would exceed the maximum allowable temperature of F82H (550°C). This result shows that the sector should be transported to hot cell within 40 hours in the case the cool down time is one month. In the horizontal sector transport maintenance, the maintenance time including removal of cooling piping, drain of cooling water and sector transport to hot cell is about 32 hours. Furthermore, the tritium release in the sector transport can be suppressed because the components temperature drops by forced-air cooling system.

*FIG. 9. Temperature evolution of reactor components in sector transport maintenance.*
Reference


