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Design of the in-wall shielding for the ITER neutral beam port

H.S. Kim[a,*], J.W. Sa[a], B.C. Kim[a], H.J. Ahn[a], J.S. Bak[a], G.W. Yun[b], I.T. Bae[b], H.H. Bae[b], X. Wang[c], C.H. Choi[c], K. Ioki[c]

[a] *National Fusion Research Institute, Yuseong-gu, Daejeon, Republic of Korea*
[b] *Il-Sung Co.: 917 Wonsan-Li, Onsan-Eub, Ulsan, Republic of Korea*
[c] *ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France*

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ABSTRACT

The ITER neutral beam port is composed of connecting duct, port extension and port stub extension. The spaces between inner and outer shells of the port extension and port stub extension are filled with pre-assembled blocks, called in-wall shielding. The main purpose of IWS is to provide neutron shielding for the superconducting magnet, thermal shield and cryostat from the main vessel during plasma operation. In order to provide effective neutron shielding capability with the cooling water, 40 mm thick flat plates (steel type 304B4) are used in almost all areas of the volume between port shells. The IWS is composed of shield plates, upper/lower brackets and bolt/nut/washers. Major activities during design work are to develop installation concept of the IWS blocks for easy assembly into port structures and to perform structural analysis to assess sufficient strength, fabrication feasibility study and 3D modeling including drawing works.

In this paper, major results of mechanical design are introduced. First, the design requirements for IWS and the developed IWS designs for easy assembly into the port structure are introduced. Second, is introduced the engineering analysis results to assess structural integrity. And then the fabrication feasibility study results are presented for major fabrication processes. Lastly, conclusion and future works are mentioned.

1. Introduction

The mechanical design of ITER neutral beam (NB) port in-wall shielding (IWS) is currently being finalized. Total five different designs (A, B, C, D and E) have been developed depending on the port position to satisfy various design requirements. Five designs are inevitable considering various shapes of assembly space where IWS shall be assembled according to NB port position. This paper presents the mechanical design finalization of the ITER NB port IWS.

2. Design development

ITER vacuum vessel (VV) has three NB ports at the equatorial level and all NB port components are double wall box structures cooled by water. Fig. 1 shows section view of the ITER NB port #06 as an example. An IWS is installed in the spaces between the inner and outer shells of the ITER NB port extension (PE) and port stub extension (PSE) to provide neutron shielding during plasma operation [1]. Pre-assembled IWS blocks are assembled into the NB port PE and PSE during port fabrication at port shop, but field joint IWS is assembled after field joint welding at MV shop or IO site.

2.1. Basic design requirements

There are several design requirements for the NB port IWS. The most significant requirement is the IWS shall be able to assemble into the port structure under T-rib condition during port fabrication. This requirement is most critical to the NB port IWS design due to the assembly difficulty by T-rib (as shown in Fig. 2) and complex shape of the port structure. For easy assembly of IWS, the IWS block can be inserted directly into the vertical direction without interfacing with T-rib.

Another significant requirement is all IWS plates have to be placed with poloidal direction to the ITER VV global coordinate system in order to prevent excessive EM load. Other requirement is the space between inner and outer shells of port shall be filled more than 60% with IWS to ensure neutron shielding performance. This filling factor criteria was determined considering VV cooling performance.

The code requirements are also important. RCC-MR 2007 is applied for pressure bearing part. In this code, full penetration welding and 100% volumetric inspection are required for all

* Corresponding author. Tel.: +82 42 719 1135; fax: +82 42 719 1119.
E-mail address: hskim@nfri.re.kr (H.S. Kim).

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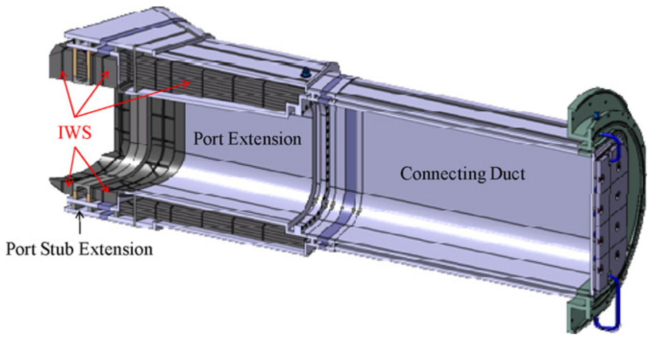


Fig. 1. Section view of the ITER NB port IWS.

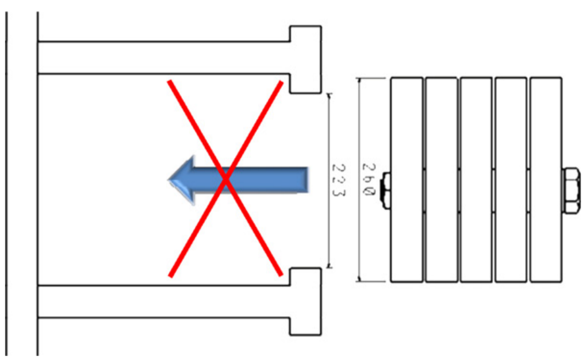


Fig. 2. Assembly difficulty of IWS block under T-rib condition.

permanent welding on pressure bearing part, e.g. port shell [2]. The tab hole on pressure boundary is also prohibited in this code. The NB port IWS itself is considered as not safety important components (not-SIC) and non pressure bearing part in the sense of Nuclear Pressure Equipment Order and French Decree 99-1046 [3]. Therefore, the NB port IWS shall comply with ASME III NC (NG for bolts) in the design and fabrication.

The other critical design constraint condition is actual maximum thickness can be produced is 40 mm for SS304B4 plate. By this thickness limitation of shield plate, the pre-assembled shield plates are used for the IWS block. Finally, total five different designs have been developed which can satisfy the design requirements. Table 1 shows NB port IWS design classification according to NB port position.

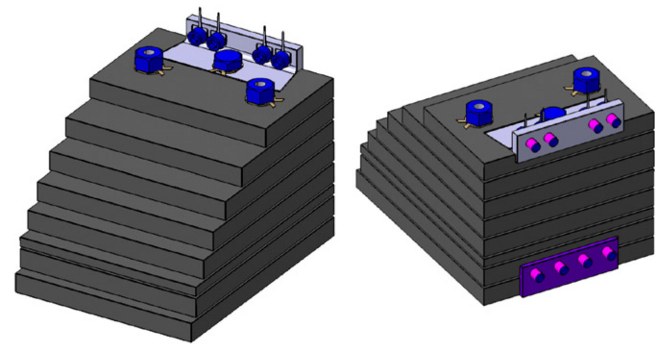
2.2. Design-A for lateral corner of NB port extension

The design-A is for lateral corner area of the NB port PE. In this area, the IWS block can be assembled into the port without any design modification by relatively enough assembly space. Therefore, the design concept is exactly same with MV IWS's.

Fig. 3 shows the typical IWS block of the design-A. Each block consists of 3–10 shield plates according to its position on the port. The pre-assembled IWS blocks are finally installed on the PE lateral

Table 1
Design classification of NB port IWS.

Design type	Location	No. of blocks
Design-A	PE lateral corner	88
Design-B	PE lateral	123
Design-C	PE upper/lower	134
Design-D	PSE Inner space	23
Design-E	Field joint	160
Total		528



(a) Front side (b) Back side

Fig. 3. Typical IWS block of the design-A: (a) Front side; (b) Back side.

rib using upper and lower brackets with M20 bolts during the port fabrication.

2.3. Design-B for lateral area of NB port extension

The design-B has been developed for lateral area of the NB port PE. Basically, design-B has similar configuration with design-A. However, the single plate (SS304B4) has been newly introduced to fill the space under T rib.

Fig. 4 shows the typical IWS block of the design-B and basic assembly scheme. The basic assembly scheme is, firstly the lower bracket is installed on the T-rib using M20 bolts, then single plate is installed on the T-rib using M20 bolts. After that, pre-assembled IWS block is inserted vertically and placed on the lower bracket. The next step is setting of upper bracket and fastening of central M30 bolt, then finally upper bracket is installed using M20 bolts. Through this procedure, the IWS block can be assembled into the NB port.

2.4. Design-C for upper/lower area of NB port extension

The design-C has been developed for upper and lower area of the NB port PE. Fig. 5 shows the typical IWS block of design-C. Design concept is similar with design-B, but the IWS plates are placed with poloidal direction. Six M24 bolts are used for IWS block pre-assembly by plate direction change.

The pre-assembled IWS block is supported by the upper and lower bracket like the design-B. So, assembly scheme is similar with that of the design-B.

2.5. Design-D for inner space of NB port stub extension

The design-D has been developed for inner space of the PSE. In this design, the pad has been newly introduced between the port shell and IWS block in order to comply with RCC-MR 2007. Fig. 6 shows design concept of the platform for IWS installation. Design is similar with the ITER VV ELM-coil support. The platform shall be welded on the port shell before the IWS assembly. Welding shall be full penetration and be inspected 100% volumetric. Manual or auto GTAW (Gas Tungsten Arc Welding) can be used for the welding.

Fig. 7 shows the typical IWS block of the design-D. Six lateral M20 bolts are used for assembly of the IWS block on the platform.

2.6. Design-E for field joint area of NB port

Each NB port has two field joints between (1) MV port stub and PSE, (2) PSE and PE. The IWS at field joint area shall be assembled through the narrow space after field joint welding at the MV shop

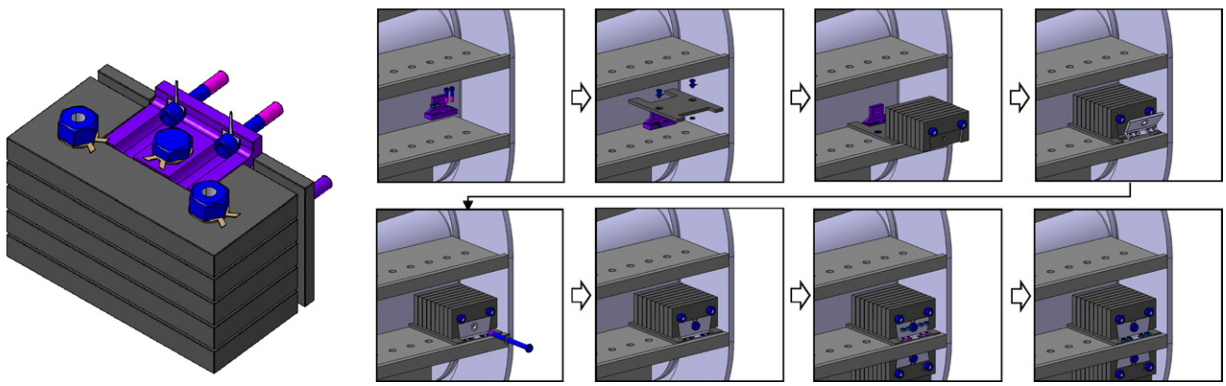


Fig. 4. Typical IWS block and basic assembly scheme of the design-B.

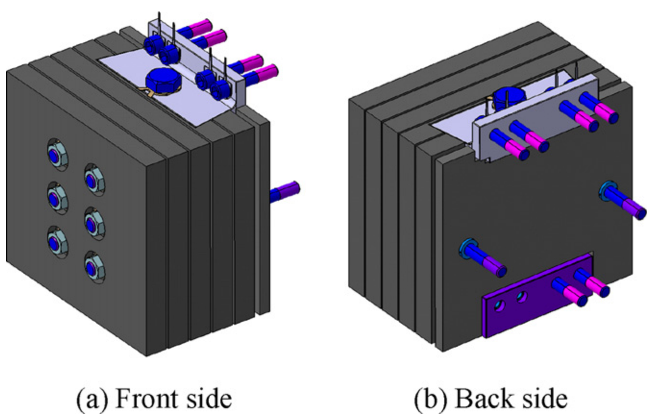


Fig. 5. Typical IWS block of the design-C: (a) Front side; (b) Back side.

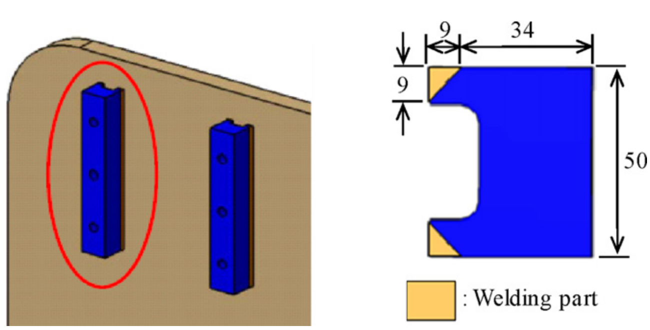


Fig. 6. Design concept of platform for the design-D.

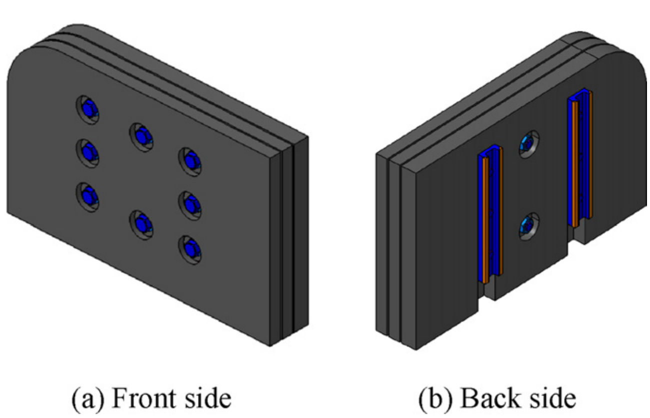


Fig. 7. Typical IWS block of the design-D: (a) Front side; (b) Back side.

or the ITER site. The design-E has been developed considering the assembly after field joint welding.

Fig. 8 shows the typical IWS block of design-E. There are two differences between other NB port IWS designs. The first is single block configuration to avoid high thermal stress by nuclear heating. The second is application of the SS316L(N)-IG as a block material because the SS304B4 can make complex problem in plasma vacuum boundary. Similar to the design-D, the platform has been introduced to avoid bolting on pressure boundary. Design concept of the platform is similar with design-D's. So, the full penetration welding and 100% volumetric inspection are also required.

Fig. 9 shows basic assembly scheme of the field joint IWS. Firstly, platform is welded on the MV shell or PSE shell, then lower bracket is installed on the platform using M20 bolts. After that, IWS block is inserted and placed on the lower bracket. The next step is installation of the upper bracket with M20 bolts, then finally IWS block is fixed by both lower and upper brackets through two M24 bolts. The block at corner area shall be assembled firstly before the assembly of the typical blocks. Especially, thickness of IWS block at corner has been decreased from 160 mm to 125 mm to avoid crash with other platform during assembly. The minimum gap between blocks is 19 mm, respectively.

3. Analysis for structural assessment

3.1. Design criteria and load condition

Structural analysis has been performed to assess the structural integrity of each NB port IWS design. All analysis results are shall be satisfied with ASME III design criteria. For the structural

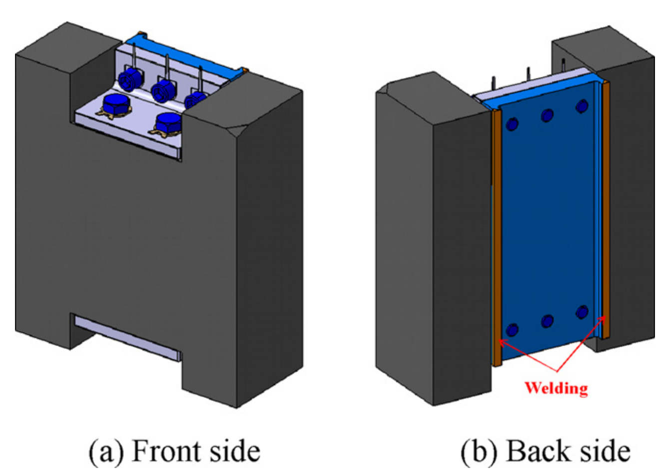


Fig. 8. Typical IWS block of the design-E: (a) Front side; (b) Back side.

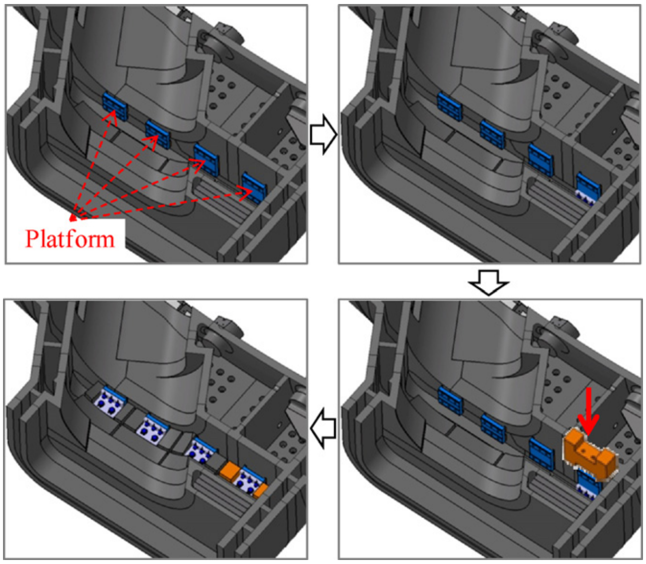


Fig. 9. Basic assembly scheme of the design-E.

Table 2
Load combinations for NB port IWS structural verification.

Category	Load combination	# of events
II	(1) Gravity + VDEII	300
	(2) Baking	500
III	(3) Gravity + SL-1 + VDEII + MFD	1

assessment of the NB port IWS design, 3 load combinations were selected as shown in Table 2 [4,5]. Since the IWS plates are water-cooled in the port shell, uniform temperature (110 °C for normal operation, 200 °C for baking) has been applied during the structural verification [3,5].

The Category II load combinations for NB port IWS analysis are presented in Table 3. For IWS, the considered load combinations are based on the following points: (1) normal operation coolant pressure does not impact IWS, (2) according to estimation based on existing analysis during toroidal/poloidal flux change, the load on IWS due to magnet coil charge (MFD) is relatively small. So, it can be ignored. The influence of MD II to IWS is smaller than VDE II. So for the Category III, just load combination SL-1 + VDE II should be analyzed [4].

Table 3
Category II loads for typical NB port IWS structural verification.

Loads	SL1 + VDE II + MFD		
	Radial	Toroidal	Poloidal
Gravity [m/s^2]		Dead weight	
VV dynamic loads [m/s^2]	5.2	5.8	3.2
EM loads[a]			
Force [N]	14,275	3043	−17,197
Moment [N m]	−4450	1297	−11,436
M30 upper bolt [N]	140	410	−2931
M30 middle bolt [N]	443	603	−4440
M30 lower bolt [N]	38	405	−2908
Pre-loading			
M20 bolt [N]		22,610	
M30 bolt [N]		103,900	
Cooling [°C]		110	

[a] Safety factor 1.5 has been applied considering EM analysis uncertainties.

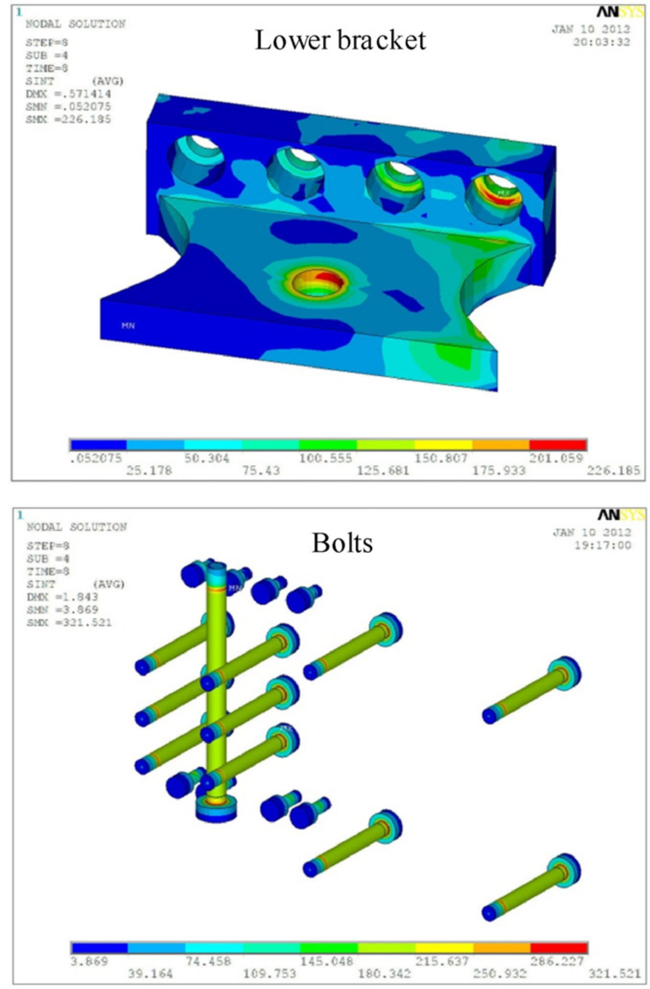


Fig. 10. Stress intensity contours of lower bracket and bolts of design-C under category II load condition.

3.2. Analysis results

Structural analysis results for the NB port IWS components of the design-C under Category II load condition is presented in Fig. 10 and Table 4. Linear elastic stress analyses according to ASMEIII of all 4 components were performed for the load conditions specified in the NB port IWS load specification. All stresses are within the allowable. In the future, the fatigue still need to be verified, but there are no issue to be expected with the structural integrity of the NB port IWS.

Table 4
Evaluation of analysis results of design-C under category II load condition.

Component	Stress intensity [MPa]	Allowable [MPa]
Lower bracket	$P_m = 107.1$[a]	$\le k \cdot S_m = 147$
	$P_L + P_b = 200.7$[a]	$\le 1.5 \cdot k \cdot S_m = 220$
	$P_m + P_b + Q = 226.2$	$\le 3 \cdot S_m = 441$
Upper bracket	$P_m = 79.8$[a]	$\le k \cdot S_m = 147$
	$P_L + P_b = 104.6$[a]	$\le 1.5 \cdot k \cdot S_m = 220$
	$P_m + P_b + Q = 114.3$	$\le 3 \cdot S_m = 441$
IWS plate	$P_m = 87.8$[a]	$\le k \cdot S_m = 129$
	$P_L + P_b = 92.0$[a]	$\le 1.5 \cdot k \cdot S_m = 193$
	$P_m + P_b + Q = 97.0$	$\le 3 \cdot S_m = 387$
Bolts	$P_m + P_b + Q = 321.6$	$\le 1.33 \cdot 0.9 \cdot S_y = 384$

[a] Secondary stress components are included.

Table 5
Major requirements for NB port IWS fabrication.

Process	Requirements
Cutting	- High quality cutting processes shall be applied to minimize cutting damage
Machining	- All machined surfaces shall not exceed Ra 8.3 μm. The other surface of IWS components shall not exceed Ra 12.5 μm
Anti-rotation locking	- All bolts to be fixed by anti-rotation locking to prevent them loosening
Dimension inspection	- At every important manufacturing stage, each component of IWS and each block assembly of IWS shall be dimensionally inspected
Bolt preload	- Preloading is required to be applied for the bolts in the block - M30: 104 kN - M20: 23 kN

Table 6
Materials for NB port-IWS.

Component	Material	Standard
Bracket	SS316L(N)-IG	ITER Grade
IWS plate	SS304B4	UNS S30464
Bolt/nut/washer	SS XM-19	UNS S20910

4. Fabrication feasibility study

4.1. ITER requirements and major fabrication process

There are several ITER requirements related to the fabrication process of the NB port IWS [6]. Table 5 shows NB port IWS requirements for major fabrication process.

Basically the NB port IWS is composed of brackets, IWS plates, bolts/nuts and washers. The major fabrication processes for each components are cutting, machining and anti-rotation locking. Cutting will be performed after material inspection. High quality cutting process shall be selected to minimize cutting damage and distortion. For this, the water jet method will be used for cutting of the shielding plates made of SS304B4. Another method may also be used. If plasma or laser cutting is used, an heat affected zone shall be eliminated. The next major fabrication process is machining. The machining process should not damage the material especially for SS304B4. All machined surfaces are required to have a smooth finish and shall not exceed Ra 8.3 μm. All machining fluids shall be water soluble. After block assembly, all bolts, except the bolts used for IWS assembly in the port shop, are required to be fixed by anti-rotation locking to prevent them loosening during ITER operating. The spot welding will be used as a basic locking method for NB port IWS, but a mechanical method using anti-rotation washer also can be used simultaneously to ensure better performance. In addition, the identification number will be marked on all parts and pre-assembled IWS blocks using low stress marking methods such as low stress stamping or vibro etching. All bolts are preloaded during the block pre-assembly and assembly into the NB port at on-site. Applied preload is 60% of yield strength of bolt material. The required preload will be applied using a torque wrench. The application of the required preload is no issue considering existing tool capacity, sizing and assembly space.

4.2. Material procurement

The major materials for the IWS are SS304B4, SS316L(N)-IG and SS XM-19. Detail standards for each material are shown in Table 6. Each material will be procured in accordance with the specification which approved by IO before material production [6].

4.3. Tolerances

Basic fabrication tolerance of each IWS shielding plate is ±1 mm for poloidal, toroidal and radial direction. And overall preassembly tolerance of the shield block is also ±1 mm for each direction. So, total fabrication tolerance of shield block is ±2 mm for each direction [6]. Detail tolerance study will be carried out for more reliable IWS fabrication and assembly into the NB port.

5. Concluding remarks

Mechanical design of the ITER NB port IWS is presently being finalized by KO DA through Task Agreement with IO. Total 5 different designs have been developed and accepted considering the ITER design requirements and assembly into the NB port. Structural analysis has been performed to assess the structural integrity of each NB port IWS design. The fabrication feasibility study shall be performed more so as to guarantee the fabrication reliability and improve the design maturity.

Design of NB port IWS will be completed early of 2012 and it is planned to make a contract for NB port IWS fabrication on middle of 2012.

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