ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 957–961

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Section 9. Materials for near term devices, facilities and test techniques

Design and fabrication methods of FW/blanket, divertor and vacuum vessel for ITER

K. Ioki *, V. Barabash, A. Cardella, F. Elio, C. Ibbott, G. Janeschitz, G. Johnson, G. Kalinin, N. Miki, M. Onozuka, G. Sannazzaro, R. Tivey, Y. Utin, M. Yamada

ITER JCT Garching, VV & Blanket Division, Boltzmannstraße 2, 85748 Garching, Germany

Abstract

Design has progressed on the vacuum vessel, FW/blanket and Divertor for the Reduced Technical Objective/Reduced Cost (RTO/RC) ITER. The basic functions and structures are the same as for the 1998 ITER design [K. Ioki et al., J. Nucl. Mater. 258–263 (1998) 74]. Design and fabrication methods of the components have been improved to achieve ∼50% reduction of the construction cost. Detailed blanket module designs with flat separable FW panels have been developed to reduce the fabrication cost and the future radioactive waste. Most of the R&D performed so far during the Engineering Design Activities (EDAs) are still applicable. Further cost reduction methods are also being investigated and additional R&D is being performed. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The performance specifications for the Reduced Technical Objective/Reduced Cost (RTO/RC) ITER [2] are as follows: (i) to achieve extended burn in inductive operation with $Q > \sim 10$ not precluding ignition with an inductive burn duration between 300 and 500 s, (ii) to aim at demonstrating steady-state operation using non-inductive current drive with $Q > \sim 5$, (iii) to use as far as possible technical solutions and concepts developed and qualified during the Engineering Design Activity (EDA), (iv) to reach a direct capital cost about 50% of the 1998 ITER design.

2. Vacuum vessel [1–4]

2.1. VV design for RTO/RC ITER

The RTO/RC ITER VV(vacuum vessel) is similar to the earlier VV in basic features such as the structure (double wall), the basic shape (torus) and the material (SS 316L(N)-IG, ITER Grade: 0.06–0.08% nitrogen). However, if the back plate were eliminated, the blanket modules will be supported directly by the VV and the blanket cooling channels would be structurally part of the VV double wall. The inner and outer shells are both 60 mm plates and the stiffening ribs 40 mm plate. The space between the shells will be filled with plates made of SS 304 with 2% boron (SS 30467). The ferromagnetic SS 430 is used to reduce toroidal field ripple effectively even in the 50% lower toroidal field operation envisaged for hydrogen experiments. The RTO/RC ITER VV would be fabricated in the factory as sectors each spanning 40° or 36° instead of sectors each spanning 18°. The larger sector configuration has important advantages from design, fabrication, and assembly standpoints.

2.2. VV fabrication methods

Two concepts have been developed for the vessel sector fabrication scheme. The main feature of the first scheme is that the inner shell is completed as the first step because the inner shell is the most important component. Butt welds are fully used on the inner shell, and inspections can be easily performed. After all ribs are welded to the inner shell and shielding plates are installed, the outer shell is welded. In the second scheme

---

* Corresponding author. Tel.: +49-89 3299 4428; fax: +49-89 3299 4422.

E-mail addresses: iokik@itereu.de, iokik@ipp.mpg.de (K. Ioki).

0022-3115/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(00)00165-3

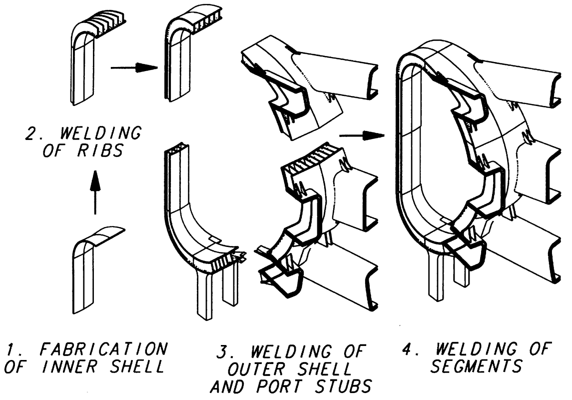

Fig. 1. VV fabrication scheme (Option 2).

(Fig. 1), poloidal segments of a double wall structure are fabricated first. This scheme was used for the full-scale vessel sector fabrication in the L-3 R&D project [5]. The following requirements of the vessel are of particular importance during the fabrication phase. To assure structural integrity, the vessel will be designed and constructed to the ITER VV code which is based on the ASME Code Section VIII (Div. 2). The leak rate of the plasma side surface for each 36° sector must be $<1\times10^{-9}$ Pa m^3/s. The fabrication tolerance of the sector height and width will be ±20 mm, which is consistent with the L-3 R&D performance. The sector reference points will be defined so that surface tolerances will be ±10 mm.

2.3. Cost reduction approaches

To reduce the VV fabrication cost, the employment of forged and/or cast structures has been investigated. The bottom of the VV (as shown in Fig. 2(a)) is a highly-stressed region, requiring numerous reinforcements. Instead of a shell-welded structure, a forged structure would be a workable solution to reduce the fabrication cost and improve the fabrication tolerances. The bottom of the VV with 1 m × 1 m × 2 m and the vertical leg with 3 m length are assumed to be fabricated by forging, then welded together. The structures of the ribs and cooling channels are formed by machining. A preliminary comparison of the fabrication cost between the forged structure and the all-welded structure shows a cost benefit for the forged structure. Feasibility of a concept without the back plate has also been investigated. In this case, the vessel requires 1564 blanket support housings (see Fig. 2(b)) to be welded in place, which represents 20% of the total vessel welding. Precision casting or forging of the housings would be a more cost-effective solution. The maximum weight for the precision casting would be limited to be ~100 kg. Although sand-casting is an attractive method for larger structures, the material properties of sand-cast structures are generally not satisfactory and additional machining will be needed to achieve the required tolerances and surface finish. In addition, the lower strength of weld joints for cast stainless steel than for the base metal will be a structural problem for the VV. The fabrication cost of the precision-cast structure and the forged structure has been evaluated, and both of them look cost-effective.

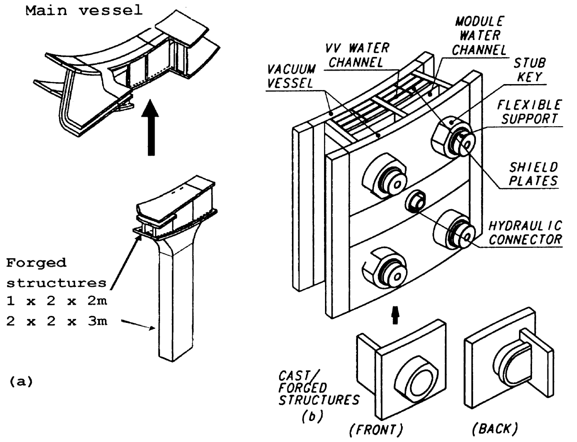

Fig. 2. Alternate VV fabrication methods.

3. FW/blanket [1,2,6,7]

3.1. FW/blanket design for RTO/RC ITER

The basic concept of the FW/blanket system has also stayed the same as that for the 1998 ITER design maintaining a modular configuration with a mechanical attachment system. The most important changes result from efforts to reach a 50% cost reduction: (i) A reduction in the inlet coolant temperature of the blanket and divertor system from 140°C to 100°C is based on a reassessment of the irradiated mechanical properties of the Cu alloys used for the PFC heat sinks. This reduction has potential safety and cost advantages. The lower inlet temperature will also minimise the vessel thermal stress due to the rapid blanket inlet temperature drop that results when a heat exchanger control valve fails to close. (ii) The back plate could be eliminated completely and its previous functions could be transferred to the vessel. (iii) In a later phase it is planned that the shielding blanket is converted to the breeding blanket partially (outboard region only).

The RTO/RC ITER blanket module design has been improved from that of the 1998 ITER design: (a) to reduce the module unit manufacturing cost, (b) to reduce the nuclear waste associated with module replacement, (c) to reduce EM loads on blanket modules due to disruptions/VDEs. The new module configuration now consists of a shield body to which a separable first wall is mounted. The separable first wall has a facet geometry consisting of multiple flat panels, where 3-D machining will not be required. The application of multiple flat panels for the FW simplifies the unit design and reduces the associated machining costs. Several FW panels can be produced in each HIP cycle. The use of smaller separate FW panels will reduce considerably the scrap rate. The separation of the shield body allows the application of less expensive manufacturing processes, and solid HIP will be used only for the FW panel fabrication. The use of multiple panels also makes possible the replacement of individual damaged units reducing nuclear waste volume, and simplifies the repair and replacement methods. A deeply slitted configuration minimises the induced eddy currents and EM loads. The new module design has two options: Option A and B, as described below.

3.2. Option A blanket module

This module (Fig. 3) consists of six separable FW panels attached to the shield block using a system of M12 bolts and small shear ribs, to support EM loads and to prevent sliding due to thermal expansion. For the first wall panel fabrication, SS tubing is wound around a grooved core, and they are embedded between an SS and a DS copper grooved plate (see Fig. 4). A single step solid HIP (possibly also powder HIP) at 1050°C and $>\sim 100$ MPa is envisaged to bond the Cu and SS parts. The plasma facing Be layer will be joined by a further HIP process at lower temperature.

The radial flow of the coolant allows the production of the shield part in two halves about 200 mm thick, which can be made from rolled plates rather than forged. The cylindrical or conical shape is obtained by cold bending followed by a stress relieving heat treatment to ensure dimensional stability. The rough body is then machined and drilled. The half blocks are completed with plates holding cooling passages. They are stacked together and are welded in the internal poloidal ribs. The sealing is accomplished by 25 mm welds around the perimeter. The 30 mm front access holes are butt welded with a torch entering the bore. The external welds are then UT inspected and leak tested. Alternative fabrication methods by casting and powder HIPing are also under assessment. The open shape of the front and back halves is suited for a production by casting. One issue of concern is the stress corrosion resistance, particularly for the welds.

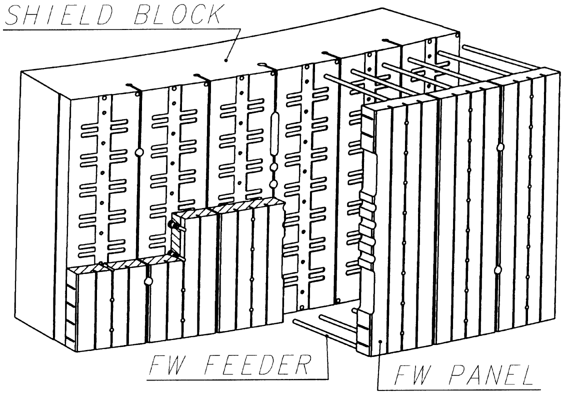

Fig. 3. Blanket module design (Option A).

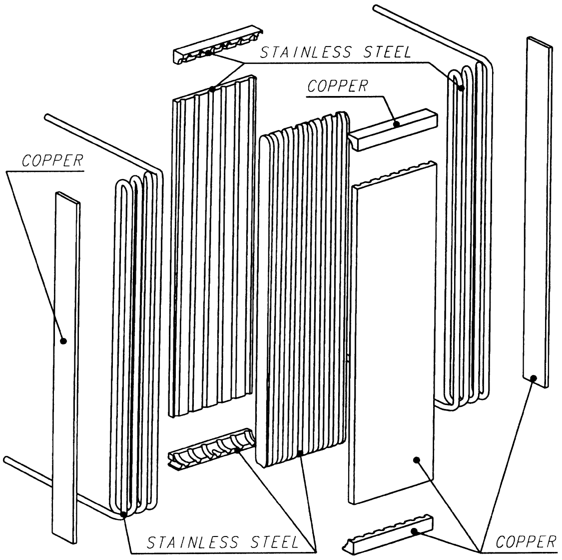

Fig. 4. FW fabrication method (Option A).

3.3. Option B blanket module

This blanket module consists of four separable FW panels mounted with a central mechanical attachment which is bolted to a shield block at its rear side (Fig. 5). The FW panel is manufactured using solid HIP, the shield block is made from flat forged blocks and the coolant channels are produced simply by drilling and plugging. The manufacturing procedure for the first wall is schematically shown in Fig. 6. The Cu-alloy and SS plates are machined to produce: (a) a foot for attaching the supporting beam in the SS panel, (b) semi-circular grooves for inserting SS cooling tubes in the Cu-alloy plate, and (c) coolant headers. The FW assembled parts are joined by one step solid HIP ($T = 980$–$1050°C$, $p = \sim 150$ MPa, $t = \sim 2$ h). The cooling channels for the SS plate, the intermediate collectors and the supporting beam are made by drilling. Based on earlier EDA R&D, HIP using a Ti interlayer is a prime candidate for joining the Be armour to the Cu-alloy heat sink. The supporting

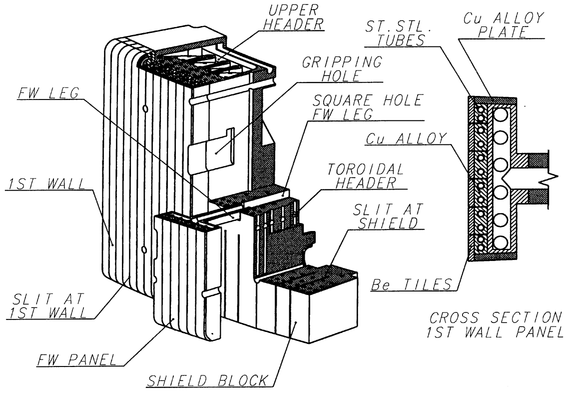

Fig. 5. Blanket module design (Option B).

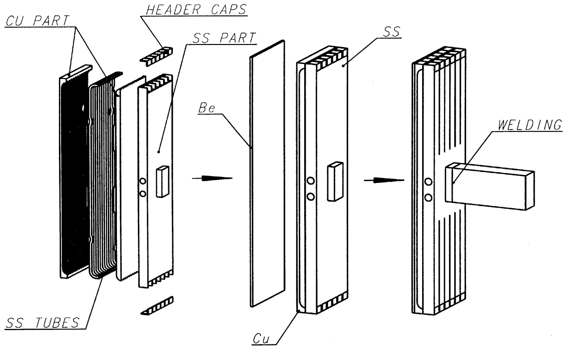

Fig. 6. FW fabrication method (Option B).

beam and the header closure caps are attached by welding.

The manufacturing of the shield part is basically made by drilling and milling. The manufacturing steps will: (i) produce four separated forged blocks, (ii) drill the cooling channels inside the blocks and produce the front access penetrations and the intermediate toroidal collectors, (iii) EB weld the four blocks together, (iv) mill cut-outs for the keys and machine the flexible holes, (v) mill main groove for branch pipes and make the hole for the centre pin, (vi) cut the additional poloidal slots in the shield block, (vii) mill upper and lower headers, (viii) weld closure plates, (ix) assemble the first wall panels on the shield and weld the hydraulic connections to the respective inlet/outlet headers. Powder HIPing can also be used as a fabrication method of the shield part.

3.4. Cost estimation and further cost reduction approaches

Preliminary cost estimations have been performed by industry, and the estimated reduction in the unit blanket module cost comparing with the 1998 ITER design is ~29% and ~43% for Option A and B, respectively. An additional substantial cost reduction for the FW can be obtained by the selection of CuCrZr instead of DS-Cu. The use of alternative Be/Cu-alloy joining techniques such as brazing or diffusion bonding could also result in cost saving, if the feasibility of these techniques is demonstrated by an appropriate R&D programme. Another cost reduction approach is to use larger contact surface roughness for solid HIPing of the FW panel. The feasibility of using powder HIP for the FW has not been proven yet, and the achievement of required tolerances is still a concern.

4. Divertor PFC and cassette body [1,8]

The implications on the divertor of the RTO/RC ITER design were assessed and it was concluded that it is feasible to incorporate a similar divertor (Fig. 7) to that in the 1998 ITER design, while still maintaining similar heat flux on the Plasma Facing Components (PFCs). Efforts are aimed at developing PFCs with fewer component pieces, as well as simpler geometry and manufacturing processes to reduce the cost. The increase in the coolant sub-cooling due to the lower inlet temperature allows the use of a lower coolant velocity while maintaining sufficient margin to the Critical Heat Flux limit. This brings cost savings, since a single heat transfer system can be employed to serve the entire divertor. Furthermore, a preliminary assessment of the CuCrZr heat sink predicts an improvement in lifetime for the lower coolant inlet temperature.

4.1. Cassette body fabrication methods

The cassette body will be fabricated from 316L(N) IG casting, HIPed casting, powder HIPing, or forged plates and the selection will be made on the basis of R&D. For the HIPing options, the maximum size of existing HIP facilities, would require the cassettes to be

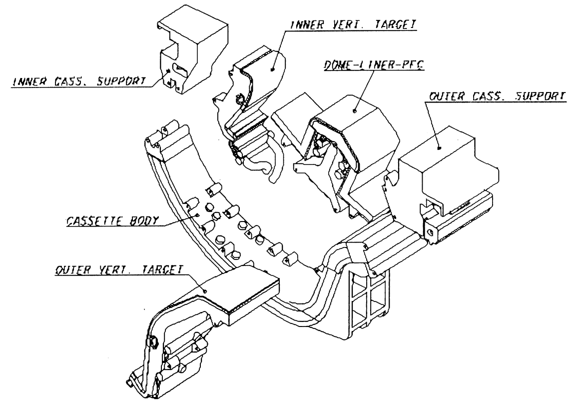

Fig. 7. Divertor structure.

fabricated from eight pieces. However, R&D has demonstrated that unHIP-ed casting will be acceptable, which allows cost saving to be made by fabricating the cassettes from two toroidal slices. Each slice is machined to create the coolant channels and the channels which are closed out by welding cover plates. The two slices are welded together along their perimeters to form the cassette body. Interrupted welds of about 100 mm deep sustain the mechanical loads during operation. The assembled cassette body will be stress relieved prior to machining the close tolerance attachment locations for the PFCs, and the attachment points for the support shoes.

4.2. Vertical target fabrication

Each vertical target is based on a number of thin elements, ~23 mm wide. The reference design is being adapted for a CuCrZr heat sink which necessitates changes in the manufacturing process. A joining method has been developed for the monoblock which uses the precipitation hardening cycle of the CuCrZr to maintain good mechanical properties of the Cu alloy by avoiding over-aging. The new process based on HIPing is carried out at ~500°C whereas the braze joining was performed at ~900°C. It was observed that the CHF limit of a CfC armoured monoblock was ~20% below that predicted from testing with all Cu mock-ups and was attributed to poor contact between the swirl tape and the inner wall of the Cu tube and/or circumferential cracking in the CfC. In both cases the lower temperature joining process is expected to improve the situation. High temperature joining of the armour to the Cu heat sink can be improved by fast brazing (~880°C). Approximately 80% of the mechanical properties of the CuCrZr have been measured on joints fabricated using this method [9].

In addition, the reduction in the coolant inlet temperature from 140°C to 100°C could allow the use of wider CfC monoblocks, which means fewer parts, hence lower costs. An annular flow concept with larger tubes is also being investigated, and this offers the twin advantages of having fewer components and simplified manifolding. Flat tile designs have advantages in possible cheaper construction and ease of more extensive NDE. Cascade failure is a possible concern on flat tile designs, and is being investigated analytically and experimentally. Also as a part of the flat tile investigation the hypervapotron is being considered, where it has superior thermal-hydraulic performance.

5. Conclusions

1. The applicability of alternative fabrication methods for parts of the VV has been investigated for cost saving. The employment of forged structures will be cost beneficial without causing additional issues. Other methods such as casting or powder HIP are being further investigated.
2. Design improvements for the blanket modules have been pursued using separable FW concepts (faceted geometry). The concepts result in considerable cost reductions compared to the 1998 ITER design. Further cost reductions proposed are: (i) use of CuCrZr instead of DS Cu, (ii) Be joining to Cu-alloy by brazing instead of solid HIPing, (iii) powder HIPed FW panels, (iv) casting instead of forged drilling or powder HIPing for the shield block manufacturing.
3. The reduced coolant inlet temperature achieves a cost saving for the divertor PHTS and increases the fatigue lifetime of the PFCs. Further improvements proposed for the divertor PFCs are: (i) low teemperature HIPing (~500°C) instead of brazing (~900°C) for CfC-CuCrZr joining, (ii) the annular flow concept with larger coolant tubes, (iii) flat CfC tile designs (including cascade failure analysis).

References

[1] K. Ioki et al., J. Nucl. Mater. 258–263 (1998) 74.
[2] K. Ioki et al., FW/Blanket and Vacuum Vessel for RTO/RC ITER, ISFNT-5, Rome, 1999.
[3] M. Onozuka et al., Design and Analysis of the Vacuum Vessel for RTO/RC ITER, ISFNT-5, Rome, 1999.
[4] K. Ioki et al., in: Proceedings of the 20th SOFT, Marseille, September 1998, p. 1393.
[5] K. Koizumi et al., IAEA-CN-64/FP-6, 1996.
[6] K. Ioki et al., Fusion Eng. Des. 39&40 (1998) 585.
[7] F. Elio et al., Engineering design of the ITER blanket and relevant R&D results, FED 46 (1999) 207.
[8] R. Tivey et al., ITER Divertor, Issues and R&D, FED 46 (1999) 159.
[9] I. Mazul, private communication.