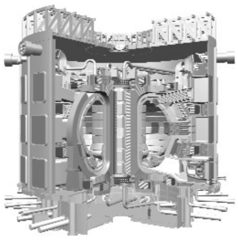

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FUSION PROGRAMME OF THE REPUBLIC OF KOREA

by Dr. Jung-Hoon Han, Head, International Cooperation Unit, National Fusion R&D Center, Korea Basic Science Institute

Introduction. After a period of small-scale basic plasma experiments in university laboratories in the 1970s and 1980s, the Korean fusion programme initiated the KSTAR (Korea Superconducting Tokamak Advanced Research) project with a substantial investment. Prior to this there had been a period of testing of plasma experimental devices that were of relatively large-scale compared with the previous device, HANBIT, a linear mirror machine, constructed and operated by the governmental research institute.

The goal of the Korean fusion programme is to contribute to world fusion energy development through participation as a full partner in the joint implementation of the ITER Project including the provision of useful technical information, via KSTAR, for ITER operation and to join the future foreseen world fusion energy development path, including projects such as DEMO and PROTO.

KSTAR Project. As a core part of the Korean fusion programme the KSTAR project was launched in December 1995. The mission of the project is to develop a fully superconducting tokamak of a medium size (Fig. 1) similar to ASDEX-U in Germany and DIII-D in the United States of America, which are D-shaped

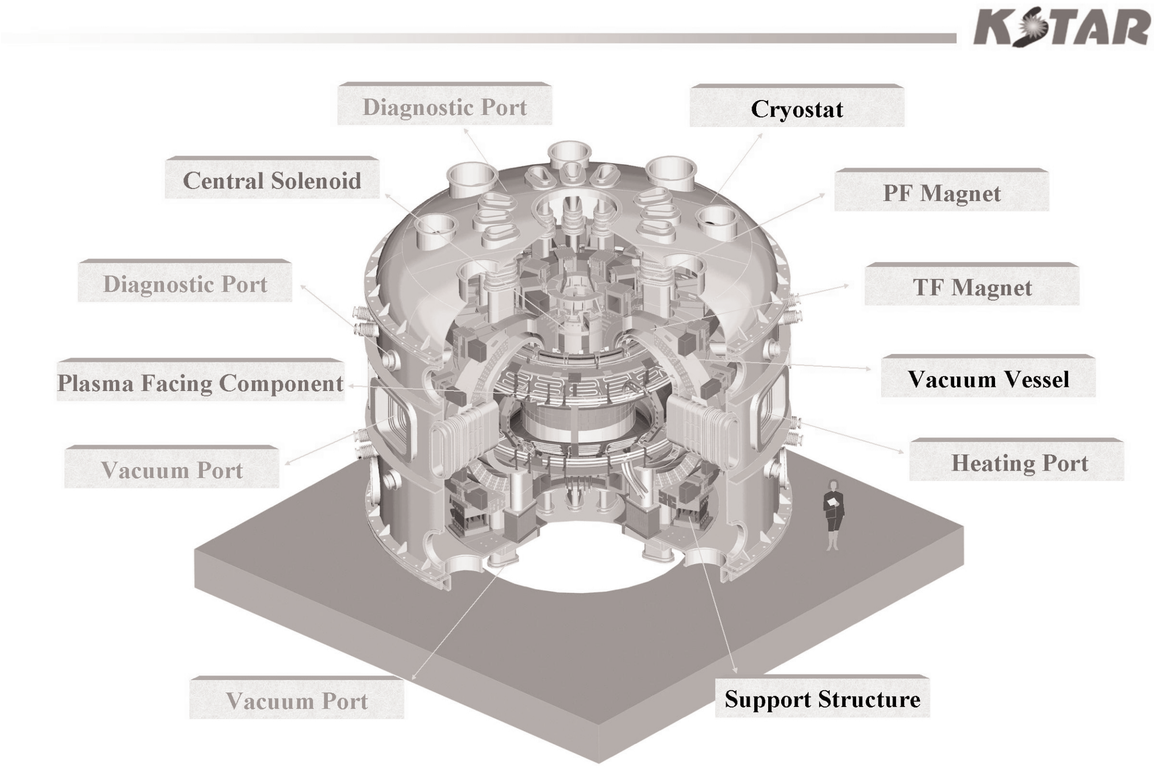


Figure 1

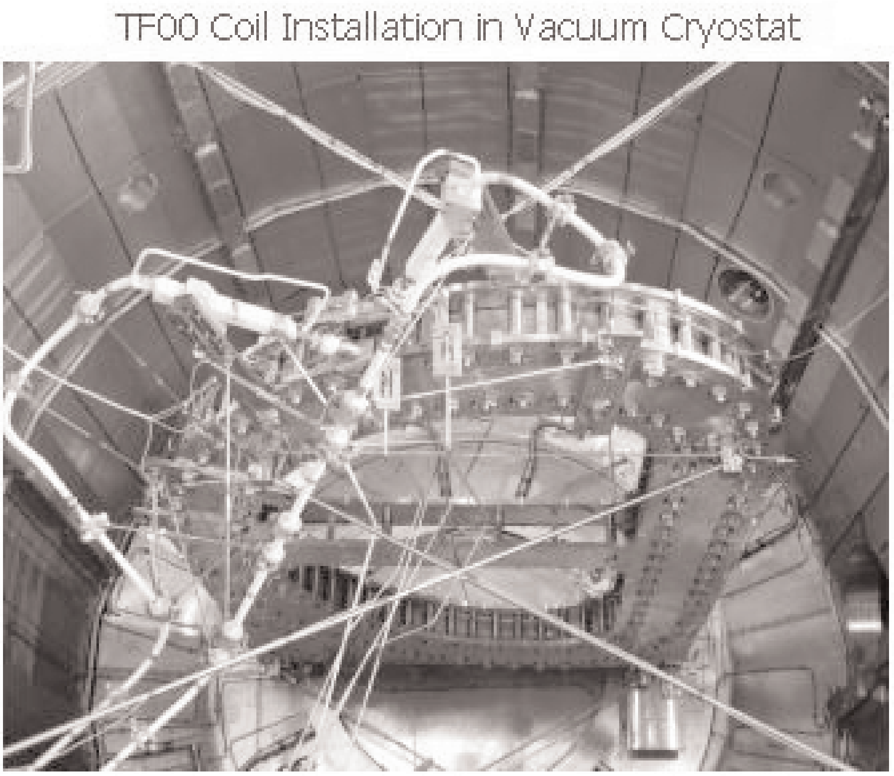


Figure 2

poloidal divertor tokamaks equipped with normal copper magnets. KSTAR could produce D-shaped single null to double null plasmas with its poloidal divertor and would have a capability for steady state operation from 20 seconds up to 300 seconds thanks to its fully superconducting magnet system.

The KSTAR magnet system consists of 16 Nb_3Sn DC TF magnets, 10 Nb_3Sn AC PF magnets and 4 NbTi AC PF magnets. Along with the magnet system development, KSTAR requires intensive R&D efforts on its in-vessel and plasma facing components for long-pulse operation.

Korea expects to participate to the ITER construction providing, like other partners, a significant number of components contributed in kind, and then to participate fully in the following operation phase. KSTAR would be expected to serve as a useful pilot experimental device for ITER operation owing to its long pulse D-shaped plasma characteristics and the modest operation cost of a medium sized tokamak. Its 4 – 5 years of high power long pulse operation prior to ITER operation might provide useful technical information and data for ITER operation.

At present, prototype TF and PF magnet testing (Fig. 2) and the fabrication of other torus components (Fig. 3) and in-vessel components are proceeding in parallel with engineering R&D on other components such as the in-vessel control coil system and plasma facing components. Engineering R&D and procurement of the thermal shield and cryogenic system are also being carried out in parallel.

Foreseen Activities and International Cooperation. After joining the ITER Negotiations in June 2003, the Korean fusion programme is in a transitional period of shifting from basic science to atomic energy development. The Korean nuclear energy sector, which brought about the present Korean nuclear energy development, supplying 40% of Korea's electricity, has been mobilized and is in a process of reorganizing part of its R&D infrastructure for ITER development. Besides this partial reorganization it is also preparing a dedicated unit for ITER.

KSTAR would be utilized as an ITER satellite tokamak like other existing and to-be-constructed tokamaks. International cooperation with the ITER Parties on ITER is a natural and logical step to facilitate this. Joint

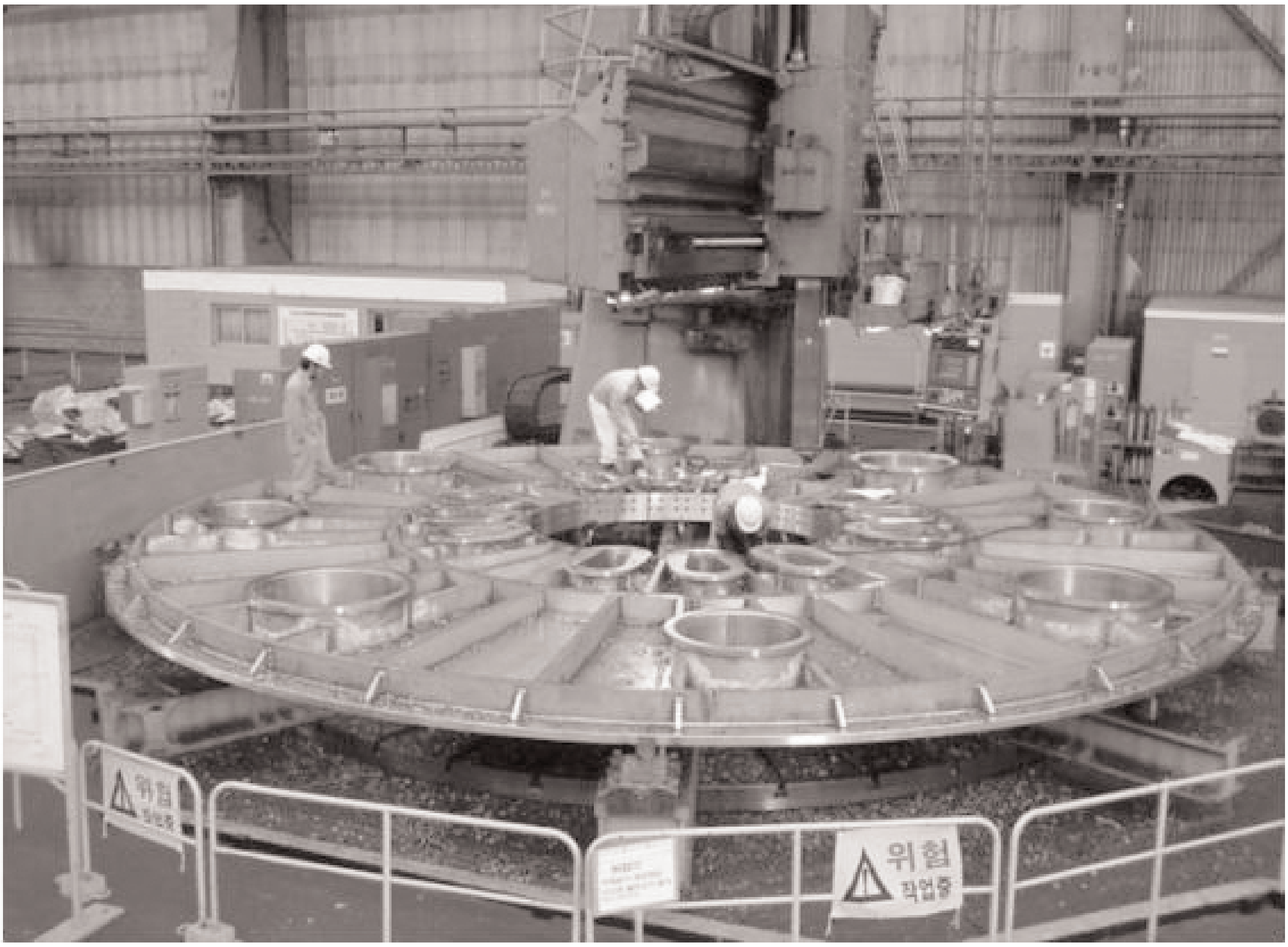


Figure 3

utilization of KSTAR and co-development of its future upgrade would be implemented through international cooperation.

The establishment of both governmental and institutional bilateral collaboration schemes is in progress or has already been completed. Also, Korea has joined multilateral cooperation schemes such as the IEA ASDEX Implementing Agreement (IA) and plans to participate in IEA fusion materials and technology IAs.

The Korean fusion programme, based on its KSTAR project and a programme of other complementary fusion technology R&D, will actively participate in the future reactor technology programme and related experiments via close cooperation with the ITER Parties. To support these activities from the Korean side, its strong domestic nuclear programme would be gradually reoriented towards fusion reactor development.

ROGRESS IN ITER VACUUM VESSEL DESIGN AND PROCUREMENT PREPARATION

Dr. K. Ioki, Division Head, Vacuum Vessel and Blanket Division, ITER Garching JWS

The ITER vacuum vessel (VV) will provide the primary confinement boundary surrounding the plasma and all plasma-facing components. It is a very large structure which must withstand high electromagnetic loads during plasma disruptions and vertical displacement events (VDEs). It will normally be operated under ultra-high vacuum (10^{-10} atmoshpheres for hydrogen) but under accident conditions must withstand an internal pressure of 2 atmospheres.

Although by the middle of 2001 the design had been developed in sufficient detail to obtain a good estimate of the cost, since the middle of 2001 work on the ITER VV has focused on design improvements leading to increased confidence in the cost, on preparation of the procurement specifications (the manufacturing of the vessel needs to begin as soon as the construction licence is issued), and on the R&D necessary to underpin the manufacturing and assembly processes.

Vacuum Vessel Design

The vacuum vessel (see Table 1) has a double-walled structure, a toroidal shape, and is predominantly made from 316L(N)-IG (ITER Grade) stainless steel. The inner and outer shells are made from thick plates. Stiffening ribs run between them in both poloidal and toroidal directions. Support housings for the blanket module flexible attachments also link the shells and provide stiffening. These support housings also function as part of the first confinement boundary. They connect inner and outer shells, and additional ribs are used for reinforcement. The number of continuous poloidal ribs is minimized to reduce the vessel fabrication cost. The VV would be fabricated in the factory as 9 sectors each spanning 40° (see Fig. 1). This large sector configuration has advantages with respect to design, fabrication and assembly. Blanket cooling manifolds and supports for the divertor will be mounted on the plasma-side surface of the VV inner wall.

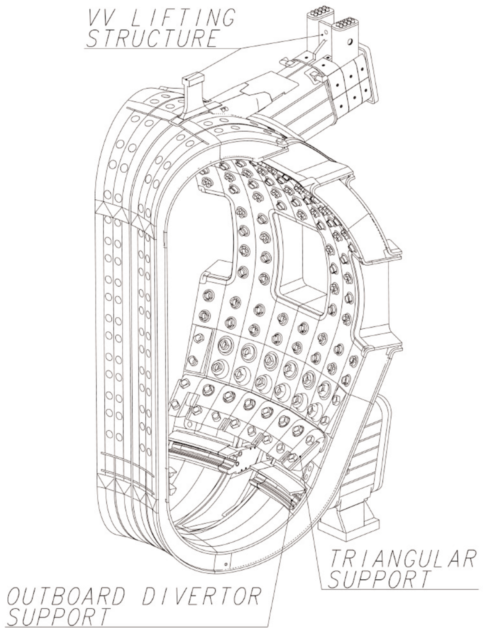
Table 1. Vacuum Vessel Parameters

Torus height/OD	11.3 m/19.4 m
Total double wall thickness	0.34 m – 0.75 m
Number of sectors	9 (40° sector)
Shell/rib thickness	60/40 mm
Toroidal/poloidal resistance	8.8/3.8 μΩ
Interior surface area	943 m^2
Total mass (without water)	6500 t
Heat load	10 MW
Coolant inlet temperature	100 °C
Coolant inlet pressure	1.1 MPa
Total coolant mass flow rate	950 kg/s

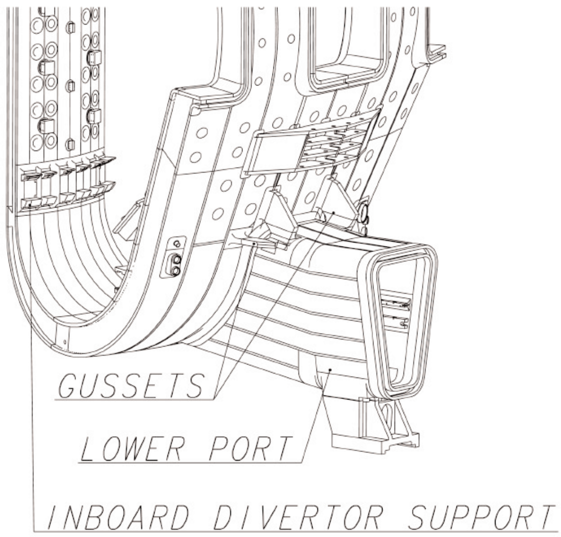
While the space between the shells will be filled with plates made of SS 304 with 2 % boron (SS 30467), those located under the TF coils are made of ferromagnetic SS 430 to reduce toroidal field ripple. These shielding plates are installed at the factory before shipment to the site.

Although the main concept of the VV envisages a double wall structure, a single wall structure is feasible in some regions (for components near to the cryostat) and is a simpler solution in VV port extensions in particular where the blanket cooling system penetrates. Detailed design of the upper port (see Fig. 2) has progressed to take into account the fabrication method and the assembly. The locations of the upper port field joints and the layout of the connecting cooling pipes have been optimized considering the welding distortion during the port assembly and the assembly schedule of the blanket cooling pipes.

Fabrication of the sector must be to a height and width tolerance of ±20 mm, which is consistent with the capability demonstrated in the Vessel Sector Large R&D Project in 1998 (see below). The sector reference points will be defined so that surface tolerances will be ±10 mm. The inner shell is fabricated as the first step as it is the most important for confinement. Butt welds are used on the inner shell, and inspections can be performed easily. Most weld joints will be radiographically inspected to assure 100% weld efficiency. Electron beam welding will be used for joints between the inner shell and the blanket keys or housings for flexible supports (see Fig. 3). These welds will be code/standard qualified. However, the one-sided weld joints between the outer shell and the ribs/housings, and the field joints, cannot be radiographically inspected and so will be inspected by ultrasonic testing (UT), by “progress LPT (liquid penetrant dye test)”, or by photothermal camera, and a “code case” will be justified by testing. The current approach is to minimize required code cases. The layout of welds on the inner and outer shells is very tight considering accessibility for welding and non-destructive examination requirements defined in the design codes.



(a) 40º sector



(b) Lower half of 40º sector

Fig. 1. The ITER Vacuum Vessel

The inboard triangular support has been eliminated, which simplifies the VV structure and reduces the electromagnetic loads on blanket modules. The outboard triangular support (see Fig. 1) plays an important role in the plasma vertical stability control during minor disruptions, and its position and configuration have been optimized based on plasma vertical stability analysis. A detailed design has been developed taking account of the fabrication method and the structural integrity.

Integration of the divertor rail supports into the VV inner shell reduces the support's cross-section and promises to simplify its manufacture. More space then becomes available at the field joint area to allow access for UT inspection tools. The volume in the interspace between the inner and outer shells in field joint regions is now fully isolated to permit independent leak detection during VV assembly.

The upper port design has been improved to avoid large chamfers at the connection with the main vessel. Access for the VV thermal shield assembly, fabricability of the port stubs and plasma vertical stability are all improved. Additional structures for lifting during the assembly have been designed at two locations in the upper region of the vessel, as shown in Fig. 1.

Forces on the vessel support system are now transmitted directly to the cryostat and the building via the lower ports, rather than through the magnet system. This gives more margin in the structural performance and better access for assembly and maintenance, because more space is available under the lower ports. The number of lower ports has also been halved, providing only those needed for remote maintenance (3), torus pumping (4) and diagnostics (2). Feedthroughs for divertor cooling are, however, provided on all segments. The vessel structure in its gravity support region is highly stressed, and horizontal and vertical gussets (100 mm thick) reinforcing the lower port stub region (see Fig. 1) have been optimized based on analysis under gravity, seismic and VDE downward loads.

The use of forged structures is being considered for the port stub areas and penetrations for cooling pipes and the in-vessel viewing system, instead of a shell-welded structure. If workable, this solution would cut costs and raise reliability, as well as improving the tolerances.

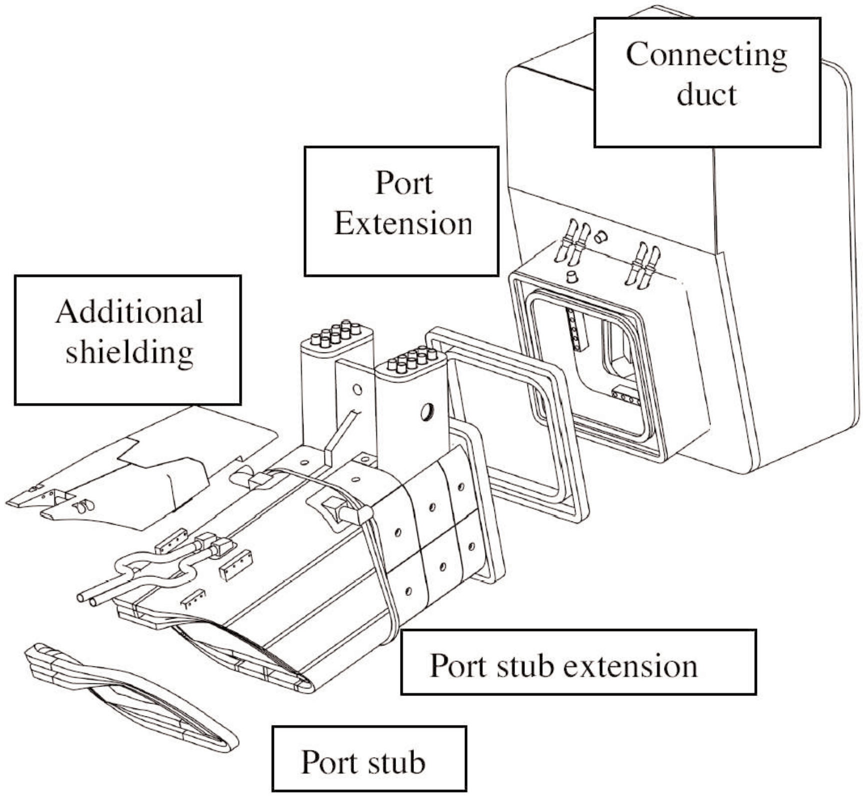
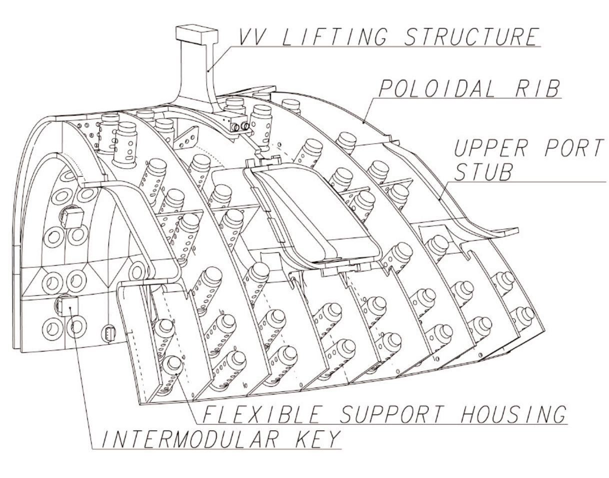
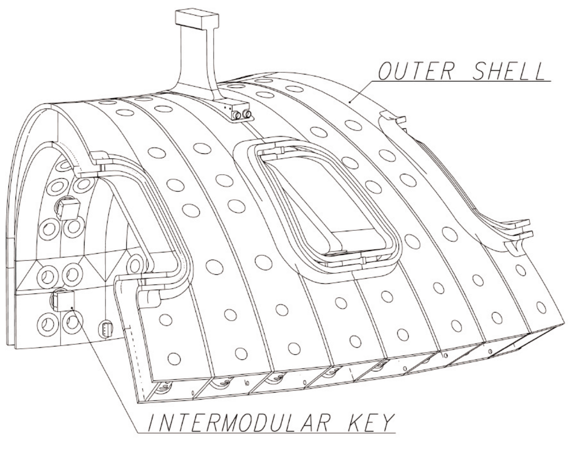


Fig. 2. Exploded view of upper port structure



(a) Upper segment before outer shell assembly



(b) Upper segment after outer shell assembly

Fig. 3. Double wall vessel with keys and flexible support housings

Results of Vacuum Vessel R&D

VV R&D began with the fabrication of the Vessel Sector Large Project completed in 1998, and has continued to improve the manufacturing and assembly procedures.

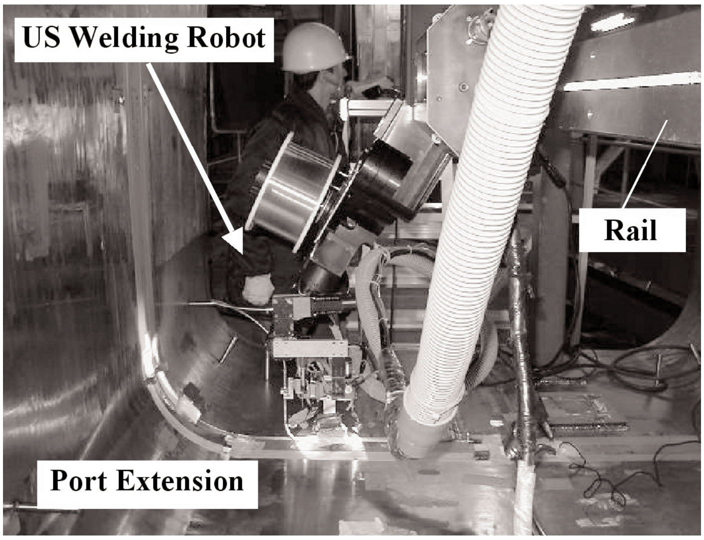


Fig. 4. Port extension assembled to VV sector (JAPT, USPT, RFPT)

Fig. 5. Integration of port extension (JAPT, RFPT)

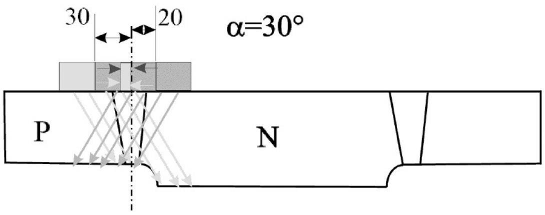
The full-scale VV sector model and a port extension model were fabricated and tested to provide critical information on the fabrication technology required to produce a high quality component, and to test the magnitude of welding distortions and achievable tolerances. Such information was necessary to complete the design and could not be obtained with a small model. The full-scale sector model consisted of two 9° half-sectors. The overall dimensions of the half-sectors were 15 m height and 9 m width, larger than the current ITER VV. The basic structure was a double wall design with the inner and outer shells made of welded plates 40 to 60 mm thick and connected by ribs which space the shells 0.45–0.83 m apart. The design of each half-sector was different to allow several fabrication methods to be investigated. The full-scale port extension achieved tolerances within 4 mm.

Field joint welding was tested during the assembly of both half-sectors. Automatic TIG (tungsten inert gas) welding machines mounted on guide rails were used to make the weld joints between two half-sectors. Based on the results, the tolerance to radial mismatching of the field joint welding without machining is now taken in the VV design to be 5 mm.

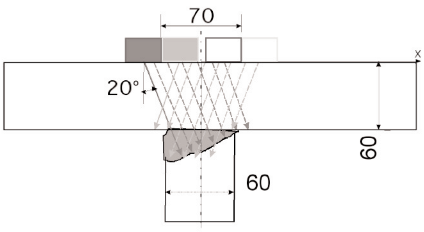
An integration test of the port extension was performed with the full-scale sector model using remotized welding, cutting and non-destructive testing (NDT) systems (see Fig. 4). The shape of the field joint between the sector model and the port extension was a rectangle 3.4 m high and 2.2 m wide (see Fig. 5). A butt weld joint was employed for the outer shell field joint, while splice plates were used for the inner shell field joint. Remotized welding and NDT systems were used. After the port integration test, the port extension was cut manually and deformation was measured to demonstrate the fabrication, assembly and maintenance. The results show that 3–4 mm local distortions due to welding were to be expected, and that defects as small as 23 mm in diameter and 5 mm in length could be detected for 60 mm thick austenitic stainless steel plate.

More recently, R&D has been carried out on one-sided UT of 60 mm thick plate in the inner and outer shell configuration. Considering the limited access, the use of waves launched at an angle of 20 or 30° as well as 45 and 60° has been tested, as shown in Fig. 6. Regarding the surface inspection of welds, the applicability of LPT (liquid penetrant dye test) during the initial assembly phase has been assessed, and it is proposed to select a suitable liquid penetrant with a very low level of impurities (sulphur and halogen) and a limited amount of high temperature vaporization components. As a possible alternative to LPT, the residue from which may compromise the vacuum purity, a novel photothermal camera method has been investigated. It reliably detects cracks within 0.5 mm of the surface with the inspection equipment located up to 2 m away. A 120 W YAG (yttrium–aluminium–garnet) laser line is raster-scanned between passes in both directions across the welded surface at a speed of 5 mm/s and the surface temperatures are recorded. By computer analysis and subtraction of the images obtained, defects are distinguished from surface irregularities and changes in reflection. In inspections carried out on weldment surfaces from narrow gap TIG in 60 mm stainless steel (shown in Fig. 7), the results proved that the photothermal camera is generally more sensitive and reliable than LPT and better discriminates between linear (>1.6 mm) and rounded (>4 mm) flaws. The method will need to be qualified as a code case in the future.

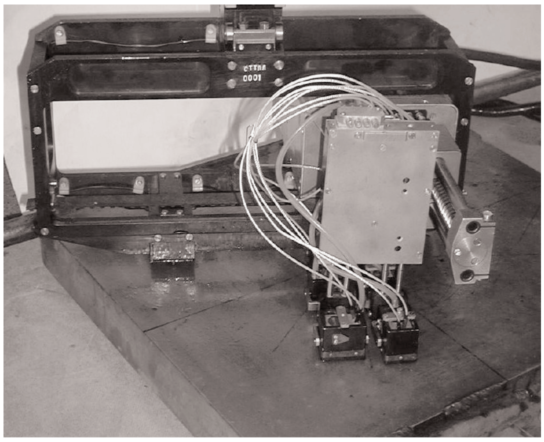
Advanced methods of cutting, welding and NDT for the VV have also been developed in order to increase the potential for improved cost and technical performance, such as maintaining the stringent tolerances, tight



(a) Welding for flexible support housing



(b) Welding of poloidal rib to inner shell



(c) UT inspection system during testing (RFTP)

Fig. 6. UT inspection tests on welded 60 mm plates

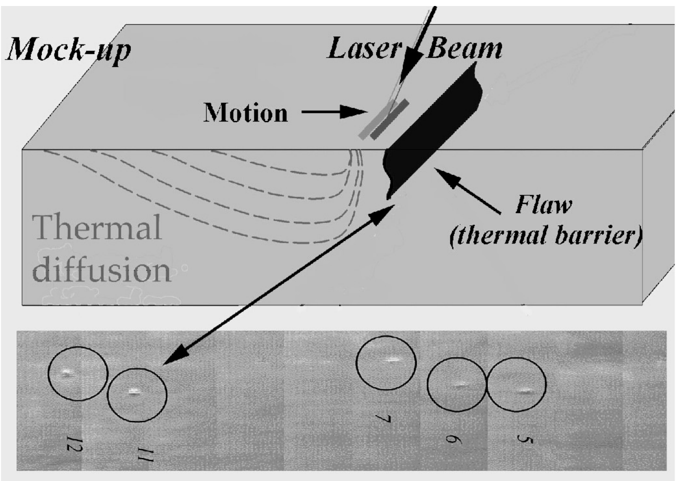


Fig. 7. Photothermal camera as a surface crack inspection method and detected defects in a mock-up test (EUPT)

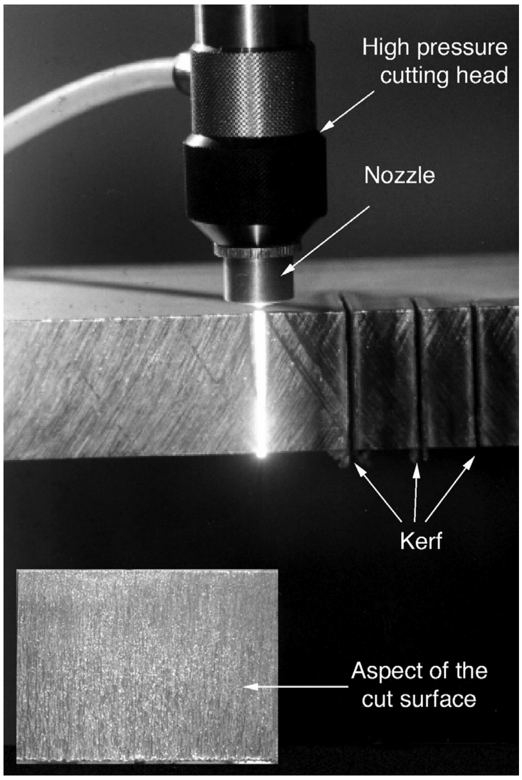


Fig. 8. Thick plate cutting with NdYAG Laser (EUPT) (40 mm thick plate cutting in the photo and 60 mm thick steel, 6 kW NdYAG with nitrogen gas cutting speed: 0.003 m/min)

space constraints, and reweldable surface conditions. The investigated methods include NdYAG laser cutting (see Fig. 8) and welding, reduced pressure electron beam (RP-EB) welding, and ultrasonic testing systems including phased array methods. A NdYAG laser, with power up to 11 kW, has been used with filler wire to achieve stable and reliable welding of 60 mm thick stainless steel.

To cover the eventuality that the electrical supply to coolant pumps could fail, the VV cooling has been designed to remove, after plasma shutdown, all the heat from all components inside the vessel by natural convection, with heat exchange with the atmosphere. Thermal-hydraulic tests have therefore been performed to confirm the VV cooling parameters, as they are very important for future licensing. The tests were focused on studying heat transfer in differently oriented and non-uniformly heated rectangular channels, flow distribution and stability in parallel channels at extremely low water velocities (few millimetres per second), thus modelling the cooling flow between shielding plates, and on studying the development of natural circulation in the entire VV cooling circuit in a close to full height (30 m) model of the entire circuit. The detailed results, which support the VV cooling approach and performance, will be taken into account in the VV cooling system design.

Additional R&D, such as the fabrication of a partial VV sector model including the attachments of the blanket modules, may be required to confirm the improved fabrication technology and associated tolerances.

Preparation of VV Procurement Specifications

Following the establishment of working groups in March 2002, the International Team and Participant Teams have been working together to prepare technical specification documents (TSDs) for the VV, involving also contributions from industry. The EUPT and the JAPT have been contributing mainly to the main vessel TSD, and the RFPT has been contributing to the Port TSD. Additional assembly and component drawings have been generated for the TSDs by the International Teams and Participant Teams. Descriptions of the fabrication methods, welding methods, NDT methods and required tolerances are still under discussion, and will be finalized when the ITER site is selected.

The main vessel, blanket coolant manifold and port TSDs have been prepared in draft. The documents include a description of the scope of supply, contract stages, delivery schedule, ITER and supplier's responsibilities, and supporting documentation to be provided by the supplier. The document also lists the top level requirements and acceptance standards. A series of sketches/figures consistent with the latest vessel design have been inserted into the text in order to aid understanding. The detailed information is restricted to annexes. These include material specifications, detailed drawings of a vessel sector (including tolerance requirements), weld qualification requirements, cleaning specifications, pressure testing, leak testing, etc., and a suggested manufacturing procedure.

Material specifications for the VV are under preparation, in close contact with possible manufacturers. These specifications are based on the ASME/ASTM specifications and additionally include ITER specific requirements such as chemical composition (reduction of the cobalt and niobium content, reduction of boron for rewelded components) and some requirements for specific properties (saturation of magnetic flux for steel 430), etc. The specification for austenitic stainless 316L(N)-IG steel is being prepared using the extensive experience of the RCC-MR Code. Thanks to an optimal combination and tight specification of the main alloying elements, such as carbon, nitrogen, nickel, chromium, manganese and molybdenum, this steel has high minimum tensile mechanical properties combined with good ductility, toughness and corrosion resistance.

A set of related documents, such as a component list and interface documents, has also been prepared in draft. These documents are important to define the scope of the TSDs for the VV to keep consistency with other components, such as the blanket, the in-vessel diagnostics and the cooling system.

Items to be considered for inclusion in the ITER ITA Newsletter should be submitted to C. Basaldella, ITER Office, IAEA, Wagramer Strasse 5, P.O. Box 100, A-1400 Vienna, Austria, or Facsimile: +43 1 2633832, or e-mail: c.basaldella@iaea.org (phone +43 1 260026392).

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