CONSTRUCTION, ASSEMBLY AND COMMISSIONING OF KSTAR MAIN STRUCTURES

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The KSTAR device succeeded in first plasma generation on 13th June of 2008 through comprehensive system test and commissioning. Among various kinds of the key factors that decisively affected the project, success in the construction and assembly of the major tokamak structure was most important one. Every engineering aspects of each structure were finally confirmed in the integrated commissioning period, and there were no severe troubles and failures prevented the KSTAR device from operating during the commissioning and the first plasma experiments. As a result, all of the experiences and technologies achieved through the KSTAR construction process are expected to be important fundamentals for future construction projects of superconducting fusion devices. This paper summarizes key engineering features of the major structures and of the machine assembly.

KEYWORDS : KSTAR, Vacuum Vessel, Cryostat, Thermal Shield, SC Magnet Structures, Assembly, Vacuum Commissioning

1. INTRODUCTION

Since the KSTAR (Korea Superconducting Tokamak Advanced Research) project started from the end of 1995 in the development of an advanced superconducting tokamak to establish a scientific and technological basis for an attractive fusion reactor [1], all related systems have been rigorously developed through various types of R&D. The R&D period provided key technologies and a crucial basis for the actual construction of the machine, which started in early 2002 [2]. The machine construction phase proceeded from 2002 and was finished by August of 2007. Figure 1 shows an outside view of the KSTAR device after the end of construction of the first plasma experiments. Successful results in the integrated commissioning and the first plasma experiment [3], which were implemented by July 2008, proved that every main system as well as every sub-system had been satisfactorily developed for the initial goal of the KSTAR project.

During the construction period, the KSTAR project included several major construction areas. Among these were the main tokamak system, the control and diagnostic system, the heating system, and the building of power supplies for the SC magnet. The main tokamak system was divided into the three categories of the main structures, the SC magnet system, and ancillary systems for the SC magnet including SC bus-lines and a He piping system. The main structure system is the most important system, as it forms the backbone of the KSTAR and provides an interface between different systems. The main structure system includes i) a vacuum vessel (VV), ii) a cryostat, iii) thermal shields, iv) SC a coil structure, v) a pumping system, vi) a gas fueling and discharge cleaning system, vii) in-vessel components, and viii) machine assembly and system integration for the main tokamak system. Among the main structures, the VV, the cryostat, the thermal shields, and the SC coil structure are crucial components of which the quality and schedule could decisively affect the success of the KSTAR construction efforts. Furthermore, machine assembly and system integration for the main structure system represent highlights of KSTAR engineering due to the difficulties and complications associated with these

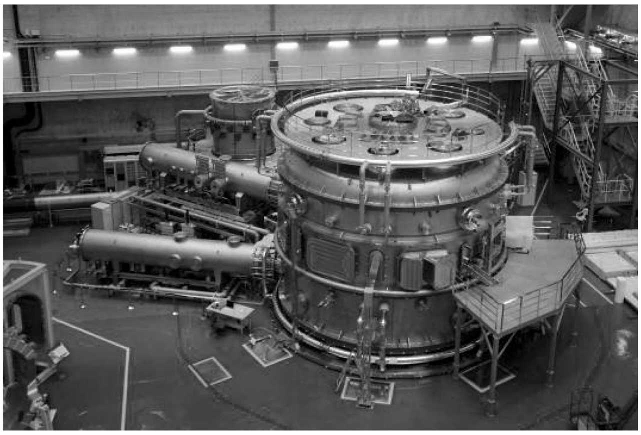

Fig. 1. Outside View of KSTAR after its Construction

Table 1. Major Parameters of the KSTAR Vacuum Vessel

Parameters	Values
Inner radius of the torus	1.1 m
Outer radius of the torus	2.99 m
Height/width	3.387 m/ 1.880 m
Rib thickness	20 (40) mm
Double wall thickness	50-190 mm
Total weight	72 ton (with support)
Surface area (inner shell)	100 m2 (without port)
Relative permeability	<1.10 (after welding)
Shell thickness	12 mm
Resistance (VV+ in-vessel comp.)	> 40 mΩ

procedures. This paper describes the general design features, construction and assembly process for the main tokamak structures mentioned above. Moreover, several interesting commissioning results for the main structures are briefly introduced.

2. DESIGN AND FABRICATION OF THE MAIN STRUCTURES

2.1 Vacuum Vessel (VV) and VV Ports

The VV of the KSTAR is one of the most important structures as it provides ultra-high vacuum conditions for the generation and confinement of the tokamak plasma. Therefore, all structures and fabrication techniques for the VV should meet the general requirements as described in detail in the literature [4]. In particular, the VV must be compatible with not only a high magnetic field but also with an ultra-high vacuum condition, of which the target pressure is 1.33×10^{-6} Pa after VV baking. To protect the superconducting magnets from the plasma heat and nuclear heating, the VV provides a heat removal mechanism. In the normal operation phase, the VV temperature should be kept to a maximum of 35 °C The VV cooling mechanism is also utilized in VV baking period under a hot pressurized (0.3 MPa) condition with a temperature as high as 130 °C Moreover, the VV should withstand all the mechanical loads including its dead weight, vacuum pressure, as well as thermal and electromagnetic loads. The VV was designed by the end of 2001 to meet the requirements by both the KSTAR staff and by Hyundai Heavy Industries (HHI).

The VV consists of a double-walled, D-shaped body structure that has 72 ports with bellows and leaf-spring-style VV supports. The D-shaped VV is made of SA240-316LN. The thickness of each shell is 12 mm. For the reinforcement of the double-wall structure of the vacuum vessel, 32 equally spaced poloidal ribs and two toroidal rings were installed in the inter-space of the two shells. The two shells, the port stub walls, and the ribs form a water flow channel for the vessel baking and cooling operations. The volume of the VV including the ports reaches 100 m^3. The major parameters of the KSTAR VV are illustrated in Table 1. The VV body was fabricated in a shop as two large sectors and one small sector. One sector, here termed Sector I, forms 180° of the total. The other sector, termed Sector II, accounts for 157.5°. A final sector has a span of 22.5° to make a full torus. The small sector consists of 24 small pieces. Each sector is composed of two quadrants (Sector I: two quadrants, Sector II: one quadrant + a 67.5° semi-quadrant). The sub-structures of a quadrant are the lower, upper and middle parts. The most important sub-structure of the vacuum vessel is the part containing the seven types of ports. It allows access from the outside to the inside of the vacuum vessel. Each port consists of a stub section, a bellows and a flange, and the port structure is welded between the vacuum vessel body and the cryostat port stub at the final stage of machine assembly. Each port is equipped with a bellows, which functions to offset the relative movement of the vacuum vessel to the cryostat. Among the total of 72 ports, 56 ports provide access to the vacuum vessel interior, while 16 ports are dedicated to the baking and the cooling of the vacuum vessel. A schematic as well as cross-section views of the vacuum vessel with various ports are shown in Fig. 2.

Since fabrication of the VV and the VV ports started in 2002, the VV and the VV ports have been successfully fabricated at the factory. VV sectors I, II, III were delivered to the site in the middle of July of 2004. Figure 3 shows the pre-assembled VV sector I and sector II for

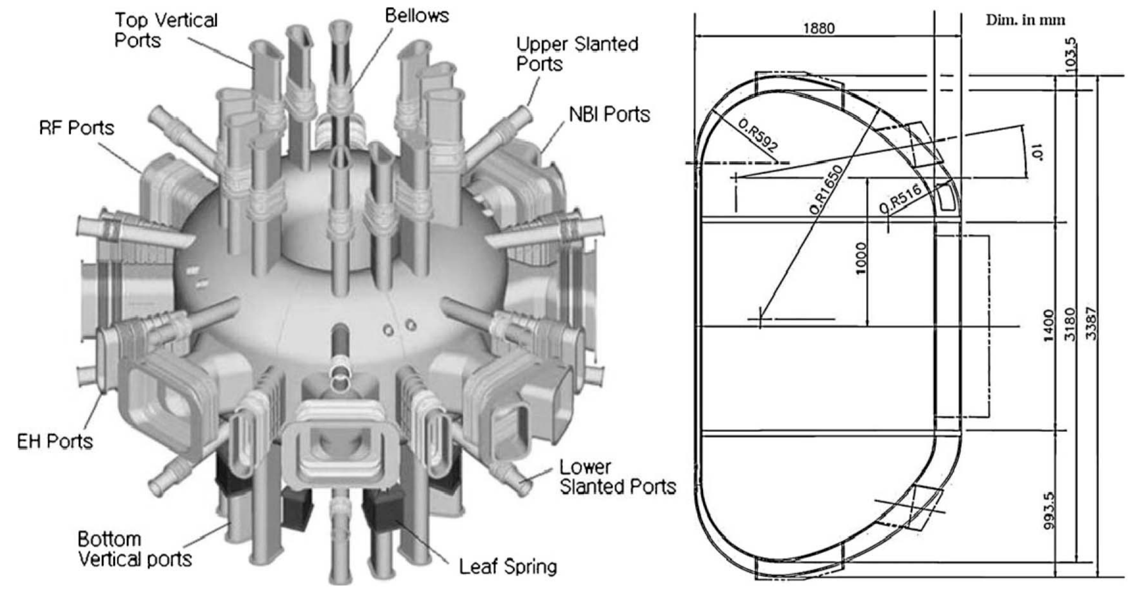

Fig. 2. Schematic and Cross-Sectional View of the VV Body

the final measurement of the geometry before site delivery. VV sectors I and II were welded together to form a sector that measured 337.5 ° at the site [5], and the remaining 22.5° of sector III was finally welded to form a complete torus after the assembly of the TF magnets was complete. Figure 3 shows an inside view the completed VV.

2.2 Cryostat

The cryostat is a single-walled vacuum vessel that provides a vacuum environment for the entire space in which all of the SC magnets and sub-systems are contained. This cryostat structure is mainly composed of large three parts: the base, the cylinder, and the lid. It achieves a target vacuum pressure ($< 1 \times 10^{-2}$ Pa) to allow the cool-down start of the cold mass. The cryostat base, which is supported by eight supporting beams embedded in the concrete floor, is a flat structure made of SS304 with external reinforcement ribs to support the entire VV and all of the SC magnets. The cryostat cylinder is a cylindrical body for the cryostat of which the nominal inner diameter reaches 8.8 m. The dome-shaped cryostat lid was designed to be removable for maintenance of every system contained in the cryostat after assembly or in the operation stage. The total weight and height of the cryostat are 180 tons and 8.56 m, respectively. U-shaped lip seal structures are attached to the cryostat base, cylinder and lid through site welding for vacuum sealing between the cryostat base and the cylinder, or between the cryostat cylinder and the lid.

The fabrication of the cryostat started in middle of 2002 by HHI. As the diameter of the cryostat is 8.8 m, as mentioned above, it was impossible for the entire cryostat structure to be transported from the factory to the site. This technical problem was solved through the breakdown of the fabrication of the cryostat system into several sub-units in the factory. These sub-units were finally welded together at the site. Two halves of the cryostat base were completed in the fabrication process at the factory by the end of 2003 and were welded to each other at the site to form the entire base structure by February of 2004. The cryostat cylinder was divided into

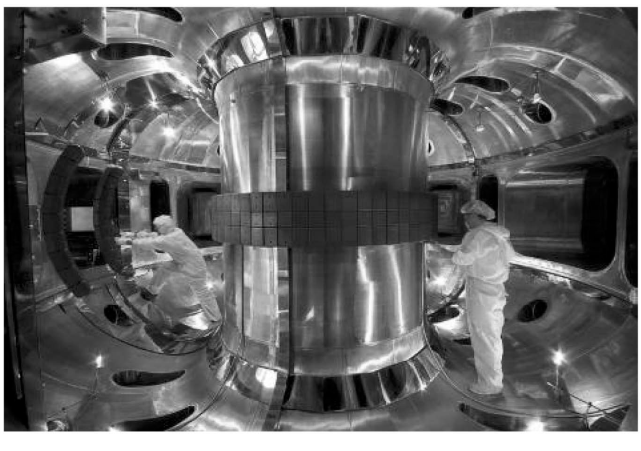

Fig. 3. Inside View of the KSTAR Vacuum Vessel

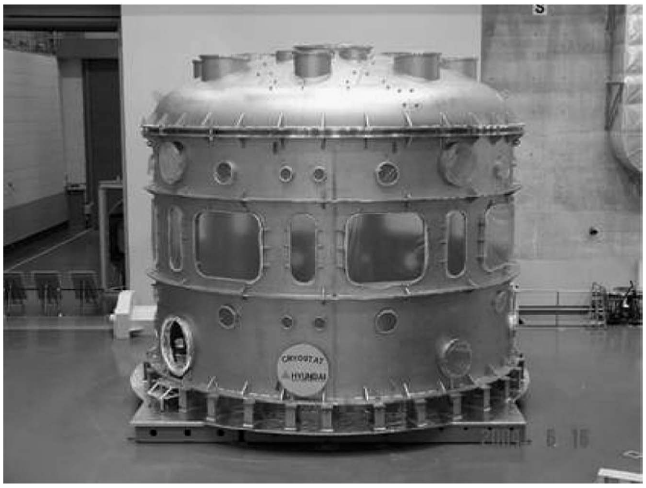

Fig. 4. The KSTAR Cryostat lid and Cylinder

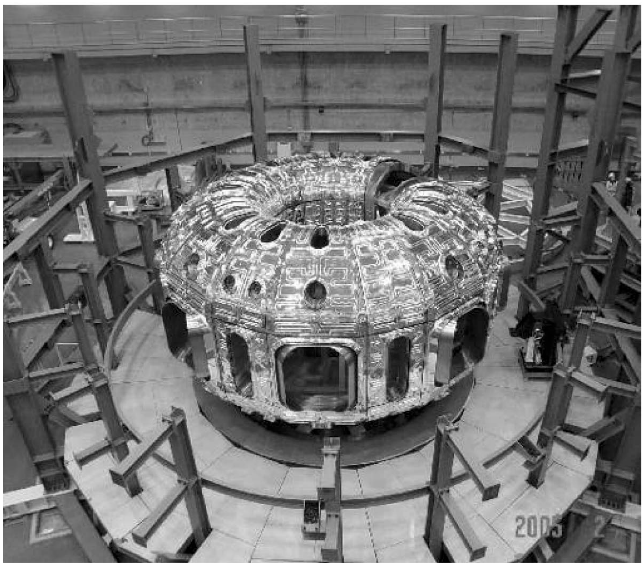

Fig. 5. The KSTAR VV Thermal Shield Mounted On the VV

four quadrants, and the cryostat lid was divided into three pieces of a knuckle and a crown with ports. Both the cylinder and the lid were delivered to the site in early 2004 and were completed through site welding in June of 2004. The welding of the cryostat was performed by Gas Tungsten Arc Welding (GTAW) and Flux Cored Arc Welding (FCAW) according to ASME code Section IX [6]. The FCAW process was used for the full penetration welding of the thick plates at the shop. The GTAW process was used for the root passes, the cover passes exposed to the vacuum environments, and the site welding. Every component was fitted up with consideration of welding distortion, which should be offset to meet the allowable fabrication tolerances. Figure 4 shows the completely fabricated cryostat cylinder on which the cryostat lid is temporarily mounted.

2.3 Thermal Shield

There are three types of KSTAR thermal shield: a vacuum vessel thermal shield (VVTS), a cryostat thermal shield (CTS), and a port thermal shield (PTS). The main shield panel is fabricated from a 316L plate 3 mm in thickness and a stainless steel pipe with a 7 mm ID. A wall with a thickness of 1.5 mm is welded on the panel. The shield panel has roughly two types of support made of epoxy glass to minimize heat transfer by conduction. As the VVTS is placed in the narrow gap between the TF superconducting magnet and the vacuum vessel, the VVTS panel is coated with silver at a thickness of 10 μm in place of the use of multi-layer insulation (MLI) [7]. The shield panel is toroidally segmented into 16 sectors of 22.5° each and is poloidally partitioned into 4 pieces to reduce the electromagnetic force from the eddy current induced by plasma disruption. It is impossible to access to the VVTS for maintenance without disassembling the magnet system; accordingly, the VVTS has a double-pipeline configuration for redundancy. The CTS is positioned on the inner surface wall of the cryostat. The CTS consists of three parts: the lid TS, the body TS, and the base TS in the cryostat. Each part is toroidally divided into 16 sectors like the VVTS. Its space is such that 30 layers of MLI are used to mitigate the effects of thermal radiation from the cryostat surface to the superconducting coils. There are 72 penetration ports classified into seven types to connect the vacuum vessel body and the cryostat. PTS coated with silver covers these ports.

The VVTS fabrication started from the middle of 2004 according to the engineering design. Electroplating baths were used for the silver coating. After completion of the VVTS by the end of 2004, the VVTS was independently installed on the VV surface except for the 45°-sector for the installation of the TF magnet, as shown in Fig. 5. The remaining panels were installed after the completion of the TF magnet assembly in accordance with the KSTAR tokamak assembly procedure. During the CTS fabrication, the major fabrication process for the shield panel included (1) surface polishing of the raw material, (2) tube welding on the panel, (3) laser cutting of holes and edges, (4) final buffing, (5) cleaning, and (6) MLI blanket installation. After the installation of the base TS, the cryostat cylinder with the thermal shield was lifted by a crane and very carefully assembled on the cryostat base to avoid any collisions with other components such as bus line, helium line, and base

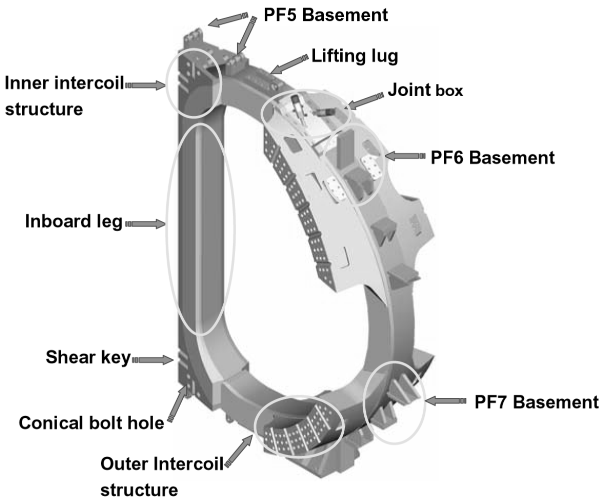

Fig. 6. General Configuration of the TF Structure

Fig. 7. A TF Structure Under Final Machining

thermal shield during the assembly. Finally the cryostat lid was assembled to the cryostat cylinder.

The fabrication procedure for the PTS is nearly same as that of the VVTS. The bottom vertical PTS has been installed once the base thermal shield was installed. Before the assembly of cryostat cylinder, all median ports including the slanted ports were temporarily placed and adhered closely to the vacuum vessel side in advance, because it is impossible to insert the PTS in the cryostat. The top vertical PTS, which is the last thermal shield to be installed, was installed after the assembly of cryostat lid. After that the piping work began. The connection between the pipelines was made with welded with sleeve joints.

2.4 TF Coil Structure

The TF structure that encases the TF coil is an important system in the SC tokamak structure as it enhances mechanical stability. The dimensions of the TF coil structure are as follows: 4.2 m in height, 3.5 m in width, and a toroidal angle of 22.5°. The TF structure also provides a mounting platform for all of the PF parts and for the CS coil structure [8]. Figure 6 shows the general configuration of the TF structure (type III). The D-shaped TF coil structures are wedged together along inboard legs to sustain an in-plane centering force. Each inner inter-coil structure (IIS) on the structure contains three shear keys and three conical bolts to provide pre-loading in the toroidal direction and to resist in-plane and out-of-plane forces, which are the most critical loads on the TF magnet system [9]. Additionally, each outer inter-coil structure (OIS) has four (or five) shear keys and 33 (or 47) bolts according to the structure type. Electrical insulation is inserted into the contact surfaces between the structures in the inboard leg, the OIS, the shear keys, the conical bolts, and the hexagonal bolts to prevent the flowing of eddy currents in the toroidal direction of the structure. The thickness of the insulation is 3 mm for the inboard leg and 4 mm for the outboard leg.

There are 18 cooling tubes with an outer diameter of 8 mm and an inner diameter of 4 mm embedded inside the structure around the coil. Two cooling tubes with an outer diameter of 10 mm and an inner diameter of 7 mm are attached to the surface of the OIS. The coolant is 4.5 K of supercritical helium. Cover plates are welded in the joint box to reinforce the open part of the structure and to support the coil leads. Various types of the material were chosen for the different parts of the structure, including stainless steel 316LN for the base metal of the TF coil structure, Inconel718 for the shear key and the conical bolt, stainless steel 316L for the cooling tubes, and G-10 for the insulation. Representative allowable tolerances of the inboard leg and the outboard leg of the structure are ±1 mm and ±2 mm, respectively. A gap of 5 ~ 10 mm between the coil and the structure is necessary to clear the fabrication tolerance of the coil and the structure. The location and shape tolerances of the shear key hole and the conical bolt hole are ±0.1 mm and +0.03 ~ +0.07 mm, respectively. Angle tolerance for the toroidal angle of 22.5° is 0.015°, which is absorbed by the insulation sheet. The allowable leak rate of the structure cooling line is 1×10^{-10} mbar l/s after 3 cycles with 30 bar for 10 minutes at 300 K.

Using the aforementioned fabrication requirements, the fabrication of the TF structure started in May of 2004. The fabrication procedure of the TF structure can be summarized as follows: i) Fabrication of the case and

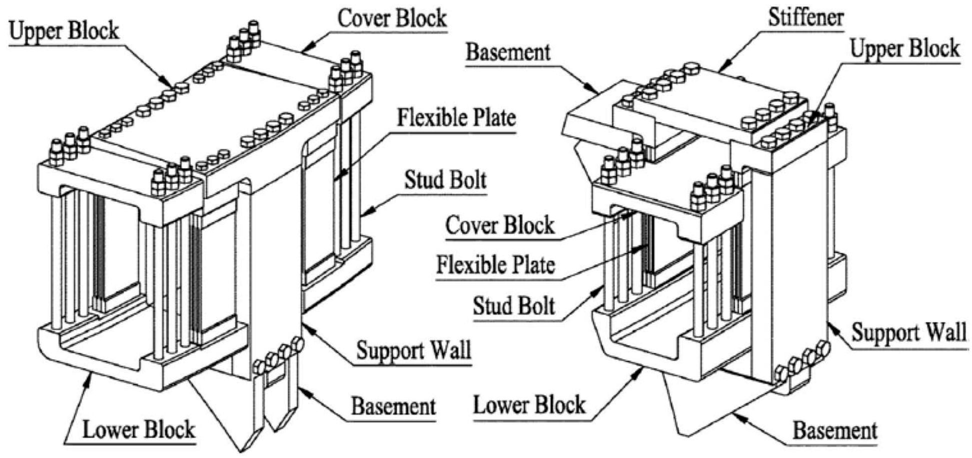

Fig. 8. Structures for the PF6U Coil (a) and the PF7U (b)

the cover structures, ii) coil encasing, iii) enclosing weld, iv) vacuum pressure impregnation (VPI), and v) outer surface machining. Figure 7 shows a TF structure under final machining. A more detailed fabrication procedure is described in the literature [10]. The fabrication of the TF structure was successfully carried out by Doosan Heavy Industry (DHI), and the first TF structure was delivered to the site in March of 2005. The sixteenth TF structure was delivered to the site by January of 2006. The 16 TF structures were also individually assembled by May of 2006. The assembly tolerance in these cases was kept within ±1mm.

2.5 PF Coil Structures

The poloidal filed (PF) coil system of KSTAR is composed of seven pairs of PF coils. As four pairs of the PF coil (termed here as PF1, PF2, PF3, and PF4) are positioned at the center of the KSTAR device (known as the central solenoid (CS) coils), the naming of the PF coil generally represents the outer three pairs of the PF coil that are mounted on the outside of the TF coils. The PF coil structures was designed to allow free radial expansion of the coils, as each of the PF coils is self-supporting with regard to the radial magnetic loads [11]. Each structure is equipped with hinges or flexible plates that can deflect to allow different radial displacements between the PF coils and the TF coil case at cryogenic temperature, and also accounts for electromagnetic loads and assembly tolerances. However, this mechanism is rigid in the vertical and in toroidal directions to sustain the design loads such as those caused by gravity, seismic loads, and electromagnetic loads on the PF coils. Each PF5 coil has only eight supports connected to every TF coil case due to the small diameter of the PF5 coil. The support has two hinges to resist the considerable vertical compression. The sixteen flexible plate-type structures support the PF6 and PF7 coils, which produce a relatively small amount of buckling force, as shown in (a) and (b) of Fig. 8. With the aforementioned design requirements, the fabrication of the PF structures started in the middle of 2005 and was completed by March of 2006. As the structure geometry was relatively simple and has little technical complexity, the fabrication proceeded without any severe problems. The operational properties during the machine cool down process and the first plasma experiment were also satisfactory.

2.6 CS Coil Structures

The CS coil system, which has a height of 4.5 m and a diameter of 1.5 m, consists of four pairs of SC coils with up-down symmetry and a supporting structure that is electrically isolated, as shown in Fig. 9. The most important function of the CS structure is to protect the CS coils from electromagnetic and thermal loads. In particular, the structure should withstand high magnetic forces such as hoop forces, vertical attractive/repulsive forces, and lateral forces. The CS structure is divided into three parts: a preload structure, a TF interface structure, and a coil lead supporting structure. The major function of the preload structure is to apply axial compression to the CS stack and to sustain the repulsive forces between the coils. The TF interface structure is designed to connect the CS system to toroidal field (TF) coil structures and to absorb the radial displacement difference between the TF and CS structures during the cool down stage. There are also two long coil leads inside each CS coil, which have two bending regions and a length of 4 m. A support structure of the coil leads that

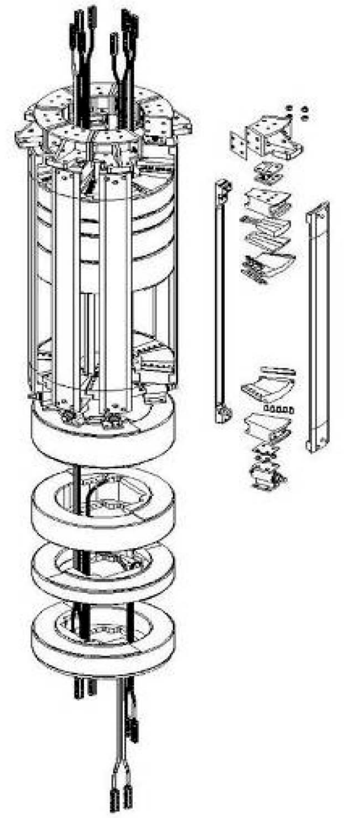

Fig. 9. Detailed View of the KSTAR CS Structure

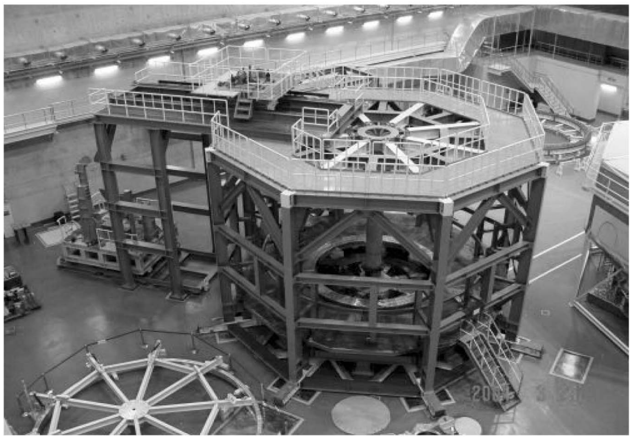

Fig. 10. Main Assembly Jigs System

are exposed to high magnetic fields was designed. The fabrication of the CS structure proceeded simultaneously with that of the PF coil structures by DHI. The most important and difficult process in the CS structure was the sub-assembly of the CS coil and structures.

After the CS structures were delivered to the site, the CS coils were stacked on the structures and finally loaded with pre-compression to prevent the CS coil from lateral movement during the operation. The pre-compression process was implemented by heating the inner and outer shells to 140 °C to cause a thermal expansion and to create space between the coil and the structure. The heating process was followed by cooling down of the heated shells to room temperature after the space adjustment. The thermal contraction finally loaded the pre-compression to 760 tons at room temperature [12]. The CS structure was also satisfactory in terms of He leak tightness, and was successfully cooled to 4.5 K.

However, the expected further pre-compression could not be achieved after the cool down due to the relatively different thermal contraction characteristics between the coils and the structures. Therefore, more investigation is needed into the operational limits of the CS system in the future operation stages.

3. KATAR ASSEMBLY

3.1 Assembly Procedure and History

The KSTAR assembly procedure was divided into four major stages according to major milestones of the KSTAR construction process.

3.1.1 First Assembly Stage

The first stage was initiated at the beginning of 2004 and lasted until June of 2004. It included the assembly of the lower parts of the cryostat support, the cryostat base, and the gravity part. During this period, the main assembly jigs system as described in the literature [5] were also constructed. After installation of the eight cryostat supports and the lowest part of the main tools system (termed the base frame) on the floor of the assembly hall, the cryostat base was positioned on the tokamak pit and was finally welded onto the cryostat supports. The subsequent procedure was the assembly of the magnet gravity support on the cryostat base by February of 2004. The final assembly process of the first stage was the installation of the main assembly jigs as shown in Fig. 10.

3.1.2 Second Assembly Stage

The second stage started in July of 2004 after completion of the main assembly jigs system. The second stage included assemblies of most important major structures, including the VV, VVTS, TF magnets, and VV supports. In the VVTS installation on the VV, of which sectors 1 and 2 had previously been welded on site, the main tools system was partly removed for installation of the VV and VVTS assemblies on the tokamak pit. The two largest lower PF coils, termed PF6L and PF7L, were temporarily positioned before the

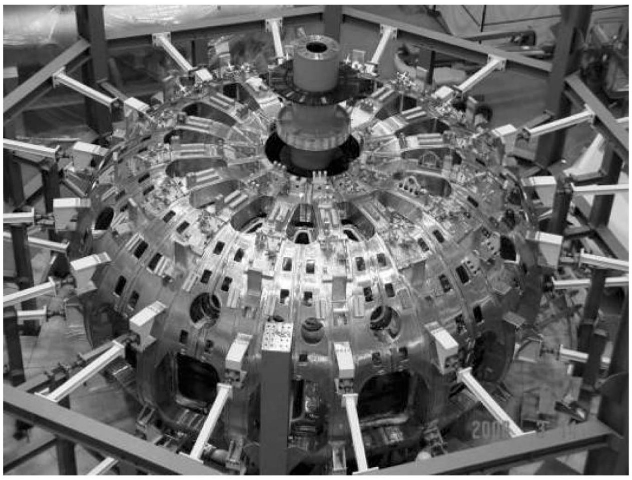

Fig. 11. TF Magnets after Completion of their Assembly

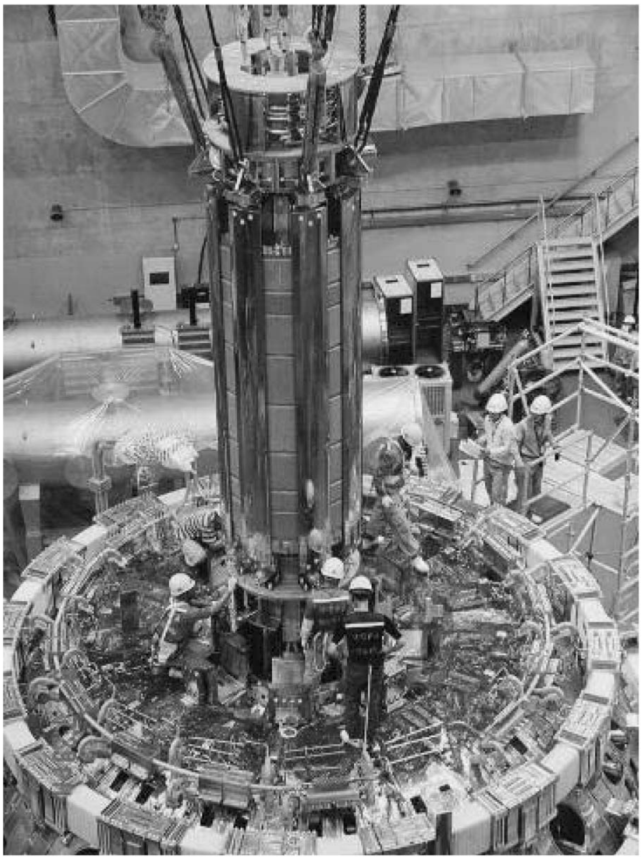

Fig. 12. The CS Coil System Under Final Assembly

final positioning of the VV, as the large PF coils could not be installed in the presence of the VV and TF magnets. In March of 2005, the main jig system was partly removed and the VV and VVTS were installed on the tokamak pit, as shown in Fig. 4 in the previous chapter. After the VV and VVTS were accurately installed on the tokamak pit, the TF magnets were assembled from April of 2005 to May of 2006. Figure 11 shows the 16 TF magnets after the completion of this assembly process. The last sectors of the VVTS and VV, as well as that of the VV supports, were assembled in turn by June of 2006 as the final assembly step of the second stage.

3.1.3 Third Assembly Stage

The third stage assembly mainly comprised all of the PF and CS coils. The PF6L and PF7L coils were lifted and assembled onto the TF structure with the help of special tools. Sequentially installation of the upper PF7 coil, the upper PF6 coil, the lower PF5 coil, and the upper PF5 coil were performed by October of 2006. In particular, the CS coils were sub-assembled in the main experimental hall during the assembly period of the PF coils. The CS coil system after the sub-assembly process was finally assembly on the TF magnet system by October of 2006, as shown in Fig. 12. Although the main scope of the third stage involved the assembly of the PF coils, partial installation was done of the in-vessel components including the inboard limiter and the magnetic diagnostics. The third stage also covered final installation and system tests for all in-cryostat components of the SC bus line, various types of joints, the liquid helium supply and the return piping system, as well as all of the sensors.

3.1.4 Fourth Assembly Stage

After most of the in-cryostat components were installed in the third stage, the cryostat cylinder was lifted to the top of the assembled machine by a 150-ton overhead crane in early January of 2007, as shown in Fig. 13. The completion of the installation of the cryostat cylinder provided a condition for the final welding of the median, slanted, and B&C ports of the VV, a process that continued for two months. Subsequent procedures were the assembly of the cryostat lid and the assembly of the vertical ports. Two pumping duct systems for the VV and cryostat were simultaneously assembled during the assembly of the vertical port. As a final step for the machine assembly, all of the VV ports were blanked for vacuum sealing by the end of April of 2007.

3.2 Key Features in the Assembly Concept [13]

3.2.1 Coordinate System

The coordinate system of the KSTAR assembly comprises two sets of "coordinate data" according to the assembly progress. The first set of the "coordinate data" was established from a comprehensive survey and fitting on the geometry of the CR base. This set is termed as the "pit data". The pit data provides all of the references for

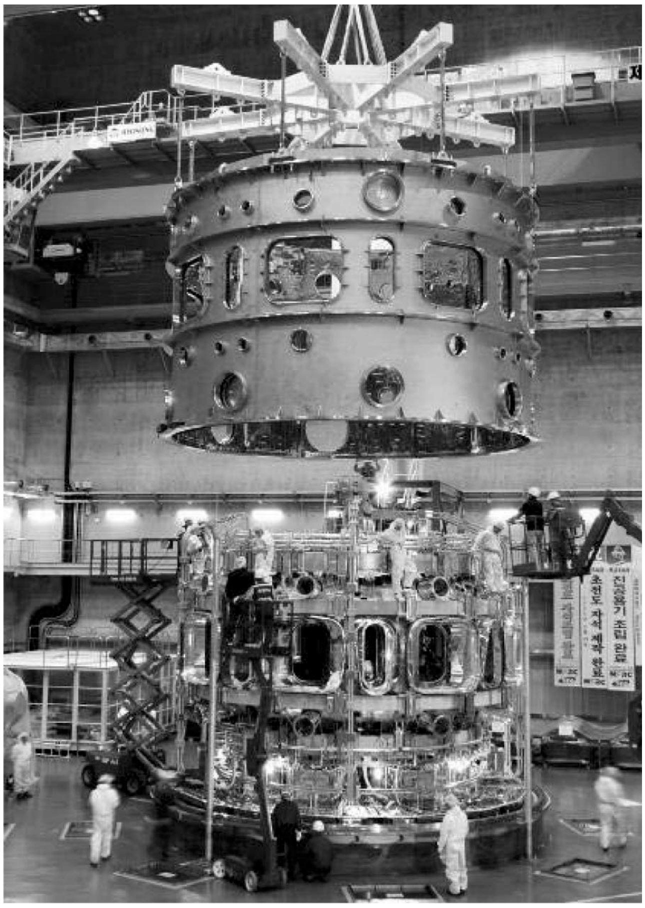

Fig. 13. The Cryostat Cylinder Under Final Assembly

the site assembly until the TF magnet system is assembled. The second set (termed as the "tokamak data") was produced after the completion of the assembly of the TF magnet to provide a reference set for the SC magnets. As SC magnets thermally shrink under cryogenic temperatures, the mid-plane in the tokamak data is offset from the pit data by 5 mm to ensure that the two sets coincide when in operation. That is, the mid-plane in the tokamak data is 4,205 mm from the zero level instead of the 4,200 mm that comes from the pit data. The tokamak data also provides the basis for the TF magnet to be assembled at 7 mm outward in a radial direction from the designed position under cryogenic temperatures.

3.2.2 Assembly of the VV and TF Magnets

The unique feature of the KSTAR assembly process is assembly of the VV and TF magnets. The 337.5° sectors of the VV and the VVTS were completed through site welding. After the final installation of the VV and VVTS, each of the sixteen TF magnets passes through the 22.5° gap of the VV. Next, each TF magnet rotates around the VV to the final position. However, a tool system is needed for the assembly of the TF magnet owing to the narrow clearance between the VVTS and TF magnets. As a result, the remaining 22.5° sector of the VV (known as VV sector 3) and the VVTS should be assembled inside of the TF magnet system. This configuration implies that the VV sector 3 must be composed of 24 pieces, which are welded from inside of the VV. As the VV 337.5° sector is formed through site welding of the 180° and 157.5° sectors of the VV, the site weld should be controlled as accurately as possible for the assembly of the TF magnets and for the final welding of the three components of the VV sector.

3.2.3 Sub-Assembly of the CS Coils

The KSTAR central solenoid (CS) module is composed of 8 Nb3Sn superconducting coils and structures that hold the coils robustly during operation. Figure 4 shows the detailed configuration of the CS module. The difficulties in the sub-assembly of the CS coils mostly stem from the configuration of the coil leads that come out from the inside of the coil, which leads to a complicated geometry and a small space to work inside of the coil stack. Another feature is the pre-loading on the CS coils. Given that the CS coils are sustained by the compressive force and friction between each coil, applying a pre-load during the room temperature assembly is very important. Electromagnetic load calculations on the basis of the operation scenario show that several hundred tons are needed for the CS module to be safely sustained from repulsive and lateral force. According to the requirements, the assembly plan includes a special jig system for stacking the complicated CS coils as well as pre-loading of the CS coils.

4. COMMISSIONING RESULT

4.1 Vacuum Commissioning

As a first step in the integrated machine commissioning of the KSTAR, the final vacuum commissioning started in early March of 2008. The vacuum pressure of the VV reached less than 5.0×10^{-7} mbar within 12 hours from the start of the vacuum pumping, and the pressure was maintained in the range of $2.5 \sim 3 \times 10^{-8}$ mbar before the commencement of vacuum vessel baking. The base pressure in the cryostat reached 2.7×10^{-6} mbar at room temperature within one day of the initiation of vacuum pumping. After the machine was cooled down to 4.5 K, the vacuum pressure was maintained in the range of $2.0 \sim 2.5 \times 10^{-8}$ mbar. This result satisfied all the design values and proved that both the VV and the cryostat had been successfully developed and fabricated in the construction phase.

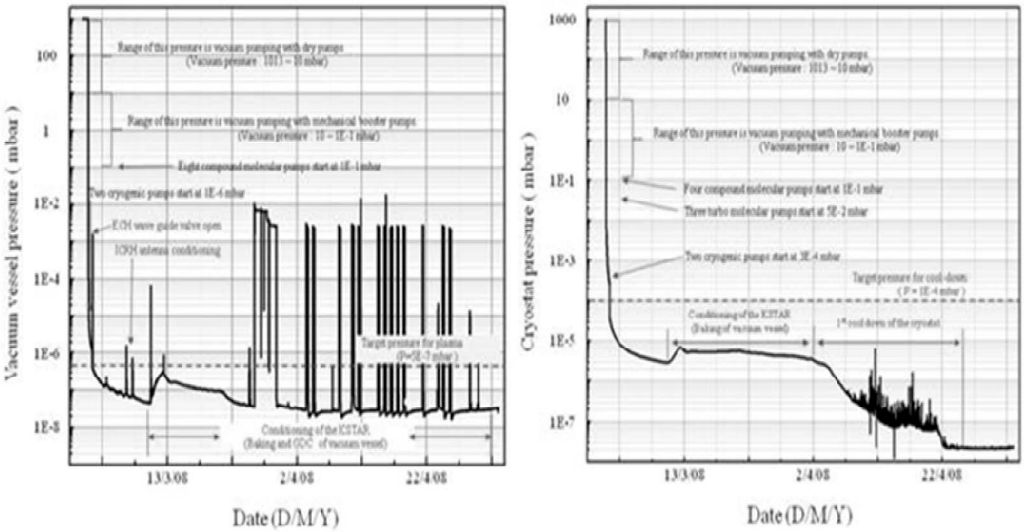

Fig. 14. Vacuum Pressure Changes During Commissioning (a) in the Vacuum Vessel and (b) in the Cryostat

Figures 14 a) and b) are the histories of the vacuum pressure changes in both the VV and the cryostat, respectively.

4.2 Cool Down Results of the Thermal Shield

After tight inspection and overcoming of the minor He leak problems as reported in the literature [14], the thermal shield was simultaneously cooled down with the SC magnet system during the cool down commissioning period. The first cool down of the KSTAR started on April 3 of 2008, and the cool down was successfully completed on April 26. When the SC coil was cooled

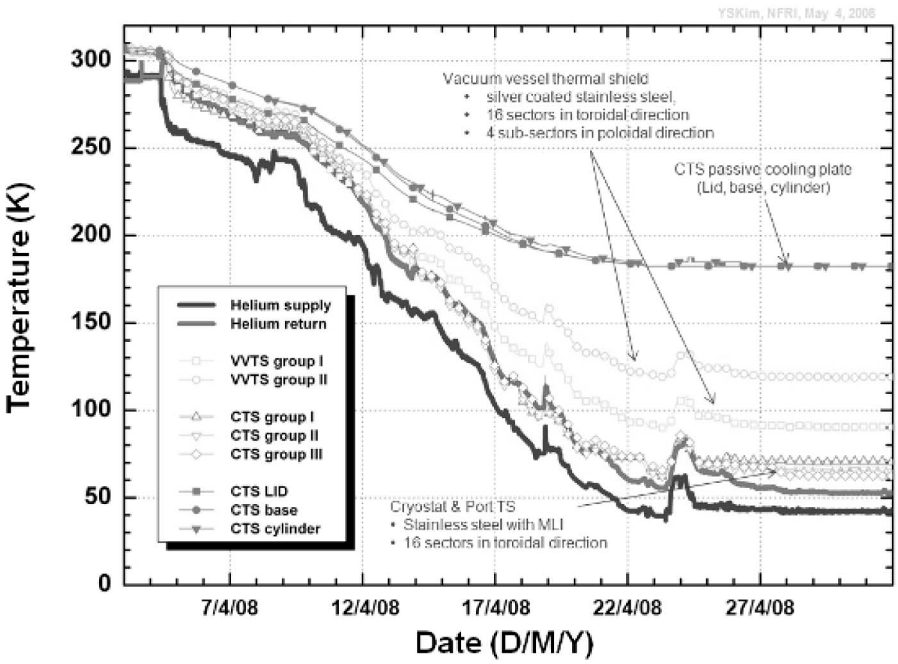

Fig. 15. Temperature History of the Thermal Shields During the Cool Down Process

down to 50 K, the vacuum in the cryostat was stabilized at 2.6×10^{-10} mbar. The cryostat thermal shields were cooled below 70 K, as shown in Fig. 15, and the temperature difference was not shown in nearly every sector. However, a temperature of 180 K was measured by the sensors on the blank cover plate without cooling paths. Most sensors of the vacuum vessel shield installed where a hot spot was found in the analysis indicated temperatures from 90 K to 120 K. The highest temperature, however, was found to be nearly 160 K in one sector.

4.3 Initial Operation of the SC Coil Structures

The vacuum commissioning result showed that all of the SC coil structures had good vacuum and helium leak tightness. The cool down commissioning result [15] also showed that the coil structure was successfully cooled down to 4.5 K without any severe problems. The mechanical behavior of the structures was also measured during and after the cool down process. The stresses in the TF structures were maintained in the range of 60 MPa ~ 82 MPa, which is within 12.6 % of the maximum allowable stress. Maximum hoop stress of 93 MPa was observed at the lower outboard leg due to a relatively larger hoop stress as there are more constraint structures on the lower part. On the other hand, tensile and compressive stresses were observed in the PF7 and PF6 structures. The KSTAR central solenoid (CS) was mechanically preloaded at room temperature. The achieved preload at room temperature was close to 747 tons, which is 58 % of the required preload of 1300 tons estimated by a numerical analysis. However, the reduced preload by the cool down itself was approximately 146 tons. As a result, the remaining preload of the CS structure after the cool down process was nearly 600 tons.

4. CONCLUSION

The major tokamak structures of the KSTAR were successfully designed, fabricated, installed, and operated in the integrated commissioning stage. Most of the design requirements for the first plasma experiment were successfully achieved without any trouble or failures that prevented the machine from operating during this stage. The KSTAR assembly process was finally completed by May of 2007 with several unique strategies, as mentioned above. This concept proved to be very effective in the assembly of the superconducting tokamak. The assembly work also was verified in terms of quality control through successful vacuum commissioning. This result will be reported in a future paper. All of the experiences and technologies achieved through the KSTAR construction process will be key fundamentals for future construction projects of superconducting fusion devices.

However, every major structure that is described in this paper should be carefully monitored and maintained in future KSTAR operation stages, as the operational condition in the first plasma experiment was not the final condition for the original mission of the KSTAR. Furthermore, a number of key structures, including the plasma facing components (PFCs), should be upgraded from the next campaign, which implies that additional demanding engineering research should be dealt with before the KSTAR can play the important role of a world-renowned fusion research device.

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