Key Features and Progress of the KSTAR Tokamak Engineering

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Abstract. Substantial progress of the KSTAR tokamak engineering has been made on major tokamak structures, superconducting magnets, in-vessel components, diagnostic system, heating system, and power supplies. The engineering design has been elaborated to the extent necessary to allow a realistic assessment of its feasibility, performance, and cost. The prototype fabrication has been carried out to establish the reliable fabrication technologies and to confirm the validation of analyses employed for the KSTAR design. The completion of experimental building with beneficial occupancy for machine assembly was accomplished in Sep. 2002. The construction of special utility such as cryo-plant, de-ionized water-cooling system, and main power station will begin upon completion of building construction. The commissioning, construction, fabrication, and assembly of the whole facility will be going on by the end of 2005. This paper describes the main design features and engineering progress of the KSTAR tokamak, and elaborates the work currently underway.

1. Introduction

After the completion of its preliminary conceptual design in 1998, the extensive engineering work of the main tokamak subsystems had been progressed with industrial manufacturers by May 2002. As of Sep. 2002, the project is in the fabrication and procurement phase. The fabrication of vacuum vessel, cryostat, and supporting structures is launched and well progressed. The manufacturing work of coil and prototype magnet structure is also proceeding favorably. For the in-vessel components and thermal shields, we are aiming to finish engineering design by Dec. 2002. The tokamak assembly will start from March of 2003 after site preparation and assembly jig. Figure 1 shows the inside of the KSTAR experimental hall.

2. Vacuum Vessel

The KSTAR vacuum vessel is an all-metallic, all-welded, double-walled, and D-shaped structure. It consists of the inner and outer shell, horizontal, vertical and slanted ports, and the leaf spring style supports. Double walls are connected by poloidal and toroidal ribs and filled with water for bake-out, cooling and neutron shielding. 32 equally spaced poloidal and 2 toroidal ribs provide a robust reinforcement. The shells and ribs form the flow passage for the vessel cooling water. The torus structure of the vessel is welded into 3 sectors and they are assembled using splice plates at on-site by field welding. The vacuum vessel has 7 different port structures that will be used for device installation, utility feed-throughs, vacuum pumping, and access for maintenance. The details of the extensive stress analyses and the fabrication of vacuum vessel are summarized in Ref. [1]. Table I shows the major parameters of the KSTAR vacuum vessel. The vessel material is ASME section Ⅱ Part A SA240-316LN. All of the loading conditions including electromagnetic, seismic, operational pressure, thermal and test loads, and load combinations have been categorized and classified to permit the allowable stress to be defined in accordance to ASME code. The most severe load condition for the vacuum vessel is the load combination of static and electromagnetic load due a vertical disruption event. The calculated stresses in all of the load conditions and load combinations are below the allowable values. To monitor the behavior of vessel, there will be instrumentation using thermocouples, pressure gauges, strain gauges, and acceleration sensors.

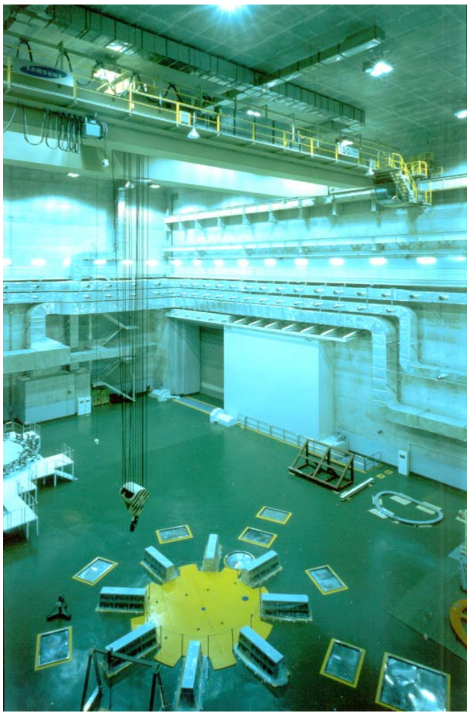

FIG. 1. Inside of the experimental hall

TABLE I: PARAMETERS OF VACUUM VESSEL

Parameters	**Values**
Height/width	3.387 m / 1.880 m
Shell, rib thickness	12 mm, 20(40) mm
Wall thickness	50 ~ 190 mm
Total weight	72 ton (with support)
Surface area (inner shell)	100 m^2 (without port)
Base pressure	1×10^{-6} Pa
Material	SA240-316LN
Baking temperature	130℃ @inner shell
Magnet permeability	1.10 (after welding)
Loop resistance	≥40 μΩ
Number of shell plates	180
Number of rib plates	120
Number of ports	72
Length of welding joint	1,542 m (×7)

To develop and establish the reliable fabrication technologies, Hyundai Heavy Industries (HHI) has built a full-scale vacuum vessel with 62-degree sector in toroidal direction. In the manufacturing process of the prototype vacuum vessel, we optimized the arrangement of welding jigs and fixtures considering the expected deformation and the difference of the rigidity of double-walled structure in inboard and outboard segment. The prototype has satisfied the dimensional accuracy of ±8 mm to the total height, and ±5 mm to the total width. In the helium leak test, any leak larger than 7.5×10^{-9} Pa·m^3/s were not found at inter shell vacuum of 1.5×10^{-5} Pa.

For the main vacuum vessel fabrication, we purchased stainless steel 316LN of 154 tons from NKK in Japan. To minimize the final assembly time on site, and to deliver a vessel structure with a high quality, the vacuum vessel is to be fabricated in the factory as two large sectors (180, 157.5 degrees) and one small sector of 22.5 degrees span. The advantages of these large sectors are as follows: (i) the improvement of dimensional stability due to the reduction in field joint welding, and (ii) the reduction of assembly cost by reducing the number of field joints. The practicality of transporting such large sectors from the factory to the site is already checked through the road survey.

3. Magnet Structure

The KSTAR magnet structure consists of 16 TF structures, one CS structure and 80 PF structures. The major functions of the TF coil structures are mechanical, electrical, and thermal protections of the TF coil and support for the gravity of the CS and the PF magnet system. The CS magnet system is mounted on the top end of the TF structures. The each segmented PF structure basement locates on the TF coil case. The engineering design of KSTAR magnet structure had been performed by the HHI and reviewed by Efremov Institute.

The TF structure consists of the TF coil case, the intercoil structure, and the auxiliary structures that contain the PF structure basements, the joint box, and the toroidal ring basement [2]. The TF structure is a wedge shape to sustain the strong centering force due to the TF coil energizing. Each TF structure is bolted in intercoil structure with shear key and insulation. Specially, conical bolt is adapted in inner intercoil structure for enlarging endurance for shear stress. Cooling line is embedded in inner surface of the TF coil case and attached on outer surface of the intercoil structure. The CS structure is a wedge-type for providing pre-compression in order to prevent free motion due to repulsive force between the CS coils [3]. It is segmented in octant through toroidal direction that is connected by bolting with insulation. The PF structures are of hinge-type for PF5 and of flexible plate-type for PF6 and PF7. It is designed for allowing radial displacement relative to the TF structure due to cool down and energizing of the PF coils, and restricting vertical displacement. Figure 2, 3 show some fabrication procedures of prototype TF structure. Prototype fabrication of TF structure will be finished by early next year.

FIG. 2. Inboard leg structure

FIG. 3. Outer intercoil structure

4. Cryostat

The KSTAR cryostat is a large vacuum vessel surrounding the entire tokamak machine with single-walled cylindrical shell, dome-shaped top lid, and a flat bottom lid. It provides feed-through penetrations for all the connecting components inside and outside the cryostat. There are 102 ports including 72 vacuum vessel port penetrations with bellows to compensate the displacements of ports due to EM loads and thermal loads within allowable limits. The cryostat is mounted on a base plate for transferring the loads to main building support structure through 8 supporting beams. The dome shaped lid structure will be removable for assemble and major maintenance activities. Extensive information about cryostat structural analyses can be found in Ref. [4]. HHI has been fabricating the cryostat vessel since May 24, 2002. Now they are preparing the stainless steel 304L of 267 tons, and manufacturing drawings and procedures.

5. Thermal Shields

There are four types of thermal shields: (i) the vacuum vessel thermal shields (VVTS) located 5 cm off the outer wall; (ii) the cryostat thermal shields (CTS) located 15 cm off the inside cryostat; (iii) the transition thermal shields (TTS) that enclose the port connection ducts; and

(iv) the support thermal shields (STS) that enwrap the gravity supports and base plate. In case of the VVTS, MLI (Multi-Layer Insulation) is not used due to the narrow gap of 55 mm between vacuum vessel and superconducting coils and for reliability, while the cryopanel is covered on both sides with a thin, low emissivity layer of silver. The VVTS has to closely follow the shape of the vacuum vessel for space reason. The CTS and TTS are not constrained spatially, and have more relaxed tolerances. Therefore MLI will be used between the panels and the cryostat wall. The cryopanel is made of two stainless steel plate and rectangular stainless steel pipe welded in between. At present, the detailed design of the thermal shields is actively progressed. The main fabrication will be started from Aug. 2003 and will be finished by May 2004.

6. In-vessel Components

6.1 Plasma Facing Components

The engineering design on the plasma facing components (PFCs), including the thermal and structural analyses has been carried out since Sep. 2001. All baseline PFCs will be water-cooled on plasma operation to maintain the surface temperatures of graphite and CFC tiles less than 600 ℃ and 1200 ℃, respectively. And, the baking temperature of the PFCs, at least 300 ℃, can be achieved within 12 hours. Hot nitrogen baking gas for the PFCs is supplied through separate routes. Stress analyses for the situations of normal operation, plasma disruption, and bakeout have been carried out using ANSYS. According to the stress analyses, the baking imposes severe thermal stresses on the PFC support structure.

One sector of prototype inboard limiter, shown in Fig. 4, has been fabricated to confirm the assembly difficulties. It consists of a stainless steel 316LN back-plate, 25 mm t x 470 mm x 690 mm, 20 IG-43®graphite tiles, two 0.5 mm thick PF-50HP® carbon sheet, and 4 sets of Ti-6Al-4V supports. Baking/cooling channel exists inside of back-plate. Helium leak test and hydraulic pressure test up to 22 bars have passed.

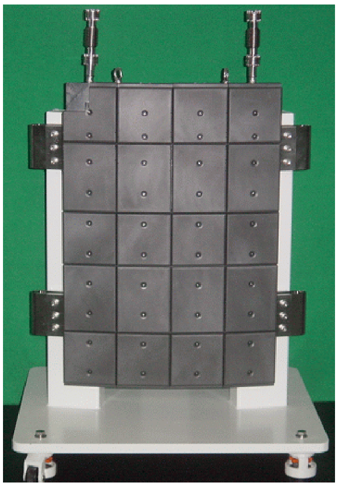

FIG. 4. Prototype inboard limiter

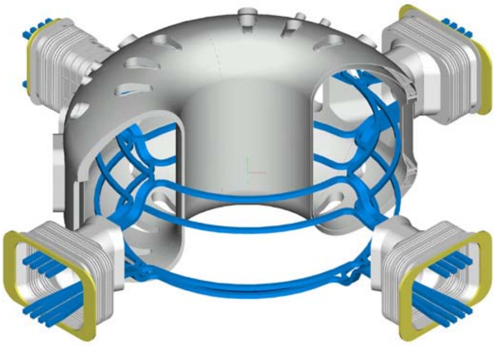

FIG. 5. Configuration of segmented IVCC

6.2. In-Vessel Control Coils (IVCC)

Since middle of 2001, the KSTAR IVCC system for inner plasma position control (IC), field error correction (FEC), and resistive wall mode (RWM) has been changed to be a toroidally segmented configuration as shown in Fig. 5. This IVCC system is composed of 4 coil sets such as top, upper, lower, and bottom IVCCs along the vertical position. These every 4 coil sets are again divided by 4 segments. Each segment consists of eight copper bars that are partially grouped for IC and FEC/RWM part, several insulation layers, and case material. All the coil specifications are determined through 3D structural analyses because the IVCC should endure severe conditions such as electromagnetic and thermal loads due to the non-uniform system, which means that carrying several different currents in a segment. The detail designs on segmented coils and its support system are almost fixed.

7. Assembly

The engineering design for assembly was started from Aug. of 2002, and will be completed within one year. The definition of the assembly engineering design is to develop the assembly sequences, the jig & fixtures, and logistics, and to estimate the assembly schedule and cost. The scope of the assembly job includes pre-assembly of the components, sub-assembly of the integrated assembly units, and final assembly on position. Presently, the cryostat supporting beams are already installed in the experimental hall. The cryostat base and the gravity support for the magnets will be installed on May of 2003. The major assemble activities will be started in the beginning of 2004 when the vacuum vessel sectors, magnets, and assemble jigs are delivered. All the assembly activities for the first plasma will be finished by June of 2005.

8. Conclusion

The engineering design and prototype fabrications of the major parts of the KSTAR have been finished and the results of these activities defined a machine with unique set of capabilities. As of Sep. 2002, the project is in the fabrication and procurement phase. The vacuum vessel, cryostat, and supporting structures are being manufactured by Hyundai Heavy Industries. Main vendors for the magnet structures and cryogenic system will be contracted soon and site assembly will be commenced from March of 2003. Upon its successful commissioning in year 2005, the KSTAR will be delivered and served for the world fusion community as an international fusion collaboratory.

Acknowledgement

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