ITER CENTRAL SOLENOID MANUFACTURING R&D

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Abstract

The International Thermonuclear Experimental Reactor (ITER) Engineering Design Activity (EDA) includes the development of high performance superconductors, high current joints between superconducting cables and insulating materials. Also in the EDA, the resulting products of this R&D are incorporated in a Central Solenoid Model Coil which utilizes full size conductors. The manufacturing of the model coil and components has led to the development of the design, materials, tooling and process which are fully applicable to the manufacture of the ITER relevant CS coil. The R&D is essentially complete and final stages of the CS Model Coil manufacturing are underway.

1. INTRODUCTION

The extensive program of superconducting magnet development undertaken during the ITER Engineering Design Activity (EDA) includes the design, fabrication and testing of a Central Solenoid Model Coil (CSMC) with 3 exchangeable insert coils and superconductor development for the ITER coils. The model coil program will confirm the design criteria and performance of the ITER conductor, develop and verify manufacturing tooling and processes, and verify material performance following fabrication processes. The CSMC [1-3] is being constructed using full size ITER CS conductors (2 grades) and consists of an inner module of 10 layers (total 328 turns) and an outer module of 8 layers (total 272 turns). The coil which has an inner diameter of 1.58 m, an outer diameter of 1.78 m and a height of 2.78 m including two, 0.5 m high lead regions, stores an energy of over 600 MJ. The model coil will be supported by a 70 tonne stainless steel structure which will provide gravity support and also provide preloads necessary for the operation. The coil peak field will be 13 Tesla at the operating current of 46 kA and the coil will be tested at a nominal field change rate of 1.2 T/s. The two modules and the insert coils will be connected to each other and to the power supply using superconducting busbars. The inner module, the support structure and the busbars are being fabricated by the United States Home Team (USHT) while the outer module and the test facility are being fabricated by the Japanese Home Team (JAHT). The CS insert coil and a niobium-aluminum insert coil are being fabricated by the JAHT while the RFHT is fabricating the TF insert coil. The installation of the model coil and the insert coils in the test facility at Japan Atomic Energy Research Institute (JAERI) in Naka will be led by

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the JAHT. The Joint Central Team (JCT) provides the coordination of the program and activities and provides support for technical evaluation and design of interfaces.

2. SUPERCONDUCTOR FABRICATION

The conductor (two grades are used in the model coil) is a round cable of about 1100 Nb_3Sn superconducting strands within a heavy-walled Incoloy 908 jacket with a square outer section (about 5 cm x 5 cm) [4]. About 25 tonnes of Nb_3Sn strand (approx. 0.8 mm diameter) for the CSMC program has been manufactured by 6 companies in the 4 Home Teams and cabled (about 1100 strands per cable) by 4 companies. About 6000 m of heavy walled, square Incoloy 908 jacket material from the USHT, as well as cabled superconductor from the European Union (EUHT), JAHT and USHT were supplied to the EUHT for jacketing. The jacket was delivered in lengths of 8 - 10 m, then butt welded to obtain the required lengths of up to 220 m. The finished cable was then pulled into the jacket which was compacted around the cable to control the He void fraction. All of the cables for the 18 layers of the CSMC have been jacketed by the EUHT and supplied to the JAHT and USHT. In addition, the superconductors for the insert coils have also been fabricated. The production issues and quality issues for the jacket fabrication were identified and resolved and lessons have been learned for the production requirements and in-process Quality Assurance (QA). The development of jacket welds has led to a detailed understanding of the welding process and material requirements. The superconductor fabrication has demonstrated long length production capability for the ITER coils and the quality of conductor produced for the CSMC has proven to be adequate for the fabrication of the CSMC.

The SAGBO (Stress Assisted Grain Boundary Oxidation) sensitivity of the Incoloy 908 jacket material to the heat treatment environment has been quantitatively understood with an extensive program of SAGBO studies [5] in the JAHT and USHT. The requirements for SAGBO-free heat treatment can be and have been achieved reliably. The jacket material characterization program has resulted in a wealth of data on the strength and toughness of the Incoloy 908 material before and after heat treatment. Additional extensive R&D studies have also been carried out on the weld metal characteristics before and after heat treatment.

3. JOINTS

The outer module has butt joints [3,6] between the layers and lap joints are to be made between the busbars and the terminals. A butt joint prototype [Fig. 2] with a U-shaped cable showed a satisfactory DC resistance of 3.8 nano ohms and an AC loss time constant of only 70 ms. The lap joint has shown lower resistance of 2.7 nano ohms, but has a higher although adequate time constant of 500 ms. The inner module uses lap joints between layers and to the terminals. A preprototype joint and a prototype joint [7] have been tested. The prototype joint which is essentially of the same design as the inner module has a low DC resistance of 2.1 nano ohms and an adequate time constant of about 400 ms. The intensive development of high current joints between superconductors has resulted in highly satisfactory design options for joints for ITER.

4. CS MODEL COIL FABRICATION

The conductor for the ITER CS is layer wound, four-in-hand, to limit the maximum cooling path length to about 1000 m. Both the inner and outer modules for the CSMC are layer wound (two-in-hand), leads formed and terminations for the joints are added and the layer is heat treated. For the inner module, thick sections of tension plates and shear plates of Incoloy 908, which provide support against lead forces, are welded to the leads prior to heat treatment, while only tabs are welded on the leads in the outer modules and additional sections are added afterwards to link the leads. The conductor has been wrapped with 1.5 mm thickness glass-Kapton-epoxy sheet for turn insulation. Between the layers a 4 mm thick space has been provided including 2 mm thickness layer insulation. The layers are assembled with buffer zone segments, provided at the top and bottom of the winding in order to support the leads. Tension links have been provided between the conductors joined to withstand hoop forces generated during coil operation. The layers are epoxy impregnated by the Vacuum-Pressure-Impregnation (VPI) process. The outer module joints are assembled prior to impregnation while the inner module joints are assembled after the VPI. (See also ref. 1 for fabrication and process details).

4.1 Winding, lead forming and termination

The winding of two different sizes of conductors and corkscrewing of the wound coil to form two-in-hand layers of the inner module was achieved reliably with a short cycle time. While, the variation in radius after winding was large (up to 25 mm) for the inner module, the average radius was well controlled to the specification required for the assembly process. For the outer module, much closer variation (~5 mm in radius) was required and achieved.

After much development work, the lead forming and tension plate welding processes were finalized and a well controlled process was obtained. The tension and shear plate welds on the inner module required a high degree of QA and the process was improved to eliminate weld defects. Similar experience was also gained on the outer module.

The main effort on the inner module termination development was related to brazed and welded joints between Glidcop, Monel and Incoloy components. An extensive development was carried out for adding a low resistance / low loss interface between the conductor cable and the U-shaped cable of the butt joint. All the materials and joints for these terminations and joints have been qualified for the requirements to operate the modules in the JAERI facility. All the leads and terminations were completed with correct geometry.

4.2 Heat Treatment

The most sensitive part of the fabrication is the heat treatment of the layer wound coils. Since the residual stresses in the Incoloy 908 jackets are high and the heat treatment temperature is in the SAGBO regime, the environment of the furnace and the cable space was controlled. The turns and lead supports were shot peened to place the Incoloy surface in compressive stress. The heat treatment of the inner module layers was carried out in vacuum and the cable space was intensively purged to remove all contamination including any oil. For the outer module layers, the elimination and pump out of the contaminants was done up to the temperature of 520 C in vacuum and the heat treatment at higher temperatures was carried out in high purity argon. Witness samples of strands and conductors were added to the coils and tested. For both modules, the oxygen content was less than 0.1 ppm and the water vapor content was below 5 ppm during the heat treatment. All the 18 layers were successfully heat treated and the co-heat treated strand samples have been tested and show good performance. The JAHT has carried out tests on co-heat treated full size samples and these also show adequate performance.

4.3 Turn Insulation

The insulating process is carried out with the coil horizontally for the inner module and vertically for the outer module. In both cases, turn insulation, consisting of prepreg glass/Kapton tapes, is applied and cured on each layer before the layer is assembled on the coil. While the insulation on the main turns was done with an automatic process [2], the tension link and lead areas were insulated by lay ups and a convection furnace for curing.

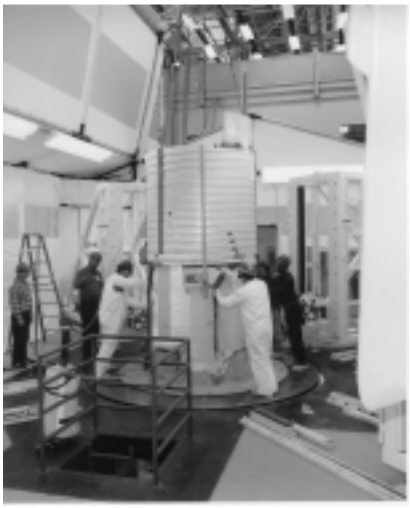

FIG. 1. Layer on layer assembly of the inner module

FIG. 2. Butt joint of the outer module

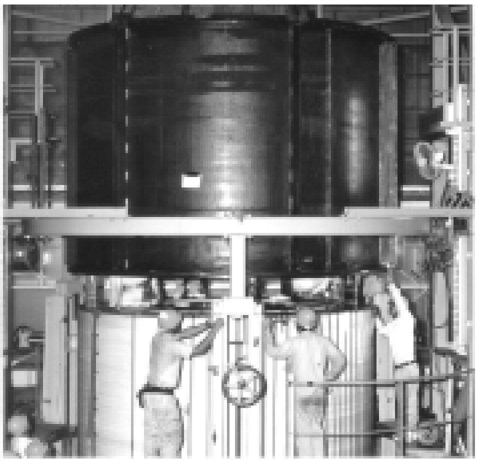

FIG. 3. A mould for VPI is being installed on the outer module

4.4 Coil assembly

The assembly of each of the modules is carried out by placing the innermost layer over a mandrel and a bottom plate and then assembling the outer layers one over the other. The assembly tool is rotated while the turns are compressed. In each case the buffer zone pieces and layer insulation are added and welding of tension links is carried out at the appropriate steps. For the inner module, the assembly (Fig. 1) is carried out starting from a slightly larger coil and then compressing it by pushing on the turns. The correct radius and azimuthal location of the coil leads is obtained simultaneously. The combination of turning the coil and pushing of the turns was optimized to minimize the damage to the dry glass wrap. For the outer module, since the layers are wound in a slightly smaller diameters than the final, each layer is expanded a little and lowered over the inner layer and pushed to get the final geometry. All the layer assemblies in both modules have been completed and the lead locations have been obtained to an accuracy of ±1 mm and the inner module inner and outer radius which are constrained is also within ±1 mm.

4.5 Vacuum Pressure Impregnation (VPI)

Each of the modules is impregnated with epoxy and cured at a temperature of about 120 C. For the outer module, the coil is baked out in vacuum of around 1 Torr at 120 C, cooled down to 50 C. The epoxy is mixed with the hardener as a batch in a mixing tank and injected from a height at a temperature of 50 C while both the tank and the coil are in vacuum. The coil and the epoxy are raised to the curing temperature of 120 C and a pressure of 6 atm and cured. The impregnation has been completed for the outer module successfully.

For the inner module, preparations for the impregnation are under way and two VPI trials have been conducted. The selected process uses an in-line mixer for the epoxy and hardener while being injected. The bake out is to occur at 90 C in vacuum. The epoxy is injected at 50 C and then gelled at a temperature of 90 C. The pressure is then to be raised to 2 atm and the epoxy is cured at 120 C.

5. CONCLUSIONS

The fabrication of the CS Model Coil is nearing completion. The fabrication of the 8 layer outer module is essentially complete, while the inner module is being prepared for vacuum epoxy impregnation after which the interlayer joints will be made to complete fabrication. It will then be shipped to the JAERI facility. All the heavy and complex structural parts have been fabricated. All the busbars except for one and all the helium plumbing are complete. All these components will be assembled and testing is expected to begin in the summer of 1999. The R&D effort has led to the full development of the process of fabricating the high performance ITER superconducting strands, jacket materials and conductors, high current joints with stringent DC and AC performance requirements, insulating materials for coil turns, layers and leads and process of insulating. The process of fabricating a CS coil with the heavy walled conductors to precise geometry with strict limits on conductor strain during fabrication, heat treatment of the conductors while eliminating any SAGBO risk in Incoloy jackets and finally the assembly process of the layer and VPI process have been fully developed.

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