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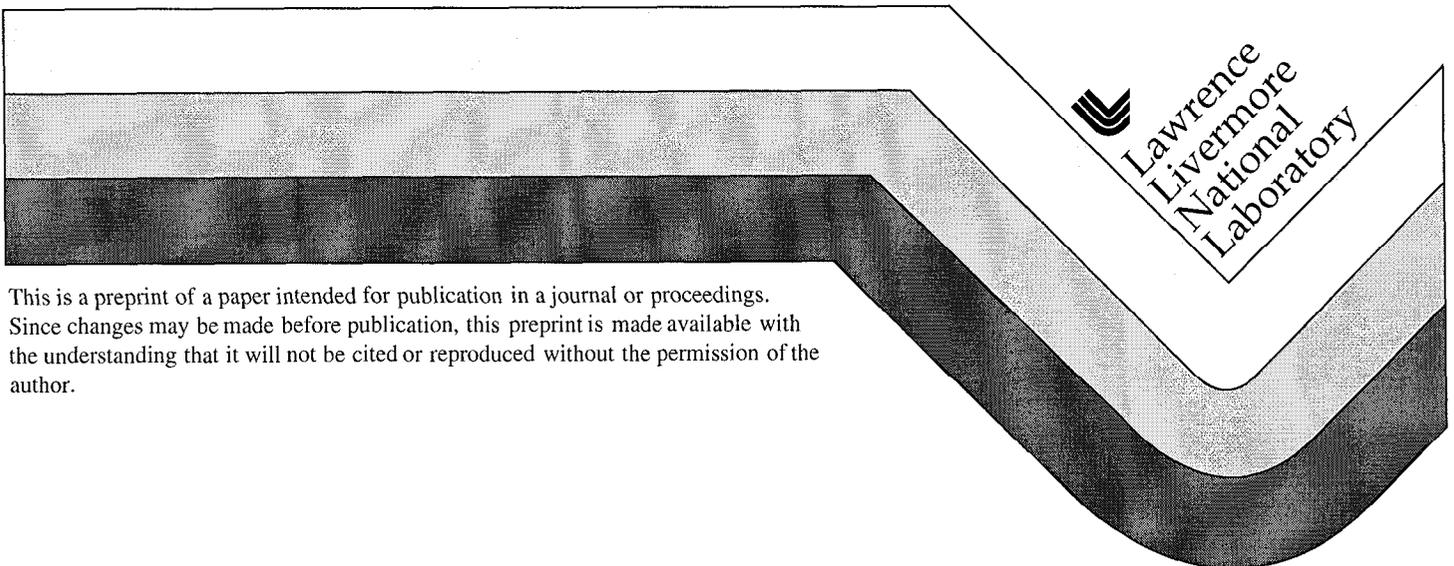
PREPRINT

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Fabrication of the Inner Module for the ITER Central Solenoid Model Coil

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Abstract

The Central Solenoid (CS) designed for the International Thermonuclear Experimental Reactor (ITER) is a 13 T, 42 kA coil with a winding pack mass of 863 t, cooled by supercritical helium.

To demonstrate the feasibility of the design and performance of the CS a CS Model Coil project was carried out during the ITER Engineering Design Activity in 1994-1999.

This paper describes the R&D and fabrication effort during this project with a focus on the construction of the Inner Module of the CS Model Coil by the US Home Team.

Introduction

Design of the ITER magnet system is given in [1]. Construction of such a large system, orders of magnitude larger than cable-in-conduit magnets built so far requires representative fabrication trials, conductor and insulation development and testing. During the ITER Engineering Design Activity, a CSMC (CS Model Coil) project was launched to address these issues on a representative model of the CS. Similar program was started on the Toroidal Field Magnets in European Community at the same time.

This CSMC project includes the design, fabrication and testing of a Central Solenoid Model Coil with three 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 CS Model Coil [1-3] has been constructed using full size ITER CS conductors (2 sizes) 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 height of lead regions, stores an energy of over 600 MJ. The model coil will be supported by a 70-ton stainless steel structure that will provide gravity support and also provide preload 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 up to a ramp rate of 1.2 Tesla/sec. The two modules and the insert coils will be connected to each other and to the power supply using superconducting busbars. The United States Home Team (USHT) has fabricated the inner module, the support structure and the busbars while the Japanese Home Team (JAHT) has fabricated the outer module and the Test facility. The CS insert coil and a niobium-aluminum insert coil are being fabricated by the JAHT while the Russian Federation HT is fabricating the TF insert coil. The installation of the model coil and the insert coils in the JAERI test facility in Naka is led by 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.

The characteristics of the CSMC are either identical to or of the same order as those required for the ITER CS (Table 1) except for the height of the coil system and the maximum weight to be handled. Smaller diameter of the Model Coil added a lot of challenges to fabrication and assembly of a very stiff layers, a problem much easier handled on a full scale ITER CS.

The sequence of the CS Inner Module fabrication was the following:

1. Conductor fabrication
2. Layer winding
3. Assembly a layer of two conductors
4. Lead bending

5. Welding reinforcement plates on the layer
6. Installation of the terminations for joints
7. Heat treatment of the conductor
8. Installation of the turn insulation
9. Layer assembly into module
10. Vacuum pressure Impregnation
11. Joint Assembly
12. Installation of the ground plane insulation

Table 1 CSMC Module features compared with the ITER CS

Feature	CSMC Inner Module	CSMC Outer Module	ITER CS
Max magnetic field, T	13	7	13
Operating current, kA	46	46	42
Coil ID, m	1.6	2.75	3.8
Coil OD, m	2.69	3.6	5.4
Height with joints, m	4.5	4.5	15.3
Total turns	328	273	3373
Conductor piece length, m	86-146	154-192	760-1040
Coil mass	47	50	863
No of joints	19	15	52

Conductor Fabrication

The conductor (two grades are used in the model coil inner module) is a round cable of about 1100 Nb₃Sn superconducting strands within a heavy-walled Incoloy 908 jacket with a square outer section (about 5 cm x 5 cm) [2]. About 25 t of Nb₃Sn strand (approx. 0.8 mm diameter) for the CSMC has been manufactured by 6 companies of all 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 delivered in lengths of 8-10 m, 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 the 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 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 developed QA/QC procedures.

The SAGBO (Stress Assisted Grain Boundary Oxidation) sensitivity of the Incoloy 908® jacket material to heat treatment environment has been quantitatively understood with an extensive program of SAGBO studies [3] in JAHT and USHT. The requirements for SAGBO-free heat treatment can be and have been achieved reliably, although required very careful procedure, which eliminated cracking of the conduit material. 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.

Fig. 1. shows preparation of the inner module layer for heat treatment in a vacuum furnace.

Joint development:

The inner module uses lap joints between layers and to the terminals in a "praying hands" configuration (see Fig.2). The joint design provides a strong support to react electromagnetic and cooldown forces and gives a secondary containment to the joint assembly, thus enhancing reliability of the joint.

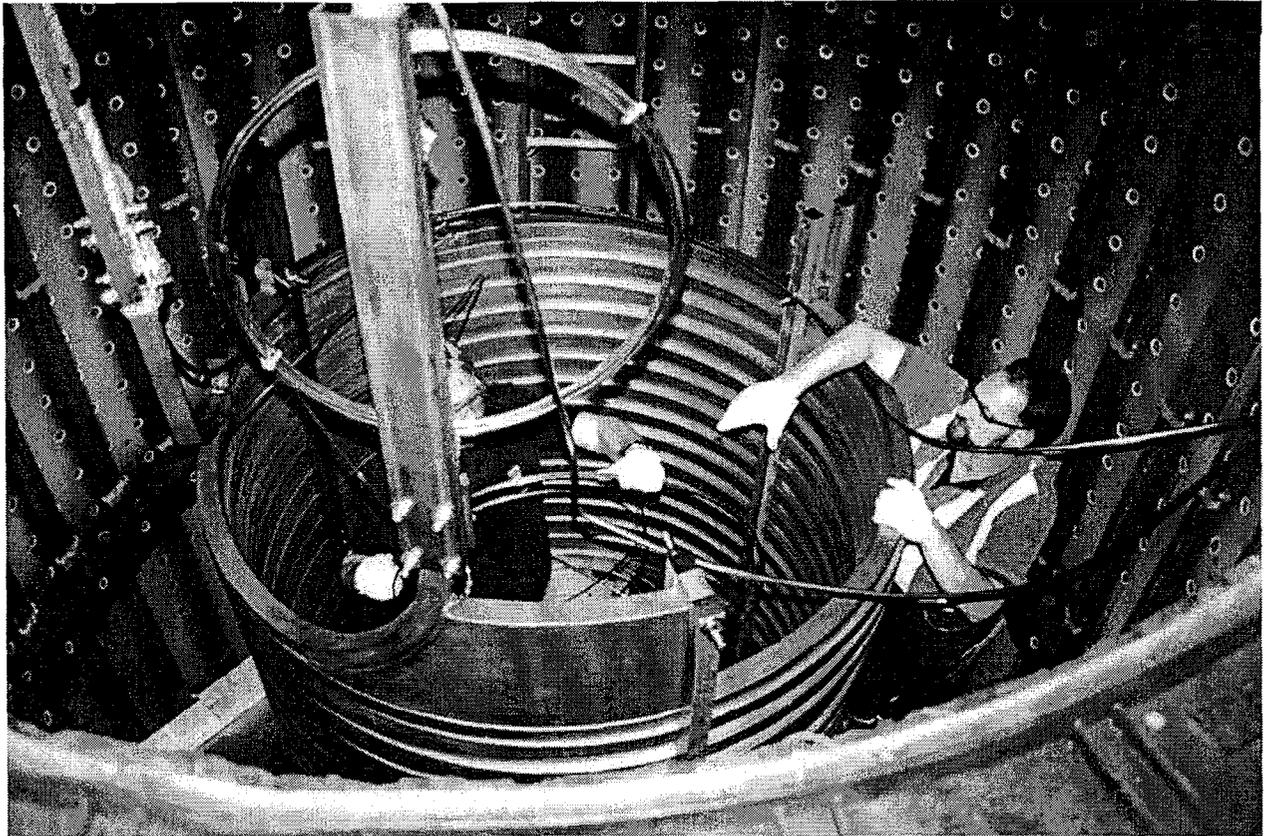


Fig. 1. Installation of the layer in the furnace

A Preprototype joint and a prototype joint 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 manageable losses in the ITER relevant scenarios. The intensive development of high current joints between superconductors has resulted in highly satisfactory design options for joints for ITER. JAHT developed a butt joint, which met ITER specifications as well [4] with somewhat higher resistance (3-6 nOhm) and significantly lower losses.

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. Extensive R&D were required to achieve such tight radius control in winding. The average radius was well controlled to specification required for the assembly process. This allowed placement of each layer within space envelope allocated for an ideal layer ± 1.5 mm at the final assembly, required by the specifications.

After much development works the lead forming and tension plate (seen in the foreground in Fig.1) welding process were finalized and a well controlled, although it

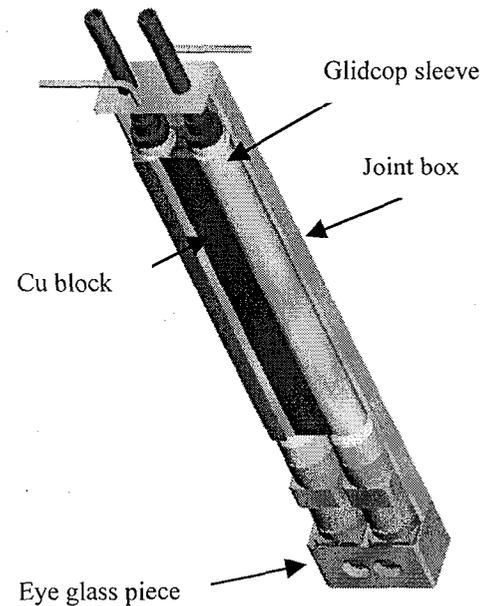


Fig. 2 ITER CSMC praying hands joint

was a laborious and tool intensive process. The maximum deviation from the ideal position of the lead was within +/- 2 mm.

The tension and shear plates welds on the inner module required a high degree of QA effort 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.

Turn Insulation

Turn insulation, developed for the full ITER CS was employed for the CS Model Coil. The turn insulation is 1.5-mm thick composite of interleaved layers of kapton and radiation resistant prepreg required a cure before assembling the layers in the coil. With a requirement of 3 kV dielectric strength for the turn insulation, it was tested successfully up to 25 kV. It turned out to be a very strong and a robust insulation, which helped tremendously at layer assembly stage. The insulating of all the layers were carried out successfully. While the insulation on the main turns was done with an automatic process (Fig. 3), the tension link and lead areas were insulated by lay ups and a convection furnace for curing.

Coil assembly

The assembly of each of the modules is carried out by assembling 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. 4) 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. All the layer assemblies in both the 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

Vacuum Pressure Impregnation (VPI)

The Inner Module is impregnated with epoxy and cured at a temperature of about 120 C.

The selected process used an in-line mixer for the epoxy and hardener while being injected. The bake out was carried out at 90 C in vacuum. The epoxy is injected at 50 C and then jelled at a temperature of 90 C. The pressure then was raised to 2 atm and the epoxy is cured at 120 C.

The impregnation process went well and no major defects were detected after

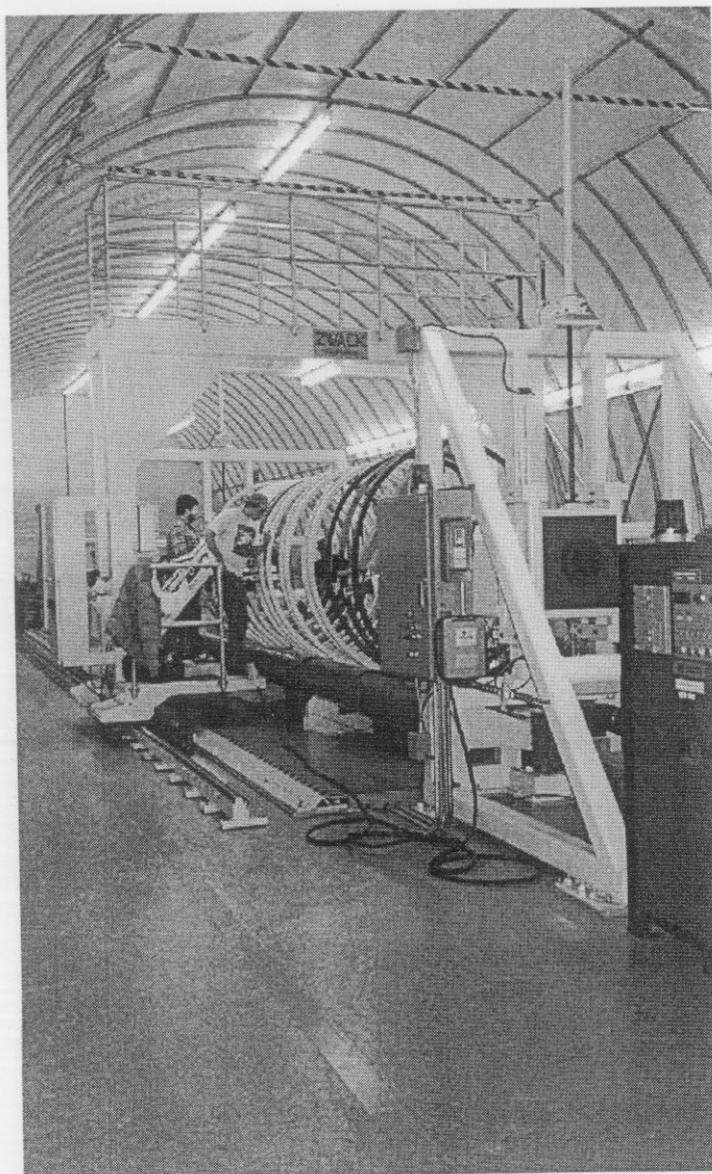


Fig.3 Turn insulation machine

removing the mold.

To our knowledge, the Inner Module was the largest volume impregnated in the US in one step.

Conclusions

The fabrication of the CS Model Coil is complete and installation of the coil for testing is underway. 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 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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Fig.4. Inner Module assembly - installation of a layer

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