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# ITER Central Solenoid Module Fabrication Program

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General Atomics (GA) is currently under contract to manufacture the ITER Central Solenoid Modules (CSM). The contract is managed by the US ITER at Oak Ridge National Laboratory, under the sponsorship of the Department of Energy Office of Science. The contract includes the design and qualification of manufacturing processes and tooling necessary to fabricate seven CSM (6 + 1 spare) that constitute the ITER Central Solenoid. The modules will be produced and delivered to the ITER site during 2017–2019.

GA has established a fabrication facility that combines 1,500 m$^2$ of offices with 6,000 m$^2$ of fabrication space. Extensive building modifications were made in anticipation of the first tooling station which arrived in February of 2014. The facility utilizes several cranes with up to 35T capability to handle and move delivered conductor and wound hex and quad pancakes during the winding, joint and lead fabrication, and stacking operations. The 110-ton coil is moved from station to station via a self-propelled air-bearing cart designed specifically for this application.

Critical systems have been designed, built and initial testing completed for use in fabricating the CSM. The winding stations were designed, built and successfully tested at the Tauring S.p.A factory in Turin Italy. The reaction heat treatment furnace has been designed, built and tested at Seco-Warwick facility in Sweibodzin, Poland. Insulating wrapping heads were completed by Ridgway Machines Ltd of Leicester, England and shipped to GA. GA has designed and built several other key tooling stations for joining the coil segments, insulating the turns and vacuum pressure impregnation. Qualification of the equipment is accomplished with Factory Acceptance Tests at the supplier's facility, Site Acceptance Tests and commissioning at GA, and is completed with the production of the mockup coil prior to using the station for the fabrication of the first CS module.

Keywords: Magnets, superconducting, ITER

## 1. Introduction

General Atomics (GA) is currently under contract to UT-Battelle/Oak Ridge National Laboratory to manufacture the central solenoid for ITER. The design of the Central Solenoid Module (CSM) is the responsibility of the US ITER team [1]. GA is responsible for designing the processes and tools, and then qualifying them by building a mockup coil prior to initiating the manufacturing of the first of seven modules. Ten process stations have been developed for the manufacturing process.

A 6,000 m$^2$ facility has been established in which to build the coils. In preparing the facility, General Atomics replaced the existing concrete floor with 0.6 m thick reinforced concrete with tight requirements on the flatness to support the 110 tonne coils and manufacturing workstations. Three cranes were installed to assist in moving spools of conductor, tools and materials in the facility. The cranes will be used to load the conductor on the winding station and move the wound hex/quad pancakes from the winding table to the station where the CSM is joined into a 110-tonne coil at the fourth process station. From this station on, the CSM will be moved using a specially designed transporter using air bearings. The Coil Transport Tool (CTT) designed and built by AirFloat of Decatur, Illinois has been delivered to GA. Using four air bearings, the CTT floats the tool and coil across the floor to the next process station. The tool was proof loaded and tested using 200 tonnes of steel plate. The test confirmed its capability and the recently poured concrete floor flatness (3 mm over 3 m). The CTT interfaces with a common stand used at all process stations. In addition, a frame is used underneath the CSM for support and to distribute the load from the four lift points of the CTT.

## 2. Process Stations

A total of ten process stations comprise the CSM manufacturing line. As part of the development process, each process station undergoes a series of four reviews with the final review being a Manufacturing Readiness Review. At the review's successful conclusion, processing of a mockup coil with dummy copper cable can commence. The mockup coil is processed identical to a CSM except it has only sixteen layers as compared to forty for a CSM; the mockup serves as the final qualification step. Each process station has specific travelers and procedures for completing the manufacturing process at that station.

### 2.1 Conductor Receiving

The conductor is received at the GA manufacturing facility where it is unloaded from trucks, inspected and prepared for winding. Lifting fixtures, designed and built to interface with the conductor-shipping fixture, are used to transfer the conductor to a custom wheeled cart. The cart transports the conductor from the receiving area to the winding station.

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### 2.2 Hex/Quad Pancake Winding

At the winding station, the 900 or 600 m length spools of conductor are continuously wound into hex/quad pancakes. Each pancake consists of fourteen turns. The winding station consists primarily of a custom designed and built system by Tauring SpA, a maker of computer controlled bending machines. Due to the potential variability in the material properties of the conductor, precise forming of the conductor was not viewed possible. Instead, the length of each conductor turn is measured as it is formed and these formed turns are aligned on the winding table using reference marks made during the forming process. With this process, the average turn radius must lie within the acceptable limits.

The first process of the winding station is the loading of the conductor spool onto a de-spooler, where it is lowered directly into a three roll straightener. The straightener peels the bottom turn off the spool, and straightens the conductor. The straightened conductor is sandblasted to roughen the surface prior to entering the bending machine. At the entrance of the bending machine, the conductor is measured and marked using a set of rotary encoders and an inkjet printer. The shape of the conductor is formed by a multi-axis bending machine where the position of the rolls is controlled by Tauring's proprietary software Wintau. A calibration curve is generated at the beginning of each spool of conductor to account for variability between spools.

After forming, the turns are placed on a winding table with four axes of motion, (X,Y,Z, rotation). The spacing of the turns is maintained using hardspacers manually placed after the turns are placed on the table. Rigid tooling defines the limits of the outside and inside diameters.

The winding system was tested at Tauring's facility using hollow tubing. After installation at GA, the system was commissioned using lengths of conductor. Winding of the mockup coil has commenced. The mockup conductor can be seen in Fig. 1.


Fig. 1. Tauring's winding system installed with 900 m of mockup conductor loaded onto the de-spooler.

### 2.3 Joint Preparation Station

After winding, the hex/quad pancakes are transferred to the third station, the Joint Preparation Station. At this station, a length of the jacket, approximately 900 mm, is removed from around the cable in preparation for making the joints at the Joining Station. To remove the jacket, specialty tools are used. The first is an orbital cutting tool which functions much as a portable lathe, cutting the jacket to within 1 mm of the cable. Next a portable mill tool creates a longitudinal slot to within a 1mm of the cable. Hydraulic tools are then used to sever the last 1mm from each cut and the split jacket is slid off the end of the cable. A reverse plating process is used to strip the chrome from the exposed cable strands for preparation of the joint.

### 2.4 Joining Station

The conductor of the coil is joined together at this station. A large structure was designed to support a 16 tonne hex pancake while the outer lower turn is separated to allow creation of the joint (Fig. 2). The joint is made by splicing the conductor together much like a rope splice is made. After the cable is spliced, jacket material is welded back over the joint. The jacket is welded together using automated welding equipment developed by Liburdi Dimetrics Inc. Helium leak tests are performed after each joint is completed. After the joints are welded, penetrations through the jacket are milled for helium inlets and outlets. The penetrations are milled within 0.5 mm of the conductor. The penetration is completed by using a hydraulically powered punch. Bosses are welded to the jacket using another Liburdi designed welding machine. All welds undergo a process qualification and all welders are similarly qualified using an approved plan. The qualification is monitored by an independent inspector.

Fig. 2. The tool for supporting and lowering the hex/quad pancakes installed in GA's facility.

### 2.5 Reaction Heat Treatment Station

The formed and joined coil must be heat treated to react the cable into a superconducting material. The reaction process occurs at 650°C for 200 hrs. The allowable temperature difference of 10°C during reaction drove a furnace design using fans to circulate argon within the furnace.

Seco-Warwick of Sweibodzin, Poland designed and built a furnace system that met the design requirements for temperature uniformity and time. Heat transfer and computational fluid dynamic analyses were performed to evaluate the conductor heating. These analyses were confirmed by system testing at Seco-Warwick's facility prior to shipment of the equipment to GA. The furnace can also be used to perform a helium leak check of the coil before and after the heating cycle. The system has been installed at GA's facility (Fig. 3) and initial testing has commenced.


Fig. 3. The Seco-Warwick furnace prior to the start of testing at GA.

**2.6 Turn Insulation Station**

After heat treatment, each turn of the CSM is insulated. The insulation scheme is a combination of fiberglass and Kapton® tape wrapped around the conductor. However, after heat treatment the conductor is strain sensitive and strain on the cable must be limited to 0.1%. GA has designed the station which will lift the CSM, separate each turn while staying within the strain limits, and then rebuild the coil as it was wound. While the turns are separated, three wrapping heads designed and built by Ridway Machines LTD, wrap the layers of glass and Kapton around the turns. As part of the insulating process, vision systems are used on each wrapping head to perform a 100% inspection. When the insulation of a given layer is completed, an impulse test is performed to confirm the electrical integrity of the insulation. The wrapping heads have been tested and delivered to GA.

For the turn insulation system, the main element is a large structure capable of lifting the CSM and was built by Springs Fab of Colorado Springs. The CSM is held by a set of nine links on the inside and outside diameters of the module. These links can release one hex/quad pancake at a time to a conductor lowering system which can in turn release one turn at a time to be insulated. At every third layer, the insulated turns are compressed to compact the glass insulation. The whole system process is monitored by a control system to maintain the safe operation of the station. Installation of the station has begun at GA's facility.

**2.7 Ground Insulation Station**

Ground insulation is applied to the external surfaces of the CSM. The ground insulation is comprised of fiberglass and Kapton sheets overlapped to achieve a design goal of 150 kV standoff capability. The insulation layers are overlapped to attain a 175 mm tracking distance from the coil surface to the outside of the insulation. The application of the ground insulation is a manual process. The ground insulation for the underside of the CSM is placed on a second support base. When the coil is lifted at the onset of the turn insulation process, the original base is swapped with the new support base. The first layer of insulated turns are placed directly on the ground insulation.

Special areas of insulation are required where the module terminals exit the coil and also around the helium penetrations. For each of these areas, custom molded polyimide shapes are used in conjunction with fiberglass sheets to meet the insulation requirements. Scale tests of these special areas have been performed and tested to verify the design and manufacturing processes.

**2.8 Vacuum Pressure Imgregnation (VPI) Station**

At this station, the insulated coils are impregnated with a two-part resin. The resin is injected at 50°C, jelled at 90°C, and cured at 125°C. During resin impregnation testing of simulated coils, it was observed that the coil system reduced in height. Additional testing isolated this shrinkage to compression of the glass insulation before and after resin injection. It was determined that the shrinkage could be predicted if a load was applied to the coil in the vertical direction. Testing confirmed that the optimum pressure on the coils during injection should be 0.07 MPa. The system is designed to apply a load to the top of the coil during the process.

The impregnation process starts with the installation of metal panels designed to apply radial compression to the ground insulation on the vertical surfaces of the coil. The panels on the outside coil diameter will remain part of the coil whereas the panels on the inside diameter are removed after the resin is cured. With the compression panels installed, rigid cylindrical molds are placed around the coil. A load plate placed directly on top of the coil is used to distribute the vertical load applied by hydraulic cylinders during impregnation. The mold is closed out with a top plate. Redundant o-rings seal the mold. A space between the o-rings can be used for vacuum leak checking the mold.

A vacuum pumping system is used to evacuate the mold. The coil is raised to 50°C during injection by a dc power supply passing current in the conductor providing volumetric heating. The external surfaces of the mold are heated by pad heaters to reduce thermal losses from the coil. The two part resin is injected into the mold from after mixing in metering pumps. After curing the mold is removed and resin flash removed.

Manufacturing of the external mold is complete and will be delivered to GA soon. Design of the compression panels is being initiated. The components of the vacuum pumping and resin pumping systems have been procured and are being assembled at GA.

### 2.9 Piping Station

To install the pipes, the coil must be inverted. Each coil is manufactured with the terminals down. A special coil turn over tool has been designed by GA. The coil is clamped between two frames which are then bolted to large wheels, approximately 3m diameter. The coil is then rolled over using the wheels. Once inverted, insulated helium pipe assemblies are welded in place. Over the weld joints, insulation is applied to maintain the 150kV standoff design requirement for the ground insulation. Each joint is helium leak checked after welding.

### 2.10 Final Test Station

Each CSM undergoes a two-step testing process. First is a series of tests at room temperature followed by tests at 4K. Electrical and helium leak tests are first performed at room temperature. The electrical tests consist of 30 kV dc hipot followed by Paschen tests to verify the integrity of the ground insulation. Upon successful completion of electrical tests, the module is then cooled down to 4K. A series of operational tests are performed including full current operation. The first module has more extensive testing than the modules 2-7 as depicted in Table 1 to confirm the module design.

Table 1. Comparison of tests for mockup coil and CSM Modules

| Test | Mockup | CSM 1 | CSM 2-7 |
|---|---|---|---|
| **Room temperature tests** | | | |
| Global leak test at 3 MPa | X | X | X |
| Paschen test (30kV) | X | X | X |
| **Cold Tests** | | | |
| Cool to 4K | X | X | X |
| Charge/discharge cycle (full current) | | X | X |
| Joint/terminal resistance measurement | | X | X |
| Current sharing temperature measurement (10 double pancakes) | | X | |
| AC loss measurements (10 double pancakes) | | X | |
| Ten charge/discharge cycles | | X | |
| Current sharing temperature measurement, Test 2 (10 double pancakes) | | X | |
| Global leak test at 3 MPa (4 K) | X | X | X |
| **Final Room Temperature Tests** | | | |
| Global leak test (3 MPa, 4 K) | X | X | X |
| Paschen test at RT | | X | X |
| 30 kV Hi-Pot test | | X | X |

## 3. Conclusion

Manufacturing tools and processes for the ITER CS are under development and testing by GA. The design of the process stations is nearly completed and many are manufactured and tested. The winding of the mockup coil has started. After successful completion of the mockup at each process station, the station will be utilized to manufacture the CSM.

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