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HIGHLIGHTS FROM THE ASSEMBLY OF THE HELICAL FIELD COILS FOR THE ADVANCED TOROIDAL FACILITY*

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Abstract: The helical field (HF) coils in the Advanced Toroidal Facility (ATF) device consist of a set of 24 identical segments connected to form a continuous pair of helical coils wrapped around a toroidal vacuum vessel. Each segment weighs approximately 1364 kg (3000 lb) and is composed of 14 water-cooled copper plate conductors bolted to a cast stainless steel structural support member with a T-shape cross section (known as the structural tee). The segment components are electrically insulated with Kapton[†] adhesive tape, G-10, Tefzel, and rubber to withstand 2.5 kV. As a final insulator and structural support, the entire segment is vacuum impregnated with epoxy. This paper offers a brief overview of the processes used to assemble the component parts into a completed segment, including identification of items that required special attention.

Introduction

The ATF is a type of stellarator known as a torsatron that will be used for magnetic plasma confinement experiments and is under construction at the Oak Ridge National Laboratory (ORNL). The device must generate a variety of magnetic configurations, including a helical magnetic axis, so that their plasma stability boundaries can be explored. The need for precise positioning of the HF field coil current center (to within 1 mm of the theoretically desired location) has required the development of special fabrication and assembly processes for the HF coils, since each conductor turn must be precisely located on its structural tee and must meet all electrical and mechanical requirements. The steps involved in assembling a segment are listed in Fig. 1. Figure 2 shows the components involved. The following sections provide a detailed review of each process step and the specific techniques employed.

Method of Assembly

Structural Tee

The structural tee is the principal support and load-carrying component of the segment. Preparation for mounting the conductor turns on the tee includes installation of ground plane insulation and special planar surfaces, which allow controlled movement of the conductor turn bundle during operation to accommodate thermal growth.

Initial Preparation: The 304L stainless steel tee is cast as a single piece with the basic helical geometry controlled by the mold. Machined features for connecting the tee to the conductor turns and for installing the segment in the device are in place when this member is received by ORNL. The first preparation activity on this component is a test of the magnetic permeability (not to exceed 1.02). The entire tee is then checked for burrs or protrusions that could penetrate the electrical insulation. After deburring, the tee is cleaned with a solution (Genesolv-DE) to remove any grease, dirt, or foreign matter. At this point, the tee is ready for insulating, which is a white-glove operation.

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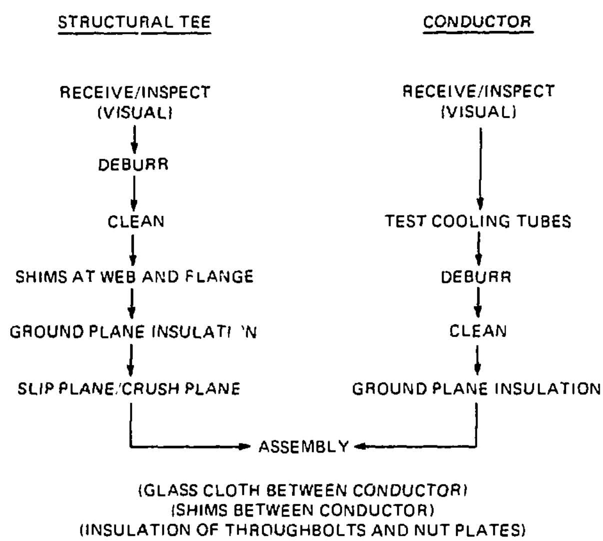

Fig. 1. Steps involved in segment assembly.

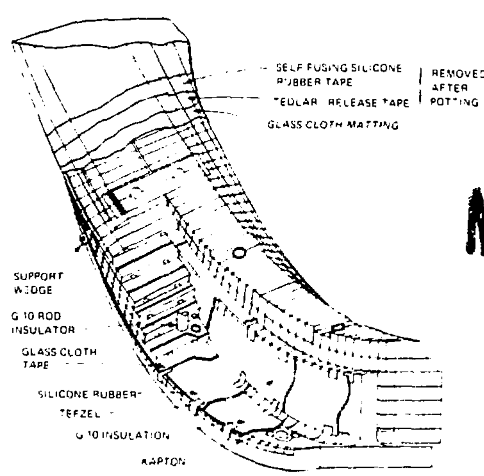

Fig. 2. Assembled segment, showing components involved.

Ground Plane Insulation: Figure 3 shows the steps involved in the insulating procedure.

Step 1. Installing Kapton adhesive tape: Kapton adhesive tape 1 in. wide and 0.0035 in. thick is applied to the tee to reduce the possibility of arcing from sharp corners between the grounded tee and adjacent conductors. The primary areas insulated with Kapton tape include: (1) toe of flange, (2) fillet, (3) stem of web, and (4) end of flange. The Kapton tape is cut at alternating lengths to avoid a common terminating plane of the tape and is applied half-lapped to provide full surface coverage.

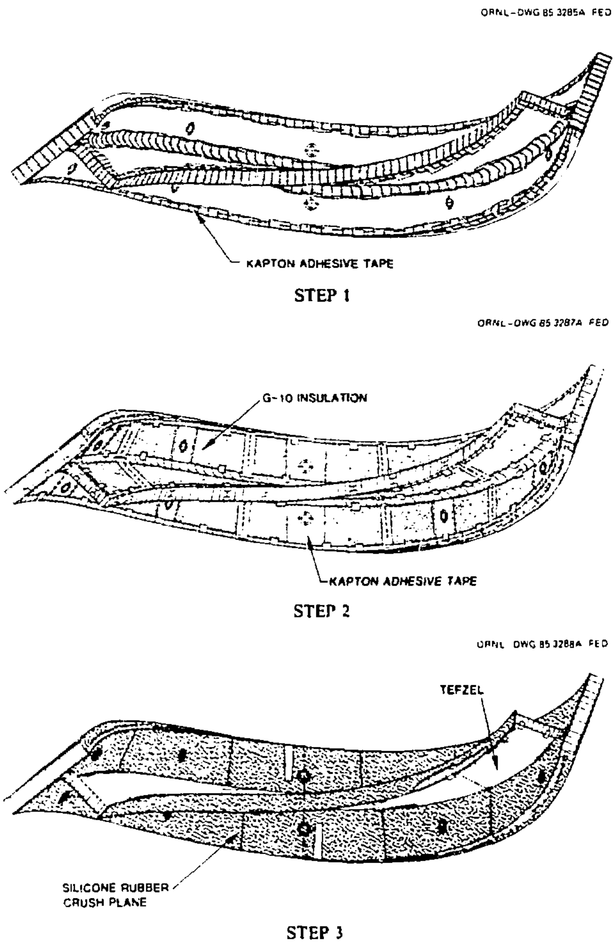

Fig. 3. Steps in insulating the structural tee.

Step 2. Installing G-10 insulation: G-10 insulation (0.015 in. thick) is cut and installed between the holes in the flange, between each end hole and the end of tee, and along the web of the tee. The G-10 along the web is held in place with 1-in.-wide, 0.0035-in.-thick Kapton adhesive tape. On the flange of the tee, the G-10 is terminated 2 in. on either side of the ten through-holes and is held in place with 5-in.-wide, 0.0035-in.-thick adhesive tape overlapping the G-10 by 0.5 in. The 5-in.-wide Kapton tape provides a bearing surface against the cast tee for installation of the shims, which are positioned approximately 1.5 in. on either side of the ten through-holes. The shims locate the conductor turns to their required position tolerance.

Because of the helical contour of the tee, the G-10 insulation does not lie flat against the flange without some force or pressure. This does not create any problems in the assembly process.

Step 3. Installation of crush plane and slip plane: Silicone sponge rubber (0.125 in. thick) is cut and placed along the inside of the flange of the tee and along the stem of the web. The silicone rubber acts as a crush plane for the entire conductor pack as the coil is energized. The major movement of the conductor toward the flange of the tee (y-axis) is approximately 0.033 in. The silicone sponge rubber is joined to the tee using GE RTV 162 adhesive, which is a noncorrosive silicone. A bead of RTV (approximately 0.25 in. to 0.375 in. wide and 0.25 in. high) is applied to the tee near the toe of the flange, across each end of the flange, and along the web near the point of tangency of the fillet. The silicone sponge rubber is then laid into the beads of RTV and compressed to allow the RTV to ooze to the edges of the silicone sponge rubber, thus creating a positive bond and a seal that will prevent epoxy flow under the rubber during impregnation. Along the web of the tee, a single 0.005-in.-thick layer of fluoropolymer film (Tefzel) is installed from the top of the tee web (attached with Kapton adhesive tape) to the silicone sponge rubber at the tee fillet, where the Tefzel overlaps by 0.5 in. The Tefzel prevents any bonding of the copper conductor to the tee after epoxy impregnation and also allows the copper conductor to move as a unit during energization. A bead of RTV 162 (0.25 in. wide and 0.125 in. high) is placed along the silicone sponge rubber to secure the Tefzel lap.

Summary of Insulation Process: To insulate the tee with Kapton adhesive tape, a total of 72 yd of 1-in.-wide tape is required. Total insulation of the tee including Kapton tape, G-10, Tefzel, and silicone sponge rubber takes approximately 48 work hours (2 persons working 8 h per day for 3 days).

Copper Conductor

The copper conductors or turns (ASTM B152) are approximately 1.125 in. thick by 5.5 in. wide and about 72 in. long. The turns are received by ORNL with copper cooling tubes (0.5-in.-OD copper tubing with a 0.065-in.-thick wall) in place and turns formed to the configuration required, which allows precise nesting in the structural tee. Further, all holes have been line drilled with each complete stack of turns. Figure 4 shows a partially insulated turn.

Initial Preparation: Each turn must successfully pass three checks before it is insulated. First, a flow test is conducted to ensure that there are no obstructions in the cooling tubes. A 0.3125-in.-diam stainless steel ball is passed through the cooling tube at a maximum air pressure of 3 psig. The criterion for acceptance is passage of a 0.25-in.-diam stainless steel ball. Second, a leak test of the cooling tube is carried out using 30-psig instrument air in the tube and soap solution applied to the exterior of the tube. If soap bubbles are detected, the turn is rejected until repairs are made and the criterion is met. Third, a hydrostatic test is carried out by pressurizing the cooling tubes to 375 psig and monitoring them for pressure decay for 10 min. The cooling tubes are then purged of moisture using instrument air. The turn is checked for any burrs or protrusions that could penetrate the electrical insulation. After deburring, the turn is cleaned with Genesolv-DE, and a white-glove operation is in effect until the turn is insulated.

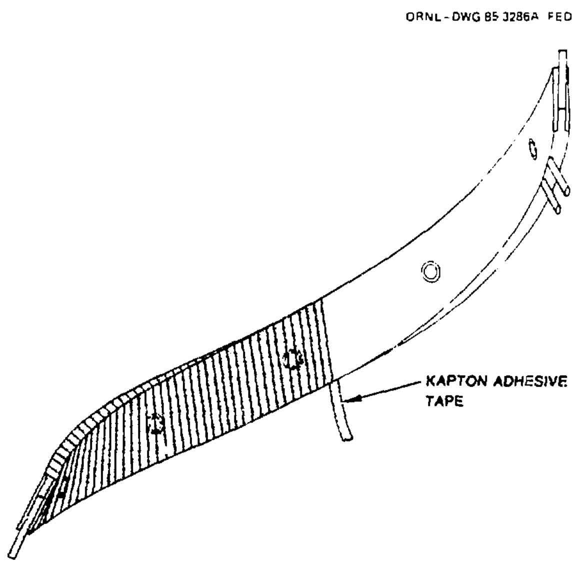

Fig. 4. Partially insulated conductor turn.

Insulation: The conductor turns are insulated with 1-in.-wide, 0.0035-in.-thick Kapton adhesive tape. The insulation process is a continuous taping (wrapping) operation from one end of the turn to the other end except where tape splices are necessary. During the wrapping, several problems were encountered. Because of the geometric configuration of the copper turns, the Kapton adhesive tape must be started at the end of the turn and at an angle of 10° to 15° in relation to the starting edge. As the tape is pulled around each edge of the conductor, it projects at a different angle from the course it followed before reaching the edge. There is very little elasticity to the Kapton tape; thus, a consistent half-lap is difficult to achieve with each revolution of tape around the turn. Variations experienced in lapping of the Kapton ranged from 0.5 in. to a full lap. Also, if the Kapton tape is pulled too tight when wrapped, stresses are introduced in the tape; when the Kapton is cut out around the through-holes, the tape will buckle.

Summary of Insulation Process: It takes approximately 72 yd of tape for each turn or 1008 yd for the full complement of 14 segment conductors. All 14 turns can be insulated in about 64 work hours (2 persons working 8 h per day for 3.5 days).

Segment Assembly

Each insulated tee receives a set of 14 insulated copper conductors. This unit then makes up a single HF coil segment assembly. The cutaway view of Fig. 2 shows how the tee and turns are assembled to produce the prototype HF coil segment, as described in this section.

Conductor Positioning: The position of each turn in terms of height (y-axis), width (x-axis), and length (z-axis) is controlled to a precise location in order to meet electrical and mechanical design criteria. Dimensions of the tee and turns are precisely measured using a coordinate measuring machine (CMM). These data are then used to define insulation shim spacers, which are placed between tee and turns and between turns to position the conductors as close as is practical to the defined locations. The distance between the copper conductors and the cast tee web and the distance between the two turns adjacent to the tee flange vary with each segment because of allowable fabrication tolerances. In the space, or void, between the tee surfaces and the first pair of turns, a 0.625-in.-diam insulating shim is installed (thickness determined by the CMM) and positioned at each end and center of the tee on both sides of the web. In addition, a pair of 0.625-in.-diam shims is located on each side of each end through-hole on the tee flange. Stainless steel wedges, each sandwiched between 0.625-in.-thick Teflon spacers, with properly sized shims affixed on top of the top spacer, are located near the center of the tee flange on both sides to position (vertically) the first turns. The wedges maintain a positive standoff of the turns against the silicone sponge rubber crush plane during assembly and epoxy impregnation. After impregnation and curing of the epoxy, the wedges are removed.

Clamps hold the turns against the shims located on the web of the tee. After each turn is in position on the tee and before the adjacent turns are installed, two 0.625-in.-diam shims are installed, one on each side of the through-holes at the turn center and each turn end, to ensure that the turn is properly located. Again, the shim thickness is determined by the CMM, which measures the surface of the turns in position with respect to the locations of the adjacent turns. Before the adjacent turns are installed, each turn is covered with three plies of 6-in.-wide, 0.012-in.-thick glass cloth. Also, the space between the turn and the web of the tee is packed with 0.25-in.-thick glass matting. The glass cloth and matting provide reinforcement for the impregnated epoxy. As turns are stacked, a 10.625-in.-long G-10 tube with an inside diameter of 1 in. and an outside diameter of 1.125 in. is inserted from the bottom of each of the tee through-holes into each turn. During assembly, it is unreasonable to attempt to position a turn in any position other than that in which the turn was manufactured. If a turn is not in its manufactured position during assembly, this becomes evident by the excessive force required to insert the ten G-10 tubes.

To prevent the epoxy from migrating onto the electrical contact surfaces at the ends of a turn, a dam is created at the end of each turn by applying a bead of RTV 162 (0.25 to 0.325 in. wide and 0.25 in. high) across the end of the turn with an approximate 1-in. return on each side. Before the RTV bead is fully cured, the next turn is installed, so that the RTV "oozes" between the two turns, ensuring a positive dam. After the last turns are in position and properly clamped, five 0.3125-in.-thick stainless steel nut plates are inserted through the top two turns and into the G-10 sleeves. Before it is installed, each nut plate is insulated with a single sheet of 0.005-in.-thick Kapton, using hospital-type folds at the corners to eliminate possible arcing from sharp corners or points. Eastman 910 is used to attach the Kapton.

Stainless steel (A-286) studs, 1 in. in diameter, 12 in. long, and threaded on each end, are inserted through the G-10 tube, or sleeve, and threaded into the nut plates. A G-10 bushing, wrapped with 0.060-in.-thick silicone sponge rubber, is then inserted over the G-10 sleeve at the tee flange. The silicone rubber is attached to the bushing with RTV 162. The bushing length is determined by the thickness of the tee flange plus the standoff distance between the surface of the two lower turns and the inside of the flange surface.

A G-10 insulated washer, a stainless steel washer, and a stainless steel hex nut are installed over the through-bolt at the flange of the tee. The G-10 bushing and the nut plate on the other end of the stainless steel bolt act to clamp the copper conductors together as a unit. The nuts are torqued to 80 ft/lb, completing the assembly stage of coil segment assembly.

Preimpregnation

Before the epoxy impregnation, the outside of the segment is wrapped with 0.0625-in.-thick, 6-in.-wide glass cloth to enhance the epoxy structurally. On top of the perimeter glass cloth wrap, 4 feed and 13 return fittings are installed. The entire segment is wrapped with 0.005-in. thick, 2-in.-wide Tedlar release tape. The final wrap is a self-fusing, 1-in.-wide, 0.060-in.-thick silicone rubber tape. After the final wrap is in place, the entire segment is brush coated twice with RTV 3140. To further protect the electrical contact surfaces at the ends of the conductor turns from migrating epoxy, a nylon "boot" is placed around each end of the segment and filled with RTV 12. The RTV 162 dam between the ends of turns keeps the RTV 12 from migrating into the areas that must be filled with epoxy. A nylon boot is also placed around the protruding cooling tubes and filled with RTV 12 to further seal the silicone rubber wrap.

The sealing operation is one of the most difficult because the outer wrap functions as a vacuum seal during the epoxy impregnation. Any leaks to atmosphere during this process will introduce pockets of air, which are structurally unacceptable, especially between the conductor pack and tee web at the segment midsection. Leaks in the outer wrap are located using an ultrasonic leak detector, and any needed repairs are made using RTV 732. An acceptable vacuum is 10–15 mm Hg, with a decay rate not exceeding 25 mm Hg per minute.

Impregnation

The final stage in completing an HF coil segment is epoxy impregnation. This step is not covered here because data are not yet available.

Summary

The HF coil for ATF is one of the most complicated geometric configurations to be fabricated in recent years. The prototype segment has provided valuable practical experience in evaluating materials and assembly techniques under actual conditions.

The insulation of the stainless steel tee and copper conductors was performed well and in a shorter time than originally planned. However, during segment assembly, difficulties arose when conductors were not placed at the exact height for which they were manufactured. Any change in conductor height changes the radial angle of each through-stud, which prevents stacking of the turns.

Essential equipment for assembling the HF coil includes a three-axis CMM for critical measurements of the close tolerances of the irregular shapes involved in the helical geometry.

Actual assembly of the prototype segment, including insulation, has been reduced to approximately two weeks after incorporation of the various lessons learned, compared with the four weeks originally planned for this task.