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THERMAL AND ELECTRICAL JOINT TEST FOR THE HELICAL FIELD COILS IN THE ADVANCED TOROIDAL FACILITY*

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R. L. Brown and R. L. Johnson
Oak Ridge National Laboratory
Bldg. 9204-1, MS 14, Y-12
P.O. Box Y
Oak Ridge, Tennessee 37831

Initial feasibility studies of a number of configurations for the Advanced Toroidal Facility (ATF) resulted in the selection of a resistive copper continuous-coil torsatron as the optimum device considering the physics program, cost, and schedule. Further conceptual design work was directed toward optimization of this configuration and, if possible, a shorter schedule. It soon became obvious that in order to shorten the schedule, a number of design and fabrication activities should proceed in parallel. This was most critical for the vacuum vessel and the helical field (HF) coils. If the HF coils were wound in place on a completed vacuum vessel, the overall schedule would be significantly (≥12 months) longer. The approach of parallel schedule paths requires that the HF coils be segmented into parts of ≤180° of poloidal angle and that joints be made on a turn-by-turn basis when the segments are installed. It was obvious from the outset that the compact and complex geometry of the joint design presented a special challenge in the areas of reliability, assembly, maintenance, disassembly, and cost. Also, electrical, thermal, and force excursions are significant for these joints. A number of soldered, welded, brazed, electroplated, and bolted joints were evaluated. The evaluations examined fabrication feasibility and complexity, thermal-electrical performance at approximately two-thirds of the steady-state design conditions, and installation and assembly processes. Results of the thermal-electrical tests were analyzed and extrapolated to predict performance at peak design parameters. The final selection was a lap-type joint clamped with insulated bolts that pass through the winding pack.

Summary

The decision to segment the HF coils for ATF in order to shorten the schedule led to the identification of a program for development and testing of a joint to connect the conductors in mating segments. Both permanent and demountable joints have been used in large-cross-section conductor coils on a number of fusion research devices: the Impurity Study Experiment (ISX), the Poloidal Divertor Experiment (PDX), ASDEX, and Doublet II and III. However, none of these joint applications possessed the geometrical complexity of ATF, on which the conductor is both curved and twisted in the region of the joint. Also, none of these joints was required to demonstrate high-current, steady-state capability. The need for this program was reinforced in the report of a Department of Energy (DOE) review committee in July 1983 [1]:

> "The committee as a whole feels that the HF joint is now the critical element in the design."

The resulting program evaluated a number of soldered, welded, brazed, electroplated, and bolted joints. The evaluation examined fabrication feasibility and complexity, thermal-electrical performance at approximately two-thirds of the steady-state design conditions, and installation and assembly processes. A lap joint clamped with insulating bolts that pass through all of the joints was selected. Several of the most critical conductors have coaxial water-cooling tubes attached to the lap tangs.

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Requirements and Constraints

The present design [2] of the HF coils for ATF is illustrated in Fig. 1. In order to closely match the ISX-B coil power supply and still provide the desired magnetic field, 14 turns of copper with a cross section of approximately 40-cm^2 (6.2-in.^{2}) became the reference coil design. The cross section for the turns is such that a number of joint configurations can be envisioned. The joint requirements based on this design are:

Steady-state current	62.5 kA
Pulsed current	125 kA
Pulse length	5 s
Repetition rate	600 s
Peak temperature limit	150°C
Joint resistance at peak temperature	≤3 μΩ
Current path repeatability joint-to-joint	±0.1 cm (±0.040 in.)

Each joint must also accommodate loads and stresses at design conditions, serve as a lead/crossover with minor modification, and fit within the geometric constraints of the vacuum vessel. In operation, the joints must be adjustable and reliable, and the cost should be low.

Fabrication and Testing Program

Thermal analysis of the HF coil turns, early in design, indicated that steady-state operation at 62.5 kA was a much more stringent requirement than was pulsed operation at 125 kA for 5 s. This steady-state requirement was thought to be even more restrictive for coil joints, since the current density is high in most joints. For these reasons, steady-state thermal-electrical tests on candidate joints were performed as a first step in the selection process.

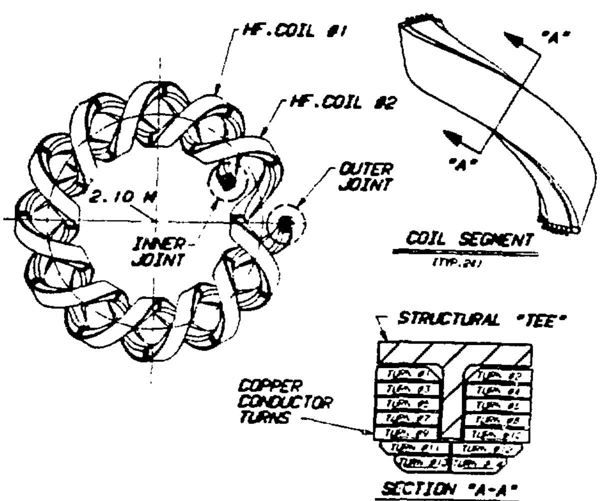

Fig. 1. ATF HF coil segment concept.

A 30-kA, 10-V dc power supply available in the Magnetics & Superconductivity Section was convenient to a laboratory in which cooling water and the required instrumentation were also located. Since most joint concepts exhibited side-to-side symmetry, the plan was to fabricate joints that were a full-turn thick but only half a turn wide. Then results from the 30-kA power supply would require only modest extrapolation to the adjusted steady-state design current of 31.25 kA. Due to lead and cable losses, the maximum current that could be obtained through the samples was 22 kA, but results were extrapolated to design values in a meaningful fashion. When allowance was made for cooling access and lead attachment, the test assembly was approximately 60-cm (24-in.) long.

Instrumentation was located on the test assembly to monitor temperature rise in the bulk copper, temperature rise as near the joint as practical, temperature rise in the insert (if applicable), temperature rise in the cooling water, water flow rate, and voltage at 2.5-cm (1-in.) intervals along the assembly (where possible).

In order to calibrate all measurements, a standard "no-joint" reference sample was fabricated with the same cross section, cooling geometry, length, and instrumentation as the joint samples. The reference sample and all joints were fabricated from OFHC copper with cooling lines brazed in place with ASTM B-Ag 8. This is the same construction as the HF coil turns.

The fabrication and testing program ignored the geometric complexity of the HF coils and joints in order to minimize cost at this stage. That is, all samples were fabricated flat and straight. However, it was noted that some welded and soldered joints that could be assembled on a bench could not be made up on the device due to an unfavorable orientation.

Testing Results

Many people contributed joint designs and suggestions. Over 30 design concepts were investigated and most of them were fabricated and tested. Some of these were retested after alterations and variations. A typical joint ready for testing is shown in Fig. 2 with numerous thermocouples and voltage taps attached. Figure 3 shows the overall test facility (with safety cages removed). A hydraulic jack (not shown) could apply over 1000 kg (2200 lb) of tension to a joint that was carrying current. (A thorough description of

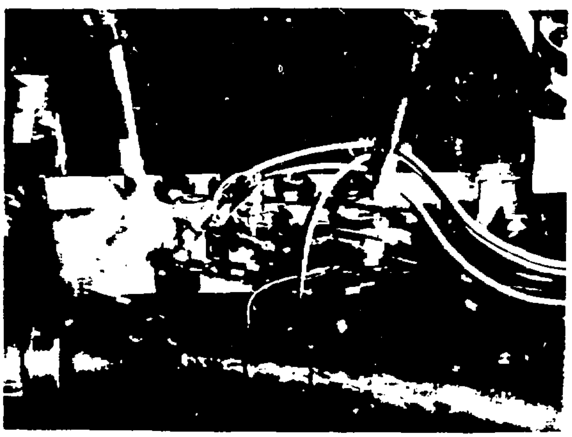

Fig. 2. Typical test joint with thermocouples and voltage taps in place.

mechanical and fatigue testing is given in another paper [3].) An explanation of the terms used in discussing the test results follows.

Voltage Drop. Except for water inlets and outlets, a voltage tap was placed at every thermocouple location. A typical joint had approximately 20 such locations. The voltage drop between points gives an indication of the current distribution in the copper. The voltage drop across the contact surfaces gives an indication of the quality of the contact.

Electrical Resistance. By measuring the current (A) and voltage drop (mV) over a precise length that includes the joint, the resistance (Ω) can be calculated. Subtracting from this the resistance of an identical length of the reference bar will leave a resistance R_{joint} (Ω) that represents the resistance increase due to the joint. Typically, the resistance was measured over a length of 15.24 cm (6 in.). Where this length was not available or not practical, the available voltage was divided by its distance to obtain a measurement in volts per centimeter, which was then multiplied by 15.24 cm to obtain V/15.24 cm. This provided a measure for comparing all joints.

Water Flow. Water passages for both sides of joints were connected in series. Some joints were provided with additional water cooling as near the contact surfaces as possible. A flow meter in the outlet line measured the flow rate. The water that flowed in test pieces was connected thermally to the power lead connections and therefore was heated (or cooled) by the water-cooled leads. It was assumed that this was not a great influence on the test, but its effect is unknown. Thermocouples were used to monitor the water temperature.

Copper Temperature. Approximately 20 iron-constantan thermocouples were placed on the joint at (or close by) points expected to be of greatest interest. These measurements may have been influenced by the presence of water-cooled leads, as discussed for the water flow measurements. However, the measurements indicate that cooling located some distance from the heat source did not have much effect.

Initially the system would stabilize at the inlet-water temperature. All differential temperatures therefore were derived by subtracting the inlet-water temperature from the copper temperature. An indication of the rate of temperature rise during a pulse was obtained by raising the current as rapidly as possible (using manual controls) and measuring the hot-spot

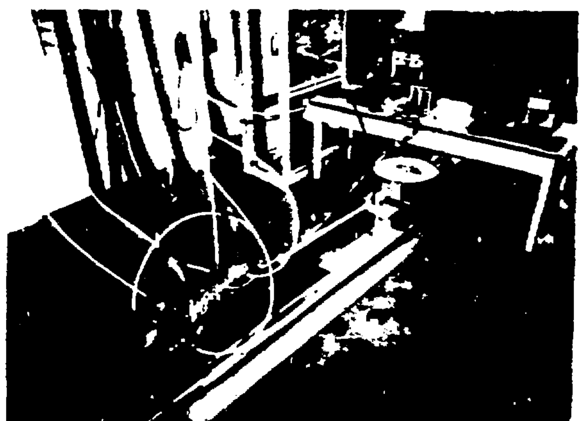

Fig. 3. Joint test faclity with safety cage removed.

temperature for a period of 10 s. (This period should not be confused with the pulse length for ATF, which will be 5 s.)

Full-Size Conductor, Predicted Performance

Steady-State Hot-Spot Maximum Copper Temperature. This value is extrapolated by measuring the maximum copper temperature on a test joint at a known power level and predicting the maximum hot-spot copper temperature at the steady-state power level ($I = 62{,}500$ A), starting with the ratio:

$$\frac{\Delta T_{max\,(test)}}{(I_{test})^2[\rho_{test}\,\ell/(wh/2)]} = \frac{\Delta T_{max\,(ss)}}{(I_{ss}/2)^2[\rho_{ss}\,\ell/(wh/2)]}$$

where ΔT is in °C, I in amperes, and resistivity ρ in Ω·cm and ℓ, w, and h are conductor dimensions in centimeters.

The accuracy of this extrapolation depends on an assumption that the current distribution is symmetrical about the centerline of the conductor. Therefore, the current and temperature distributions in the half-width conductor test are identical to those in the missing half-width of conductor. It follows, then, that when the extrapolation is made with a half-width conductor the steady-state current must be divided by two. Further, the conductor dimensions (ℓ, w, and h) will cancel. The copper resistivities (ρ_{test}, ρ_{ss}) vary with copper temperature (T_{Cu} in °C) and are closely appropriated by:

$$\rho = k_1 + k_0\,T_J \quad \Omega\cdot\text{cm}$$

The constants are $k_0 = 7.02(10^{-9})$ and $k_1 = 1.53(10^{-6})$ and after substitution:

$$\Delta T_{max\,(ss)} = \frac{T_{ir} + \left\{\dfrac{I_{ss}^2 k_1 \Delta T_{max\,(test)}}{I_{test}^2\,[k_1 + k_0 T_{max\,(test)}]}\right\}}{1 - \left\{\dfrac{I_{ss}^2 k_0 \Delta T_{max\,(test)}}{I_{test}^2\,[k_1 + k_0 T_{max\,(test)}]}\right\}} - T_{ir}\ (°C)\ .$$

This proved to be very accurate for predicting copper temperatures at higher power levels from data taken at lower power levels.

Pulsed Hot-Spot Maximum Copper Temperature. This value was arrived at in the same way as the steady-state value, except that an average copper temperature was used to calculate the steadily rising copper resistivity. This gives

$$\Delta T_{max\,(pulse)} = \frac{T_{ir} + \left\{\dfrac{I_{pulse}^2 \Delta T_{max\,(10\ s)}\,[k_1 + (k_0/2)T_{ir}]}{I_{test}^2\,[k_1 + (k_0/2)\Delta T_{max\,(10\ s)}]}\right\}}{1 - \left\{\dfrac{I_{pulse}^2 (k_0/2)\Delta T_{max\,(10\ s)}}{I_{test}^2\,[k_1 + (k_0/2)\Delta T_{max\,(10\ s)}]}\right\}} - T_{ir}\ (°C)\ .$$

Steady-State Joint Resistance. Test data indicate that a joint's characteristic resistance remains relatively constant regardless of the current flowing in it, at least for joints that do not reach excessive temperatures. Also, the resistance of the reference bar compares closely with a calculated resistance in which the temperature of the entire bar is assumed to be uniformly the hottest copper temperature. The copper resistance might be expected to be close to the average of the hot-spot temperature and the cooling-water temperature. There are two possible explanations why this is not the case: (1) some of the copper cross section is cut away for the water passage, and (2) the water temperatures are very different from any copper temperatures because of a large water film drop. A review of the copper temperature data shows that most of the temperatures are fairly close to the hot-spot temperature.

Joint resistance is the sum of at least three elusive components: (1) variable copper resistivity due to a complex temperature distribution, (2) geometry that may distort current paths, and (3) contact resistance that varies with the quality of the contact. To further complicate matters, all components can affect each other.

Nevertheless, once the overall voltage drop has been measured, the test-joint resistance can be determined and an assigned temperature $T_{assigned}$ can be derived that will represent the sum of all these components. Of course, this will always have a value higher than any real temperature, but it is convenient for calculation purposes. The overall resistivity is:

$$\rho_{test} = \frac{R_{test\ (wh/2)}}{\ell} = k_1 + k_0 T_{assigned}\ (\Omega\cdot\text{cm})\ ,$$

$$T_{assigned} = \left(\frac{R_{test\ (wh/2)}}{\ell} - k_1\right)/k_0\ (°C)\ .$$

We have previously determined, by extrapolation, the copper hot-spot temperature increase at steady state $\Delta T_{max(ss)}$. We can add this temperature increase to $T_{assigned}$ and recalculate to determine the full-size joint resistance (R_{ss}):

$$\rho_{ss} = \frac{R_{ss}wh}{\ell} = k_1 + k_0(T_{assigned} + \Delta T_{ss} - \Delta T_{test})\ (\Omega\cdot\text{cm})\ ,$$

and

$$R_{ss} = \frac{\ell}{wh}\left\{k_1 + k_0\left[\frac{[R_{test}(wh/2)]/\ell - k_1}{k_0} + \Delta T_{ss} - \Delta T_{test}\right]\right\}\ (\Omega)\ .$$

Pulsed Joint Resistance. Pulsed resistance is determined in the same way as steady-state resistance. Assigned temperatures are the same for steady-state and pulsed resistance, since they are only used for determining the resistance characteristics of a joint. The extrapolated ΔT_{pulse} is used in place of ΔT_{ss} when the recalculation is made.

Calculating assigned temperatures may appear risky, but if a joint's extrapolated temperature increase is used to calculate the copper resistance, the results should come close to the same value. Using the assigned temperatures eliminates the burden of estimating the average temperatures over a joint.

Evaluation and Joint Selection

The criterion of fabrication and installation feasibility eliminated a number of joints that had been conceived and some that had been fabricated. Two soldered joints were abandoned because the joint installation geometry would not allow the filler metal to remain in the joint area. Welded joints were eliminated for the same reason, even though several joints were fabricated on the bench and tested.

An electroplated joint was fabricated only under the most favorable conditions and was rejected because of process uncertainty. A laser-welded joint fabricated by an outside vendor was excluded because a long and potentially expensive development effort would have been required to qualify the process for use on ATF. However, a low-level development effort has been initiated to better understand the process and its limitations.

Two joint designs required machining to extremely close tolerances in order to have the contact surfaces match at assembly. They were abandoned on that basis.

Some bar joints were conceived midway through the joint program. While they exhibited some desirable features, it was thought that their thermal-electrical performance would not be very different from that of similar bar joints that had already been fabricated and/or tested.

An integrally cooled bar joint passed the testing in good fashion. However, the number of clamps and added complexity of O-ring seals in the joint made it extremely undesirable when the number of coil joints was considered. For this reason, the joint was rejected from further consideration.

A summary of thermal-electrical testing results leads to the following conclusions:

1. Joints with inserts will work only if the insert is actively cooled.
2. Laminated inserts run too hot, and there is no obvious way to cool them.
3. Lap joints pass the tests due to the short length of the joint and proximity of cooling.

The joint judged most likely to succeed is a lap-type joint clamped with insulating bolts that pass through all of the joints, as shown in Fig. 4. The innermost conductors are smaller, and extra cooling will be added to the end of one tang of the joint. The highest operating temperature rise for this joint when pulsed is extrapolated to be ≈100°C and its resistance will be $\approx 1.0 \times 10^{-6}$ Ω. The larger joints that do not

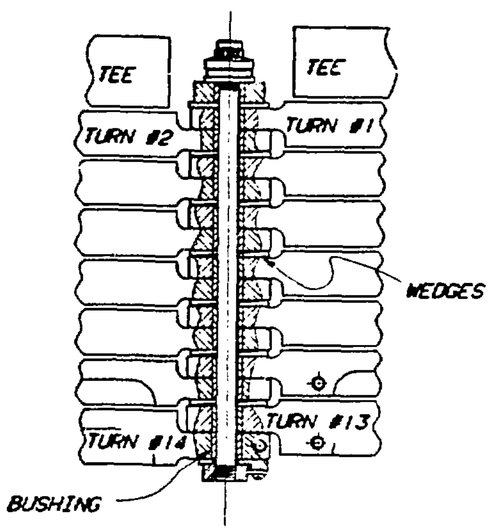

Fig. 4. The joint judged most likely to succeed.

have extra cooling are extrapolated to have a steady-state maximum temperature rise at of ≈140°C and a joint resistance of $\approx 0.6 \times 10^{-6}$ Ω.

Acknowledgment

Many people contributed to this program. Their interest and efforts were invaluable in our search for the best ATF helical field coil joint.

References

[1] DOE ATF Review Panel, July 1983.

[2] R. L. Johnson, "The Advanced Toroidal Facility (ATF)," presented at this conference.

[3] B. E. Nelson, W. E. Bryan, P. L. Goranson, J. E. Warwick, "Mechanical Testing and Development of the Helical Field Coil Joint for the Advanced Toroidal Facility (ATF)," presented at this conference.