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MECHANICAL TESTING AND DEVELOPMENT OF THE HELICAL FIELD COIL JOINT FOR THE ADVANCED TOROIDAL FACILITY

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Abstract: The helical field (HF) coil set for the Advanced Toroidal Facility (ATF) is an M = 12, ℓ = 2, constant-ratio torsatron winding consisting of 2 coils, each with 14 turns of heavy copper conductor. The coils are divided into 24 identical segments to facilitate fabrication and minimize the assembly schedule. The segments are connected across through-bolted lap joints that must carry up to 125,000 A per turn for 5 s or 62,500 A steady-state. In addition, the joints must carry the high magnetic and thermal loads induced in the conductor and still fit within the basic 140- by 30-mm copper envelope. Extensive testing and development were undertaken to verify and refine the basic joint design. Tests included assembly force and clamping force for various types of misalignment; joint resistance as a function of clamping force; clamp bolt relaxation due to thermal cycling; fatigue testing of full-size, multiturn joint prototypes; and low-cycle fatigue and tensile tests of annealed CDA102 copper. The required performance parameters and actual test results, as well as the final joint configuration, are presented.

Introduction

The ATF is a moderate-aspect-ratio torsatron now under construction at the Oak Ridge National Laboratory (ORNL) [1]. A principal feature of the device is the pair of HF coils. To allow for parallel assembly operations, these HF coils will be manufactured as a set of 24 identical upper and lower segments, as shown in Fig. 1. Each segment consists of 14 copper conductors separated with fiberglass insulation, bolted to a T-shaped structural support member, and vacuum impregnated with epoxy. The segments are connected in the field via joints in the copper conductors.

The HF coil joint must be adequate thermally, electrically, and mechanically to meet the performance requirements in Table 1. Many different joint concepts were proposed and discarded before the through-bolted lap joint design shown in Fig. 2 was adopted. Critical features of this joint include (1) flat contact surfaces, (2) adjustable wedge insulators to provide assembly clearance and prevent tolerance buildup due to copper tab thickness variations, (3) match-reamed bushings and wedge insulators for good load transfer to the through-bolts to prevent slipping of contact surfaces, (4) high-strength Inconel 718 studs with a centerless ground coating of fiberglass epoxy for extra insulation and tight fit. The inner joints, which occur at 180° of poloidal angle, and transfer the current straight across the joint within the same layer of conductor. The outer joints provide a "crossover" function and transfer the current from layer to layer. Each outer joint is a crossover to preserve symmetry. Current feeds are introduced at 4 of the 12 outer joints, and shunts are used at the remaining 8.

The joints are machined while the individual copper conductors are in the flat condition, then carefully positioned during forming and assembly of the HF coil segments with close tolerance fixtures. This fabrication method reduces the penalty for machining errors and provides the maximum amount of copper in the joint tabs or contact regions.

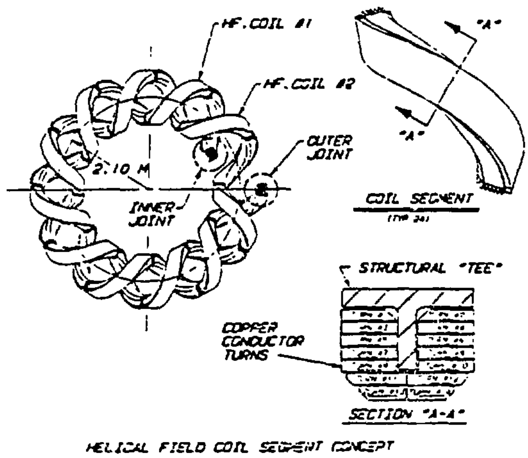

Fig. 1. HF coil segment concept.

Table 1. HELICAL FIELD COIL PARAMETERS

Material:	OFHC copper
Number of turns:	14 per coil
Current:	125 kA for 5 s; 62.5 kA continuous
Current density:	3350 A/cm^2 ohms per coil
Resistance:	2 × 10^{-3} ohms per coil 1 × 10^{-6} ohms per contact

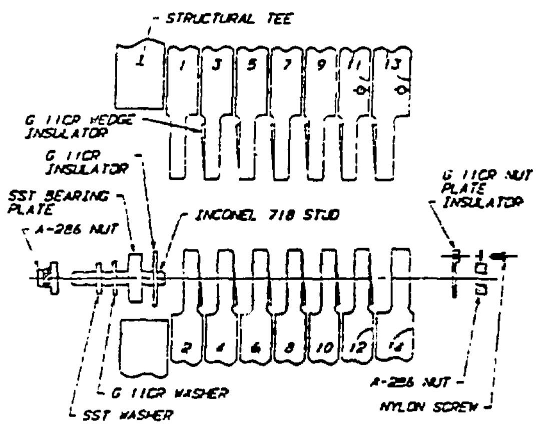

Fig. 2. Joint configuration.

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To ensure that the chosen joint concept will match its performance criteria, an extensive test and development program was undertaken. The significant issues included both thermal/electrical and mechanical characteristics. A series of high-current, half-scale, single-contact tests has verified the thermal and electrical performance of the joint. These tests are discussed in another paper in these proceedings [2].

Another series of tests addressed the critical mechanical issues. These include:

1. Assembly/Fit. Can the joint tabs of mating segments be meshed with reasonable force, without damaging the contact surfaces?

2. Clampup. Once the joint tabs are meshed, is enough clamping force available from the through bolts to provide an adequate electrical connection at all 14 contacts? Will this clamping force survive thermal cycling?

3. Fatigue life. Can the joint survive the induced magnetic and thermal loads?

4. Material properties. Does the copper material have the expected tensile and fatigue properties, and does the G-11CR insulation exhibit adequate creep strength at operating temperature?

The tests designed to address these issues and the test results are the subject of this paper.

Assembly/Fit Test

Fabrication and assembly tolerances of the HF coil segments dictate that some of the individual lap joints that make up a typical segment-to-segment joint assembly will experience a material interference or overlap during installation. As the upper segment is vertically lowered into place, some lap joint tabs will be forced by the interferences to bend and slide past one another. The determination of the "worst-case" interference is a separate study. That study yielded a target interference of 0.052 in. for turns 1-12, and 0.034 in. for turns 13 and 14. Consequently, one pair of laps representing turns 1 and 2, and one pair of laps representing turns 13 and 14 were tested.

The objectives of this test were to evaluate:

1. the load required to force the assembly of the interfering tabs,

2. the mutual "flare-out" of the tabs resulting from the assembly, and the force required, if any, to pull the flared ends of the tabs back into contact in the assembled position, and

3. rubbing degradation of the lap surfaces.

The four test specimens were dimensioned as the actual tabs of individual turns will be fabricated, excluding twists and curvature effects. The contact surfaces of the tabs were silver plated after the specimens were fully annealed in an inert atmosphere.

The tabs were bolted to a special retaining fixture and mounted in an MTS Model 311.21 load frame as shown in Fig. 3.

The tabs were meshed several times and the loads recorded. The maximum compressive force required while the 0.25-in. by 15° chamfers were in contact was about 525 lb. Then as the bases of the chamfers passed each other, the angle of attack of the laps changed and the silver-plated surfaces came in contact. At this point, the force dropped to about 225 lb. The force climbed back to about 475 lb as more material was deflected until full assembly was reached.

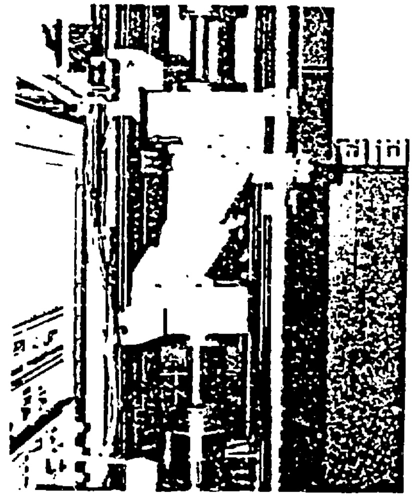

Fig. 3. Side view of assembly test.

While in the assembled position (Fig. 4), the tab flare-out was inspected. There was virtually none. A 0.0015-in. feeler gage could not detect any gaps. The tabs matched contours to a very high degree.

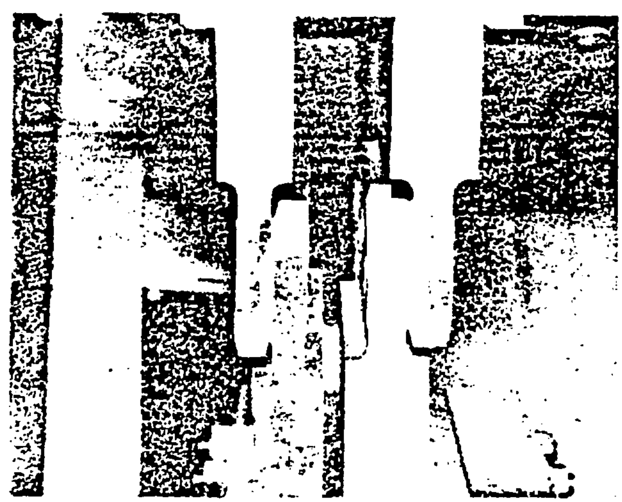

Fig. 4. Front view after assembly.

When the specimens were separated, the plated surfaces showed definite rub marks, but every contact area still had a continuous layer of silver. No gouging through the silver into the copper occurred.

The rub marks were also fairly evenly distributed over the contact areas, indicating even contact pressure. No galling was evident.

This test indicates that even a substantial mismatch of mating segments is tolerable and should not prevent joint assembly. The extrapolated total load to "mesh" the joint tabs on both ends of a segment is less than 8000 lb, which is within the capacity of the assembly fixture.

Joint Clampup and Clamp Load Relaxation Tests

Successful operation of the HF coil depends on achieving low resistance at all lap joints, those in the center of the stack as well as the outside. A test program was undertaken to simulate a stack of seven typical turn elements and measure the resistance between the seven lap joints under prototypic conditions. Two series of tests were made — the first to evaluate initial joint clampup and joint resistance vs clamp force, and the second to evaluate the effects of thermal cycling on the clamping force. Both series used essentially the same joint mock-up consisting of seven pairs of silver-plated copper turns connected in series electrically and energized by a 20,000-A dc power supply. This mock-up simulates all the geometrical features of an actual joint (Fig. 5).

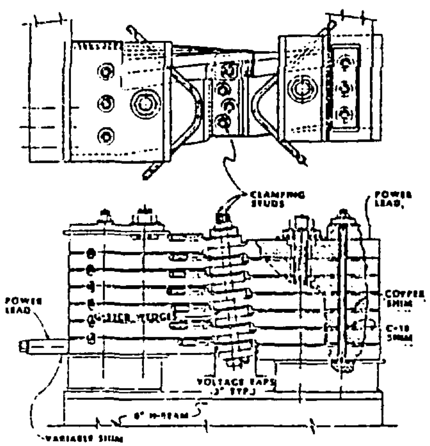

Fig. 5. Seven-turn joint mockup for clamp tests.

Initial Clampup

The mock-up was prepared for the clampup tests by fixing each set of copper turns solidly to an 8-in. H-beam, then torquing the joint studs to 80 ft-lb. Tests were run with the stacks nominally square to each other and with 0.5-mm shims under opposite edges to create a "twist" mismatch. A current of 10,000 A was applied, and the electrical resistance across each contact was calculated from the voltage drop (measured between two points 1.5 in. on either side of the joint midplane).

Table 2. JOINT CLAMPING RESULTS
[Turn resistance (μΩ) normalized for 20°C]

	Torque (ft-lb)						
Joint	20	30	40	50	60	70	80
1-2	.87	.88	.88	.88	.88	.87	.87
3-4	.93	.95	.95	.95	.95	.95	.94
5-6	.97	.97	.96	.96	.95	.94	.93
7-8	.87	.87	.86	.87	.86	.86	.86
9-10	.98	.95	.94	.93	.93	.92	.91
11-12	1.00	.98	.97	.96	.96	.96	.95
13-14*	1.06	1.04	1.03	1.03	1.03	1.02	1.02

*Only 3 studs clamp this contact.

The test was repeated for various torque values, and the resistance values are shown in Table 2. The results indicate that: (1) resistance of all joints is 1.02 μΩ or less at the prototypic joint load of 80 ft-lb torque per stud, (2) joint resistance has little variation through the stack, (3) shims under the stack had no measurable effect because the copper was so malleable that the 0.015-in. gap due to shimming could be taken out by finger tightening the studs, and (4) torque beyond 50 ft-lb caused only small decreases in resistance.

Thermal Cycling

The first series of tests indicated a torque loss in the joint studs during each test. To evaluate these phenomena, special strain-gaged studs ("Strainsert" Model DWI-D) and load-indicating washers (Lebow Model 3711) were installed to monitor stud tension as the joint was thermally cycled.

The first phase of testing used the strain-gaged studs, which were limited to about 10,000 lb. The second phase used the load-indicating washers, which could tolerate the design preload of 12,000 lb. The test results in Fig. 6 indicate that: (1) stud tension in the stack drops sharply after initial torquing and thermal cycling; (2) retorquing of the studs results in a significant increase in the residual bolt tension after subsequent thermal cycles; (3) after five to six retorques, a tension level of 90% is maintained during the following thermal cycles; (4) if the studs are unloaded, the "settling-in" process must be repeated, and (5) the tension loss appears related to both the number of cycles and to long-term creep.

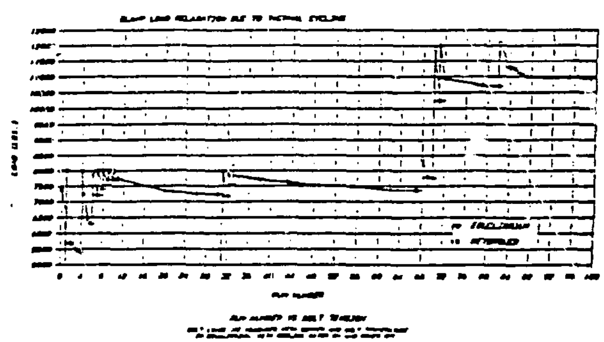

Fig. 6. Clamp load relaxation due to thermal cycling.

Fatigue Testing

After establishing that the HF coil joint can be assembled and clamped, it must be shown that the joint is structurally adequate and will remain that way for the life of the machine.

The HF coil experiences radial and transverse magnetic loads as well as Joule heating. This translates into hoop tension in the conductor that must be carried across the joints. The tension is not uniformly distributed over the joint but tends to be higher in the innermost turns, 11-14. A complex stress and fatigue analysis of these turns indicated reasonable fatigue life.

To confirm the analysis, tests were run to determine the actual fatigue life of the two joint configurations (the inner and outer ends of a coil segment) under peak load conditions. Each of the two test specimens consisted of a partial two-turn joint stack (turns 13 and 14 and turns 11 and 12) as shown in Figs. 7 and 8, that was load cycled in tension and compression with the peak operating loads.

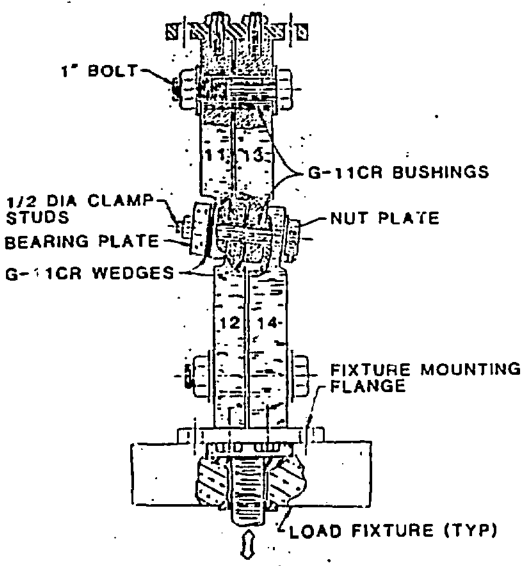

Fig. 7. Fatigue test specimen #1.

The specimens were tested in a load-controlled manner at 1 Hz on an MTS Model 311-21 load frame. The inner joint prototype was built and tested first and performed as follows.

In the first phase, the prototype was load cycled 82,000 times between 6,200 lb compression and 26,000 lb tension . Strain gages indicated about 1% plastic strain at first, but no plastic strain after about 1000 cycles. The test was stopped to increase the load.

In the second phase, the prototype was cycled 45,000 times between 6,200 lb compression and 35,500 lb tension to simulate the higher loads that occur at the outer joint. Strain gages showed additional plastic strain at first, but settled in. The test was stopped due to failure of the load fixture.

Inspection of the prototype showed no damage of the properly loaded joint (11-12). The other joint (13-14) had been overloaded by about 75% and showed some fretting and elongation.

Fig. 8. Fatigue test specimen #2 in load frame.

The outer joint specimen was tested using the same test machine and methods used for the inner joint. However, instead of strain gages, the outer joint turns were coated with a photoelastic plastic coating to provide a full field measure of the stress patterns in the specimen. A strain-gaged bolt was also installed in place of one of the joint through-bolts in an effort to determine any relaxation of the bolt tension that might occur due to load cycling. Just like the inner joint, the outer joint was full size and had the approximate twist and offset, but not the curvature, of the actual joint. An attempt was made to cycle the joint at loads of 15,400 lb compression to 34,800 lb tension, which simulate the loads induced on the joint from a 2-T, 5-s pulse of the ATF device, but the friction produced by tension in the through-bolts was inadequate to keep the faces of the turns from sliding.

The compression load was reduced to 6,200 lb and cycling continued for 134,320 cycles before the load fixture failed. When an attempt was made to restart the cycling mode, the test specimen was inadvertently loaded to 62,000 lb tension and turn 12 was damaged. A crack in the fillet area ran almost all the way across the turn. Cycling was resumed until a total of 230,200 cycles was obtained, when the crack in turn 12 worked its way through. Strain data taken from the photoelastic coating indicated high plastic strain during initial loading but little additional plastic strain on subsequent cycles.

Fatigue testing results for these joint prototypes show a marked redistribution of stress within each turn. This effect is not included in the stress analysis, so the fatigue life is considerably more than predicted, as summarized in Table 3.

Table 3. JOINT FATIGUE LIFE SUMMARY

Required number of cycles	Condition	Predicted life (cycles) From analysis	Predicted life (cycles) From test
10,000	2 T, 2 s	14,000*	2×10^5
25,000	1 T, 10 s	10^{6}*	
15,000	1.5 T, 5 s	10^{5}*	
1,000	1 T, steady state	10^{6}*	

*Includes safety factor of 10

Materials Testing

The low cycle fatigue analysis required detailed material property data. Although these data exist for OFHC copper in various conditions, a test program was conducted to determine material properties and fatigue data on samples of the CDA102 copper plate that will be used to fabricate the HF coils. These data are summarized as constant life curves and are shown in Fig. 9.

The joint stud relaxation tests indicate some creep in the G-11CR wedge insulators. To quantify this effect, creep tests were conducted on stacks of 0.115-in.-thick G-11CR samples. Results are shown in Table 4.

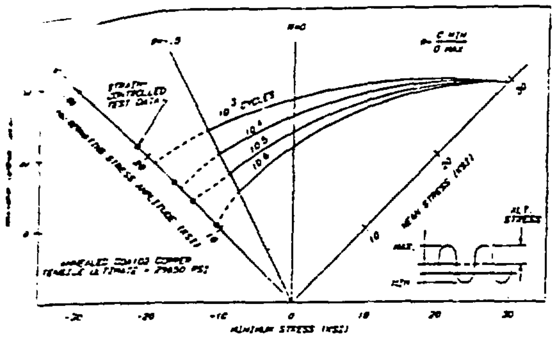

Fig. 9. Constant life diagram for CDA102 copper.

Table 4. G-11CR CREEP TEST RESULTS (Constant load on .46-in. stack; Deflection in 24 hours)

Temp.	6000 psi	12000 psi
Room temp.	0.00%	0.00%
Room temp.	0.00	0.02
70°C	0.00	-
70°C	0.00	0.09
90°C	0.06	-
90°C	0.00	0.09
110°C	0.26	0.37
110°C	0.28	0.24

Conclusion

An extensive test program has been conducted to confirm the mechanical performance of the HF coil joint design. The tests indicate that (1) the joints can be assembled, (2) good electrical contact can be achieved and maintained, (3) the joints have more than adequate fatigue life, and (4) material properties are consistent with the design assumptions.

References

[1]. R. L. Johnson, "The Advanced Toroidal Facility (ATF), these proceedings.

[2]. R. L. Brown, R. L. Johnson, "Thermal and electrical joint test for the helical field coils in the Advanced Toroidal Facility (ATF), these proceedings.