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ABSTRACT

The design and fabrication process of a 15-T, 4000-A, Nb_3Sn test coil are described. In the Conductor Performance Qualification (CPQ) coil, it is intended to demonstrate the reliable performance of cable-in-conduit conductors (CICC) produced in large quantities from internal-tin process, multifilamentary, Nb_3Sn composites. In addition, techniques appropriate for the insulate-wind-react-impregnate method of coil construction using CICCs, such as joints and insulations are developed and demonstrated. The coil is designed to operate at a maximum field of 15 T as an insert to the High-Field Test Facility Solenoid at LLNL [1]. It consists of four grades of CICCs, each made of the same number, but a different size, of composite wires. Operating current density over the first-grade conductor winding is 40 $A \cdot mm^{-2}$ at 15 T. Also presented is a novel ripple heating scheme to inject heat at specific levels appropriate for a close simulation of ac and nuclear heat loads in a fusion reactor. Up to 100 W of heating power can be simulated within the coil winding, allowing the effects of such heating on the coil performance to be investigated.

INTRODUCTION

Technology to produce high magnetic fields over large regions for the confinement of fusion plasma has advanced dramatically in recent years [2]. To meet the increasing demand, Nb_3Sn magnet technology development has also progressed steadily. In a recent design study [3], the International Thermonuclear Experimental Reactor (ITER) calls for both toroidal and poloidal coils of 12 T or more and large sizes, which require high-current niobium-tin conductors to operate under conditions of high stress, cyclic loading, and ac or nuclear heating. Fundamentally, such high performance is attainable, but development and verification are required. The CPQ coil represents the first series of such efforts to provide much needed engineering data on crucial materials and processes.

MAGNET DESIGN CONSIDERATIONS

The first major objective of the CPQ coil is to determine and verify the superconductor scaling parameters of Ti-modified, internal-tin process Nb_3Sn composite wires produced in large quantities and fabricated in a cable-in-conduit form. The coil is designed to produce a maximum field of 15 T in the winding as an insert to the HFTF. Field contour plots for the coil windings are shown in Fig. 1. It is wound with four grades of CICCs, each made of the same number, but different sizes, of composite wires. The coil specifications are given in Table 1.

The cable is wound with 125 composite strands in a 5^3 configuration. Major parameters of four grades of CICCs are listed in Table 2.

SUPERCONDUCTING COMPOSITE

The composite conductor is an internal-Sn conductor manufactured by Intermagnetics General Corporation. The conductor is made using seven subelements, each measuring 0.1–0.127 mm diameter, depending on the final wire size. The local copper to Nb ratio is about 1:1 with the Nb filaments having 1.2 wt/o Ti added to improve high-field properties. The copper stabilizer is 50% by volume and is separated from the subelements by a Nb diffusion barrier with Cu interlayers to improve bonding. The final conductor has A-15 filament sizes of 3.5–4.5 μm, depending on wire size, and about 8% residual Sn in the bronze.

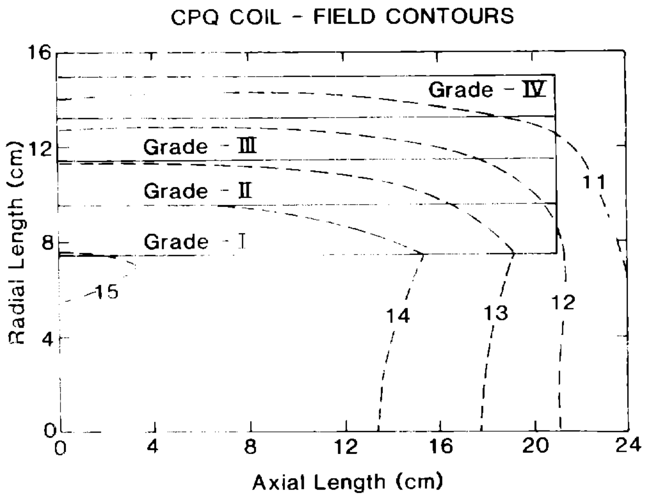

Figure 1. Field contour plots for one-fourth coil winding. Field label is in tesla, and operating current is 4145 A.

TABLE 1
CPQ COIL SPECIFICATIONS

Inside diameter	150 mm
Outside diameter	300 mm
Coil height	420 mm
Operating current	4145 A
Number of turns	405
Number of layers	8
Grading	4
Conductor length	292 m
Maximum field	15 T*
Forced-cooling temperature	4.3 K
Operating pressure	1–2 MPa
Total mass flow rate	5 g/s

*Operated with HFTF magnets.

TABLE 2. CICC CONDUCTOR PARAMETER

Grade No.	Sheath* Dimensions (mm – square)	Composite Strand Diameter (mm)	Length (m)	Winding Pack Current Density $(\mathrm{A \cdot mm^{-2}})$
1	9.42	0.574	48	40
2	8.61	0.546	66	48.8
3	7.91	0.491	81	57.1
4	7.59	0.460	97	61.8

*Thickness of the sheath (SS 321) is 0.81 mm for all grades.

CICC

The CPQ coil CICCs were also manufactured by Intermagnetics General Corporation. The tube material is seamless, 321 stainless steel, chosen on the basis of availability and low cost, as compared to the precipitation-hardening alloys. Although sensitized and somewhat embrittled by the reaction heat treatment, 321 stainless is acceptable due to the low electromagnetic stresses in the CPQ coil. The conduit was assembled in three steps: 1) pulling the finished superconducting cable through oversized tubing, 2) die-drawing of the tubing to achieve the desired level of compaction and helium void fraction, and 3) Turk's head rolling to square cross section. The four finished CICC grades are thus free of welds and associated defects.

COIL WINDING AND COOLING SCHEME

The CPQ coil was wound in eight layers with four different grades of CICC conductors. Electrically, all conductors are connected in series by means of five joints and two current-lead connections. A cross-sectional view of the winding as it is mounted on a coil winder is shown in Fig. 2. Figure 3 shows the flow scheme for the conductors. Hydraulically, the winding consists of four parallel flow paths, the longest of which is about 100 m (Grade IV). An additional cooling path is provided for cooling all five joint blocks. The flow distribution can be controlled with four return control valves. Total maximum flow rate is 5 g/s at inlet pressure up to 2 MPa. Instrumentation is provided for temperature, flow, and pressure measurements to assess heat loads during coil operations. In addition, a heater circuit at the inlet is designed for injecting either heated, gaseous helium slug for transient current-sharing measurement, or raising inlet temperature for elevated temperature tests.

INSULATION AND EPOXY IMPREGNATION

In the insulate-wind-react-impregnate method, all components wound into the winding should be made of materials capable of withstanding high heat-treatment temperature excursions. Here, chosen for conductor insulation, is a 50% overlap wrap of Nextel ceramic fiber tape, with a thickness of 0.25 mm. Additionally, a layer of Nextel sheet of the

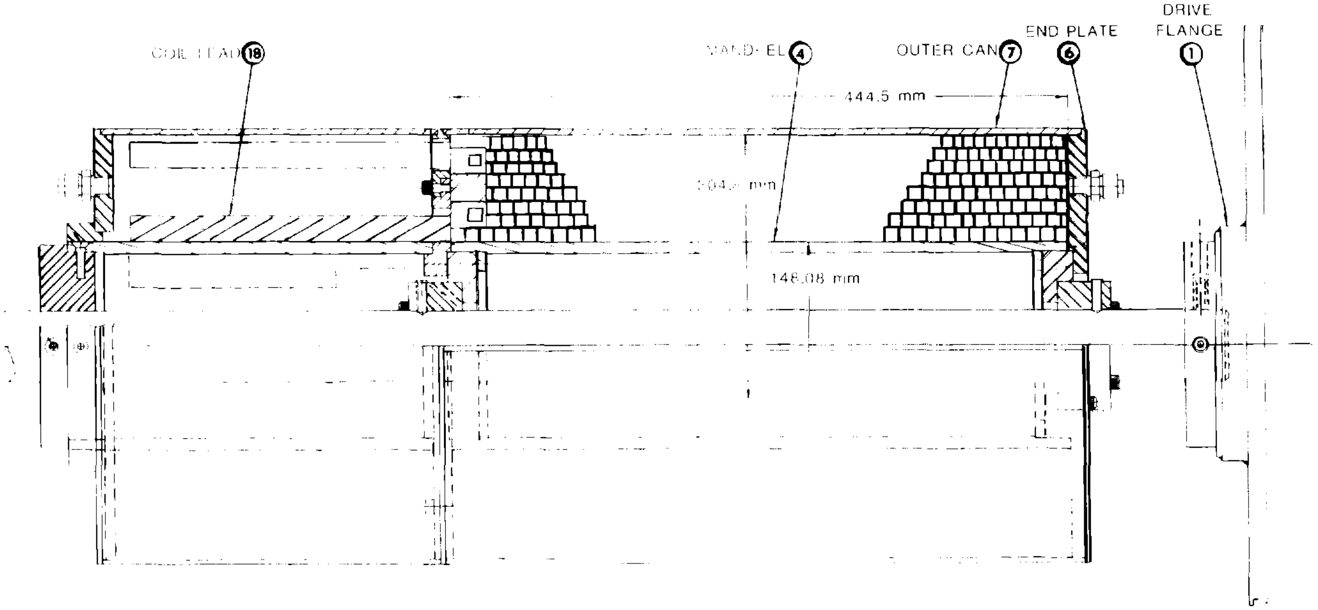

Figure 2. Cross-sectional view of coil winding as it is mounted on the coil winder.

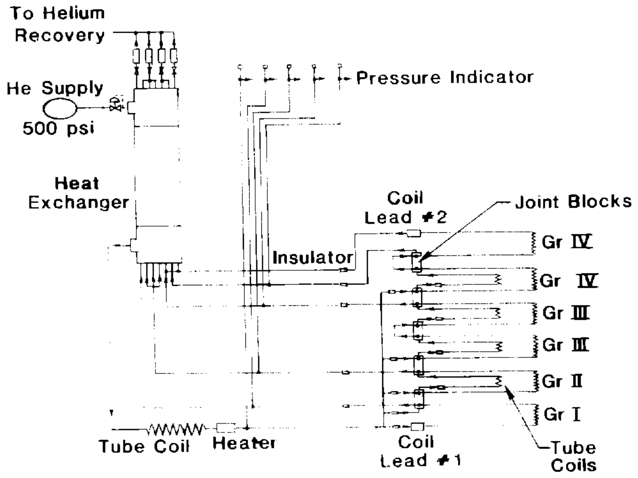

Figure 3. Flow schematic of the CPQ coil.

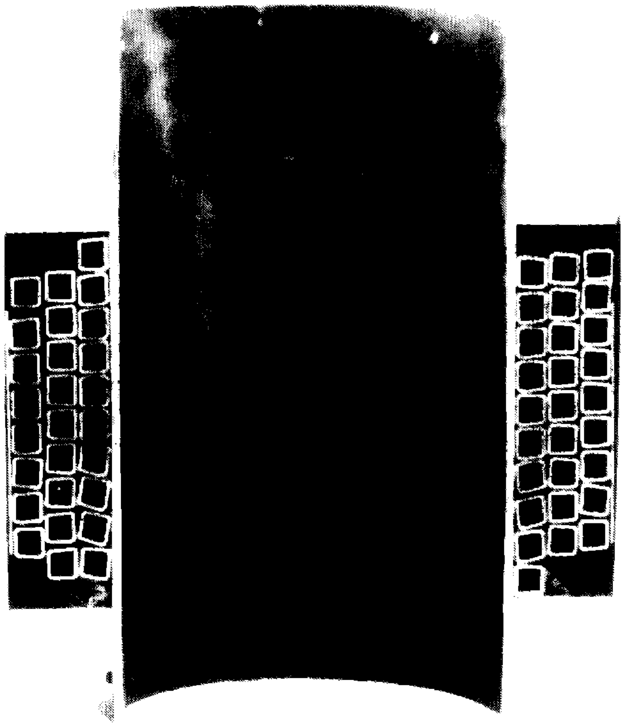

Figure 4. A practice winding coil impregnated with the GY6010/D230 resin system. The entire magnet pack, as well as the conduits, were easily impregnated with epoxy resin.

same thickness is used as an interlayer insulation. Because of its relatively low initial viscosity, the long working time, and the excellent history of cryogenic service, resin (GY6010/D230)[4] is selected for the epoxy materials. Its wettability with the Nextel insulations was tested in one of the practice windings that underwent the specified insulate-wind-react-impregnate process. Figure 4 shows a cross section of the practice winding after impregnation with the resin. The winding is completely filled with minimal voids. The coil was also thermal shocked by rapid immersion in liquid N_2. Cracking of the epoxy was not observed in the body of the winding pack.

JOINTS

Considerable efforts have been made on joint development for the CPQ coil. Figure 5 illustrates the schematic for the final design. The lap joint is made within a preshaped, bent, copper block with two predrilled holes. A stainless-steel adaptor is vacuum brazed with Nioro to the end of each hole. A stripped section of cable is inserted into the joint block until its remaining sheath fits the adapter. The lip of the adapter is then welded to the sheath to form a seal. Some unique features of the joint design are worth noting:

1. A welding procedure has been devised for sealing the ends of the cable strands against possible tin leakage

2. Practical cleaning and fluxing techniques have been developed for processing the joint after the reaction heat-treatment. In addition, a heater element has been devised and incorporated in the joint block to provide uniform and well-controlled heating for easy soldering. The soldering is performed by filling Sn–40% Pb solder through predrilled solder holes

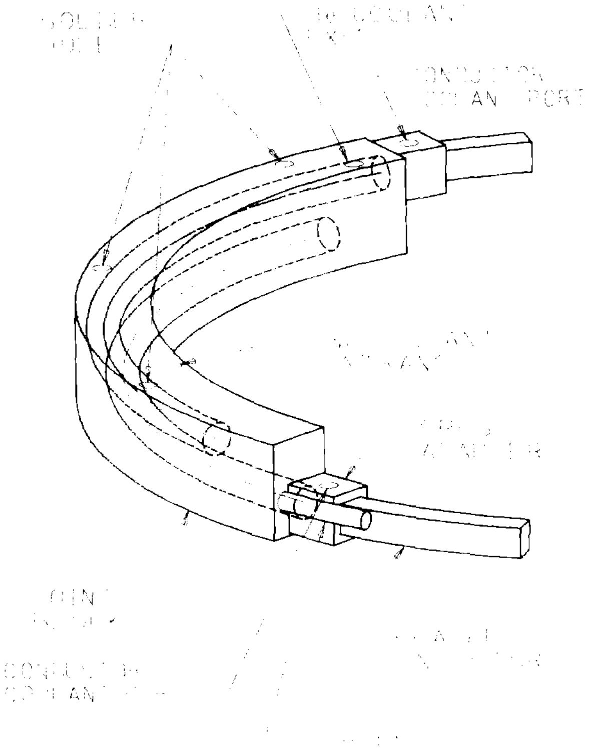

Figure 5. Schematic of CPQ joint design.

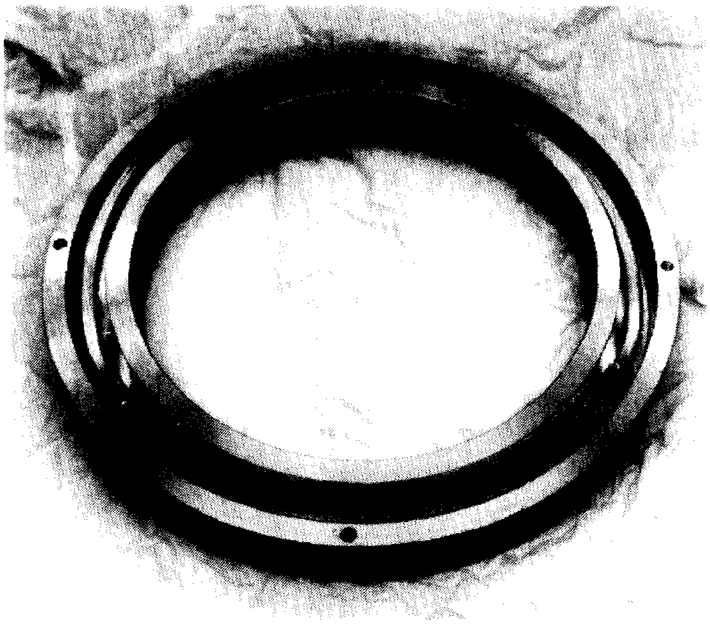

Figure 6. A shorted-turn CICC sample with a joint block ready for heat treatment.

3. An independent cooling path is also provided for the joint block.
4. The joint design can be easily scaled up to ITER application.

A number of joints have been fabricated and physically evaluated. In the last practice winding, two joints were successfully wound into the winding; the testing through remaining processes is still in progress. Also in progress is the electrical testing of such joints at high fields. Shorted-loop samples, as shown in Fig. 6, have been fabricated and will be tested by an induction method [5].

RIPPLE HEATING SYSTEM

Fusion magnets are required to operate reliably while subjected to nuclear-radiation and ac-loss heat loads. In designing the CPQ coil, a novel ripple heating system was devised. Instead of buying a large, expensive power supply that is capable of ramping the entire coil current at rates fast enough to induce these losses, a ripple heating power supply was developed that can inject a 60 Hz ripple current through a portion of the coil. Figure 7 illustrates a schematic of the ripple heating scheme. The CPQ coil will be operated from one of the existing low-voltage, high-current dc power supplies as normal. The ripple heating will be accomplished by injecting a 60 Hz ripple current into taps within the CPQ coil. For a 10-V ripple input, as much as 100 W of ac losses can be injected. With a winding volume of 0.023 m^3 the power density in the winding pack will be 4.5 $kW \cdot m^{-3}$. This system can inject heat at specific levels and distributions appropriate for a close simulation of the ITER environment of nuclear and ac loss loads. As mentioned earlier, instrumentation is provided for measuring the heat load and the heat removal capability.

During the design phase, the coupling effects of the ripple current and its

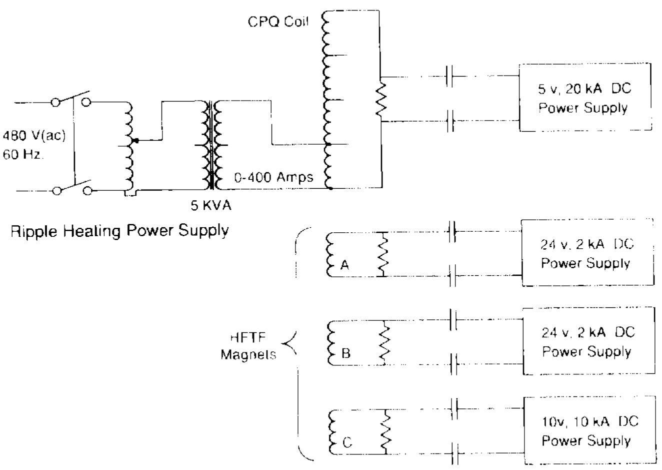

Figure 7. Schematic diagram for the ripple heating system.

induced voltages to the HFTF magnets had to be predicted. The HFTF magnet system has been modeled for several years with the electronic circuit simulation code, SPICE, on the NMFECC Crays. The standard SPICE model for the HFTF magnets was modified to include the CPQ coil, modeled as four series-connected coils with the ripple heating supply connected across one of the sections. Due to the symmetrical layout of the HFTF magnets to the test coil and the very large time constants in the magnet/dump resistor circuits, the coupling effects into the magnets were shown to be negligible.

SUMMARY

The design and fabrication process of a 15-T Nb_3Sn test coil is presented. It intends to demonstrate the reliable performance of CICC produced in large quantities of internal-tin process, Nb_3Sn composites. It also has developed and demonstrated many techniques appropriate for the insulate-wind-react-impregnate method of coil construction using CICCs such as joints and insulations. Also presented is a novel ripple heating scheme for investigating the effects of heating on the coil performance.

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REFERENCES

1. Miller, J. R., Chaplin, M. R.,Leber, R. L., and Rosdahl, A. R., A Flexible superconducting facility for fusion magnet development. IEEE Trans. on Magnetics, 1988, **MAG-24, No. 2,** pp. 1425–1428.
2. Haubenreich, P. N., Komarek, P., Shimamoto, S., and Vecsey, G., International development of superconducting magnet for fusion power Fusion Technology, 1989, **Vol. 15, No. 2, Part 2B,** pp. 909–914.
3. Henning, C. D., and Miller, J. R., Design considerations for ITER magnet system. Fusion Technology, 1989, **Vol. 15, No. 2, Part 2B,** pp 915–921.
4. Wilson, M. N., Superconducting Magnets, Clarendon Press Oxford, 1983, p. 313.
5. Schmidt, C., Critical current, stability and ac-loss measurement on the Euratom LCT conductor. IEEE Trans. on Magnetics, March 1983, **MAG-19 No. 3,** pp. 707–710.