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# DESIGN, FABRICATION, AND TESTING OF THE PULSE COILS FOR THE LARGE COIL TEST FACILITY*

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## Summary

The Large Coil Test Facility (LCTF) will be able to test up to six large superconducting coils similar to those required for a tokamak reactor. In order to simulate the transient vertical field that will be part of the magnetic environment of an operating tokamak reactor, a set of pulse coils will be used in the facility. This set of two coils can be positioned in the bore of any of the test coils to provide a transient magnetic field to that particular coil. This paper describes the final design of the pulse coils and discusses the fabrication techniques used to build these coils. An extensive testing program has been carried out during fabrication to ensure that the coils will function satisfactorily.

## Background

The different design concepts for simulating transient vertical magnetic fields in the LCTF were extensively studied and reported in 1977 [1]. The current design, two vertical axis coils mounted on a movable box beam, was a direct result of this study. The system to move the pulse coils around the facility in the bore of the test coils was described in 1981 [2], as were the design of the pulse coils and the test program [3]. In order to supply the pulse coils with the appropriate liquid nitrogen cooling, a pulse coil cooling system has been designed and fabricated [4] (see Fig. 1).

## Final Design Description

The pulse coil system consists of two 1321-mm-diam solenoid coils mounted on the top and bottom flanges of a 914-mm-tall box beam. Each pulse coil consists of 768 turns of copper conductor wound two-in-hand into 16 two-layer pancakes. This forms a solenoid winding pack with a 495-mm-tall by 370-mm-wide cross section and an outside diameter of 1184 mm. The copper conductor is extruded 14-mm$^2$ conductor with a 7.6-mm-diam hole centered for coolant. The pancake leads are provided with the appropriate electrical jumpers so that all the windings are in series electrically. The leads are isolated and manifolded so that there are 32 parallel cooling paths for forced-flow liquid nitrogen ($LN_2$) cooling. The winding pack is contained in a sealed stainless steel case completely potted with epoxy resin. A complete coil weighs about 5000 kg. A schematic view of a pulse coil is shown in Fig. 2. The inner windings of a typical test coil can be subjected to a 1500-G field using the pulse coil system in its normal configuration.

The final design incorporates several interesting features that have proved to be successful. The coil uses a split manifold design with two supply manifolds and a single return manifold. This feature has allowed cooling of the two-in-hand winding pack without any external connections of small-size tubing. The manifolds are connected to the pulse cooling system using 38-mm-OD tubing. The winding pack is electrically isolated from the pulse coil case using ceramic insulating breaks (see Fig. 3).

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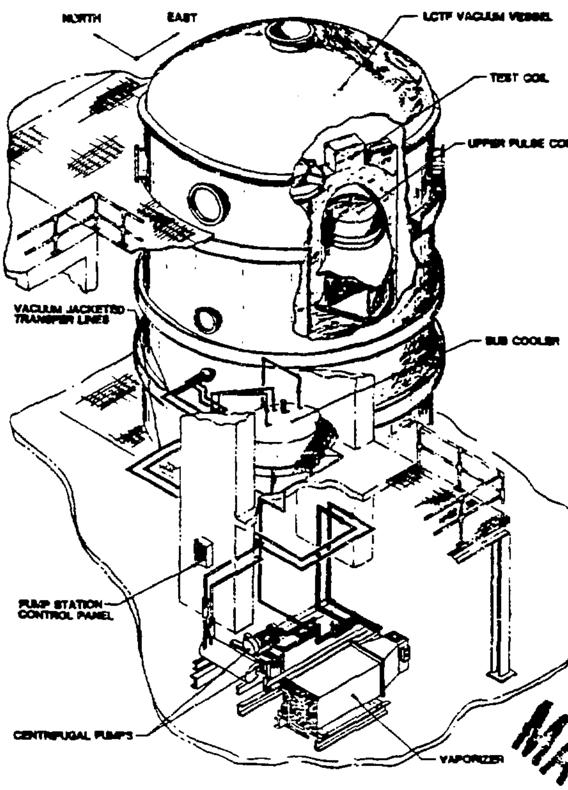

Fig. 1. Pulse coil in LCTF.

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Another related design feature is the insulating feedthroughs for the power connections. These feedthroughs are a special design item suitable for welding to the pulse coil case and brazing to the copper (see Fig. 4). The copper rod for the power connection is inserted into a special transition on the winding pack after the pack is placed in the coil case.

The pulse coils were designed to be epoxy potted in a one-step operation using the structural case as the mold. This procedure eliminated the expense of a separate mold and seemed to expedite the fabrication.

## Design Analysis

Several analysis activities were conducted as part of the final design process. Two of the more interesting analysis activities were the calculation of conductor length and conductor thermal performance. An extensive finite element analysis of the pulse coil case was conducted to determine the stresses due to magnetic forces.

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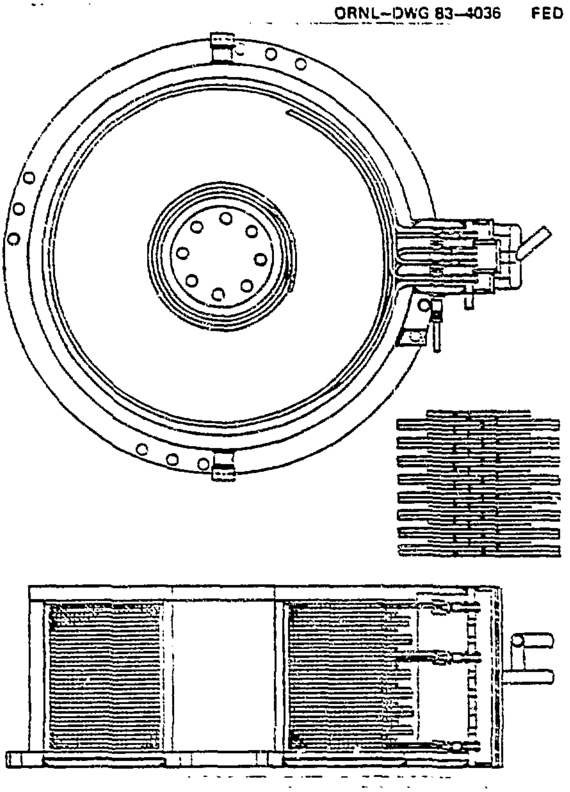

Fig. 2. Pulse coil schematic.

## Conductor Length

The conductor length calculation was important to determine requirements for conductor procurement and pressure drop. The length of conductor in a pancake is given by

$$L = 4 \sum_{n=1}^{24} \pi r_n ,$$

where

$L$ = length,

$r_n$ = radius of nth turn.

This equation was solved with a programmable calculator, and the result showed that each pancake used 121 m of copper conductor.

## Conduit Flow

A conduit flow calculation was performed for a 121-mm flow path and a conventional one-in-hand winding scheme. For this case the flow rate was inadequate using the differential pressure available from the pulse coil cooling system. A two-in-hand winding scheme with a flow path of about 61 m was analyzed, and it was determined that with a differential pressure of 275 kPa an adequate flow rate of 3.2 L/s per coil can be achieved.

## Thermal Performance

A thermal performance calculation to predict the exit nitrogen temperature was performed using a finite difference technique code called TACC [5]. The TACC code was modified slightly to use the properties of $LN_2$ rather than water. The normal operating condition for the pulse coils is 2000 A in each coil for a 30-s pulse with a repetition rate of 150 s. The results of the transient response calculation at the exit of the pulse coil are shown in Fig. 5. The maximum exit temperature of 90 K is below the boiling temperature of nitrogen at an exit pressure of 690 kPa. A high-current test using 4000 A can also be accommodated, but the maximum pulse length is 13 s to avoid two-phase flow conditions.

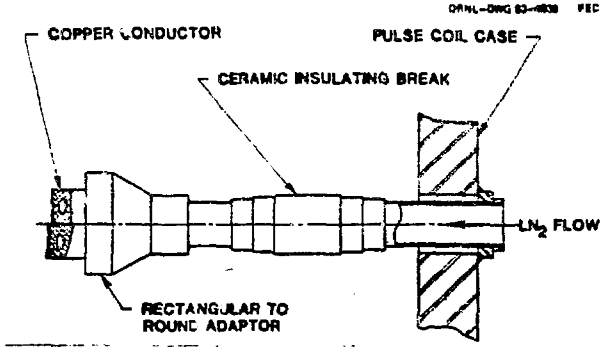

Fig. 3. Insulating break.

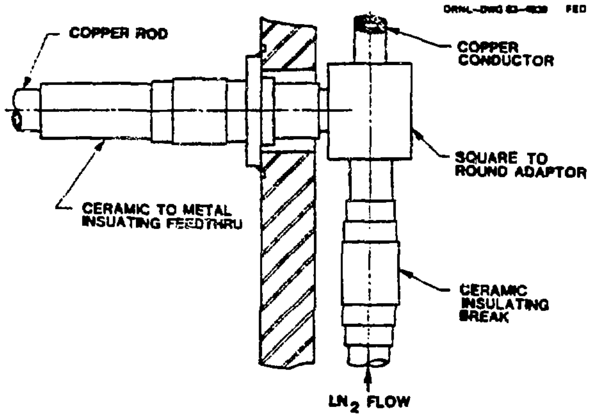

Fig. 4. Power feedthrough.

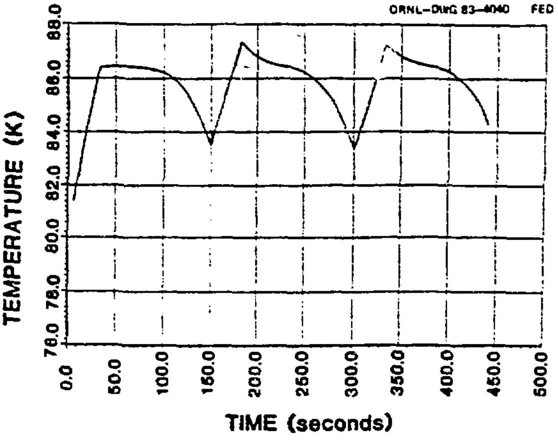

Fig. 5. Transient temperature response of exiting $LN_2$.

### Stress Analysis

The stress analysis of the pulse coil case was largely accomplished using the finite element code PAFEC [6]. The mesh for the calculation is shown in Fig. 6. During a pulse, a large moment is imposed on the pulse coil case, which attempts to twist the coil so that its axis lines up with that of the test coil. During this condition for the test case involving 4000 A, the moment approaches $6.8 \times 10^6$ N·m. The stresses in the pulse coil for this worst-case analysis were calculated to be 300 MPa in a small area of the upper cover plate. An additional strengthening member was added to this portion of the case, and supplemental hand calculations indicate that the stresses in the final design do not exceed 248 MPa.

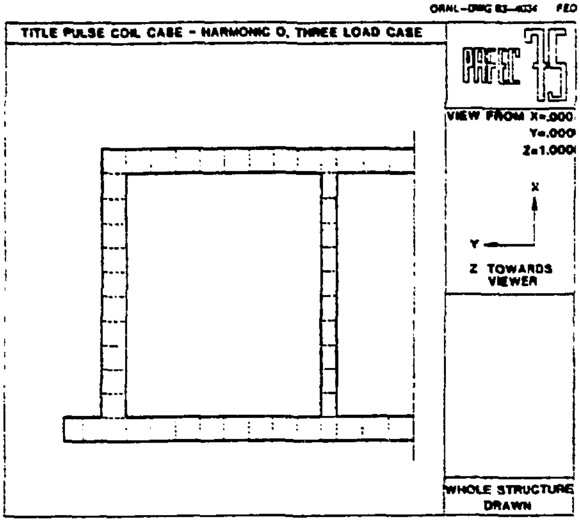

Fig. 6. Finite element mesh for pulse coil model.

### Fabrication

The pancakes for the pulse coils were wound at Magnetics Corporation of America (MCA) in Waltham, Massachusetts, using a 1524-mm winding table. The coils were wound using copper conductor (ASTM B187) in 27-m lengths. The conductor lengths were connected at braze joints, as shown in Fig. 7. The insulation consists of Kapton tape half-lapped along the entire length of the conductor and fiberglass tape half-lapped on top of the Kapton.

The complete pancakes were stacked in order so that the special transition adaptors could be brazed into place (see Fig. 3) on the ends of the conductor. The ceramic breaks and associated tubing were also brazed into place before the winding pack was placed in the case.

The coil cases were fabricated in parallel with the winding of the pancakes by RANOR, Inc., Westminister, Massachusetts, a subcontractor to MCA, and then shipped to MCA for insertion of the winding packs. After the winding packs were inserted into the coils, the assemblies were shipped back to RANOR for the final case closure welds and final machining.

The coils were potted using a CIBA 6005 epoxy formulation introduced directly into the coil case. The potting procedure was accomplished inside a large heat-treating oven to control pour and cure temperatures (see Fig. 8). Each coil required about 145 L of epoxy mix to completely fill the coil case. Sample pours into a small rectangular mold were made at the time each coil was potted.

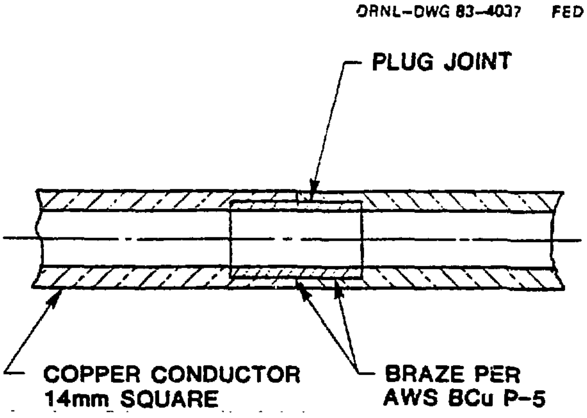

Fig. 7. Conductor braze joint.

Fig. 8. Pulse coil during potting in oven.

### Testing

During fabrication, an extensive testing program was carried out to ensure that the coils will function in accordance with the Large Coil Program test plan. Each butt joint on the conductor was individually helium leak tested, and the electrical resistance of each joint was measured. Incoming inspection for the conductor included a test of the cooling passage diameter using a steel ball 6.35 mm in diameter that was blown through the cooling passage using pressurized air.

Completed pancakes were subjected to a "ring test," in which a voltage spike was applied to the leads and the voltage oscillations were examined using an oscilliscope. The damping pattern of each pancake was compared with the damping pattern of a known good pancake. All the pancakes tested positively.

Supplemental laboratory testing of the ceramic insulating break has been performed. At a temperature of 77 K, the break was tested up to 20,000 V; no breakdown was observed (see Table 1). The break was also cold shocked at 77 K and helium leak tested. Again, no leaks were observed. This gives confidence that the breaks will perform satisfactorily.

The epoxy potting samples were machined into tensile specimens and tested at room temperature and at 77 K. The results from this testing are shown in Table 2.

Table 1. Voltage test results

| Voltage, V dc | Time of voltage, min | Comments |
|---|---|---|
| 5,000 | 5 | No breakdown |
| 10,000 | 5 | No breakdown |
| 15,000 | 1 | No breakdown |
| 20,000 | 1 | No breakdown; slight audible corona discharge |

Table 2. Ultimate strength and elastic modulus of pulse coil epoxy samples

| Sample number | Test temperature, K | Ultimate strength, MPa | Elastic modulus, MPa |
|---|---|---|---|
| 5 | RT[a] | 132 | 2816 |
| 6 | RT | 143 | 2759 |
| 7 | RT | 133 | 3251 |
| 1 | 77 | 171 | 2204 |
| 4 | 77 | 176 | 2451 |
| 3 | 77 | 216 | 3003 |

[a] Room temperature.

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