TEST RESULTS OF THE U.S.-LCT POOL-BOILING COILS IN THE INTERNATIONAL FUSION SUPERCONDUCTING MAGNET TEST FACILITY (IFSMTF)*

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Abstract

The international Large Coil Task (LCT) has designed, built, and successfully tested six different toroidal field coils. Each has a 2.5- $\times$ 3.5-m D-shaped bore, a current between 10 and 18 kA, and is designed for stable operation at 8 T, with a superimposed pulsed field of 0.14 T in 1.0 s, and simulated nuclear heating. Included in the torus are two pool-boiling coils designed and fabricated by U.S. firms, General Dynamics/Convair Division (GD) and General Electric/Oak Ridge National Laboratory (GE). Both coils were well instrumented for studies of electromagnetic, mechanical, and thermodynamic properties. Testing of the torus started early in 1986 and was successfully completed on September 3, 1987, although the pulsed tests with GD and GE had to be deleted from the test program because it was not feasible to devote the required few months to repair the mechanism for moving the pulse coil system to these two test coils. Both coils performed well and met design specifications. In later "extended-condition" full-array tests beyond the design values, both operated stably at 100% design current and above 9 T, even with bath temperature higher than 4.3 K. The mechanical behavior of both coils was generally in good agreement with calculations. Both coils were also safely discharged several times in the extended-condition tests. All results indicate that the technology developed for these two pool-boiling LCT coils can be directly applied for future large-scale applications.

Introduction

The Large Coil Task (LCT) is a collaborative effort of the United States, EURATOM (EU), Japan (JA), and Switzerland (CH) in large-scale development of superconducting toroidal field coils for fusion reactors[1]. The United States provides the test facility at Oak Ridge National Laboratory and three of the six test coils; the other participants provide one coil each. Included in the torus are two pool-boiling coils designed and fabricated by U.S. manufacturers, General Dynamics/Convair Division (GD) and General Electric/Oak Ridge National Laboratory (GE). The GD coil is layer wound, with interlayer spacers to direct helium flow produced by boiling away from the sides and up to the stack. The GE coil is pancake wound with insulation that blocks interpancake cross flow of helium. Each coil was well instrumented with 200 to 300 sensors and voltage taps for studies of electromagnetic, mechanical, and thermodynamic properties. The major characteristics of the two coil designs are listed in Table 1.

Since April 1987, the two coils have been extensively tested in single-coil mode and in the full array. Previous publications have reported successful preliminary design-point test results [2,3,4]. This paper summarizes the complete test results, including the extended-condition test in which both coils demonstrated capability for operation well beyond design points. Table 2 lists the highlights of all major experiments since April 1987 that involved the GD or GE coils.

Test Configurations

Full-Array Force-Field Model

Because of the different designs of conductor, structure and cooling scheme employed in each coil, the LCT full array is asymmetrical from both electromagnetic and mechanical

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Table 1. Design Comparison of the GD and GE Coils

	GD	GE
Design current (A)	10,200	10,500
Ampere-turns (MAT)	6.41	6.53
Conductor material	NbTi	NbTi
Conductor type	Flattened cable in extended surface copper bar	16 subelements spiraled around copper core
Winding	Edge wound in 14 layers on bobbin	Flat wound in 7 double pancakes
Grading scheme	3 (8.0, 6.3, 4.4 T)	3 (8.0, 6.0, 4.0 T)
Helium conditions	Pool boiling (4.2 K, 1 atm)	Pool boiling (4.2 K, 1 atm)
Stability	Fully cryostable	Cryostable via end conduction
Structural material	304L SS	316LN SS
Structural configuration	Fully welded case	Case welded and bolted

points of view. A computer model based on exact coil winding geometries was thus developed for full-array field and force analysis. Figure 1 shows the model for full-array configuration. The current distribution of six coils varies widely from test to test, determined by the test objectives and practical limitations. The test configurations for design-point tests of the GD and GE coils are listed in Table 3.

Table 2. Highlights of LCT Test Program for the GD and GE Coils

Test	Date	Configuration	Objectives
Design-point tests	8/21/86	Full-array GD—Test coil (Standard-1)	To achieve stable operation at design current and field (8 T) and perform recovery tests
	11/3/86	Full-array GE—Test coil (Standard-1)	To achieve stable operation at design current and field (8 T) and perform recovery tests with simulated nuclear heating
Extended-condition tests	4/22/87	Single-coil GE—Test coil (Alternate-C)	To determine maximum operating current
	5/7/87	Single-coil GD—Test coil (Alternate-C)	To determine maximum operating current
	8/8/87	Full-array GE—Test coil (Alternate-A)	To reach reference field = 9 T
	8/11/87	Five-coil EU/GE—Test coil (Alternate-B)	To achieve stable operation with out-of-plane force = 23.5 MN
	8/14/87	Five-coil GE/JA—Test coil (Alternate-B)	To achieve stable operation with out-of-plane force = 20.0 MN
	8/18/87	Five-coil GD/CH—Test coil (Alternate-B)	To achieve stable operation with out-of-plane force = 21.4 MN
	9/2/87	Full-array GD/JA—Test coil (Alternate-A)	To reach 9-T peak field in both GD and JA coils
	9/3/87	Full-array (Maximum torus)	To reach 9-T peak field in all coils

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Fig. 1. LCT full-array model for field and force analysis.

Table 3. Test Configuration for Design-Point Tests

Test coil	Parameters	EU	WH	GE	GD	JA	CH
GD	I* (%)	77.1	77.1	77.1	99.8	77.1	76.8
	B ₀ (T)	6.7	6.4	6.9	8.0	6.8	6.9
	F _x (MN)	31.5	35.9	31.0	37.9	32.1	27.2
	F _y (MN)	-4.5	-0.2	-1.1	-0.3	-5.8	-0.3
GE	I* (%)	80.8	74.3	99.5	85.1	80.3	81.2
	B ₀ (T)	7.1	6.5	8.0	7.5	7.1	7.8
	F _x (MN)	35.3	38.6	38.6	36.6	34.8	33.1
	F _y (MN)	-1.7	-3.7	-1.6	-3.3	-0.6	-0.2

I* (%) = fraction of the design current

B₀ = field at reference point (at the surface of the conductor nearest the inner bore of the coil, in the equatorial plane and midplane.)

F_x = net centering force

F_y = out-of-plane force (counterclockwise from above)

The test configuration for the Alt-B tests of the GD and GE coils is listed in Table 4, and Table 5 lists those for the Alt-A tests.

Table 4. Test Configuration for Alt-B Tests of the GD and GE Coils

Test coil	Parameters	EU	WH	GE	GD	JA	CH
EU-GE ^a	I* (%)	97.3	0	93.4	92.1	85.9	94.2
	B ₀ (T)	7.1	2.8	6.9	7.7	7.3	7.9
	F _x (MN)	29.8	0	26.7	35.5	35.9	32.4
	F _y (MN)	22.9	0	-22.9	-2.0	0.8	0.3
GE-JA ^a	I* (%)	72.3	55.6	80.9	0	82.8	71.8
	B ₀ (T)	5.9	4.9	5.8	2.4	6.0	6.2
	F _x (MN)	23.5	21.9	18.5	0	20.4	20.6
	F _y (MN)	0	0.4	14.6	0	-14.6	0.4
GD-CH	I* (%)	62.5	55.3	63.8	66.0	0	70.7
	B ₀ (T)	5.2	4.7	5.2	5.0	1.9	5.3
	F _x (MN)	17.8	19.0	16.3	14.0	0	13.4
	F _y (MN)	-1.7	0.2	1.9	10.6	0	-11.6

^a Test terminated at this point due to a quench in a background coil.

Test Results and Analysis

Measurements of Electromagnetic Properties

The electromagnetic data of Table 6 are surprising only in the low voltage withstand capability of the GD electrical system. The flaw(s) are thought to be at a few instrumentation feedthroughs containing cables from both ends of the coil. Similar repairs were successfully made earlier [5] but in the present instance were not allowed by the LCT schedule. Instead, the dump voltage was reduced by more than half, giving GD by far the longest decay time constant (83 s), with interesting but harmless mechanical and thermal consequences on dump.

Table 5. Test Configuration for Alt-A and Maximum Torus Tests of the GD and GE Coils

Test coil	Parameters	EU	WH	GE	GD	JA	CH
GE	I* (%)	92.9	103.0	109.0	93.7	96.6	85.4
	B ₀ (T)	8.1	8.3	9.0	8.4	8.2	7.9
	F _x (MN)	46.6	58.9	50.7	46.2	45.1	36.8
	F _y (MN)	-11.7	-4.8	9.4	3.1	4.2	0.1
GD-JA	I* (%)	97.6	100.2	98.1	100.3	107.2	90.7
	B ₀ (T)	8.4	8.1	8.5	8.8	8.9	8.4
	F _x (MN)	49.5	57.4	47.2	49.6	51.4	40.7
	F _y (MN)	-9.4	0.3	5.6	-2.6	4.5	1.8
All coils ^a (maximum torus)	I* (%)	106.2	108.3	105.6	97.8	105.7	98.6
	B ₀ (T)	9.1	8.7	9.1	8.8	8.9	9.0
	F _x (MN)	57.1	65.7	52.8	50.7	53.2	46.0
	F _y (MN)	-11.2	1.2	10.0	-0.2	1.6	-1.1

^aTest terminated at this point due to a quench in the WH coil

Alt-C Tests of GE Coil: As summarized in Table 7, the GE Alt-C test was carried out in an attempt to achieve 140% design current as a single coil. During the test the compensated voltage (i.e., the resistive voltage obtained by subtracting the inductive components from total coil voltage was recorded on a strip chart. As the coil current went from 133 to 139%, the compensation voltage rose in an exponential fashion to about 40 mV above the baseline. The current was held, reduced 2%, and raised 1% in steps, with the compensated voltage following appropriately. The current was then ramped to zero. This was the first time that current-sharing voltages have been observed in a NbTi coil with the coil remaining well behaved and controllable. Concurrent traces of coil current, helium level, and helium pressure illustrating the current-sharing effect are shown in Fig. 2.

Alt-C Tests of GD Coil: The high-current test of the GD coil was terminated at 120% of design current because of a coil quench initiated from a normal zone in layer 10 (Table 7). It is believed that the critical current was exceeded in the grade-III conductor. It should be noted that the grading scheme employed in the GD coil design is optimized only for full-array operation, which would leave little margin in current-carrying capacity in low-grade conductors if the coil were operated in single-coil mode.

Heating Tests in Full-Array Mode

The heating tests of the GD coil have been reported earlier [3]. During the Standard-1 test of the GE coil, recovery tests, nuclear heating tests, and nuclear heating plus recovery tests were successfully performed up to 100% current, 8 T

Fig. 2. Test results of current-sharing effect in the GE coil (current, helium level, and helium pressure traces).

Table 6. Summary of Measured Coil Parameters (Electromagnetic Properties)

Parameters	GE	GD
Self-inductance (H)	1.81	1.84
Residual resistance ratio	121	187
Dump resistor (m Ω)	59	26/22 ^a
Ground insulation breakdown voltage (V)	>1000	>200
Maximum dump coil voltage (V)	654	269
Maximum field achieved at reference point (T)	9.1	8.8

^aThe value of 22 m Ω was used only in the Alt-C (120%) test. The center-tap grounding resistor, when used, was 1.2 M Ω .

Table 7. Description of Alt-C (Single-Coil) Tests of the GD and GE Coils

	GE	GD
Date performed	4/22/87	5/7/87
I_{max} (A)/ I_{max}^* (%)	14,591 A/139%	12,190 A/120%
B_0 (T)	7.7	6.7
Results	Current-sharing voltages of about 40 mV observed; coil current then safely ramped down	Coil quenched, from normal zone in layer 10 (grade-III conductor)

reference field. The recovery tests showed that the coil can recover from a half-turn fully normal at design current and field, as is required by the specifications. The normal zone recovery behavior was similar to that observed in the single-coil tests at lower field [3], namely, the one-third zone at the top of the coil recovered in a cold-end-recovery fashion. It took a full 4 s after the heat pulse to recover. In nuclear heating tests, the coil sustained local heating power density of up to 60 mW/cm² for 60 s at design-point conditions. Nuclear heating for 50 s, then pulse heating on a half turn produced only a slight increase in recovery time of the pulse heated half-turn over that in straight recovery tests without the presence of vapor caused

Fig. 3. Heating test of GE coil (recovery of a normal zone with nuclear heating).

by continuous heating for 50 s. The results of this ultimate stability test are shown in Fig. 3, wherein one can see that the outer-leg segment and the adjacent quarter of the central segment recover from the sides when the heater pulse terminates. This recovering zone extends by conduction farther into the central segment but with a steadily decreasing velocity, and voltage equilibrium is nearly reached by $t = 2.5$ s, when the cold boundary progressing up the straight-leg segment at approximately 1 m/s crosses VT3035. Shortly after the crossing, the velocity decreases and remains nearly constant until it approaches the other cold end, and the remaining small normal zone (~8 cm) abruptly collapses. One could speculate that at some higher current the left front might stall as the right one did, leaving a stable and possibly hazardous normal zone in the middle segment.

Table 8. Summary of GD Conductor Strain Measurements and Analysis

Sensor	ALT-C (Single-coil)		ALT-A (Full-array)			
	Measured	Calculated	Measured ^a		Max Torus	Calculated
	$I^* = 1.20$ $B_0 = 6.3$ T	$I^* = 1.20$ $B_0 = 6.3$ T	GE $I^* = 0.937$ $B_0 = 8.4$ T	GD, JA $I^* = 1.00$ $B_0 = 8.8$ T	$I^* = 0.978$ $B_0 = 8.8$ T	$I^* = 1.0$ $B_0 = 8.8$ T
SE-2	1200 ^b	854	1500	1600	1500	1034
3	960	482	1000	-	-	610
4	500	666	-	760	650	835
5	-200	-485	-	-	-	-649
6	-600	-454	-1400	-1750	-1600	-607
7	-350	-168	-	-	-	-205
8	-220	-151	-	-	-	-192
11	910	693	750	-	-	863
13	550	669	-	-	600	835
14	-200	-454	-	-	-	-607
15	1650	669	1500	-	-	835
16	600	473	1500	-	-	599
17	1100	600	1100	-	-	754
18	960	600	1000	-	-	755
19	900	600	1000	-	-	646
20	630	527	-	-	-	667

^aSee Table 5.

^b($\mu\epsilon$); positive sign indicates tension

^cNot measured.

Table 9. Summary of Measured Mechanical Properties

Measurements		GD	GE
Maximum conductor strain ($\mu\epsilon$) ^a	Single-coil	1660	2000 ^b
	Full-array	1750	2000 ^b
Maximum structure strain ($\mu\epsilon$)	Single-coil	320	500
	Full-array	300	1300 ^c
Maximum displacement (mm) ^d			
-Winding to inner bore	Single-coil	2.00	4.70
	Full-array	1.65	3.05
-Winding to sideplate	Single-coil	1.40	1.91
	Full-array	1.14	1.02

^a Positive sign indicates tension.

^b Gauges on conductor core. Higher and irregular values were observed on some subelements only

^c Very sensitive to the out-of-plane load

^d The change in gap between winding and case as current is applied.

Mechanical Behavior

Coil Response: The measured conductor strains for all three LCP pool-boiling coils were much higher than those on the cases. Furthermore, measured stresses for the conductor were higher than predicted while those for the case were lower, indicating that the designers overestimated the stiffness of the mechanical coupling. However, taking this fact into consideration, it can be shown that the agreement between measurement and prediction is rather satisfactory. Table 8 illustrates such a comparison for the conductor strain analysis for the GD coil. (Figure 4 shows the sensor locations). Table 9 summarizes over-all measured mechanical properties of the two coils. It can be concluded that both coils demonstrate satisfactory mechanical integrity, although a few anomalous strain gauge readings on GE subelements may indicate disbonding from the core at these locations.

The well-behaved coil structure can be further manifested by the mechanical measurements at the coil interface to the bucking post. In Fig. 5, the readings of strain gauges mounted on both upper and lower support collar for both coils show clearly linear dependence of current squared, as expected for the single-coil test.

Out-of-Plane Load Tests

Table 4 lists all the Alt-B tests performed on the GD and GE coils. While the magnitude of these out-of-plane loads is smaller than that of the in-plane loads, their effects are more severe than the in-plane effect and required careful attention in the coil case design. The test of the GD coil was carried out only in one direction and limited to 11 MN force. No excessive strains were measured. For the GE coil, two tests were performed, one for each direction. The measured radial strain of compression in the highest stressed area is plotted vs the out-of-plane force (in both directions) in Fig. 6. The measured results show good symmetry to both directions of force; moreover, the magnitude is close to calculated values.

Summary

Testing of the LCT GD and GE coils has been successfully completed. Both coils performed well and met design specifications. In later extended-condition full-array tests beyond the design values, both operated stably at 100% design current and above 9 T, even with bath temperature higher than 4.3 K. The mechanical behavior in all the tests of both coils was generally in good agreement with calculations.

All results indicate that the technology developed can be directly applied for future large-scale operations.

Fig. 4. Strain gauge location on GD coil (winding).

Fig. 5. Support collar strain for GD and GE coils in single-coil tests (negative sign means tension).

Fig. 6. Response of strain gauges on GE coil case in Alt-B tests (positive sign means compressive radial strain).

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