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Thermal Tests of an Insulated Coil

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Introduction On August 25, 1995, a series of thermal tests were done on a 4-m, Tesla-insulated coil, IDCL040ET (a coil intended for use as a lower coil in an IDC dipole; it has a thru-bus). This coil has a number of defects in the potting process, including three in between the coil and the thru-bus, near the lead end. The tests were done under the supervision of the authors, and participants included: Frank Juravic, Gregg Kobliska, Arie Lipski, Jay Hoffman, and Bill Pritchard. The objective of the tests was to see the effects, if any, on the defects, from stresses induced by temperature gradients between the thru-bus and the coil. The tests were continued to higher temperature gradients on August 31.

Outline of Tests The coil was instrumented with four thermocouples on the thru-bus (two on each end, with each pair having one at the top of the 4" width and one at the center) and with dial indicators on each end of the coil and each end of the thru-bus. Cold water was flowing through the coil, at a nearly constant temperature of about 23°C, and with a flow rate of about 3 GPM. The water for the thru-bus was variable in temperature, by mixing the cold tap water with hot water. Again, a flow rate of about 3 GPM was maintained. Prior to the tests, the locations and lengths of the three defects were noted. The arrangement of the instrumentation and water flow is shown schematically in Figure 1.

Test procedure The initial tests (Aug. 25) involved three levels of thermal cycles, with temperature differences between the thru-bus and coil of 2, 4 and 7°C. Each level consisted of five cycles of on and off; the time for the temperature and dial indicators to stabilize for each step was approximately 5 minutes. The thermocouples and dial indicators were read and recorded at each stage. At the end of each set of cycles, the defects were reexamined to see if they had changed. Each of us (EGP and PSM) made separate estimates of the length of the defects. (During the first set of thermal cycles, an additional defect was noted; this was clearly a hairline crack, over the thru-bus, as opposed to a potting defect between the thru-bus and coil. It had been detected in the prior inspection of the coil using dye penetrant.) The five "on" cycle measurements for each temperature level were averaged, and all 16 "off" cycle measurements were averaged for plotting in the attached data chart.

The purpose of follow-up tests on Aug. 31 was to extend the tests to higher temperature gradients. At the higher gradients, we had more difficulty with the stability of the hot water supply. Therefore, each individual measurement is plotted separately. One should assign somewhat larger error bars to these meaurements, and one should also note that the readings of the thermocouples and the dial indicators were taken in succession, not concurrently, and small changes in the course of the readings cannot be ruled out.

Discussion In the accompanying chart, the upper three charts show the defect length estimates during the initial tests. It appears that the first defect grew, while the third one did not. The reader may use his own judgement as to whether the second defect increased or not.

In the expansion data, we show the measured change in the total length of the thru-bus, of the coil, and the calculated value for copper based on a thermal expansion coefficient of 0.0000166/°C. These are all plotted vs. the temperature of the thru-bus (average of all four thermocouples). The expansion of the thru-bus is clearly much less than that of unconstrained copper, indicating that the epoxy bond is strong enough to restrain it. Similarly there is a small expansion of the coil, consistent with being one-seventh the expansion of the thru-bus. This could be caused either by heat transfer from the thru-bus, or from forces due to expansion of the thru-bus. In the second set of measurements, we also recorded the outlet temperature of the coil water, and saw no apprecable rise in temperature. We therefore conclude that the expansion of the coil is from the forces transmitted though the epoxy.

If one looks in detail at the expansion curves, one sees that only for the smallest temperature gradients, the thru-bus expands like free copper. This is consistent with the notion that in the cooldown during the impregnation process, the epoxy experiences stresses that increase with decreasing temperature, although one might have expected this behavior to continue to a larger temperature range. As the thru-bus is heated up just a couple of degrees, these stresses are released. Then, as the thru-bus heats up further, the direction of the stress is reversed, and the thru-bus expansion is substantially less than that of free copper.

Stress calculations We have requested calculations of stresses imposed on the epoxy under the conditions experienced in this test. The details of those calculations depend on numerous assumptions regarding the epoxy characteristics and how the various parts of the coil expand under the thermally-induced stresses. Even a thermal model of the system was thought to be too time-consuming to justify the effort, especially given the limited utility of the results under these extreme conditions.

Two points that came from the discussions of the stress calculations were (i) there is a fraction of length of the through-bus that extends beyond the potted-coil and is free to expand. The free length is approximately 12" out of the 253" length, i.e. roughly a 5% correction. (ii) it is questionable whether the four turns of the coil that don't contain the through-bus expand at all. The transverse sections at the ends might simply flex under the forces. Thus, the measurements at the center of the ends could be an average between the zero expansion on the one side, and twice the measured deflection on the side with the through-bus. While replotting the data modifed by these factors changes the characteristics of the data somewhat, no clear conclusions can be drawn. Other more complex coil-expansion scenarios can be envision, as well.

Summary The coil impregnation system withstood the thermal cycling with no apparent difficulty. For reference, the normal temperature gradient expected during operation is about 2°C turn-to-turn. Thus, these tests took the coil to gradients roughly ten times those that will be normally seen.

TESLA INSULATED COIL THERMAL TESTS

2 DEGREE C TEMPERATURE CYCLES									
	THERMOCOUPLES					DIAL INDICATORS			
ON CYCLES	**4**	**5**	**6**	**7**	**1(COIL)**	**1**	**2**	**3**	**4**
1	25.7	25.7	25.2	25.2	23.2	-0.07	1.7	0.1	2.2
2	24.8	24.7	24.6	24.4	23	-0.35	1	-0.2	1.2
3	25.4	25.4	25.3	25.3	23.1	-0.4	1.3	0	1.9
4	25.6	25.4	25.3	25.3	23.1	-0.33	1.4	0.1	1.9
5	25.1	24.9	24.9	24.9	23.2	-0.32	1.1	0	1.6
	25.3	**25.2**	**25.1**	**25.0**	**23.1**	**-0.3**	**1.3**	**0.0**	**1.8**
OFF CYCLES	**4**	**5**	**6**	**7**	**1(COIL)**	**1**	**2**	**3**	**4**
0	22.9	22.9	22.9	22.9	23.2	0	0	-0.3	-0.3
1	22.8	22.9	23.1	23	23	-0.3	0	-0.4	-0.6
2	22.8	22.8	22.9	23	23.1	-0.4	0	-0.4	-0.7
3	22.9	22.9	23.3	23.2	23.1	-0.35	0	-0.4	-0.7
4	22.9	22.9	23	23	23.1	-0.33	0	-0.4	-0.6
5	22.9	23	23.2	23.2	23.1	-0.3	0	-0.4	-0.5
	22.9	**22.9**	**23.1**	**23.1**	**23.1**	**-0.3**	**0.0**	**-0.4**	**-0.6**
4 DEGREE C TEMPERATURE CYCLES									
ON CYCLES	**4**	**5**	**6**	**7**	**1(COIL)**	**1**	**2**	**3**	**4**
1	27.9	27.9	27.7	27.8	23.1	-0.15	2.9	0.6	3.6
2	26.9	26.9	26.3	26.4	23.2	-0.3	2	0.5	2.8
3	27.7	27.3	27.2	27.6	23.1	-0.2	2.6	0.6	3.4
4	27.4	27.1	27.2	27.4	23.1	-0.3	2.4	0.5	3.3
5	26.9	27	26.4	26.8	23.1	-0.38	2	0.4	2.9
	27.4	**27.2**	**27.0**	**27.2**	**23.1**	**-0.3**	**2.4**	**0.5**	**3.2**
OFF CYCLES									
	4	**5**	**6**	**7**	**1(COIL)**	**1**	**2**	**3**	**4**
1	23	23	23	23.1	23.1	-0.3	0	-0.4	-0.5
2	22.9	23	23	23	23.2	-0.3	0	-0.2	-0.6
3	23	23	23.1	23.2	23.2	-0.3	0	-0.2	-0.6
4	23.2	23.2	23.2	23.2	23.2	-0.37	0	-0.2	-0.6
5	22.9	22.9	23.1	23.1	23.1	-0.57	0	-0.2	-0.7
	23.0	**23.0**	**23.1**	**23.1**	**23.2**	**-0.4**	**0.0**	**-0.2**	**-0.6**

7 DEGREE C TEMPERATURE CYCLES												
ON CYCLES	**4**	**5**	**6**	**7**	**1(COIL)**	**1**	**2**	**3**	**4**			
1	30.4	30.4	29.3	30.1	23.1	-0.12	4	1.1	5			
2	29.7	29.9	29.1	30	23	-0.25	3.8	0.9	4.5			
3	30.3	30.3	29.1	29.8	23	-0.3	3.9	1	4.7			
4	31.4	31.4	30	31.1	23	-0.2	4.1	1.2	5.1			
5	30.1	30.2	28.9	29.9	23	-0.35	3.5	1.3	4.5			
	30.4	**30.4**	**29.3**	**30.2**	**23.0**	**-0.2**	**3.9**	**1.1**	**4.8**			
OFF CYCLES	**4**	**5**	**6**	**7**	**1(COIL)**	**1**	**2**	**3**	**4**			
1	22.9	23.1	23.2	23.2	23	-0.43	0	-0.2	-0.8			
2	22.9	23	23.1	23.1	23.1	-0.5	0	-0.3	-0.9			
3	22.9	22.9	23.2	23.2	23.1	-0.61	0	-0.3	-0.9			
4	22.8	23	23.1	23.1	23	-0.6	0	-0.2	-1.2			
5	22.8	22.9	23.1	23.1	22.9	-0.7	-0.3	0.2	-1.1			
	22.9	**23.0**	**23.1**	**23.1**	**23.0**	**-0.6**	**-0.1**	**-0.2**	**-1.0**			

7-25 DEGREE C TEMPERATURE CYCLES												
ON CYCLES	THERMOCOUPLES					THERMOCOUPLES						
	ON THROUGH-BUS					ON COIL		DIAL INDICATORS			SUM	
	4	**5**	**6**	**7**	AVE.	**1**	**2**	**1**	**2**	**3**	**4**	COIL	BUS
1	30.1	30.8	30.5	30.9	**30.575**	23.2	22.9	0.2	4	1.8	6.5	**2**	**10.5**
2	37.6	38.7	37.9	39.3	**38.375**	23.4	22.8	0.9	7.25	3.3	10	**4.2**	**17.25**
3	38	39.5	38.4	39.6	**38.875**	23.4	22.9	0.8	6.9	2.6	10.2	**3.4**	**17.1**
4	38.9	40.7	39.6	41.4	**40.15**	23.4	22.8	0.7	7.8	2.8	10	**3.5**	**17.8**
5	47.3	49.5	43.3	49.2	**47.325**	23.4	23.2	0.9	11.5	3.6	19	**4.5**	**30.5**
6	43.7	45.8	39.8	44.9	**43.55**	23.3	22.9	1	10	2.9	17.6	**3.9**	**27.6**
OFF CYCLE AVERAGES													
	22.9	**23.0**	**23.1**	**23.1**	**23.1**	**-0.4**	**0.0**	**-0.3**	**-0.7**				

	T	L	COIL L	COPPER
OFF	23.0	0	0	0
2	25.2	4	0	6
4	27.2	6	0	12
7	30.1	9	1	20
	30.6	11	2	22
	38.4	17	4	44
	38.9	17	3	46
	40.2	18	4	49
	43.6	28	4	59
	47.3	31	5	70

COPPER COEFFCIENT OF THERMAL EXPANSION		
	1.66	1E-05
THRU-BUS LENGTH		
	173.1	

CRACK LENGTHS

BEFORE THERMAL CYCLES

	GALE	PHIL
1	47	52
2	47	50
3	21	29

AFTER 2 DEGREE THERMAL CYCLES

	GALE	PHIL
1	50	53
2	49	51
3	23	28.5

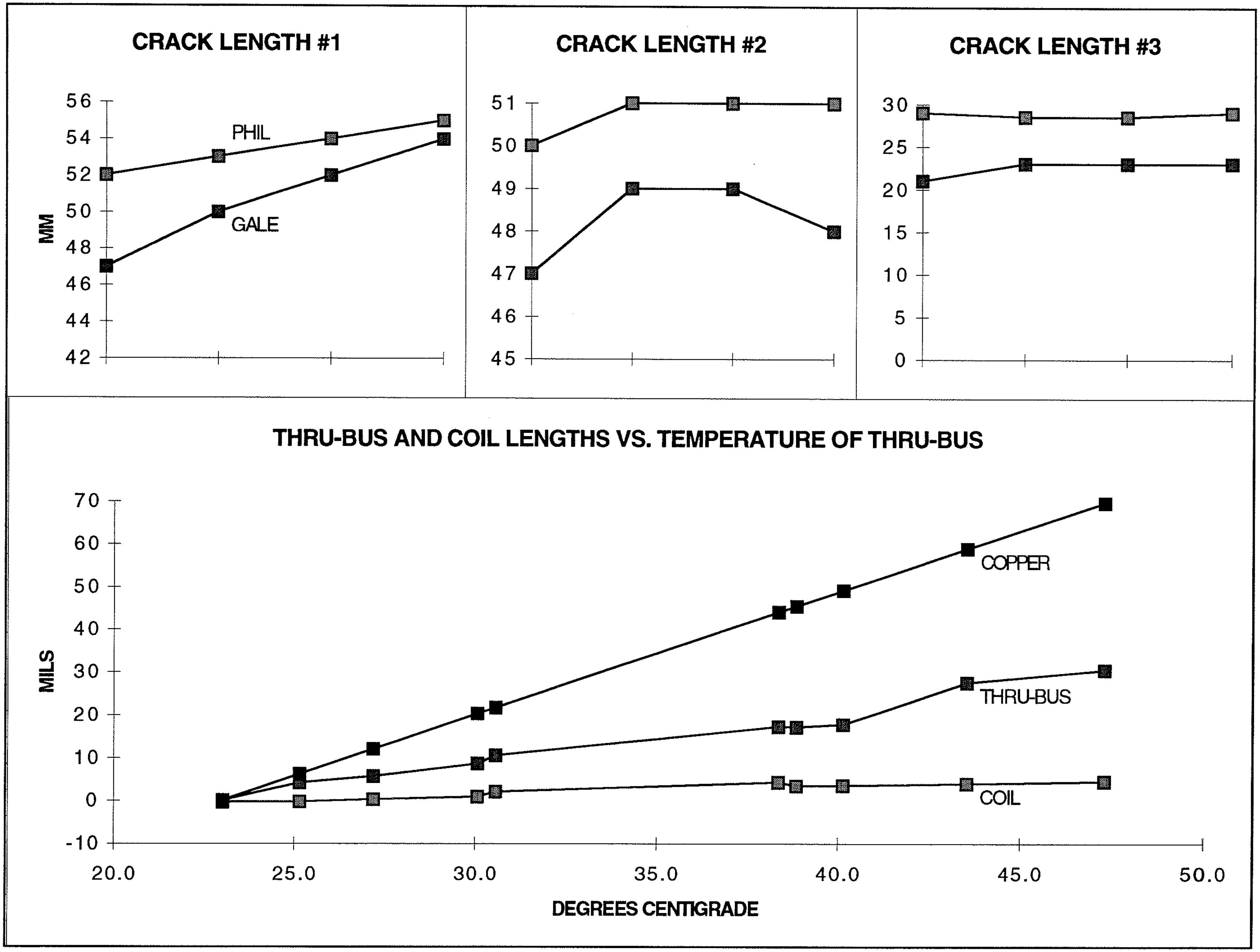
AFTER 4 DEGREE THERMAL CYCLES

	GALE	PHIL
1	52	54
2	49	51
3	23	28.5

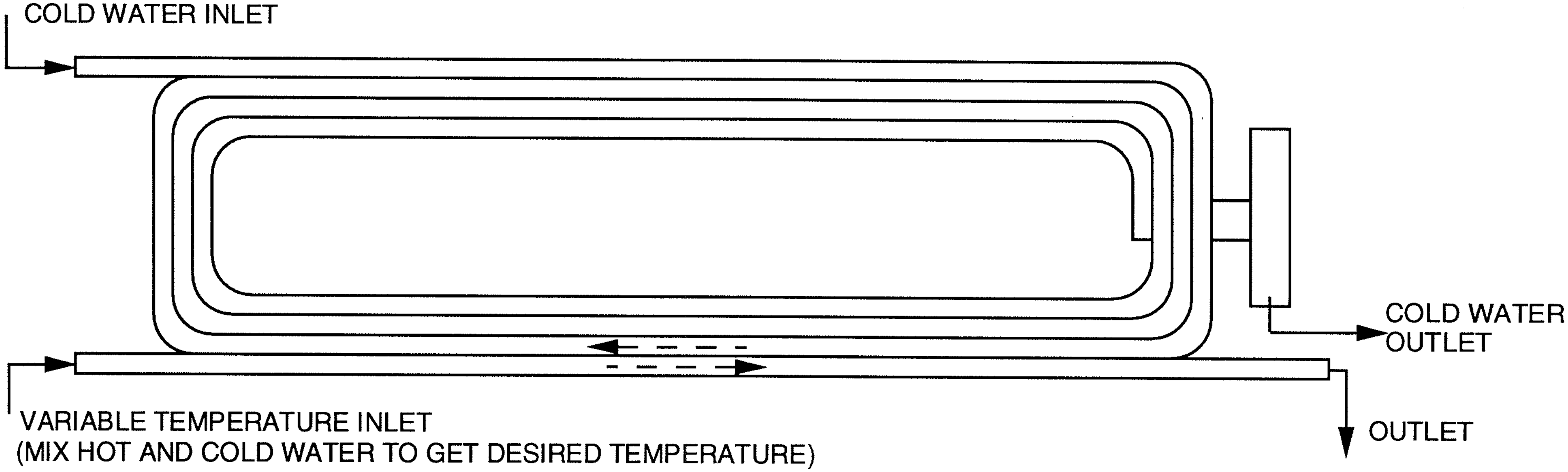
AFTER 7 DEGREE THERMAL CYCLES

	GALE	PHIL
1	54	55
2	48	51
3	23	29

	CYCLE	GALE	PHIL
CRACK 1	0	47	52
	1	50	53
	2	52	54
	3	54	55
CRACK 2	0	47	50
	1	49	51
	2	49	51
	3	48	51
CRACK 3	0	21	29
	1	23	28.5
	2	23	28.5
	3	23	29



CRACK LENGTH #1
MM
56
54
52
50
48
46
44
42
PHIL
GALE
CRACK LENGTH #2
51
50
49
48
47
46
45
CRACK LENGTH #3
30
25
20
15
10
5
0
THRU-BUS AND COIL LENGTHS VS. TEMPERATURE OF THRU-BUS
MILS
70
60
50
40
30
20
10
0
-10
20.0
25.0
30.0
35.0
40.0
45.0
50.0
DEGREES CENTIGRADE
COPPER
THRU-BUS
COIL


COLD WATER INLET
COLD WATER OUTLET
OUTLET
VARIABLE TEMPERATURE INLET
(MIX HOT AND COLD WATER TO GET DESIRED TEMPERATURE)


T1
3
1
T2*
4
2
T6 T7
T4 T5
DIAL INDICATOR
T THERMOCOUPLE
* -- SECOND TEST DAY ONLY