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GROUND-PLANE INSULATION FAILURE IN THE FIRST TPC SUPERCONDUCTING COIL

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Abstract - On August 27, 1980, an insulation failure occurred during the testing of the TPC (Time Projection Chamber) thin superconducting solenoid. The accident caused shorts between the ultra pure aluminum (UPA) secondary circuit and the superconducting coil. There were also shorts between the UPA circuit and ground. The results of an analysis of experimental data taken at 5 millisecond intervals by a data logger and a PDP-11 computer are presented. This paper discusses the results of x-ray and ultrasonic tests and the results of the coil autopsy. From the evidence, a most probable cause for the failure is given [1].

INTRODUCTION

The TPC superconducting coil is a thin solenoid which was designed to run at current densities greater than 5×10^8 Am^{-2} despite a stored magnetic energy of greater than 10 MJ. The TPC magnet was designed to be indirectly cooled by two-phase helium flowing through tubes wound into the coil package. Figure 1 shows a cross-section of the TPC magnet coil. Table 1 shows the design parameters of the TPC solenoid which was tested without iron in the summer of 1980 [2].

Table 1. Parameters of the TPC Solenoid

Coil Diameter	2.168 m
Coil Length	3.294 m
Number of S/C turns	1772
Number of Al turns	600
Design Induction (with iron)	1.5 T
Design Current (with iron)	2230 A
Magnet Inductance (with iron)	4.51 H
Magnet Stored Energy at Design Current (with iron)	10.9×10^6 J
S/C Current Density at Design Current	6.9×10^8 Am^{-2}

Because the TPC magnet stored energy and superconductor current density are high, a dominant factor in the magnet's design was protecting the superconductor against hot-spot temperature effects during a quench. Therefore, the magnet had two shorted secondary circuits.

The first circuit was a 9.5 mm thick 1100-0 aluminum bore tube. The second circuit consisted of 600 turns of UPA insulated from one another. The UPA circuit had an inductance 0.50 H (with iron) and a resistance at 4.5 K of 0.018 ohm.

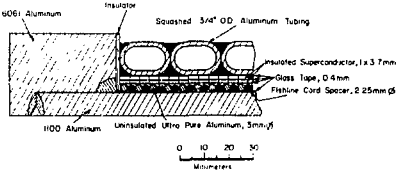

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Fig. 1. Cross section of the TPC magnet coil package.

The TPC magnet circuit is illustrated in Fig. 2. The magnet itself had two layers of superconductor wound over a layer of UPA which was in turn wound over the bore tube. The superconducting coil was closely coupled inductively to the two shorted secondary circuits. Each layer was separated by insulation. Before proceeding further, it is useful to explain the function of the well-coupled secondary circuits:

1. The low resistance secondary circuits cause the current to shift out of the coil which reduces the conductor hot spot temperature during a quench.
2. The secondary circuits, mainly the bore tube, absorb much of the magnet stored energy during a quench. Each secondary circuit absorbs the energy evenly.

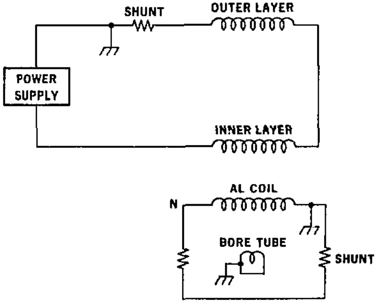

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Fig. 2. Circuit diagram for the TPC magnet coil, ultra pure aluminum circuit, and bore tube before the failure.

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3. The shorted secondary circuits permit the current to be shifted from the coil without high voltages.

4. The shorted secondary circuits cause the whole coil to go normal much faster than quench propagation in the coil would allow. This process is called quench-back [3]. The UPA circuit accelerates quench-back.

5. The shorted secondary circuits enhance the performance of external quench protection systems.

The UPA circuit leads were brought out of the magnet to a diode system which stopped current from flowing in the circuit while the magnet was being charged. The leads which connected the 4.5 K environment with the room temperature connectors were made of stainless steel.

ELECTRICAL EVIDENCE OF THE FAILURE

Before the TPC magnet failure, the magnet was deliberately quenched many times. The LBL procedure for testing high current density coils calls for inducing quenches in the coil at low currents to predict how the coil will quench at high currents [5]. The first quenches induced in the TPC magnet occurred at 475 A (below this current, the quenches would not propagate). The first quench at 475 A caused the stainless steel UPA circuit leads to overheat. The current remained on in the UPA circuit much longer than expected. As a result, a 0.1 ohm resistor was put across the UPA circuit to restrict the current flow in this circuit during the quench.

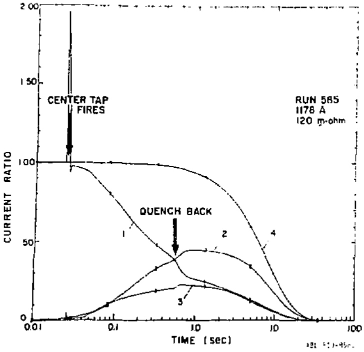
The magnet was quenched without external quench protection at currents up to 800 A. Above 800 A, a pulsed discharge quench protection system on the center tap was used [6]. This system consisted of a capacitor bank which was discharged at the center tap between the two layers. The two layers are well coupled. Thus, a positive current pulse flowed down one layer while a negative current pulse flowed down the other layer. Upon discharge of the capacitor, a portion of the coil was driven normal. During testing the center tap quench protection system became increasingly effective as the magnet current was increased.

The highest quench current prior to the failure was 1178 A. During the induced quench at this current, the UPA circuit carried up to 20 percent of the initial ampere turns, and the bore tube carried up to 48 percent. (See Fig. 3a.) The coil went completely normal though quench-back after 0.6 s. The coil failed during an induced quench at 1258 A. The quench appeared to be normal for the first 0.19 s. The quench protection circuit fired after 30 ms, and the current currents evolved as in the 1178 A case.

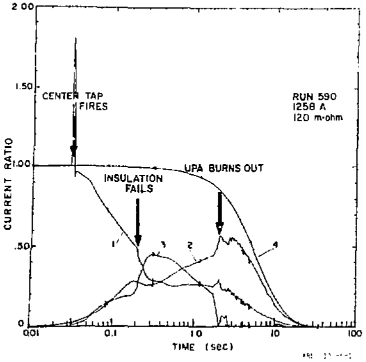
Suddenly, the current in the UPA circuit shunt dropped to zero. There was no sudden change in the current in the superconductor or in the time derivative of the magnetic flux. The superconductor current and $d\phi/dt$ remained smoothly changing until 2 seconds after the quench was initiated. Then there was a ragged behavior in current and $d\phi/dt$ for a few seconds. Both decayed away smoothly. After the quench, resistive shorts were found between the coil and the UPA circuit and between the UPA circuit and the bore tube. The inner layer of the superconducting coil was resistive at 4.5 K while the outer layer was superconducting.

An analysis of the electrical data suggests the magnet behaved normally for the first 0.19 s, when a short appeared between either the UPA circuit and the bore tube or the UPA circuit and the coil. The short occurred at a point near the north end of the magnet. (Indicated by the point N in Fig. 2.) Either kind of short would cause the current in the UPA circuit to bypass the shunt and the 0.1 ohm resistor across the leads. A reconstruction of the current in the UPA circuit was made using the measured transfer functions and the $d\phi/dt$ signal from the pickup coils [1].

At 0.19 s, the current in the UPA circuit started



a. 1175 A quench before failure



b. 1258 A quench when the insulation failed.

Fig. 3. Ratio of the ampere turns in each circuit with the starting ampere turns in the coil as a function of time.
Curve 1: Coil circuit Curve 3: UPA circuit
Curve 2: Bore tube Curve 4: Total Ni

to increase from 19 to 41 percent of the total current. (See Fig. 3b.) The higher current in the UPA circuit persisted for about 2 seconds. Then the current in the UPA circuit was extinguished. At the start of the failure, the bore tube carried about 30 percent of the total current. This was reduced to about 25 percent until the UPA current was cut off; then the bore tube current rose to around 50 percent of the magnet starting current.

There was no evidence to indicate the existance of a short prior to the failure or a short due to the gradual breakdown of the insulation. The failure was sudden and was not caused by turn-to-turn shorts in either the coil or the UPA circuit. The failure was not caused by necking or fracture of the superconductor. By the process of elimination, it was suspected that the presence of a foreign object such as a chip caused the short.

NON-DESTRUCTIVE TESTS TO FIND THE DAMAGED ZONE

As soon as the failure of the coil became evident, a resistance and inductance check of the coil and UPA circuits was made. The resistance check showed that the inner layer of superconductor was not capable of carrying over 30 A without quenching. There was a dead short between the UPA circuit and the bore tube and a resistive short between the inner layer of superconductor and the UPA circuit. From inductance measurements on the coil and UPA circuits, the following conclusions could be drawn:

1. The short between the UPA and the bore tube was about 7 cm from the north end of the coil.
2. The short between the coil and the UPA circuit was a few centimeters further along the coil than the short to the bore tube.
3. There was no short between the inner and outer layers of the coil.
4. The damage zone was extensive, extending several centimeters along the length of the coil. Resistance and inductance measurements could not determine the azimuthal location of the shorts.

X-ray photographs of the damaged zone were taken when the coil was in the cryostat. Breaks in the superconductor became evident, even in the first x-rays. The azimuthal position of the failure was found immediately. X-rays taken after the coil was removed from the cryostat showed three breaks in the superconducting coil in the first layer. They also showed substantial damage to the UPA circuit under the coil.

Direct magnetic measurements, taken when the coil had current in it, confirmed the axial location of the short but did not find the azimuthal location of the failure zone. A small movable field coil, driven by a a.c. current, induced signals into the superconducting and UPA coils. These signals were measured on various leads as the field coil was moved across the outside surface of the coil package. Using the field coil, one could determine the longitudinal and azimuthal location of the shorts within 1 cm. The field coil showed that shorts between the UPA circuit and the bore tube did not occur at the breaks in the superconductor or at the location of the short between the UPA circuit and the coil. The autopsy of the bad region showed the accuracy of the field coil.

Other non-destructive tests were also employed. For example, the location of the bad region could be determined by measuring the coil resistance while pressing various parts of the coil with one's finger. When the bad region was pressed, the coil resistance changed markedly. Ultrasonic measurements of the coil were made from the inner surface of the bore tube. The ultrasonic probe was capable of finding voids between the bore tube and the layer above. Within the bad region, the ultrasonic probe showed a void over the bore tube. (In this region, the UPA circuit was burned away.)

THE MAGNET AUTOPSY

Since the damaged region of the coil was only within 15 cm of the north end of the magnet, it was decided that the coil would be removed from the bore tube in chunks. This would permit sectioning the coil to determine the integrity of the magnet structure. The autopsy was started in a good region of the coil 180 degrees in azimuth from the damaged region to permit the comparison of the good and bad regions of the coil.

The bad region was barely evident from the cooling tube side. The bore tube under the bad region was charred in a narrow band about 15 cm long and about 2 cm wide at the widest point (see Fig. 4). Within the char, there was evidence of melted aluminum, a little of which stuck to the bore tube. The UPA layer showed substantial melting from turn 6 to turn 11. When one looked at the coil piece freshly peeled from the bore tube, the extent of damage was not evident; but, after removing the insulation layer which was between the bore tube and the UPA layer, the extent of damage became clearer.

There was considerable delamination, tearing, and charring of the epoxy-glass between the coil and the UPA. The char and delamination extended over a region about 15 cm in diameter. This damage was caused by the almost explosive evolution of volatile gases from the epoxy resin as it was heated above 250° C. Much of the superconductor adjacent to the melted UPA showed the Formvar burned away. There were three breaks in the superconductor. Two of these breaks were so straight that it was suspected they could have been caused by a tool. It was later found that these breaks were caused by buckling due to sudden heating

Fig. 4. Burned out zone after it was lifted from the more tube. (CBB 800-11822)

and cooling of the superconductor. The third break was a zone of superconductor which had melted away. The material, which had melted out of the break, was deposited on the superconductor next to the hole. It is believed that the melting was caused by arcing between the coil and the UPA. The glass between the two layers of superconductor was charred, but was intact, as was the Formvar insulation on the outer layer of superconductor.

MICROSCOPIC ANALYSIS AND X-RAY FLUORESCENCE

The bore tube and the melted superconductor were inspected with an optical stereo microscope. The bore tube, superconductor melt zone, and pieces of UPA were inspected using a scanning electron microscope. The electron microscope and x-ray fluorescence were used for an elemental analysis of the bore tube, the UPA, and the superconductor. This chemical analysis provided the clue to the cause of the TPC magnet failure.

Microscopic inspection of the straight line breaks in the superconductor showed the buckling which occurred while the superconductor was heated by an arc. The conductor buckled and was plastically deformed during heating. When the arc was extinguished, the superconductor was cooled suddenly; and the buckled conductor tried to conform to its original shape with a snap. The result was the uniform clean break shown in Fig. 5. The melted superconductor shown in Fig. 5 came from a cone shaped region under the piece of conductor. The melting was most certainly due to an arc struck between the superconductor and adjacent UPA.

Pieces of UPA wire from turns 8 and 9, which were melted near the region of failure, were examined by x-ray fluorescence. Iron was found on the side of the wires which faced the bore tube over a distance of 5 mm near the melted ends. The iron concentration greatly exceeded that which would have been contributed by other materials used in the coil fabrication. The x-ray fluorescence reflected the presence of an unknown source of iron which had been broken into many small pieces and deposited on the UPA wire.

Iron was found in small quantitites in other areas of the burned zone. These areas also contained calcium, strontium, chlorine, titanium, copper, niobium, and bromine. The strontium, calcium, chlorine, and some of the iron came from fiberglass in the magnet. Copper, titanium, and niobium came from the superconductor; and bromine came from the quick-set epoxy used to glue NEMA-GLO strips to the bore tube. Pieces of the bore tube were examined on both sides. The side facing the coil contained a much higher iron content. In addition to increased iron, the presence of manganese and trace amounts of yttrium were detected. The iron, manganese, and yttrium came from the garnet sand used during sandblasting of the side of the bore tube facing the coil. The iron found on the UPA did not contain manganese or yttrium. X-ray fluorescence provided the first evidence of an iron chip.

Fig. 5. The superconductor in the melt region. Note the melted nodule and the straight line break on the superconductor. (CB8 800-11900)

A microscopic inspection of the bore tube showed a pit. The shape of the pit suggests that a hard metalic object, such as a steel chip, had been embedded in the bore tube although the chip was not found in the pit. There was evidence of radial lines in the char emanating from the pit. These lines suggest an explosive force starting at the pit.

The LBL AMR 1000 scanning electron microscope permitted one to look at a sample with magnifications up to 20000 X. At the same time, one can do a chemical analysis on particles only a few microns in diameter by the detection of characteristic K and L x-ray emissions of the selected element in synchronization with the sweeping motion of the electron beam. Examination of the UPA near the break in the superconductor showed:

1. The UPA wire was probably drawn through a stainless steel die; the center of the wire is really pure aluminum.
2. The UPA wire which faced the molten zone of the superconductor showed traces of Nb-Ti and copper, but there was no iron.
3. The UPA side which faced the bore tube was spattered with particles (about 10 micron size) of iron.

A chemical analysis of these particles showed no manganese, chromium, or nickel. The iron pattern on the UPA pointed toward the pit in the bore tube which could have contained a chip.

Examination of the bore tube with the electron microscope showed no iron in the chip pit, but there were a considerable number of iron particles at the ends of the flame or blasted zones on the bore tube. These particles, some as large as 100 microns, appeared to be driven from the indentation in the bore tube.

Electron microscopic examination of the molten nodule on the superconductor showed that surface of the nodule contained a lot of aluminum. When the nodule was sectioned, bits of niobium were found. The copper around the niobium had a large amount of titanium in it. This suggests that the superconductor temperature reached at least 2500°C. The niobium precipitated out of solution, leaving the titanium in solution with the copper.

CONCLUSIONS DRAWN FROM THE FAILURE ANALYSIS

The most likely scenario for the failure, based on the evidence is:

1. An iron chip, which was probably lodged in the bore tube during rolling, caused a short

between the UPA circuit and the bore tube at 0.19 s into the quench. (A large number of chips were removed from the bore tube as it was being prepared for winding.)

2. The current in the UPA increased by over a factor of two as extensive melting occurred around the shorted zone.
3. The short heated the epoxy glass causing large amounts of gas to be released. This gas caused the glass to delaminate and tear.
4. There was an arc struck between the superconductor and the UPA. This caused the melting and breakage of the superconductor.
5. The UPA circuit melted out, and current ceased to flow in this circuit.

The failure was apparently caused by an iron chip rolled into the bore tube in March 1978. The ground plane insulation between the bore tube and the UPA circuit was inadequate. The insulation was thin, and it did not contain a barrier which might have prevented penetration by a chip less than 3 mm in size. The 0.1 ohm resistor put across the UPA circuit to prevent burn up of the stainless steel leads contributed because much of the 70 volt drop across the UPA circuit was across the resistor. In summary, the failure of the TPC magnet was caused by a *failure of ground plane insulation*.

ACKNOWLEDGMENTS

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