SAFETY ANALYSIS OF THE UTSI-CFFF SUPERCONDUCTING MAGNET

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MASTER

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INTRODUCTION

In designing a large superconducting magnet such as the UTSI-CFFF dipole,¹ great attention must be devoted to the safety of the magnet and personnel. The conductor for the UTSI-CFFF magnet incorporates much copper stabilizer, which both insures its cryostability,² and contributes to the magnet safety. In this paper we first present the quench analysis, followed by the cryostat fault condition analysis. Two analyses of exposed turns follow; the first shows that gas cooling protects uncovered turns; the second, that the cryostat pressure relief system protects them. Finally the failure mode and safety analysis is presented.

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MAGNET QUENCH ANALYSIS

The behavior of the magnet in the event of a quench is modeled using the program QUENCH.³ The code calculates the longitudinal quench velocity for a conductor not in contact with helium coolant. For cases involving liquid helium, this velocity can be provided as a starting parameter. The transverse quench velocities can be provided from a calculation based on appropriate thermal properties. The quench volume of the coil grows in time as an ellipse whose axes are the respective velocities multiplied by the elapsed time.

The ohmic heating in the winding structure as the stored energy of the field is dissipated can be calculated, along with the time constant of the decay, the energy extracted by the protection resistor, the peak coil temperature, and relevant voltages.

The conductor is unconditionally stable; i.e., any normal zone in the conductor collapses. But, if there is no helium in the winding voids the normal zone will spread with a velocity of ≈ 750 cm/sec. The cryostat fault condition analysis in the following section is based on this "no helium" calculation.

Table I shows the peak temperature and peak inductive voltage for several sets of quench parameters. Without the protection circuitry, the fraction of the stored energy deposited in the coil is 1.00. The "% Helium" column refers to the additional enthalpy optionally included for the vaporization of local liquid helium.

Since the code makes no heat transfer calculations, the presence of liquid helium in the winding is modeled by a lower quench velocity. To see how important turn-to-turn and layer-to-layer heat transfer is, these parameters were reduced to values corresponding to that produced by longitudinal propagation only. The table shows the peak coil temperature, peak inductive voltage, and decay time constant for each of the cases. In Fig. 1 is plotted the coil peak temperature, i.e., the temperature of the region where the quench initiated, as a function of the current decay time constant.

CRYOSTAT FAULT CONDITION ANALYSIS

The cryostat must be equipped with a vent system, to handle major faults of the system leading to a massive heat flux to the liquid helium in the cryostat. Two conditions are considered.

Magnet Quench

The normal zone grows at a rate calculated above for a coil in a helium gas atmosphere. In calculating the required rate of venting, it is assumed that there is liquid in the coil void fraction. This case appears to be very conservative because it is not real. If a coil really quenches at this rate, liquid helium is not present and does not require to be expelled from the coil. But, if liquid helium is present, the normal zone would grow very slowly if at all.

Velocity along the conductor is set at 15 meters/sec with turn-to-turn and layer-to-layer velocities about sixteen times lower. The cryostat contains a large amount of liquid helium in poor thermal contact with the coil itself, which does not participate directly in the transfer of heat from the coil. After the quench is initiated, boiling occurs inside the magnet structure; and the vapor generated displaces liquid helium out of the coil. The displaced liquid rises in the stack of the cryostat and forces gas into the vapor return line to the refrigerator, but the vapor line capacity is limited, and pressure rises in the cryostat. The quench relief valve is set at 2.3 atm (19.1 psig), and approximately 0.5 sec is required to expulse enough liquid from the coil to compress the gas in the vapor volume of the stack to 2.3 atm. At that pressure there is no more boiling in the coil and heating of a single-phase fluid occurs, starting circulation of fluid through the coil. To maintain a constant pressure in the cryostat, the rate of venting must equal the increase in volume from the heating in the coil. If the fluid vented is at 2.3 atm and 15 K, the vent line required consists of a 6 in. (0.015 m) IPS pipe equipped with a relief valve capable of handling 9,000 g/sec of helium vapor. To reduce pressure drop in the line,

the entrance should be shaped to avoid the effects of a sharp-edged orifice.

Massive Insulation Failure

The system experiences a massive vacuum failure to air. Boiling occurs on the inside of the cylindrical cryostat wall; and the vapor generated displaces liquid into the stack. Gas in the stack is compressed until the pressure reaches 2.3 atm. This takes a very short time because of the extremely high heat flux into the liquid. The quench relief valve opens and maintains cryostat pressure at 2.3 atm. Boiling stops and the cryostat contains single-phase fluid. Fluid circulates in the space between cylindrical shell and girder rings due to density differences, with velocities of order 40 cm/sec. The outside wall of the cryostat is at approximately 70-75 K, in order for air to liquify. Free access of air to the cryostat has been assumed. Heat flux through the cylindrical wall is of order 1.25 to 1.5 W/cm². The temperature of the liquid rises; and the volume increases, determined by the temperature rise and mass flow rate along the wall. This increase in volume needs to be vented to maintain constant cryostat pressure.

The required rate of venting is approximately 7,200 g/sec. The fluid temperature initially is approximately 16 K. Practically all of the heat added to the cryostat passes through the cylindrical shell. Rate of heat input to the vessel is on the order of 525 kW. The minimum rate of condensation of air (with free access to the cryostat) is 1,100 g/sec. A minimum hole area of 60 cm² (3 in. pipe) is needed to supply air at sonic velocity.

It appears that a massive vacuum break to air will automatically be followed by a quench of the magnet, but the rate of mass expulsion of the warm fluid in contact with the normal coil is not as fast as above. The mass expulsion from the cryostat may be as high as double the rate calculated for quench alone.

Finally, a vacuum failure of the liquid helium cryostat is much less serious than a vacuum failure to air because the helium gas transfers heat to the cryostat

at a much lower rate than a liquifying air. In fact rupture of the helium vessel into a vacuum space open to air will immediately reduce the rate of heat transfer from condensation because of a significant lowering of the partial pressure of air.

ANALYSIS OF EXPOSED LENGTH: EFFECT OF He GAS COOLING

The analysis of an uncooled length of conductor, as might occur from the liquid level falling below the top of the coils, is carried out with the BACKSAFE program developed at ANL using the back difference method, which permits the time increment to be changed during computation without mathematical instability. A heat balance is applied to each conductor element; the temperature changes under the combined effect of perturbing heat input, Joule heating, heat transfer to the coolant, conduction along the conductor, and turn-to-turn conduction between conductors. The curve for convective vapor cooling of the uncovered length of conductor was obtained from the heat transfer coefficients calculated for the Rayleigh number, using the temperature dependent properties of 1 atm helium vapor.

Figure 2 shows the recovery of the conductor carrying 3675A from a perturbation with 1 kJ energy deposited. The figure shows that recovery is identical whether the 1 kJ was initially distributed among 0.20 m of conductor at 72 K or 0.40 m at 57 K. If the conductor is cooled by liquid, it recovers in about 6 sec. For a 6 m one-half turn uncovered length, the temperature drops to 20-25 K in about 60 sec; subsequently if the magnet is being dumped with a time constant of 420 sec, temperature recovery is complete in 409 sec. Whether or not the dump circuit acts, the magnet is not harmed by a 1 kJ heat input, even assuming the conservative cooling curve of 1 atm helium gas.

ANALYSIS OF EXPOSED LENGTH:
EFFECT OF PRESSURE RELIEF SYSTEM

This section shows that the CFFF magnet is self-protecting even if the dump resistor circuit fails while the helium level is low and a normal zone appears.

The magnet has good thermal conductivity along the conductor (x-direction), and poor thermal conductivities along the turn-to-turn direction (z-direction) and the layer-to-layer direction (y-direction); the latter two are about 2×10^{-3} times the former. The conductor is unconditionally stable; consequently any normal zone beginning above the liquid level will not propagate below. For heat transport in a layer (x-z plane), the contribution in the y-direction is considered as a step function; a layer is counted as soon as a section of that layer emerges from the liquid. The temperature distribution along the y and z directions are assumed to be the same. Thus, the problem is that of a two-dimensional heat transport with liquid helium cooling just below the liquid level. The cooling by helium vapor is ignored.

Throughout the analysis, the steady-state boiling liquid helium heat transfer is used. The latent heat of helium is adjusted to include the enthalpy needed for raising the local liquid helium from 4.2 K to the boiling temperature. The average temperature of gaseous helium is chosen as 5 K to obtain the pressure as a function of time.

In the calculation, the normal region spreads out in the x, y, z directions and the dump resistor circuitry is inactive. The temperature distribution of the top layer, the heat generation rate, the pressure in the cryostat, and the liquid helium level are all calculated.

The results shown in Figs. 3 and 4 are for CFFF conductor with an initial current of 3.675 kA and an initial vapor volume of 1200 liters at a pressure of 1 atm. The peak temperature is about the same for different initial liquid levels; typically, it rises up to 71 K in 70 seconds.

Figure 3 shows the pressure and liquid level as functions of time for different initial liquid levels. The buildup of pressure and the lowering of liquid level are faster for the lower initial liquid level because a larger amount of conductor rapidly generates and dissipates more heat into the liquid.

Since the average temperature of the vapor will probably be higher than 5 K, the calculated pressure is somewhat underestimated. Also, the turn-to-turn cooling is neglected so the calculated conductor temperature is slightly higher than the actual temperature.

For the worst case in which initially only part of the top layer is involved, it takes about 70 seconds to build up pressure to 2.05 atm with the vapor temperature at 5 K and, the peak temperature at 71 K. If all the helium is expelled, and there is no cooling at all afterward, the peak temperature and current as functions of time are as shown in Fig. 4. The peak temperature is only 89 K, and the current decreases to 2% of the initial operating current in 135 seconds. If the pressure relief valve is set at 3.0 atm, the peak temperature is about 110 K, still a safe value.

FAILURE MODE AND SAFETY ANALYSIS

The possible failure modes, with their probabilities, associated hazards and recommended actions are listed in Table II.

Since the UTSI-CFFF magnet has an unconditionally stable coil, a trouble-free cryostat, a conservative power supply and a carefully planned alarm, protection and diagnostic system, failure events associated with these items are estimated in a low probability category. On the other hand, less critical item failures such as cryogenic piping rupture are estimated in a medium category, while a facility power failure is a likely event.

The CFFF is in Seismic Zone No. 1 which means that earthquakes may cause minor damage to structures with periods greater than 1 second and intensities that fall in the V and VI range on the M.M. scale. The probability of earthquake

occurrence at UTSI is low. Nevertheless, the CFFF magnet and its associated equipment are designed so that they will remain in place and be functional following a major earthquake in Zone No. 1.

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FIGURE CAPTIONS

- Figure 1 Calculated Coil Peak Temperature for Various Quench Conditions as
a Functional Calculated Current Decay Time.
- Figure 2 Recovery of Uncovered Length Following 1 kJ Perturbation
- Figure 3 Calculated Liquid Helium Level and Pressure versus Time .
- Figure 4 Peak Temperature and Current versus Time After All Helium is Dumped
Out

TABLE I
Calculated Quench Results for Various
Choices of Quench Velocity, Coil Protection,
and Helium Cooling

Case	Decay Time Constant	Peak Temp.	Peak Induc- tive Volts	Final Resistance	Longitudinal Quench Velocity	Ratio of Transverse Quench Velocity to Longitudinal	Fraction Energy in Coil	% Helium
1	108	59	600	0.303	3.50	~5%	.73	0
2	109	61	584	.294	2.00	~5%	.71	0
3	105	55	619	.309	15.00	~5%	.75	0
4	99	54	643	.319	31.00	~5%	.76	0
5	112	63	673	.404	7.50	~5%	1.00	0
6	118	51	517	.263	15.00	~5%	.69	20
7	118	67	545	.278	1.00	~5%	.68	0
8	125	71	526	.268	.75	~5%	.65	0
9	156	115	640	.396	.32	~5%	1.00	0
10	224	146	286	.158	.55	~1%	.40	0
11	242	124	252	.138	.55	~1%	.37	24
12	246	173	248	.134	.32	~1%	.35	0
13	266	145	219	.116	.32	~1%	.31	24
14	302	241	180	.083	15.00	~0%	.24	0
15	325	276	200	.071	1.05	~5%	.19	0
16	236	243	538	.327	.32	~1%	1.00	0
	(sec)	(Kelvins)	(Volts)	(Ohms)	(m/sec)			

TABLE II

CFFF SCMS Failure Mode and Safety Analysis

<u>Items</u>	<u>Systems Components</u>	<u>Failure Mode</u>	<u>Estimated Probability</u>	<u>Failure Effects</u>	<u>Hazard Description</u>	<u>Recommended Action</u>
1	Magnet/cryostat	Conductor going normal	Low	Dump resistor dumps magnet energy	None	None
2	Magnet/cryostat	Loss of insulating vacuum	Low	Dump magnet energy; pressure relief valve open; helium vent to atmosphere (outside building); air may be liquefied	Explosion due to liquid oxygen	Provide escape measures
3	Magnet/cryostat	Magnet coil open circuit	Low	Arcing in coil, leads, power supply, dump switch	Electrocution if in contact with these systems	Personnel must be isolated from these systems
4	Magnet/cryostat	Helium vessel relief valve fail to open during quench	Low	Burst disk will open	Explosion due to liquid oxygen	Provide escape measures
5	Magnet/cryostat	LN ₂ fill valve fails to close	Low	LN ₂ overflow	Might freeze O-ring or flesh if contact	Avoid O-ring freeze/personal contact
5	Magnet/cryostat	Current lead too hot and open circuit	Low	Arcing in coil, leads, power supply, dump switch	Electrocution if in contact with these systems	Personnel must be isolated from these systems
7	Magnet/cryostat	Over current or over field	Low	Ring girder break	Winding break apart	Provide escape measures
8	Liquid He storage dewar	Loss of insulating vacuum	Low	Emergency relief valve open	Explosion possible if liquid oxygen produced	Locate dewar in secured area and provide escape route

TABLE II (continued)
CFFF SCMS Failure Mode and Safety Analysis

<u>Items</u>	<u>System Components</u>	<u>Failure Mode</u>	<u>Estimated Probability</u>	<u>Failure Effects</u>	<u>Hazard Description</u>	<u>Recommended Action</u>
9	Liquid N ₂ flash tank	Loss of insulating vacuum	Low	Emergency relief valve open	Explosion possible if liquid oxygen produced	Locate tank in secured area and provide escape routes
10	Cryogenic piping	Rupture	Medium	Flying debris or released liquid	Injury to personnel	Secure this piping and identify these lines with warning signs
11	High pressure gas bottle (He or N ₂)	Explosion or uncontrolled attraction by magnet	Low	Release high pressure gas or high velocity impact	Injury to personnel or magnet cryostat	Secure and locate to remote area
12	Dump resistor	Failure to open during energy dump	Low	Coil temperature will rise to 100°K	None	None
13	Dump resistor	Not enough water in the tank during normal operation	Low	May open circuit unless dump switch is closed	May have some hazard as coil open circuit unless dump switch is closed in time	Interlock dump switch operation to dump resistor water level
14	Power cables to magnet	Broken cable between dump resistor and power supply	Low	May arc in coil, leads, power supply, dump switch	Electrocution if in contact with these systems	Personnel must be isolated from these systems
15	Facility power	Power fails	High	Freewheeling	None	Provide battery operated magnet current readout