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SAFETY AND STABILITY OF SUPERCONDUCTING MAGNETS
FOR FUSION USING INTERNALLY COOLED CONDUCTORS*

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SAFETY AND STABILITY OF SUPERCONDUCTING MAGNETS FOR FUSION USING INTERNALLY COOLED CONDUCTORS*

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Abstract

Vincent Arp's computer code for the stability analysis of internally cooled conductors (ICC) has been combined with ANL's TASS code to create the code SSICC for the analysis of the safety and stability of ICC. The code has been tested against the ICC experiments of Lue, Miller, and Dresner, and applied to the FED TF coil conductor.

Introduction

To be cryostable, a superconducting magnet must have enough reserve cooling available locally from the helium coolant that the magnet will recover from a short heat pulse that drives a portion of the conductor from the superconducting state into the normal state. This reserve cooling requirement is typically much larger than the heat that is generated during regular operation of the magnet (e.g., for a tokamak toroidal field (TF) coil, heat from nuclear radiation and from operation in the pulsed field of the poloidal field (PF) coils).

Consequently internally cooled conductors (ICC) appeared much more favorable for use in large cryostable superconducting magnets after it was found^{1,2} that such conductors are highly stable against short heat pulses even when the coolant, at steady state, is moving at low velocity or is stagnant. The increased transient cooling is attributed to the transient flow of helium following local heating and pressure rise.

Vincent Arp developed a computer code³ for the stability of ICC. His code incorporates one-dimensional energy, mass, and momentum balance within the helium and predicts the high velocity, high pressure helium flows, which are not predicted by simpler models.

Arp's code has been modified and combined with the TASS (Thermal Analysis for Safety and Stability) code⁴ to form the code SSICC (Safety and Stability of Internally Cooled Conductor). This paper describes testing the SSICC code against the experiments of Lue, Miller, and Dresner^{5,6} and a thermal safety and stability analysis of the TF coils of the FED (Fusion Energy Device) magnets⁷ which employ ICC.

Analysis

Heat Transfer in ICC

Arp³ discusses the uncertainties in combining the contributions of Kapitza heat transfer, transient heat

transfer into a laminar boundary layer, and steady state convective heat transfer to give an effective overall heat transfer. For steady state heat transfer coefficient, he uses the modified Dittus-Boelter correlation:

$$Nu = \text{const.} (Re)^{4/5} \quad (1)$$

where the Nusselt number Nu is the non-dimensional steady-state heat transfer coefficient and the Reynolds number Re is the non-dimensional flow velocity. Variation with Prandtl numbers can be ignored. However, the stability experiments of Lue and Miller⁵ with ICC were better fit by

$$Nu = \text{const.} (Re)^{4/15} \quad (2)$$

In the analyses described below, both correlations were used, with the constant chosen so that Eq. (1) and (2) give the same value for Nu at $Re = 10^4$.

Critical Current and Current-Sharing Temperature

The expressions of Turner and Abdou⁸ for the critical temperature:

$$T_c = 8.56 (1 - B/14.7)^{1/2} \quad (3)$$

and critical current:

$$I_c = (T_c - T) (C_0 + C_1/T) A \times 10^4 \quad (4)$$

for a NbTi conductor have been incorporated into SSICC, where

T_c is the critical temperature in K

B is the magnetic field in T

I_c is the critical current in A

T is the conductor temperature in K

A is the NbTi cross section in cm^2

$$C_0 = 3.352 - 0.3607 B$$

$$C_1 = 11.929$$

The current sharing temperature T_{cs} can be found from Eq. (4) by replacing I_c with the operating current I and solving for $T = T_{cs}$.

$$T_{cs} = \left\{ [(I + C_1 - C_0 T_c)^2 + 4 C_0 C_1 T_c]^{1/2} - (I + C_1 - C_0 T_c) \right\} / 2 C_0 \quad (5)$$

Equation (5), based on the measured variation of critical current with temperature, gives a very different value for T_{cs} than does a simple interpolation between T and T_c .

$$T_{cs} = T_c - (T_c - T) I / I_c \quad (6)$$

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Data Input

SSICC employs the same data input as TASS; i.e., of the 100 input variables, only those with values different from the default values need be specified in a run.

Comparison with ICC Experiments

The SSICC code has been applied to the experiments reported by Lue, Miller, and Dresner.^{5,6} The copper to superconductor ratio was adjusted to give the reported critical current; otherwise the input parameters were used as reported. Values of those parameters are given in Table 1.

The computations gave good general agreement on current and stability margin for a length of triplex conductor with a heated section, but did not reproduce the multiple stability regions observed in those experiments. In no case did a normal region in a conductor carrying fixed current collapse for a higher heat input and grow for a lower one.

To look for a tendency toward multiple stability regions, three characteristic temperatures were examined as functions of current I and heat input ΔH , namely the peak temperature at the end of the 10 ms heating period T_{10} , the minimum value over time of the peak temperature T_{min} , and the peak temperature at 50 ms T_{50} . Without substantial exception, all three temperatures were found to increase monotonically with I and ΔH and give no indication of a tendency toward multiple stability regions.

Thermal Response of FED Conductor

The 1981 FED design required TF coils which could be operated at either 8 T or 10 T. Several concepts for such operation were considered; an ICC operating at different temperatures for the different field levels was chosen for the design. The thermal response of the conductor to a sizeable heat pulse was modeled with SSICC.

The Model

A single channel of FED TF coil conductor, 173 m in length, was modeled. A heat pulse of 200 mJ/cm³ was applied to the metal of the central 6 m of conductor in 10 ms. Steady state conditions were first determined; the inlet temperature, pressure, and velocity were specified; and the outlet temperature and pressure and the mass flow rate were determined. Because the variation of superconductor properties with temperature is better known at 8 T than at 10 T, the 8 T, 20 kA, 4.2 K operation was modeled. Other input constants are given in Table 1.

Results

The steady state results appear in Table 2, for background (nuclear plus eddy current) heating rates of 6 to 9 W per channel. Note that for 7 W and above, the outlet temperature is greater than the current sharing temperature T_{cs} of 4.655 K, and thus there is some Joule heating in the conductor near the outlet. (This Joule heating was not considered in determining the steady-state temperature and pressure in Table 2.) Note that calculation of T_{cs} by Eq. (6) predicts a higher value of T_{cs} and no Joule heating near the outlet.

In every case considered, the 200 mJ/cm³ heat pulse resulted in a quench, for heat transfer coefficients governed by either Eq. (1) or Eq. (2).

In the following, only the 6 W/channel cases are considered, as the others are unstable even without a heat pulse. In each case, the temperature and pressure rise during the 10 ms heat pulse, then fall to a minimum (pressure a minimum at 15 ms, temperature at 20 to 25 ms) and then rise steadily thereafter. With the heat transfer coefficient given by Eq. (1), the minimum temperature (5.90 K) is greater than the critical temperature (5.78 K). With Eq. (2), the minimum temperature (5.43 K) lies below the critical temperature but well above the current sharing temperature (4.655 K). Temperature and pressures are shown in Figs. 1 and 2.

Discussion

These results should be viewed as suggestions rather than definitions. Extrapolation to a different conductor, different heated length, and much different overall length conductor, plus the superimposition of a background heating and an overall flow velocity, inevitably lead to uncertainties in the analysis.

Moreover, the results of the analysis may be quite sensitive to the geometry of the helium flow. Even the best one-dimensional modelling of the helium flow and its terminations may give a wrong prediction of the time and position variation of the helium pressure and velocity. Recovery or growth of the normal region depends on the helium velocity variation at later times, which in turn depends on those geometrical considerations and on the imperfectly understood transient heat transfer at earlier times.

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Table 1
Parameters for Stability Study of ICC Experiments FED TF Coil

<u>Parameter</u>	<u>ICC Experiments</u>	<u>FED TF Coil</u>
Cross section of NbTi	0.00465 cm ²	0.588 cm ²
Cross section of copper	0.0209 cm ²	2.643 cm ²
Cross section of helium	0.0201 cm ²	2.154 cm ²
Cooled perimeter	0.785 cm	203 cm
Hydraulic diameter	0.054 cm	0.0406 cm
Current	100 - 300 A	20 kA
Magnetic field	6 - 7 T	8.0 T
Length of conductor	5.2 m	173 m
Heated length	1.0 m	6.0 m
Heating time	10 ms	10 ms
Heat input	5 - 500 mJ/cm ³	200 mJ/cm ³ of metal
Inlet temperature	4.2 K	4.0 K
Inlet pressure	5.0 atm	5.0 atm
Inlet velocity	0 - 1 cm/s	9.29 cm/s
Background heating	0 W	6 - 9 W

Table 2
Computed Steady State Parameters

<u>Parameter</u>	<u>Units</u>	<u>6 W/Channel</u>	<u>7 W/Channel</u>	<u>8 W/Channel</u>	<u>9 W/Channel</u>
Mass Flow Rate	g/s	3.06	3.06	3.06	3.06
Outlet Pressure	atm	4.510	4.506	4.502	4.498
Outlet Temperature	K	4.624	4.689	4.753	4.811

Fig. 1 Pressure and Temperature Variation in First 0.2 s.

Fig. 2 Pressure and Temperature Variation in First 1.8 s ($Nu \sim Re^{4/15}$).