RECOVERY OF A CRYOSTABLE MAGNET FOLLOWING
A MECHANICAL PERTURBATION: ONE-DIMENSIONAL
AND TWO-DIMENSIONAL CALCULATIONS

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by

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RECOVERY OF A CRYOSTABLE MAGNET FOLLOWING A MECHANICAL PERTURBATION: ONE-DIMENSIONAL AND TWO-DIMENSIONAL CALCULATIONS*

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ABSTRACT

When a cryostable composite conductor carrying current experiences a heat input from a mechanical perturbation, a normal region develops which initially propagates and then either collapses or continues to propagate. A computer model has been devised to study this phenomenon. The model incorporates initial or continuing heat input from mechanical perturbations, heat conducted to the neighboring elements of the conductor and, if appropriate, heat conducted through insulation to neighboring turns. Heat is transferred to the helium coolant according to a specified heat transfer coefficient. If the element of conductor is in a normal or current-sharing state, resistive heating also occurs. Finally, on the basis of the net heating or cooling of the elements, the temperature changes. The following paragraphs detail the heat generation and transfer.

I. INTRODUCTION

The reliable manufacture of large cryostable superconducting magnets for MHD, fusion, and other applications requires a fuller understanding of cryostability, of how the magnets are prevented from quenching. One of the areas most requiring further study is the response of the magnet to mechanical perturbations. For the present purpose, a mechanical perturbation can be thought of as an irreversible transition from one state of elastic and magnetic energy to another. We postulate that almost instantaneously a large fraction of that energy release is deposited in the conductor of the magnet. Our analysis suggests that if the mechanical perturbation is localized sufficiently in time (less than about 10 ms) and position (less than about 1 m), then from a transient cryostability viewpoint the mechanical perturbation can be characterized by a single parameter E , the energy deposited in the conductor. The goal of mechanical perturbation studies is to predict the values of E which will occur, and the goal of transient cryostability studies is to predict the response of the conductor to the heat pulse E .

The model which has been developed to study that response is described in Section II. The biggest uncertainty in the model is the heat transfer from the heated conductor to the liquid helium in contact with it; this is discussed in Section III. Validation of the model against experiment is described in Section IV, and predications of the model appear in Section V.

II. THE MODEL

The model basically consists of a heat balance for the conductor. The conductor is discretized into elements (typically 1 cm long), and a heat balance is applied to each element for each time increment. Figure 1 shows the heat generation and transfers which are considered. Some elements experience initial or continuing heat

input from the postulated mechanical perturbation, enough heat to drive them out of the conducting state. Heat is conducted to the neighboring elements of the conductor and, if appropriate, through insulation to the elements of the neighboring turns. Heat is transferred to the helium coolant according to a specified heat transfer coefficient, which may depend on temperature difference and on time. If the element of conductor is in a normal or current-sharing state, then resistive heating also occurs. Finally, on the basis of the net heating or cooling of the elements, the temperature changes. The following paragraphs detail the heat generation and transfer.

Fig. 1 Heat Balance for Cryostability Model.

Heat Conduction and Enthalpy Change

Because the thermal conductivity and specific heat of copper vary with temperature so much over the relevant range, 4 K to 50 K, temperature-dependant values are used in the model. In order that the heat transferred out of one element equals the heat into the neighboring element, the harmonic mean of the two thermal conductivities is used to calculate the heat transfer. Even for copper to superconductor ratios of fifteen to one or higher, the enthalpy change of the superconductor is a significant fraction of the change for the conductor as a whole, because the specific heat of copper is so low near 4 K. If turn-to-turn heat conduction is incorporated, the thermal conductivity values for insulating materials recently measured at Argonne National Laboratory (ANL) are used¹.

Boundary Conditions

The model has typically been used with 40 to 90 elements per conductor (with an equal number in addition by reflection symmetry) and up to eight conductors on each side of the perturbed one. To model a large magnet, it is necessary to specify the temperature at the boundaries of the model. To do so it is assumed that the temperature gradient is constant between the last three elements; i.e., if there are N elements, it is assumed that

$$T_N = 2 T_{N-1} - T_{N-2} \quad (1)$$

If T_N calculated from Eq. (1) is less than the liquid helium temperature, it is set equal to the helium

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temperature. A similar means is used to specify the temperature of each element of the outermost conductor of the model.

Critical Current and Current Sharing

The critical current I_c is calculated from the conductor cross section, the copper to superconductor ratio, and the critical current density, which in turn is given by the empirical expression,²

$$J_c = (T_c - T) (3.352 - 0.3607 B + 11.929/T) \times 10^4 \text{ A/cm}^2 \quad (2)$$

where T and B are respectively the temperature and magnetic field at the given element and T_c is the critical temperature at field B . If the temperature for an element is so high that $I_c < I$, the total current, then current sharing occurs and a heat $I(I - I_c) R \Delta t$ is added to the heat balance, where R is the resistance of the element and Δt the time increment.

Using the Model

The FORTRAN program incorporating the model is designed so that any of 30 parameters can be changed independently of each other. Some elements are taken to be at a given temperature or receive a given heating. With the mean of two currents which are thought to bracket the recovery current, the system is iterated over time to see if the normal region grows to the boundary of disappears. The process is repeated, with the bracketing range of temperatures halved each step, until either the specified number of steps is performed or the normal region neither grows to the boundary nor disappears during the specified time. The temperature of each element is calculated each step and printed out periodically; the growth or collapse of the normal region from element to element is also printed out.

III. HEAT TRANSFER TO HELIUM

The properties described above such as thermal conductivity, specific heat, and critical current density are known relatively well; and uncertainties in their values probably have little effect on the predictions of the model. However, heat transfer from the conductor to the helium depends on temperature difference, time (i.e., transient heat transfer is required), and cooling channel size and orientation. This dependence must be adequately known; otherwise the uncertainties in the heat transfer may affect the results obtained with the model.

The model provides the option of decreasing the heat transfer on the basis of depletion of liquid helium from the cooling channels; i.e., the heat transfer is reduced by the ratio of the heat already deposited in the channel to the latent heat of the vapor which the channel will hold. Using this option causes a large decrease in the calculated recovery current. However, recent experiments at ANL by Hilal et al.,³ show that total liquid helium depletion does not occur for the relevant energy densities and channel width of 0.76 mm (0.030 in.) or more.

In the model, the transient heat transfer data of Steward⁴ are used along with a typical steady state curve. The approximate curves used in the model are shown in Fig. 2. The curves have been checked against the heat flux vs. temperature data of Hilal et al.³ For each element, time is measured from when the element heats to 0.1 K above the helium temperature. For times between 0.01 s and 1.0 s, a logarithmically weighted mean of the 0.01 s curve and the steady state curve is used.

Fig. 2 Transient Heat Transfer Assumed in Model.

For some of the results shown below, only the steady state curve was used. Comparison of the results for the same conditions using steady state and transient heat transfer shows little difference for recovery current, but much difference in where the heat is deposited. Figure 3 shows that with the transient heat transfer curves, the heat is deposited into the helium much nearer to the heated element.

Fig. 3 Heat Deposited in Helium for Steady State and Transient Transfer.

IV. VALIDATION OF THE MODEL

Measurements have been made⁵ of the recovery currents of a cryostable conductor following pulses to an electrical heater meant to simulate a mechanical perturbation. Comparison of those measurements has been made with the predictions of the model; the agreement is satisfactory. See ref. 5 for more details.

V. RESULTS

U-25 Conductor Without Turn-to-Turn Heat Conductor

Figure 4 shows the growth and possible collapse of a normal region in a conductor with the properties of that used in the United States Superconducting Magnet Systems Dipole (U.S. SCMS),^{6,7} for three currents differing by only 1 A. At 640 A, the normal front is almost stationary, permitting comparison with the static theory of stability;⁸ the agreement is excellent.

U-25 Conductor with Turn-to-Turn Heat Conduction

Figure 5 shows growth of the normal region in the perturbed conductor (Turn #0) of the interturn insulation was that of the U.S. SCMS Dipole. Note that the turn-to-turn conduction has raised the recovery current from about 640 A to about 874 A, despite the ten times larger perturbing pulse. The corresponding classical heat transfer coefficients are $q_h = 0.34 \text{ W/cm}^2$ for the one-dimensional cooling and $q_h = 0.64 \text{ W/cm}^2$ for the two-dimensional cooling. Figure 6 shows the recovery current as the function of the perturbing energy pulse.

Trade-off Between Cross Sectional Area and Wetted Perimeter

Figure 7 shows the recovery current vs. perturbing energy pulse for four preliminary conductor designs considered for the University of Tennessee Space Institute Magnetohydrodynamics Dipole (UTSI MHD)⁹. Over the range considered, increased wetted perimeter more than offsets a decreased cross sectional area.

UTSI Conductor

An early ANL design for the UTSI MHD Dipole incorporated circular saddle coils, in which each layer was wound of 2.54 cm high conductor on a stainless steel substructure with azimuthal support blocks to limit the build-up of azimuthal force. Later, the substructure concept was abandoned, and the height of the conductor increased to 3.10 cm. Figure 8 shows that even if the azimuthal force and resulting frictional energy perturbation are doubled, the recovery current is still higher because of the increased area of copper and increased wetted perimeter.

VI. CONCLUSIONS

The model is a useful tool in designing cryostable magnets. Incorporation of helium transient heat transfer data which includes the effects of channel size and orientation would increase confidence in the predictions of the model.

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Fig. 4 Growth of Normal Region: U-25 Conductor Without Turn-to-turn Conduction.

Fig. 5 Growth of Each Turn of Normal Region: U-25 Conductor with Turn-to-turn Conduction.

Fig. 6 Dependence of Recovery Current on Perturbing Heat Pulse: U-25 Conductor.

Fig. 7 Recovery Current vs. Perturbing Heat Pulse (normalized by conductor cross section) for Four UTISI Conductor Designs, Differing in Copper Cross Section and Wetted Perimeter.

A.	$A = 1.227 \text{ cm}^2$	$p = 2.29 \text{ cm}$
B.	$A = 1.194 \text{ cm}^2$	$p = 3.01 \text{ cm}$
C.	$A = 0.952 \text{ cm}^2$	$p = 4.80 \text{ cm}$
D.	$A = 0.935 \text{ cm}^2$	$p = 5.45 \text{ cm}$

Fig. 8 Increase in Recovery Current for UTISI Conductor by Going to Larger Conductor.