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CRYOGENIC RECOVERY ANALYSIS OF FORCED FLOW
SUPERCRITICAL HELIUM COOLED SUPERCONDUCTORS

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**fusion power
systems department**

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SUPERCRITICAL HELIUM COOLED SUPERCONDUCTORS

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FOREWORD

The Division of Magnetic Fusion Energy within the U.S. Energy Research and Development Administration has initiated within the fusion development program for tokamak power reactors a series of systems studies aimed at the definition of subsequent generations of tokamak devices leading to a commercial prototype reactor. Since April, 1976, a design team composed of representatives from the ORNL Fusion Energy Division and the Westinghouse Fusion Power Systems Department has been engaged in scoping studies associated with the definition of The Next Step (TNS) in the tokamak program after the TFTR. Provisional goals established for TNS include:

- achievement of ignition
- demonstration of burning dynamics
- evaluation of design requirements and solutions for long pulse operation
- features which extrapolate to a viable power reactor
- availability in the mid-to-late 1980's

It is in this context that the work reported herein was performed.

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CRYOGENIC RECOVERY ANALYSIS OF FORCED FLOW SUPERCRITICAL HELIUM COOLED SUPERCONDUCTORS

ABSTRACT

A coupled heat conduction and fluid flow method of solution was presented for cryogenic stability analysis of cabled composite superconductors of large scale magnetic coils. The coils are cooled by forced flow supercritical helium in parallel flow channels. The coolant flow reduction in one of the channels during the spontaneous recovery transient after the conductor undergoes a transition from superconducting to resistive, necessitates a parallel channel analysis. A way to simulate the parallel channel analysis is described to calculate the initial channel inlet flow rate required for recovery after a given amount of heat is deposited. The recovery capability of a NbTi plus copper composite superconductor design is analyzed and the results presented. If the hydraulics of the coolant flow is neglected in the recovery analysis, the recovery capability of the superconductor will be over-predicted.

CRYOGENIC RECOVERY ANALYSIS OF FORCED FLOW SUPERCRITICAL HELIUM COOLED SUPERCONDUCTORS

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INTRODUCTION

Cryogenic stability of composite superconductors requires that the conductor can recover spontaneously to its superconducting state after the occurrence of an event in which heat is suddenly deposited to the conductor driving a segment or the entire length of the conductor to a normal resistive state. If the conductor is cooled by a forced flow single phase fluid, the flow rate must be sufficient to remove the heat so that the conductor temperature can be cooled down to below the temperature at which current sharing begins, or the coolant temperature does not rise above this threshold temperature for the conductor to recover to its superconducting state. For a superconducting winding cooled by a forced flow single phase fluid, the usual stability analysis method has been by thermal equilibrium⁽¹⁾⁻⁽⁴⁾ in which the heat balances in the conductor material and in the coolant were solved. The hydrodynamic problem in the cooling channel was not considered. For a large scale magnetic coil with multiple layer-turns superconductors, for applications in fusion power reactors and elsewhere, the windings are likely to be cooled by networks of parallel hydraulic channels with forced flow supercritical helium. One difficulty in this arrangement of cooling arises when the conductor in one of the channels is driven to a normal state. The transition increases the resistance to flow in that channel. The system total coolant flow will be redistributed among the parallel channels resulting in a decrease of helium to that channel. A multiple channel fluid flow solution must then be considered. The thermal equilibrium method mentioned above is for a single conductor channel stability analysis and is not generally applicable to a parallel flow system. This paper presents a coupled transient heat conduction and hydraulic method for recovery

analysis in a parallel flow system using supercritical helium as the coolant. In this method the Fourier heat conduction equation and the one-dimensional conservation equations of fluid flow in space and time are solved numerically. Current sharing and temperature dependent material and coolant properties are considered. The results of a recovery capability analysis for a typical long, multifilamentary cabled superconductor with NbTi and copper composite are presented.

METHOD OF SOLUTION

The recovery to the superconducting state is a rapid transient process. The temperature distribution in the superconductor composite as a function of space and time is determined by the following Fourier heat conduction equation:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) = \rho C_p \frac{\partial T}{\partial \theta} - Q''' \quad (1)$$

$$k \frac{\partial T}{\partial n} = A_s h (T - T_b) \quad @ \text{ channel wall} \quad (2)$$

where n is the outward normal to the boundary at the channel wall and the other variables are defined in the notation section. Eq (1) shows a general equation, but one can represent the conductor composite by a one, two or three dimensional model. The term Q''' includes all components of heat generation, such as nuclear heating, ac losses, joint loss and Joule heating in a toroidal field coil of a fusion power reactor. The Joule heating is determined by the current sharing characteristic of the superconductor as follows:

$$Q_I''' = \frac{I_{cu}^2 \rho_{cu}}{f_c A_c} \quad (3)$$

The current in the copper, I_{cu} , is determined by an assumed linear relationship between the superconductor critical current density and temperature as follows:

$$I_{cu} = I \quad , \text{ for } T \geq T_{cr} \quad (4)$$

$$I_{cu} = I \left(\frac{T - T_{cs}}{T_{cr} - T_{cs}} \right) \quad , \text{ for } T_{cs} < T < T_{cr} \quad (5)$$

$$I_{cu} = 0 \quad , \text{ for } T \leq T_{cs} \quad (6)$$

where T_{cr} is the superconductor critical temperature and T_{cs} is the threshold temperature for current sharing. These depend on the local magnetic field and the superconductor operating current density.

The heat conduction equation, Eq (1), is solved by an implicit finite difference method. The general difference equation to be solved for the temperature at node i is shown below:

$$\sum (VQ''')_i + \sum_j Y_{ij} (T_i^* - T_j^*) = \frac{(\rho c_p V)_i (T_i^* - T_i)}{\Delta \theta} \quad (7)$$

where Y_{ij} is the conduction admittance from node i to node j , or

$$Y_{ij} = \frac{A_{ij}}{\frac{L_{ij}}{k_i} + \frac{L_{ji}}{k_j}} \quad (8)$$

where A_{ij} = interface area between nodes i and j .

L_{ij} = effective conduction path length in node i in the direction of node j .

L_{ji} = effective conduction path length in node j in the direction of node i .

The summation includes all adjacent nodes connected to node i , and the temperature with the asterisk is at time $= \theta + \Delta\theta$.

The transient channel fluid flow problem is solved by the following one-dimensional conservation equations:

$$\frac{\partial G}{\partial x} + \frac{\partial \rho}{\partial \theta} = 0 \quad (9)$$

$$\frac{\partial (GH)}{\partial x} + \frac{\partial (\rho H)}{\partial \theta} - \frac{1}{J} \frac{\partial P}{\partial \theta} - \frac{Q_p}{A} = 0 \quad (10)$$

$$\frac{\partial P}{\partial x} + \frac{1}{g} \frac{\partial G}{\partial \theta} + \frac{1}{g} \frac{\partial (G^2 v)}{\partial x} + \tau = 0 \quad (11)$$

where $\tau = \text{frictional term} = \frac{2f|G|Gv}{gD}$, which acts opposite to the direction of flow. In addition the equation of state of the fluid is required to determine the coolant thermal properties. The heat transfer shown in Eq (2) is the coupling term between the heat conduction and the fluid flow calculations. The above equations (9) to (11) are solved numerically using an implicit finite difference procedure in a large scale digital computer. The resulting equations are shown below with the index i designating the space coordinate and j the time coordinate:

$$G_{i,j} = G_{i-1,j} - \frac{\Delta x}{\Delta \theta} (\rho_{i,j} - \rho_{i,j-1}) \quad (12)$$

$$H_{i,i} = \frac{1}{\left(G_{i,i} + \frac{\Delta x}{\Delta \theta} \rho_{i,i}\right)} \left\{ (GH)_{i-1,i} + \frac{\Delta x}{\Delta \theta} \left[(\rho H)_{i,i-1} + \frac{1}{J} (P_{i,i} - P_{i,i-1}) \right] + \frac{Q P \Delta x}{\bar{A}} \right\} \quad (13)$$

and

$$P_{i,i} = P_{i-1,i} - \frac{1}{g} \left[(G^2 v)_{i,i} - (G^2 v)_{i-1,i} + \frac{\Delta x}{\Delta \theta} (G_{i,i} - G_{i,i-1}) \right] - \frac{2 f \bar{G}^2 \Delta x}{g \bar{\rho} D} \quad (14)$$

where

$$\bar{G} = \frac{1}{2} (G_{i,i} + G_{i-1,i}) \quad (15)$$

and

$$\bar{\rho} = \frac{1}{2} (\rho_{i,i} + \rho_{i-1,i}) \quad (16)$$

The space index i in the above equations applies at the end of a fluid node increment. The quantity $\bar{A}$ is the average channel flow area within this increment, if the channel flow area is not uniform. For a set of known channel inlet conditions, the fluid conditions at the end of each fluid node along a channel are calculated by a step-wise iteration procedure. The heat transfer quantity Q depends on the heat conduction solution in the solid material. This requires an outer loop iteration between the heat conduction and the fluid flow calculations. The accuracy of the solutions depends on the convergence tolerance and the iteration frequency specified in the input. There are three options of computation in the program: (1) the flow

system outlet conditions are determined from the specified inlet flow rate, pressure and enthalpy; (2) the flow system inlet pressure is determined from the specified inlet flow rate, inlet temperature and outlet pressure; (3) the flow system inlet flow rate is determined from the specified system inlet and outlet pressures (system ΔP) and inlet enthalpy. In all these options the conductor spatial temperature, coolant temperature and pressure distributions as functions of time along the channels are calculated.

In a parallel channel system between two common plena, where the system total flow rate is given and the system overall pressure drop is fixed by the inlet and outlet plenum conditions, the flow fraction in one of the parallel channels would decrease if heat addition to that channel is increased. The system total inlet flow will be redistributed among the channels according to the rate of heat addition to each of the channels. Since the superconductor windings of a large scale magnetic coil are likely to be cooled by systems of parallel channels, if one conductor is driven to a normal state and the others in the same flow system remain superconducting, the flow fraction to the channel with a normal resistive zone will be reduced to satisfy the system overall pressure drop. If the reduction is to such an extent that the coolant flow becomes insufficient to remove the heat generated, the conductor would not recover. The recovery capability analysis for such a cooling arrangement should therefore be carried out with a parallel channel approach.

Instead of modeling the conductor cooling channels by a parallel flow system, a simple way to simulate a parallel flow analysis is to model one conductor only. For this conductor the channel pressure drop is specified in the calculation equal to the value which would exist under normal operating conditions (with all conductors in the superconducting state). When heat is generated in the conductor, the channel inlet flow rate is calculated as a function of time during the recovery transient according to the rate of heat transferred to the fluid, while the channel pressure drop is kept constant. This is the method of solution used for the recovery analysis presented herein.

To determine the channel pressure drop under normal operating conditions, a series of transient calculations was carried out with different channel inlet flow rates according to the duty cycle depicted for the coils being analyzed. In all cases the channel exit pressure was specified to be 3.0 atm to assure that the helium in the flow system is at the supercritical region. Channel inlet and exit losses were not included in the analysis. The recovery capability at a given initial channel inlet flow rate was then determined to be from what initially imposed normal zone temperature and initial normal zone length the conductor can recover.

RESULTS OF ANALYSIS

The major design parameters of the superconductor for a toroidal field coil analyzed and illustrated herein are given in Table 1. The conductor length was taken to be 120 m consisting of several turns around the coil. The coolant enters the channel at the innermost turn where the magnetic field is at the peak value of 8 Tesla and exits at the outer turn where the magnetic field is nearly zero. The actual axial field distribution along the entire channel oscillates but decreases from the innermost turn outward. A linear distribution from 8 Tesla at the channel inlet to zero at the channel exit was assumed. From the data shown on the critical current density-field-temperature ($J_c - H - T$) diagram for NbTi (the one commonly used for field coil analysis is the IMI data given in Reference 5), the critical current density of the NbTi superconductor at 8 Tesla and 4.2 K is 50 kA/cm^2 . The operating current density was selected to be one half of the critical value or 25 kA/cm^2 providing a safety factor of 2. From the same diagram it is determined that at the channel inlet the superconductor critical temperature, T_{cr} , at 8 Tesla and zero transport current is 5.6 K. By the linear relationship between critical current density and temperature, the threshold temperature, T_{cs} , at which current sharing begins at 8 Tesla and $J_c = 25 \text{ kA/cm}^2$ is 4.9 K. Since the temperatures T_{cr} and T_{cs} depend on the local magnetic field, their values increase as the magnetic field decreases along the channel. The axial distributions of T_{cr} and T_{cs} are shown in figure 1.

The heat transfer coefficient required in the calculations is determined by the correlation developed by Giarrantano, et al. ⁽⁶⁾ as shown below.

$$h = 0.0259 \left(\frac{k}{D} \right) \left(R_e \right)_f^{0.8} \left(P_r \right)_f^{0.4} (T_w/T_b)^{-0.716} \quad (17)$$

The friction factor f in Eq (11) is determined by using Hoenig's experimental data⁽⁷⁾ on triplex conductors. The measured friction factor is about 2.8 times that predicted by the correlation for smooth, straight and round tubes. The Koo's equation⁽⁸⁾ for turbulent flow in a smooth tube as shown below was used in the calculations together with the 2.8 multiplier:

$$f = 0.0014 + \frac{0.125}{(Re)_f^{0.32}} \quad \text{for } 3000 < (Re)_f < 3 \times 10^6 \quad (18)$$

For the helium thermophysical properties the data and computer routines developed by the National Bureau of Standards and published in the NBS Bulletin No. 631⁽⁹⁾ are used in the computations.

The specific heat of the NbTi and that of the copper used in the calculations are shown in Figure 2. They are obtained from References 10 and 11, respectively. The thermal conductivity of copper is that for a coalesced copper given in Reference 12. For the NbTi and copper composite the specific heat value is determined by the following relationship:

$$C_{p, e} = f_c C_{p, cu} + (1 - f_c) C_{p, sc} \quad (19)$$

For the thermal conductivity of the composite, the value for copper was used in the calculations, since the copper thermal conductivity is much higher than that of NbTi at low temperatures. The resistivity of copper is taken to be $7 \times 10^{-8} \Omega \cdot \text{cm}$ at 8 Tesla which is the value after a prolonged period of irradiation with fluence over 10^{17} n/cm^2 . Magnetoresistance effects were not considered in the calculation. Although the magnetoresistance decreases as the magnetic field decreases around the turns of a coil, at the same time the temperature margin (temperature difference between the current sharing threshold temperature T_{cs} and the coolant temperature) increases. The use of the peak resistivity value throughout the turns would have no significant effect on the analysis.

In the calculations the initial normal zone length was assumed to be 1/5 of the entire conductor length located at the channel inlet end where the magnetic field is the highest and the temperature margin is the lowest. This represents the worst case to be analyzed. The superconductor recovery capability was determined with channel inlet flow rate ranging from 6 to 16 g/s per channel. At a given inlet flow rate an initially imposed normal zone temperature was assumed and the recovery transient was computed. If the conductor recovered, another higher initial normal zone temperature was tried until the conductor did not recover.

The case with an initial flow rate of 11 g/s per channel is illustrated as shown in Figure 3. With an initial normal zone length of 1/5 of the conductor length, the highest initial normal zone temperature from which the conductor can recover is 15.5 K. The temperature curves shown by the solid lines in the figure show the peak conductor and the peak coolant temperature profiles. The conductor recovers at about 50 ms. The calculated channel inlet flow rate variation during the transient is also shown in the figure. The flow rate variation was determined for a constant pressure drop of 1.5 atm which is the pressure drop value with an inlet flow rate of 11 g/s under normal operating conditions. During the transient the coolant inlet flow is reduced as heat is being added to the fluid. The maximum reduction is about 0.25 g/s or about 2.3%. Consequently, the heat flux is also reduced during the transient. At the time when the conductor temperature is near the critical temperature, T_{cr} , at about 32 ms as shown in the figure at which most of the sensible heat has been removed, the Joule heating is 0.0728 W/cm^2 of conductor surface area. The flow rate at that time is 10.75 g/s resulting a heat flux of 0.0780 W/cm^2 which is still higher than the Joule heating. The conductor continued to recover as shown in the figure. The recovery capability of the conductor with an initial inlet flow rate of 11 g/s is to recover from an initially imposed normal zone temperature of 15.5 K over 1/5 of the conductor length located at the channel inlet end. This is equivalent to an initial sudden heat deposition of 166 mJ/cc of conductor volume over 1/5 of the conductor length located at the peak field region.

If the initial normal zone length was assumed to be the entire conductor length of 120 m, with the same initial inlet flow rate and initial normal zone temperature the calculated peak conductor temperature and coolant temperature during the transient are shown by the dashed temperature lines in figure 3. Because of the much longer initial normal zone length but the same channel pressure drop, the flow rate reduction is considerably higher. The maximum reduction amounts to 12%. At the time the peak conductor temperature approaches T_{cr} (at about 44 ms when the flow rate is about 10.1 g/s as shown in the figure) the Joule heating is 0.0728 W/cm^2 of the conductor surface area and the heat flux is 0.0725 W/cm^2 which is smaller than the Joule heat generation, the conductor temperature did not continue to drop. The normal zone boundary first contracted toward the inlet end of the channel but spreaded again downstream. At about 75 ms after the initiation of the transient the coolant temperature rose above the current sharing threshold temperature. The conductor did not recover, even though the initially imposed normal zone temperature was the same 15.5 K as in the previous case. If the later case of recovery calculation was carried out by the heat balance approach, neglecting the hydrodynamics of the channel flow, the result showed that the entire conductor recovered. This result is hence optimistic. This illustrates the important contribution of the method of solution presented.

The recovery capability of the superconductor illustrated in this analysis is shown in figure 4. The recovery capability shown in this figure is plotted in terms of the amount of heat suddenly deposited in the conductor in mJ/cc of the conductor volume instead of the initial normal zone temperature. The dashed curve at the top of the figure shows the result obtained by the heat balance approach. The solid curve below the dashed curve is the result obtained by considering an initial normal zone covering only 1/5 of the channel length and the chained curve further below is that obtained by considering the initial normal zone covering the entire channel length. The effect of the channel inlet flow reduction due to heat addition is shown clearly by the curves. Neglecting the hydrodynamics of the fluid flow the recovery capability is over predicted. The over-prediction is about 50% over the case in which the heat was deposited in the entire length of the conductor.

The recovery capability with inlet flow rate below 6 g/s is extremely small. The conductor can recover mostly at the temperature in the current sharing region. At higher inlet flow rates, the allowable amount of heat deposited levels off to about 240 mJ/cc. Above this value the coolant temperature rises above the current sharing threshold temperature T_{cs} before the conductor temperature is lowered to the threshold temperature, unless the coolant inlet temperature is lowered to below 4 K to increase the thermal margin. The ideal pumping power requirement (at 100% efficiency) and the channel pressure drop at normal operating conditions are also shown in the figure. The difference between the peak conductor and the channel wall temperatures is about 0.3 K with an insulation thickness of 0.001 cm (assuming a thermal conductivity for the insulation of 0.035 W/cm-K) surrounding the strand. The effect of the insulation is a reduction of the allowable initial normal zone temperature of 0.5 K, equivalent to a reduction of the stability thermal margin of about 13 mJ/cc of conductor volume.

CONCLUSION

A numerical method of solution was described to determine the recovery capability of a given superconductor design in a magnetic coil in which the conductors are cooled in systems of parallel flow channels. Flow redistribution among the channels due to the difference in heat addition must be taken into consideration in the recovery analysis or the result would be too optimistic. Superconductor and coil designs can then be optimized once the conductor recovery capability is determined.

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NOTATION

A	=	channel flow area
A_c	=	cross sectional area of conductor

A_s	=	heat transfer surface area
C_p	=	specific heat at constant pressure
D	=	hydraulic diameter
f	=	fanning friction factor
f_c	=	fraction of copper in the composite
G	=	flow rate per unit area
g	=	gravitational constant
H	=	enthalpy
h	=	heat transfer film coefficient
I	=	conductor transport current
I_{cu}	=	current portion in the substrate
J	=	work-energy conversion factor
k	=	thermal conductivity
L	=	effective conduction path length between two adjacent nodes
P	=	channel wetted perimeter
p	=	pressure
P_r	=	Prandtl number
Q	=	heat flux
Q'''	=	volumetric heat generation rate
Re	=	Reynolds number
T	=	conductor temperature
T_b	=	fluid bulk temperature
T_{cr}	=	superconductor critical temperature at zero transport current
T_{cs}	=	threshold temperature at which current sharing begins
T_w	=	channel wall temperature
V	=	node volume
v	=	specific volume
x, y, z	=	Cartesian coordinates

Y = conduction admittance between two adjacent nodes
 ρ = density
 ρ_{cu} = electrical resistivity of the substrate (copper)
 θ = time

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TABLE I. DESIGN PARAMETERS OF NbTi SUPERCONDUCTORS
FOR A TOROIDAL MAGNET COIL

Peak Field	8 Tesla
Stabilizer	Copper
Copper/Superconductor Ratio	4.6
Conductor Cross Sectional Area	3.76 cm ²
Coolant Flow Area Fraction	0.40
Number of Strands	147
Nominal Strand Diameter	0.139 cm
Conductor Current	10 kA
Superconductor Current Density	25 kA/cm ²
Strand Insulation Thickness	0.001 cm
Number of Turns	630
Number of Hydraulic Paths	124
Approximate Length of Hydraulic Path	120 m
Method of Winding	4-in-hand
Coolant Inlet Temperature	4 K

Figure 1. Axial distributions of critical temperature T_{cr} and current sharing temperature T_{cs}

Figure 2. Specific heats of NbTi and copper used in the analysis

Figure 3. Conductor peak temperature, coolant temperature and channel inlet flow rate during recovery transient from an imposed initial temperature of 15.5 K

Figure 4. Superconductor recovery capability

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