SAFETY OF SUPERCONDUCTING MAGNETS FOR FUSION:
THERMAL ANALYSIS OF LARGE CRYOSTABLE MAGNETS

MASTER

by

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Safety of Superconducting Magnets for Fusion; Thermal Analysis of Large Cryostable Magnets*

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Summary

A thermal analysis program has been developed to study the response of a cryostable fusion magnet to abnormal conditions such as a localized heat input, over-current, or uncooled length of conductor. It performs a heat balance on each element. Variation of parameters with temperature, pressure, and magnetic field are incorporated. The program has been applied to a conductor with magnetic field variation along its length, carrying a high current as might occur in one toroidal field coil when a neighboring coil discharges rapidly. It is found that a stable normal region can develop, with possibly serious consequences.

Introduction

To be safe, a superconducting magnet system must respond to any credible abnormal condition in a way that will not endanger the public, the operating crew, the rest of the fusion reactor system, or the magnet system itself. A thermal analysis program has been developed to study the response of a cryostable fusion magnet to abnormal conditions such as a localized heat input, over-current, or a length of conductor not covered by liquid helium. It performs a heat balance on each element, including external heating, Joule heating, heat transfer to the coolant, conduction along the conductor, and conduction to neighboring turns.

The program calculates the pressure in the cryostat, which increases as liquid helium is vaporized and decreases as vapor or liquid is vented. Magnetic field variation along the conductor is permitted, which changes the critical current of the superconductor and the magnetoresistivity of the copper stabilizer and thus changes the propagation velocity of a quench. The current is calculated from the inductance and initial stored energy of the magnet, decremented each iteration by the power dissipated internally and in the discharge circuit. Alternatively, when the current is driven externally as in the case of one toroidal field (TF) coil inductively driven by the discharge of a neighboring coil, the current or the driving voltage may be specified explicitly.

To be sure, the complete safety analysis of a magnet involves other aspects in addition to the quench analysis; however, in this paper, the analysis is limited to quench analysis and related topics.

Inadequacy of a Stability Analysis Program for Quench Analysis

The model for the safety analysis, like that of the stability analysis described previously,¹ is based on a heat balance. The same heat generation and transfers enter. However, in a stability analysis, a current and perturbing heat pulse are specified for a conductor otherwise operating under design conditions.

Consideration of only a short time (at most a second or so) and a short length (at most a meter or so) will determine whether the normal region will collapse, grow without limit, or reach a steady state.

By contrast, in a quench analysis, the conductor is assumed to be under some abnormal conditions (e.g., coolant level low or coolant passages blocked). The abnormal conditions must be modeled explicitly in the analysis program; presumably the program must be modified for each kind of abnormality which is to be considered.

In the safety analysis, interactions between the conductor that is generating heat and the rest of the magnet system must be included. For example, by the transfer of heat from the conductor to the helium coolant, vapor is produced. This vapor can raise the pressure inside the magnet system. But this pressure rise can in turn change the heat transfer characteristics between the conductor and the coolant. Moreover the pressure rise will depend on the volume of the magnet cryostat, the volume of vapor already present, and the venting rate, as well as on the heat production and transfer.

Another example of interaction is that the heat transfer to the helium in one region of the magnet will depend on the temperature and quality of the helium which is convected there after receiving heat elsewhere in the magnet.

Both stability analysis and quench analysis deal with the thermal consequences of a section of conductor which goes into the normal conducting state. Thus both deal with the same geometrical properties of the conductor and material properties of the conductor and coolant. However, the expressions used for the temperature-dependent material properties may be different because the temperature range is different; the stability analysis typically is terminated when the conductor temperature reaches 50 to 100 K, while the safety analysis must be continued to temperatures of 600 K or more.

Inadequacy of an Intrinsically Stable Quench Analysis for Cryostable Magnets

Earlier quench analyses are typified by the program QUENCH² which was developed by Martin Wilson, to study the quench of intrinsically stable magnets, in which the conductor is not in thermal contact with liquid helium. The code calculates the longitudinal and transverse quench velocities from appropriate thermal properties. The quench volume of the coil grows in time as an ellipsoid whose axes are the respective velocities multiplied by the elapsed time.

To use QUENCH with a cryostable magnet cooled by liquid helium, the quench velocities are modified in an *ad hoc* way. In general it is not possible to know if the results of such a calculation are conservative; too high an assumed quench velocity can underestimate the maximum temperature reached by the conductor, while too low a velocity will underestimate the maximum

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voltage developed. In light of this unsatisfactory situation, it seemed appropriate to develop a new code, with heat transfer to the helium explicitly included, and with the stability code as a starting point.

Thermal Analysis

The Model

The model for the quench analysis, like that of the stability analysis,¹ is based on a heat balance. The same heat generation and transfers, those indicated in Fig. 1, enter.

Fig. 1. Heat Balance for Quench Analysis.

However, the backward difference method³ must be used to solve the heat balance equations. Experience with the stability analysis program showed that for time increments larger than about 1 ms, numerical instabilities develop in the calculations. Consequently stability calculation proved expensive for a situation in which the normal region required several seconds to collapse or grow. Safety analysis of a situation that might take many minutes to develop and resolve would have been prohibitively expensive. The backward difference method does not introduce numerical instability for any size time increment; the increment is governed only by the time scale of the temperature changes which occur. Temperatures change very fast at first but very slowly later. In the computation, the size of the time increment is halved if any element has a temperature change greater than 1 K and doubled if no element has a change greater than 0.1 K.

Heat is conducted to the neighboring elements of the conductor and, if appropriate, through insulation to the elements of the neighboring turns. Temperature-dependent values for the thermal conductivity and specific heat of copper are used in the model. Heat is transferred to the helium coolant according to a specified heat transfer coefficient, which depends on temperature difference and may be steady state or transient. 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.

Properties 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 transient heat transfer data of Steward⁴ and of Giarratano and Frederick⁵ can be represented in a simple form. The expression for nucleate boiling is used:

$$q_h = 0.8 \Delta T, \Delta T < \Delta T_{\max} \quad (1)$$

where q_h is the heat transfer in W/cm² and ΔT is the temperature difference in Kelvin between the conductor surface and the bulk helium. For steady state transfer this condition is taken to hold for $\Delta T_{\max} = 1$ K. For transient transfer, it is taken to hold up to

$$\Delta T_{\max} = -0.7806 \ln(t - t_0) - 2.617 \quad (2)$$

where t is the time and t_0 the time at which ΔT for the element first exceeds 0.1 K, t and t_0 in seconds. For $\Delta T > \Delta T_{\max}$, the expressions for pool boiling

$$q_h = 0.1271 + 0.0015 \Delta T, \Delta T > 2 \quad (3)$$

or the transition region

$$q_h = 1.45 - 0.65 \Delta T, \Delta T_{\max} < \Delta T < 2. \quad (4)$$

is used.

However, a quench typically takes place over many seconds, so the difference between using expressions for steady-state or transient heat transfer is unimportant.

Using the Model

Like the size of the time increment, the size of each element must increase as the computation proceeds. When a specified element of conductor goes normal, three elements can be combined into one. The heat transfer to the helium by the new element is the sum of the heat transferred by the three old ones; the temperature of the new element is the temperature of the middle one; and the length and electrical resistance of the new element are three times those of the old ones.

If turn-to-turn heat conduction is included, then when an element of a specified turn (e.g., the seventh nearest neighbor to the initial turn) goes normal, three turns are thereafter treated as one. The heat transferred to the helium from the new turn is the sum of the heat from the three old ones; the temperature of the new turn is that of the middle one; the electrical resistance and turn-to-turn heat conductance are decreased by a factor of three; and the width and equivalent current are tripled.

The backwards difference method is applied to each turn separately each time step. Thus the temperatures are found for each turn by solving a system of equations with a tri-diagonal matrix representing heat transfer to helium and conduction to neighboring turns, and with other heat sources such as Joule heating and turn-to-turn heat transfer included as part of the right-hand-side.

Varying Magnetic Fields

A characteristic property of tokamak TF coils, and some other kinds of cryostable magnets as well, is the variation of the magnetic field B around a turn of the coil. The field can vary by more than a factor of two over a distance of a few meters, as can field dependent parameters such as critical current, resistivity, and propagation velocity. This situation permits the possibility of a stable normal region of conductor, which never propagates into the low field region nor collapses in the high field region.

To study this possibility, several computations were carried out with a field variation given by

$$\begin{aligned} B &= 9 & x < 2 \text{ m} \\ B &= 6 - 3 \sin(\pi(x-4)/4), & 2\text{m} < x < 6 \text{ m} \end{aligned} \quad (5)$$

with B in tesla, and x in meters, measured from the center of the high field region. The length is divided into 600 1-cm long elements. The field variation models that of a TF coil with its internal straight leg at 9 T and its outer leg at 3 T.

Pressure Variation

The pressure-dependent properties of helium vapor and liquid, the initial volume of each, and the heating rate are specified, along with the diameter, length, and activating pressure of the liquid and vapor vent lines.

At each step in the calculation, the volume of liquid is decreased by vaporization due to the heating and further decreased, if the liquid vent line is open, by the flow of liquid out the vent line. The volume of vapor is increased by vaporization and decreased by the flow of vapor out of the vapor vent line, if the line is open. Then the pressure is changed so that the liquid and vapor volumes add up to the initial volume. Finally the flow velocities in the liquid and vapor vent lines are adjusted to correspond to the new pressure.

Calculation of Current

The initial stored energy of the magnet is determined from the inductance and current. The power dissipated internally at each time step is calculated. If the magnet is assumed to be discharging, the power dissipated externally is also calculated, from the current and the dump resistance. The energy is decreased by the product of the power and the time step, and the decreased current is calculated from the energy and inductance. Calculation continues until the current drops to 1 A, unless it is terminated earlier by recovery or by a temperature rising to an unacceptable value, say 500 K.

Alternatively, the current or external driving voltage may be specified explicitly.

Application to TF Coil Discharge

If one TF coil of a tokamak discharges rapidly while the others remain superconducting and are switched into a mode of free-wheeling individually, the currents can rise in the two neighboring coils and their high field regions can become resistive. The currents will remain high in the coils, driven by the discharge of the original coil. After it is discharged, the neighboring coils will discharge, and in so doing, drive their neighbors normal. The process

will continue until all the coils are normal-conducting and discharged. Some of the coils may be held at an abnormally high current for twenty seconds or more.

To study the thermal consequences of this process, the behavior of a superconductor was computed under high current conditions. A square conductor 1.45 cm on a side was considered, with a copper to NbTi ratio of 8. To simulate a bath cooled cable, the wetted perimeter was assumed to be 200% of the geometrical perimeter. The conductor was assumed to be in a magnetic field as given by Eq. (5). An initial normal region was assumed at 9 T and 60 K, lying between $x = \pm 5$ cm (total length 10 cm, total heat 460 J).

Both constant currents and constant currents preceded by a higher current pulse, e.g.,

$$\begin{aligned} I &= 20 \text{ kA} & t < 0.2 \text{ s} \\ I &= 20 \text{ kA} (1 - (t-0.2 \text{ s})), & 0.2 \text{ s} < t < 0.4 \text{ s} \\ I &= 16 \text{ kA} & t > 0.4 \text{ s} \end{aligned}$$

were considered. The formation of a stable normal region was found to be the same whether or not there was a higher initial pulse, but the pulse would permit the region to form from a smaller initial normal region, or perhaps even with no such region.

Figure 2 shows the temperature profile of the stable normal regions that develop with currents of 18 kA and 16 kA, along with the assumed field variation. The wide range of currents over which a stable normal region can persist is in marked contrast with the situation with a conductor in a uniform field, in which a stable normal region can occur over a current range of only a few tens of amperes, if at all.

A stable normal region of the form shown in Fig. 2 would be an operational concern rather than a safety concern. However, if the helium vaporized by Joule heating in the resistive region were not replenished adequately, the resistive region could continue to heat and conceivably could destroy the magnet.

Fig. 2. Temperature Profile of a Stable Normal Region for Currents of 18 kA, plus Assumed Magnetic Field Profile. The Profiles are Symmetric About $x = 0$.

Conclusions

The calculated response of a superconductor to a high current, as might occur in one TF coil when a neighboring coil discharges, shows the possibility of a stable normal region and a conceivable destruction of the magnet. It remains to be seen whether the actual currents predicted in a credible TF coil discharge could lead to that situation.

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