Consideration of the Thermal Properties of Materials in the
Design of Transiently Stable Superconducting Magnets*

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In a previous paper, a method of analyzing the transient thermal behavior of a section of magnet winding using a computerized model was described, and some preliminary results based on this analysis were presented.¹ Convincing agreement of the calculations with experiments² was demonstrated, in that both show that the stabilizing effect of materials on the operation of small, tightly wound coils is thermal rather than electromagnetic in nature. The present extension of the original analysis also demonstrates that the transient thermal response of the magnet windings to internal disturbances is determined principally by the thermal properties of the materials present in the winding. In a layer wound Nb₃Sn composite ribbon magnet, these include the three materials of which the ribbon is made, the metallic interleaving foil, and the layer to layer insulation.

The mathematical models on which the analysis is based allow the problem to be divided into two parts: first, a computation of the maximum sudden temperature rise from which the composite is able to return to the superconducting state; and second, a computation of the temperature rise which accompanies a complete collapse of magnetization within the magnet winding. By treating the problem as two separate but related parts, the relative importance of each material may

* The initial phases of this work were supported by the Atomic Energy Commission.

† Supported by the U.S. Air Force Office of Scientific Research.

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be explored in both portions of the study. Furthermore, the effects on thermal behavior of changing the thickness of any of the materials, or of exchanging one material for another, can be examined.

Review of Method

By way of reviewing the method, each of the calculations will be outlined briefly. The physical model which is envisioned assumes that the initial temperature rise is limited by the combined enthalpies of the section of ribbon in which heat has been deposited, and the interleaving in direct contact with the hot section. Following the initial sudden rise, heat is allowed to flow into the adjacent interleaving, which is assumed to remain at bath temperature during the initial heat deposition. In order for this picture to be even approximately correct, the superconducting layer must be very thin, due to its undesirable thermal properties, and furthermore, the volume of the coil in which the initial instability occurs must be small in comparison with the coil dimensions.

The first portion of the analysis produces a graph of the temperature of the superconductor as a function of time following a sudden increase in temperature. Fig. 1 shows two typical examples of this simulation. The pair of curves labelled (1) illustrates recovery and non-recovery for a transport current of 95 amperes. Curves (2) are for a current of 175 amperes. In both cases, a temperature of only 150 millidegrees separates the initial points of the recovery and non-recovery curves. By plotting the initial points for all recovery curves as a function of transport current, the curve (a) in Fig. 2 is obtained.

Second, to find the value of the sudden initial temperature rise, an effective enthalpy curve is generated, taking into account the fractional contribution of the enthalpies of all the materials in the winding. This is then balanced against the quantity of energy released during a complete collapse of magnetization

which is computed as a function of transport current.* Curve (b) in Fig. 2 shows how the computed initial temperature rise varies as the transport current is changed for the ribbon described below. By superimposing those curves, an approximate value of maximum stable transport current is indicated at the intersection of the two. These curves are applicable to silver-plated 90 mil Nb_3Sn ribbon, wound with 2.5 mils of cadmium and 1/4 mil mylar as interleaving. A background field of 40 kOe normal to the ribbon face is assumed present at the windings.

The Present Study

The results reported here represent an extension of the previous study to include a number of interleaving materials, the use of both copper and silver as the normal metal component of the conductor, and the use of thin, inorganic insulation.

In order to initially approach the study in a broad sense, the computer was used to produce a number of curves similar to (a) of Fig. 2. For this series of curves, both the thermal conductivity and the specific heat of the interleaving foil were allowed to take values ranging over an order of magnitude. Fig. 3 summarizes the results obtained by this variation of input data. These curves show the maximum sudden temperature rise from which recovery can be made, as a function of the specific heat of the interleaving foil. Three values of transport current and two of thermal conductivity are indicated. As examples, the positions on the plot occupied by some real materials, cadmium, copper, lead, and aluminum are shown. In all these cases, both the ribbon and the insulation are the same as in the previous two figures.

* This calculation was described in ref. 1. Eq. 8 of that reference should read

$$Q = (\mu D^3 / 24) J_c^2 (1 - \beta^2 - 6\beta^2 \ln \beta).$$

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A graph of this nature is of rather limited usefulness, since it does not indicate the varying influence of the various metals on the initial temperature rise. A few qualitative observations may be extracted from it, however. The most obvious aspect of these curves is that, for a given value of transport current, a conspicuous superiority of one foil over any other is not indicated. Another clear feature of this data is that, as the transport current is raised, the role played by the thermal properties of the materials becomes relatively less important during the period of time following the initial temperature rise.

With these trends as background, the properties of a number of specific materials were tried in the computation. Namely, as interleaving foil, cadmium, copper, silver and indium, and as the normal metal component of the conductor, silver plating and copper cladding. In addition to changing the materials themselves, the thicknesses of these materials were varied. In order to eliminate effects caused by factors other than the differing thermal properties, the overall current density was kept constant. That is, if the thickness of silver plating, say, was made thicker, then the thickness of interleaving foil was made correspondingly thinner so that the overall winding thickness and, therefore, the overall current density remained constant. The thickness of the conductor substrate, the superconducting layer, and the insulating layer were not changed throughout the study. Insulation was a 1/8 mil inorganic substance in all cases, and a background field was assumed with a 40 kOe component normal to the ribbon faces.

Calculations

Although the results of the calculation can most effectively be presented in graphic form, doing so for the large number of different combinations under consideration would be impractical. Therefore, only a few representative curves will be shown, with the overall features of the analysis to be shown in

a few summary curves.

An important point to be inserted at this juncture is that the slopes and relative positions of the curves shown here are sensitive to the values chosen for the thermal constants. In many cases, these values were assigned on the basis of data available on pure-annealed or single crystal samples, which were then reduced for use in these calculations by some crudely estimated factor. Inaccurate results traceable to this kind of input data inaccuracies are liable to be most serious at low values of transport current, as was indicated in Fig.3.

Table 1 lists the material properties which were used in the computations. Particular attention should be directed to the values of electrical resistivity and thermal conductivity: in a field of 40 kOe, the resistivity of the copper cladding is more than a factor of two less than that of silver plating. On the other hand, the value chosen for the thermal conductivity of silver foil is 8 times that of copper foil. These factors, along with the values for total enthalpy, are shown to have a large influence on the transient thermal behavior of the winding.

The first question that must be answered is, what temperature rise can the winding tolerate without initiating a quench? A typical response to this question is shown in Fig. 4 as the set of descending curves, applicable in this case to ribbon with 1.7 mils of silver plating, wound with 2.5 mils of the various foils. Silver foil is seen to be most effective in improving the tolerance of the winding to sudden temperature increases. The same is true if the ribbon is copper-clad, as shown in Fig. 5. The 1.7 mil thickness of cladding includes .4 mil of solder. The conditions represented in Fig. 5 are identical to those in Fig. 4 except for the normal metal cladding.

The superiority of silver, judging from the value listed in Table 1, is due primarily to its large thermal conductivity. The fact that it is even more effective when used with copper-clad, instead of silver plated ribbon,

is a result of the reduced joule heating in the lower resistivity cladding.

The next part of the problem is the calculation of the maximum temperature rise that might occur in each of the combinations of winding materials; the method for doing this has been described in ref. 1: the quantity of heat released during a collapse of magnetization is found by an integration of the product of induced electric field and critical current density within the ribbon.

If, during a complete collapse of magnetization, a given quantity of energy is released approximately adiabatically in the winding, the temperature rise is governed by the effective enthalpy of the combination of materials. Figs. 6 and 7 serve to compare the total enthalpies of windings with silver plated and copper-clad ribbons respectively.

The most common feature of these two figures is that for temperatures higher than about 4° above bath, the use of cadmium foil results in the largest total effective enthalpy. The most prominent difference is that, as a result of the use of solder with its large heat capacity in the copper-clad ribbon, there is a marked lessening of the spread among the curves at the lower end of the temperature range.

With these curves, and knowledge of the amount of energy released within the windings, the resulting increase in temperature is easily found. The rising curves in Figs. 4 and 5 again compare the silver and copper versions of ribbon. As might be surmised from the previous two figures, the presence of solder in the copper-clad ribbon reduces both the values of the temperature rise and the differences among the various foils.

The last step in the analysis is the superposition of the curves, as shown in Figs. 4 and 5. Intersections of these curves, indicated by black dots, give an indication of the maximum stable transport current that may be allowed,

providing that the transient thermal effects are dominant in the system.

One interesting feature of these results is that cadmium is the superior interleaving when silver plated ribbon is used, but silver foil is superior if copper-clad ribbon is used. Reasons for this can be surmised upon close inspection of the curves in Figs. 4 and 5. First, windings made with copper-clad ribbon are conspicuously more tolerant of temperature rises than windings in which a silver plated conductor is used, regardless of which material serves as interleaving. This can probably be traced, as mentioned earlier, to the lower resistivity of the copper-cladding, and the associated smaller rate of heat production by joule heating. Second, inclusion of copper-clad ribbon is seen to limit more effectively the initial temperature rise, a result due in large part to the presence of solder in the cladding. However, since the contribution made to the total enthalpy by the cadmium foil is so large, the additional contribution made by replacing the silver plate with copper/solder cladding is smaller than with the other foils. The net result, then, being that when used with copper-clad ribbon, silver foil interleaving is superior to cadmium.

Variation of Thicknesses

The discussion thus far has indicated what influence a change in the normal metal component of the composite ribbon might have in the thermal behavior of a small solenoid, and similarly, what effects may result by using different kinds of metal foils as interleaving. Another useful variation to make is that of the relative thicknesses of the normal metal cladding and the interleaving foil, keeping the total thickness constant in order to prevent effects of differing overall current densities from masking thermal effects. Foil thicknesses were chosen to be 1.7, 2.5, and 3.2 mils, with corresponding thicknesses of plating or cladding of 2.5, 1.7, and 1 mil.

The results of this variation are summarized in the pair of Figs. 8 and 9. There is a clear indication in both cases that there appears to be an optimum ratio of foil to normal component thickness which, while perhaps not constant with current, is about 1.5:1. There appears to be a trend for this optimum thickness ratio to increase slightly as larger stable transport currents are achieved. Or, stated from a different point of view, the optimum foil to normal component thickness ratio is different for different combinations of materials, although the difference is slight.

Properties of Helium

The foregoing analysis has been restricted to tightly wound coils purposely in order that full attention could be directed toward the properties of metals without the added complication of heat transfer to helium. However, any discussion of the influence of the environment on the thermal behavior of superconducting solenoids would not be complete without a consideration of the effects of liquid, and cold gaseous helium.

The specific heat of liquid helium at 4.2K, and a pressure of 1 atmosphere, is about two orders of magnitude larger per unit volume than the most effective metals that have been considered here. However, as long as the liquid is boiling, no quantity of heat added to the bath will raise its temperature in the slightest, by definition. Therefore, the heat capacity of a boiling helium bath can be of no use as a heat sink.

Another consideration is to prevent the liquid from boiling so that increases in the bath temperature are possible. This can most easily be done by lowering the temperature of the bath by pumping, and subsequently restoring the pressure to atmospheric. The prevention of boiling is more difficult to do by increasing the pressure at 4.2° since near 1 atmosphere, the change in boiling temperature of helium is only about 0.1° for a change in

pressure of 70 mm Hg. If boiling were stopped, however, the rate of heat transfer to the bath would be very poor, since the thermal conductivity of the liquid is about four orders of magnitude less than that of the metals discussed earlier.

The specific heat of cold helium vapor is only slightly less than that of the liquid, but its thermal conductivity is even worse. Only if the vapor was flowing, by either forced or natural convection, could use be made of the specific heat, providing that the temperature of the cooled surface was not changing rapidly with time. However, in the study of the transient thermal behavior, consideration of the specific heat of helium liquid or vapor is of relatively minor importance.

What may be of greater importance is the latent heat of vaporization of liquid helium, as the following order of magnitude calculation indicates: if the flow of heat from a warm surface to boiling helium is restricted to be 1 joule $(\text{cm}^2 \text{sec})^{-1}$, the energy released per unit area is sufficient to vaporize about $4 \times 10^{-4} \text{ cm}^3$ of liquid in one millisecond. This is the volume of liquid contained in a layer of 1/6 mil thickness.

The value of heat transfer and the time scale used in the above calculation are quite reasonable for transient problems: Iwasa has recently measured the degraded current carrying capacity of Nb-Ti wire in a variety of thermal environments.³ Results of these experiments for insulated wire in contact with boiling helium at 1 atm. show directly the transient thermal behavior, its time scale and range of temperature excursions. Heat transfer rates of nearly 1 watt cm^{-2} , lasting for periods of a millisecond or less, occur without initiating the propagation of a normal region.

Transient heat flow to helium within a solenoid, which has been made porous either by the inclusion of small spaces, or by the use of porous winding materials such as fiberglass cloth, is considerably more difficult to measure

and exceedingly complex to analyze mathematically. For, even though the structure is relatively porous, the vapor, which is generated at the rate of several $\text{cm}^3 \text{sec}^{-1}$, will be restricted in its efforts to escape, and the unvaporized liquid nearby will certainly be disturbed. Other factors which must be considered are the very rapid rise in ΔT -- a rate of several thousand degrees per second -- and the nature of the cooled surface.

Summary

In order that the results presented here not be too liberally interpreted, the range of applicability of the model on which they are based should be made explicitly clear. This has not been an analysis of superconducting magnet performance, nor are the conclusions which were drawn from the analysis meant to provide definitive design parameters for actual coil construction. Rather, this work must be viewed as a tool with which one may gain insight into some of the dynamic events that occur transiently within the body of a tightly wound solenoid. More specifically, it has dealt with the differing transient thermal responses of the magnet winding brought about by changes in the thermal environment of the conductor.

To the extent that many of the values which were used for the various thermal properties are not well known for materials actually used in magnet construction, the results may be considered semi-quantitative. More importantly, they have yielded some knowledge about the nature of the separate roles played by the specific heat and the thermal conductivity of the materials following a sudden input of heat. Also, the extent to which these results agree or disagree with actual experience provides a measure of the relative importance of transient thermal effects and electromagnetic effects, thereby helping to redirect any subsequent efforts to improve the performance of a given magnet system.

Acknowledgements

The author gratefully acknowledges the assistance provided by D. Nelson and C. Weggel in programming and in actual data runs on the computer, and to B. Montgomery for helpful suggestions, both during the analysis and in writing this paper.

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TABLE I

List of Properties

I. INSULATION

thickness	3.175×10^{-4} cm (1/8 mil)
thermal conductivity	2×10^{-3} watt (cmK°) ⁻¹

II. CONDUCTOR

A. silver plate (all thicknesses)

electrical resistivity (40 kOe)	7.5×10^{-8} Ω cm
specific heat	1.89×10^{-2} joules (cm ³ K°) ⁻¹

B. copper cladding (with .4 mil solder)

electrical resistivity (40 kOe)	3.4×10^{-8} Ω cm
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thickness	specific heat
2.54×10^{-3} cm (1 mil)	4.07×10^{-2} joules (cm ³ K°) ⁻¹
4.3 (1.7)	2.7
6.35 (2.5)	2.08

C. substrate

specific heat	7.2×10^{-3} joules (cm ³ K°) ⁻¹
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D. superconductor

specific heat (40 kOe)	4×10^{-3} joules (cm ³ K°) ⁻¹
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III. FOILS (~10°K)

material	thermal conductivity	specific heat
cadmium	2 watt (cmK°) ⁻¹	6.92×10^{-2} joules (cm ³ K°) ⁻¹
copper	12	7.7×10^{-3}
silver	16	1.89×10^{-2}
indium	1	1.1×10^{-1}

IV. HELIUM

liquid; 4.2°K, 1 atm.

thermal conductivity	3×10^{-4} watt (cmK°) ⁻¹
specific heat	.524 joule (cm ³ K°) ⁻¹
heat of vaporization	2.56 joules cm ⁻³

vapor

thermal conductivity	$\sim 10^{-4}$ watt (cm K°) ⁻¹
specific heat	$\sim .39$ joule (cm ³ K°) ⁻¹

rate of change of boiling temperature with pressure near 1 atm.,

$$1.35 \times 10^{-3} \text{ K}^\circ \text{ mm}^{-1}$$

Figure Captions

1. Effective temperature of the superconductor as a function of time, showing recovery and non-recovery. The pair of curves labeled (1) is for a transport current of 95 amperes; curves (2) are for 175 amperes. Temperature is degrees above bath temperature.
2. The descending curve (a) represents the maximum temperature rise from which the conductor can recover as a function of transport current. Curve (b) represents the sudden temperature rise resulting from a collapse of magnetization. The intersection of the two indicates the maximum stable transport current. Winding details are described in the text.
3. Sudden temperature rise as a function of specific heat of the interleaving foil for three values of transport current. Some specific materials are indicated by dots.
- 4, 5. The set of descending curves indicates the maximum tolerable sudden temperature rise as a function of transport current for four representative interleaving foils. Other winding parameters are described in the text. The set of ascending curves shows the expected temperature rise following a collapse of magnetization. The intersections, indicated by dots show the approximate maximum stable transport currents to be expected. Silver plated ribbon is represented in Figure 4; copper-clad ribbon in Figure 5.
- 6, 7. Effective enthalpy of the winding as a function of temperature in degrees above bath.
- 8, 9. Approximate maximum stable transport current as a function of foil thickness, for constant overall current density, assuming transient thermal effects are dominant over other effects.