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EXPERIMENTAL EVIDENCE OF DEGRADATION EFFECTS IN SHORT SAMPLES OF HARD SUPERCONDUCTORS

by

John C. Fakan

Lewis Research Center
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SUMMARY

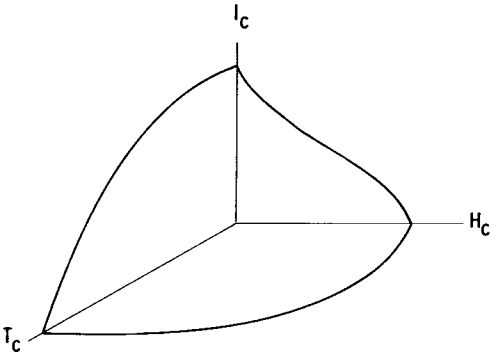
A set of experiments is described from which a model is proposed that may explain degradation of the current-carrying capacity of superconducting magnets. The model is used to explain the experimental results obtained on the basis of temperature excursions induced in the material as a result of the energy released by sporadic flux penetrations (flux jumps). Specifically, it is proposed that the current capacity of a superconducting electromagnet may be controlled by penetrations (in the temperature direction) of the critical surface that defines the superconducting region, and that these penetrations result from flux-jumping in the low-field-strength regions of the coil. Suggestions are given for minimizing or avoiding degradation in practical superconducting electromagnets.

INTRODUCTION

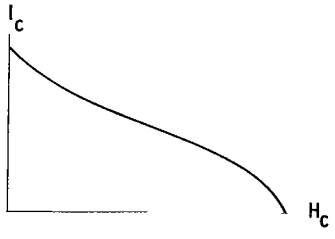
Since the discovery of the various known hard superconductors, researchers have sought to use these materials to produce strong magnetic fields. Unfortunately, it was soon discovered that superconducting wires, capable of carrying high current in intense magnetic fields, suffered a serious current degradation when wound into a solenoid. A major problem at present is explaining this current degradation and discovering means or materials to avoid it. In the light of previous experience, some experiments performed at the NASA Lewis Research Center appear to provide a possible explanation of this behavior. The results of these experiments and their significance with regard to electromagnet performance are described in this report.

PRELIMINARY CONSIDERATIONS

The boundary surface that separates the normal conducting region and the superconducting region for a given superconductive material is referred to as the critical surface and is characterized by the critical current I_c, the critical magnetic field H_c, and the critical material temperature T_c. A typical plot of the critical surface has the general appearance shown in sketch (a).



(a)



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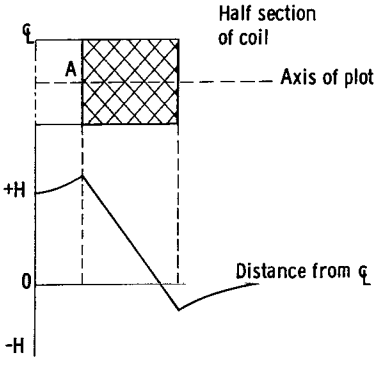
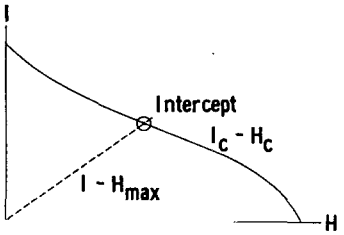


(c)

In practice, a superconducting magnet is cooled by submersion in liquid helium, which provides a constant temperature bath; since current is transported through the winding in a nondissipative manner, the material should remain at bath temperature. Thus, the operation of the magnetic conductor should be defined by the intersection of the bath-temperature plane with the critical surface. The critical current variation with magnetic field strength is shown in sketch (b)

It seems reasonable to expect that the critical current for the entire superconducting electromagnet will be determined by the material in the region of the strongest field. In an electromagnet of conventional geometry, the region of maximum field is at the center of the innermost winding (point A in sketch (c)). If a plot of field strength as a function of current $I\text{-}H_{max}$ for this region is superimposed on the plot of critical current against field strength for the material (sketch (d)) an intercept is found that should define the limiting value of current for this particular electromagnet. Experience has shown, however, that actual superconducting electromagnets seldom perform to this limit. Exceptions include solenoids that use metallic platings or spacers. While these coils do not make optimum use of the winding volume, they do provide some understanding as to what is going on.

Another important clue appears when the magnetization characteristics of the hard superconductors are observed. Plots of magnetization against applied field show that flux enters these materials in a series of discontinuities called flux jumps. It is observed in reference 1 that the large net changes of magnetization at each flux jump occur predominately at the lower values of field.



(d)

Since the flux jumps are largest for low values of field strength, it is suggested that the current degradation effect in superconducting solenoids may be due to these flux jumps in regions of the winding where the field strength is always very low, that is, near the zero field point. It has, in fact, been demonstrated (refs. 2 and 3) that solenoids may normalize at some location in the winding volume other than the high field region.

DESCRIPTION OF TESTED MATERIAL

The material used was prepared by the vapor deposition process essentially as described in references 4 and 5. This process consists of forming the gases of niobium and tin chlorides and reducing these gases with hydrogen on the surface of a heated substrate. To make continuous lengths of a superconductor for purposes of coil winding, a stainless-steel ribbon is moved through the chloride and hydrogen atmosphere where it attains a covering film of niobium tin (Nb_3Sn) to a thickness determined by the gas concentration and the ribbon speed and temperature. For reasons of convenience in current level, size, strength, and winding efficiency, the ribbon dimensions were chosen to be 0.002 by 0.085 inch with an Nb_3Sn coating thickness of 0.0002 to 0.0003 inch. A copper film approximately as thick as the Nb_3Sn film is plated on the outer surface. This plating permits easy soldering of the lead wires.

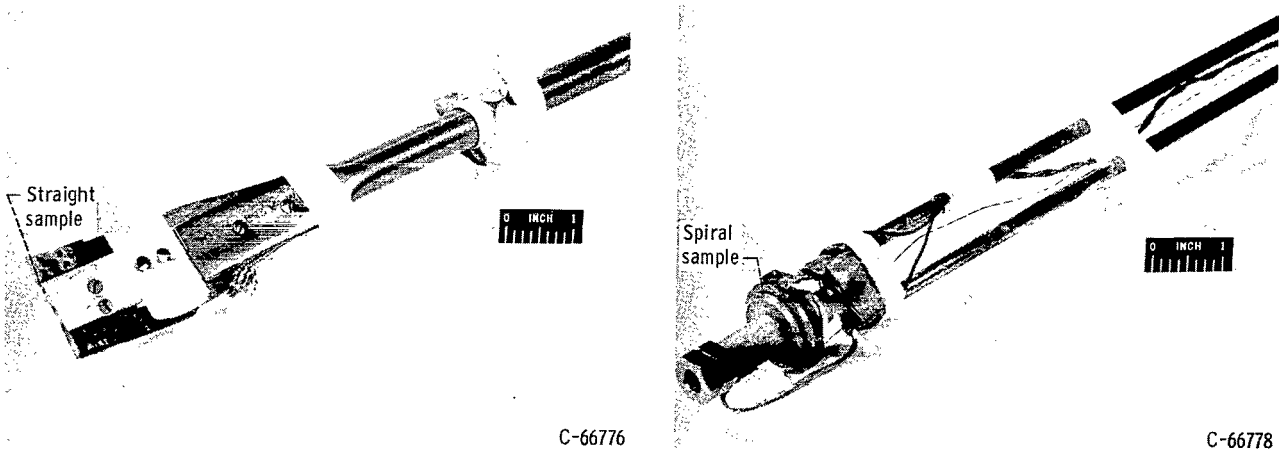
Until the type of measurements described in this report were made, the deposition process was optimized to yield the highest currents in the highest available transverse fields. No particular emphasis was given to the critical characteristics of the low field region. Subsequent to the discovery of the existence of instability in materials processed in certain ways, investigations, which are still in progress, were begun to associate these instabilities with the process technology.

The particular samples discussed herein were chosen to illustrate the principles thought to underlie one important cause limiting the fields achievable in superconducting coils. The ability to vary the stoichiometry and crystalline structure of the Nb_3Sn deposit by controlling the process variables is expected, eventually, to provide more complete answers to and solutions for the problem currently associated with such magnets.

APPARATUS AND PROCEDURE

Measurements that required high field strength were made in the Lewis high magnetic field facility. Two water-cooled copper solenoids, which are described in references 6 and 7, were available. The larger of the two magnets was used almost exclusively because of the diameter (2.2 in.) in the liquid helium Dewar. This test section diameter allowed the entire test specimen to be mounted in one plane transverse to the field direction. Detailed investigations in the low field region were performed in the 14.5-kilogauss superconducting magnet at the RCA Research Laboratory, Princeton, New Jersey.

Two sets of short samples were tested. The first set consisted of straight 2-inch lengths of material, and the second was made up of 7- to 10-meter lengths formed into tight, single-plan spirals and mounted on a sample holder (fig. 1) in such a way that the plane of the spiral was perpendicular to



(a) Straight. (b) Spiral.

Figure 1. - Sample holders.

the direction of the applied field. These spirals had a 9/16-inch inside diameter and a $1\frac{1}{4}$-inch outside diameter and utilized a 0.5 mil Mylar tape between turns for insulation. A copper shunt was provided on each probe to protect the test sample when the critical current was exceeded. This shunt was parallel with the sample, and the current through the shunt was monitored during each run as a check on the resistance of the connections to the superconductor.

Current was supplied from either of two transistorized power supplies designed and built at Lewis. One supply could deliver 150 amperes, and the other was capable of 300 amperes. Each of these supplies was controlled manually or was made to follow a signal from a source such as a signal generator. An output signal proportional to the current flow was provided to drive the Y-axis of an X-Y plotter. The X-axis of the plotter was usually provided with a signal that was proportional to the magnetic field strength in the electromagnet. This signal was derived from a Hall probe mounted in the bore of the magnet. Potential drop across the test specimen was measured with a commercial millimicrovolt meter.

Two kinds of tests were made on each specimen. In one test, the magnetic field was held constant, while the current through the sample was increased until the critical current I_c was reached. In the other test, the current through the sample was held at a constant value, while the magnetic field was increased to the critical value H_c. Specifically, a current of 40 amperes was first applied with the magnetic field at zero. The field was then increased until the sample became resistive, as indicated by the appearance of a perceptible potential across the specimen, or until a field of about 70 kilogauss was reached. Starting from this high field value, critical currents were then obtained at several constant values of H. When the curve of I_c as a function of H was well-defined, the roles of current and field were reversed, and values of critical field H_c were obtained at various constant values of current.

RESULTS AND DISCUSSION

A series of tests performed using short samples of Nb_3Sn ribbon showed a definite lack of repeatability in the critical current values as a function of field strength. The greatest scatter occurred in the lower field region. In general, all scattered points were above about 2 kilogauss and seemed to have an upper limit of from 20 to 50 kilogauss, depending on the composition of the specimen. Also, all scattered points were below the curve extrapolated from the high field data.

Figure 2 shows the results for two different straight samples. The main difference between the two is the amount of scatter and the range of critical

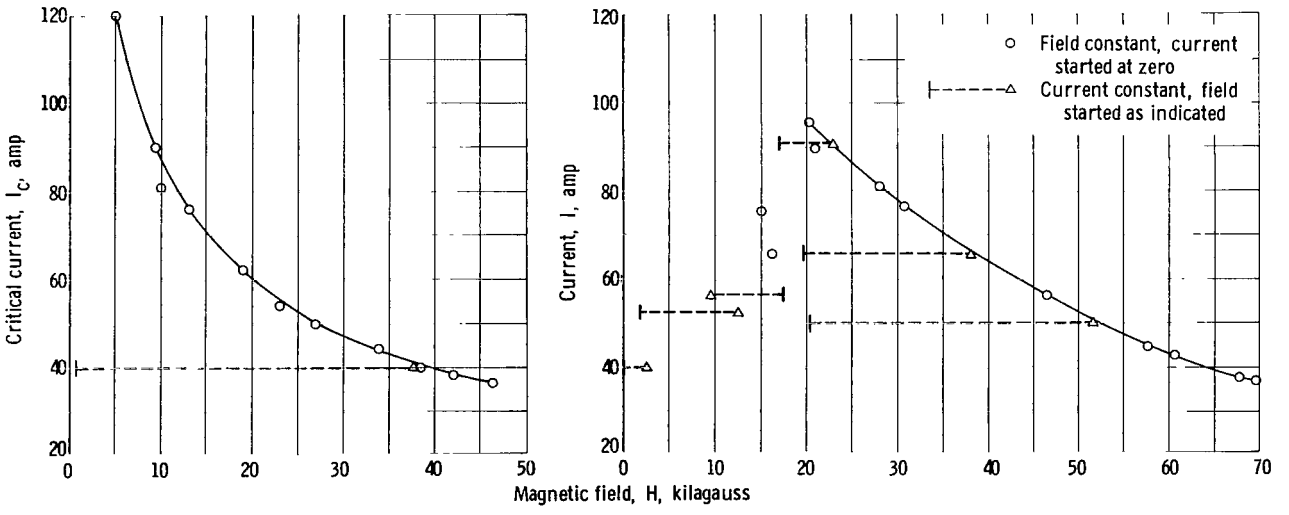
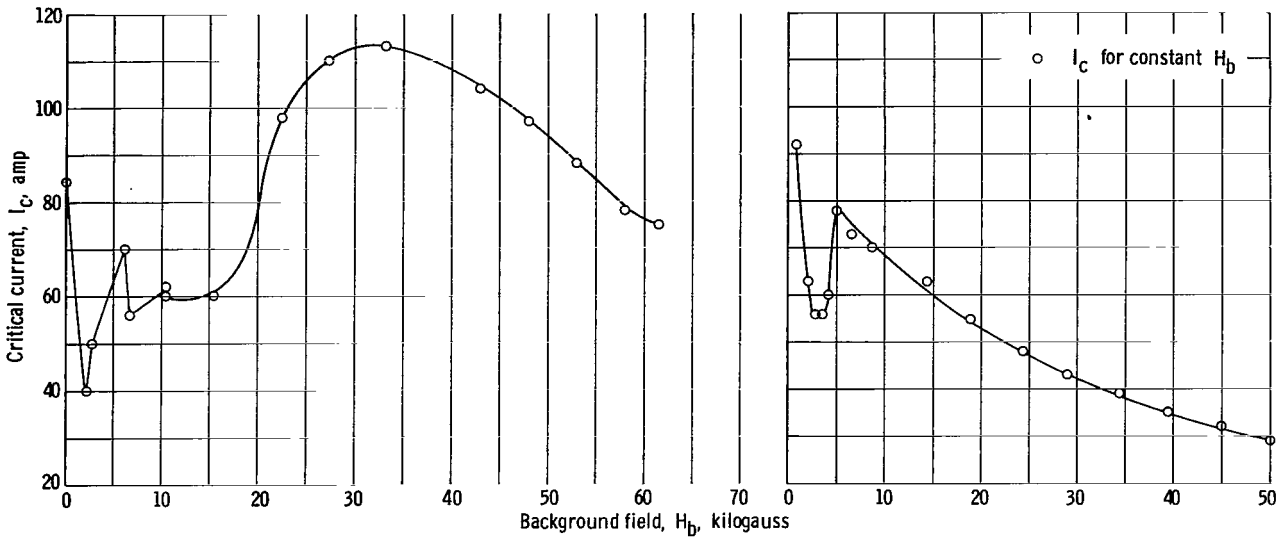


Figure 2. - Critical current as a function of magnetic field, and critical magnetic field as a function of current.

current value over which the scatter occurs. Another series of samples, which were later tested, showed no scatter at all, but in many of these cases the

critical current was, in general, lower than that for samples that showed scatter.

Typical results for the tests on the spiral samples are shown in figure 3. The most interesting feature about the data obtained from these tests is the



(a) Spiral sample A.

(b) Spiral sample B.

Figure 3. - Critical current as a function of applied background field for spiral samples.

appearance of the relatively smooth curve that dips below the straight sample I_c - H_c curve for the material. It appears that there is a definite correlation between the dipped curve for the spiral samples and the scattered points for the straight samples. The material represented in figure 3(a) displays a very large amount of scatter in straight sample runs. (Some scatter is still evident for the very low field region.) The data in figure 3(b) was obtained with one of the materials that showed almost no scatter in straight sample runs. In addition to the differences in the depth and width of the dips in figures 3(a) and (b), it should be noted that the current-carrying capacities in the high field region differ by a factor of 3.

Explanation of Critical-Current Dip

The dip in the I_c - H_c curve appears to be explainable at present only by the phenomenon of flux jumping and the energy associated with that process. Consider one region in the winding of a superconducting electromagnet cooled by immersion in a liquid helium bath and through which a gradually increasing current flows. At some location within the winding volume, a flux jump occurs that raises the temperature of the superconducting winding locally. If the increase in temperature is sufficient, the critical surface is intercepted in the temperature direction, which causes the electromagnet to normalize. If the critical surface is not reached, the material cools by dissipation of the heat into its surroundings, and the critical current of the magnet is controlled by some other region of the winding.

The effect of local temperature excursions, due to flux jumping, on the I_c - H_c characteristics of the material is illustrated in figure 4. The dash-

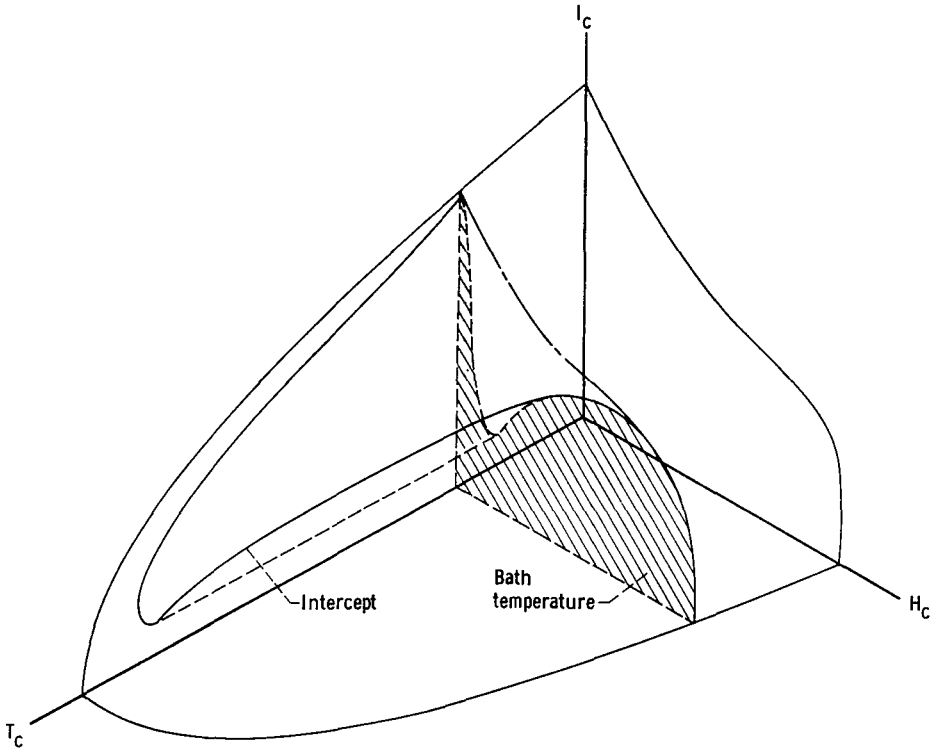


Figure 4. - Critical surface showing probable intercept.

dot curve represents the usual I_c - H_c characteristics at the bath temperature. Points along the intercept in the low field region are elevated in temperature above this plane by an amount that is some function of the flux-jump magnitude at the particular value of field strength considered.

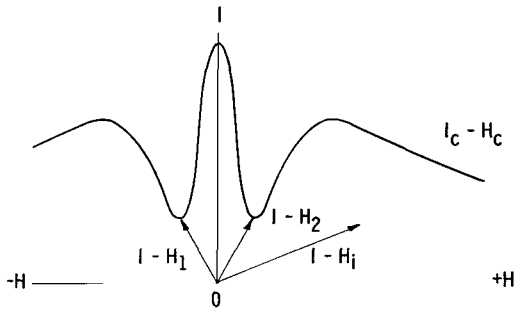
Projecting the observed intercept back to the plane of the bath temperature results in a curve with a shape similar to that observed for the spiral samples tested. If the foregoing explanation is correct, two important conclusions can be made. The longer the time between flux jumps the cooler the material will be at the occurrence of each successive flux jump. Thus, the performance will be dependent on the rate of change of field. Also, since the heat generated must be removed from the warm region, the performance will depend on the thermal properties of the immediate surroundings of the material.

An explanation of the role played by cladding the conductor with material such as copper is now possible. A low-resistivity material surrounding the superconductor will act to damp heavily the rate of penetration of flux during a flux jump, so that a lower maximum temperature excursion in the superconductor should result. The copper will also serve to facilitate removal of the excess heat. An experiment by Wolgast and Aron (unpublished data from Laurence Radiation Laboratory Rept.) serves to show, however, that the electrical char-

acteristics of the cladding are more important than the thermal characteristics.

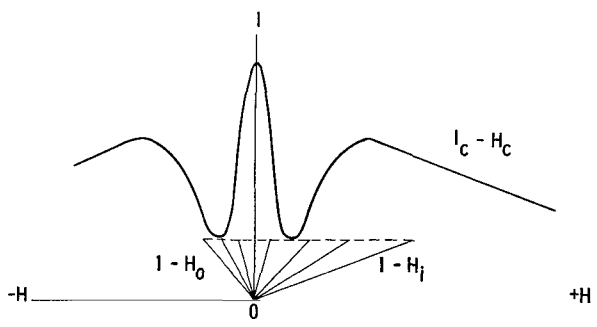
Effect of Critical-Current Dip on Solenoid Performance

The effect of the observed dip in the critical-current curve on the performance of a conventional solenoid is illustrated in sketch (e). In general, there are at least two regions in the winding that have operating lines ($I - H_1$, $I - H_2$) which intersect the curve near the minimum of the dips. (Here the sketch shows field in both directions so that all regions of the winding can be considered.) If one of the dips is intercepted before the operating line for the center of the innermost winding ($I - H_i$) reaches the high-field $I_c - H_c$ curve, the dips will determine the maximum operating current of the magnet. For the assumption that the value of the dip minimum is, in general, only a function of the material and not of the coil geometry, any coil of conventional design wound from this material would normalize at about the same value of current.



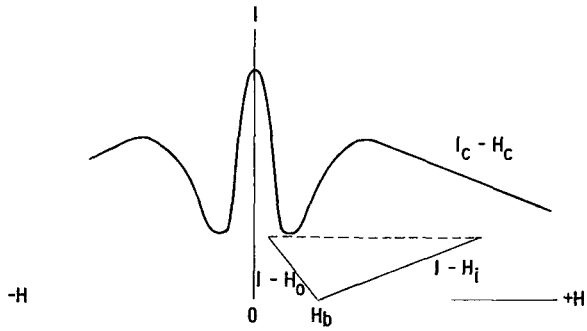
(e)

If the observed $I_c - H_c$ characteristics and all possible operating lines within a conventional superconducting solenoid are considered, it is also possible to predict the dependence of coil critical current on an impressed background field. The operating line with the smallest slope in the positive H direction will be the operating line for the center of the innermost layer of the winding ($I - H_i$ in sketch (f)). The operating line with the smallest slope in the negative field direction will be that for the center of the outermost layer of the winding ($I - H_o$). Between these two limits all other slopes are possible. Sketch (f) shows the relation between the $I_c - H_c$ curve and these operating lines. Note that all operating lines for a simple, conventional solenoid will be at the same value of current (dashed line in sketch (f)). It can be seen that the critical-current value for the solenoid will be that associated with the I_c minimum. If a background field is applied, for instance, in the direction that enhances the central field of the solenoid, the operating lines will all be moved to the right (sketch (g)) by an amount equal to the applied field.

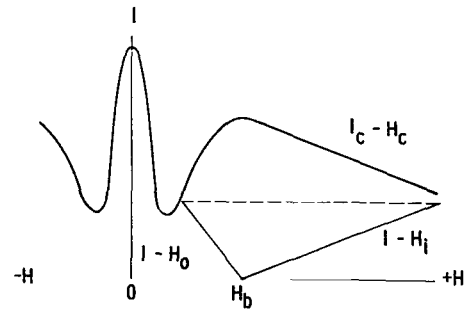


(f)

The critical current for the solenoid will still be the minimum value of I_c. The critical current will thus be constant with increasing applied background field until the point is reached where the applied field is large enough



(g)

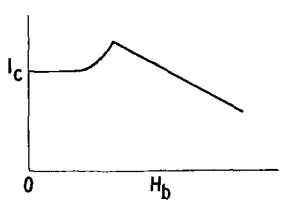


(h)

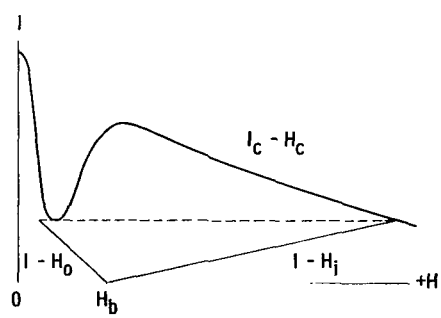
to cause the $I - H_o$ operating line to pass to the right of the current minimum on the positive H side. If the background field is increased further, the critical-current value will also increase as shown in sketch (h). The critical current of the solenoid will continue to increase with increasing background field until the $I - H_i$ operating line finally reaches the $I_c - H_c$ curve. A further increase in background field will then result in a decrease in critical current of the magnet as defined by the characteristic curve in the high field region. A plot of solenoid critical current against applied background field appears as shown in sketch (i).

It would be possible in a high-performance solenoid (one with a high value of H_i/I) that the $I - H_i$ line would intercept the $I_c - H_c$ curve before any current increase could occur, as in sketch (j). In this case, the characteristics of I_c as a function of H_b would be as shown in sketch (k).

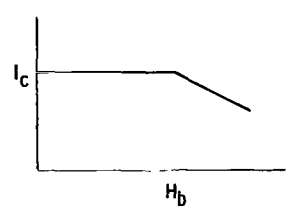
Consideration of this model also yields ideas for avoiding, or at least minimizing, degradation in superconducting solenoids. The best solution, of



(i)



(j)



(k)

course, would be to eliminate or minimize the flux-jump magnitude, possibly by means of some as yet unknown metallurgical treatment. One way to avoid the problem with present materials, as pointed out in the preceding discussion, is to immerse the solenoid in a background field of sufficient magnitude to keep

all of the windings out of the flux-jump-controlled region. Another solution appears to be the use of low-resistivity claddings in that part of the winding which limits the operation of the magnet. Other possibilities include hybrid designs utilizing various materials, or methods of coupling the critical regions of the winding more closely to the coolant bath. Solenoids that are designed to operate below the dip minimum will also avoid degradation.

Some of these methods, of course, are useful only if the reasons for the observed critical-current dip have been interpreted properly.

Further testing is planned for this material and others in an attempt to clarify the causes of degradation and other observed anomalies in superconducting electromagnets.

CONCLUDING REMARKS

The previous inability to predict the critical current of superconducting solenoids on the basis of short-sample tests was a result of the failure of the test conditions to satisfactorily duplicate the actual thermal and electrodynamic environment of the material when in a solenoidal winding. The results obtained in these experiments, wherein the scattered data points of the straight sample tests gave way to the reasonably smooth dipped curves of the spiral samples, serve to indicate that the performance of these materials is highly sensitive to the environmental changes that occur when a length of the material is wound into even a very simple coil. Further experimentation may reveal that degradation of the superconductive properties, due to flux jumping, is sufficiently complete in properly constructed small samples of material, to allow a reasonable means for predicting the behavior of full-size superconducting electromagnets.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 30, 1964

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