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SUMMARY REPORT

A STUDY OF INHERENTLY STABLE HIGH-FIELD SUPERCONDUCTORS

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North American Rockwell
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SUMMARY REPORT

A STUDY OF INHERENTLY STABLE HIGH-FIELD SUPERCONDUCTORS

Covering Period
June 25, 1968 Through July 31, 1970

By
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SUMMARY

This report covers work performed from June 25, 1968 through July 31, 1970, under NASA Contract NAS-8-21415. The purpose of this program was an investigation of the problem of stability in superconducting materials with the goal of developing an intrinsically stable superconductor. The work has included theoretical studies of the problem of stability and flux jump as well as experimental studies of flux jumping in high field superconductors and the ac losses in superconducting coils. Since some of this work will be published elsewhere only abstracts of these papers are included in this report. The study of ac losses in superconducting coils is presented in detail in this report.

The principle investigator on this project was Dr. S. L. Wipf. Dr. C. A. Guderjahn contributed substantially to the study of ac losses in superconducting coils. During the contract period Dr. Wipf was for a time a guest worker at the Oak Ridge National Laboratory in the group headed by Dr. W. F. Gauster.

I. PROJECT SURVEY

The purpose of this program was an investigation of the feasibility of an intrinsically stable high field superconducting conductor. The material presently available such as the niobium-zirconium and niobium-titanium alloys have been found to be quite unstable, that is, they show essentially random super-normal transitions in magnetic fields of the order of five kilogauss. A practical solution to the problem of this erratic behavior has been to use a composite conductor in which the superconductor is paralleled with normal metal usually copper so that in the event of a super-normal transition there is sufficient normal conductor to carry the current without overheating and so allow the superconductor to revert to the superconducting state. Unfortunately this requires a substantial amount of normal conductor and of course, seriously reduces the current density in a magnet while increasing the cost. It is obvious that an intrinsically stable conductor would have many advantages. In addition to the improvement in the current density in the coil and the reduction of the cost, it would provide a badly needed simplification in the design of superconducting devices since the critical current in the conductor could always be reached independent of the particular features of the device in which the wire is used.

There are several possible approaches to produce an inherently stable conductor. For example, it may be possible to produce a material that is inherently stable and some suggestions as to this have been made (e.g., S. L. Wipf, Phys. Rev., 161, No. 2, 404 (1967)). It may also be possible to utilize presently available materials in a particular physical shape or form so that the conductor will behave in a stable manner. The multifilament superconductors that have been introduced recently are a step in that direction. It may also be possible to design magnet structures that minimize or eliminate the instabilities in the device. The present program has considered two of these approaches. An experimental and theoretical study was made of the instabilities in Ti-Nb alloys to contribute to our understanding of the nature of the instabilities. A study was also made of the ac losses in superconducting coils to clarify some aspects of the performance degradation experienced in practical systems. The results of the instability studies have been published elsewhere so only abstracts of these papers are included in this report. The study of ac losses is presented here in completed form.

II. ABSTRACTS OF PUBLISHED PAPERS

A. Flux Jumping in Rings of Niobium-Titanium - S. L. Wipf*

An experimental study has been made of the limit between stable and unstable critical current flow in rings of Nb-Ti. If a ring is in the creep state (stable critical current) in a decreasing field, this limit is given by the first flux jump (i.e., total breakdown of the critical current). In a plot of electric field along ring versus critical current the stability limit follows a line of constant power dissipation; this power dissipation per unit surface is of the order of 10^{-5} to 10^{-4} W/cm^2 and, roughly, inversely proportional to the inductance of the rings. At high currents and correspondingly low fields, a cutoff seems to be given by flux annihilation. At low currents (high fields) the flux jumps are not complete. In comparing these experiments with existing theory it is found that the simplest criterion for full stability does not apply. According to this criterion an instability can occur if for a given temperature change the change in stored magnetic energy is equal or larger than the change in enthalpy - this has hitherto been considered a "necessary" condition for flux jumping. If applied to the present situation, flux jumps should only occur at much higher currents. Arguments are presented suggesting a modification of the criterion to allow for "hot" spots or "non uniform" flux flow. A set of three equations is given which governs the growth of an instability from an initially non uniform flux flow state.

* Experiments and part of the evaluation were performed at ORNL under Government Order No. NASA H-29278A. The evaluation was completed and manuscript written at Atomics International under Contract NAS 8-21415. This work was first published in a report ORNL-TM-2641, June 1969. A revised version was presented at the Applied Superconductivity Conf., Boulder, Colo., June 1970 and will be published in the Conference Proceedings.

B. Flux Jumps and Stabilization - S. L. Wipf

A Type II superconductor becomes resistive under the influence of too large a macroscopic current density, which may be induced or due to a transport current through the superconductor. Ideally, the resistance appears when a critical current density, j_c, given by the flux pinning strength of the material, is exceeded. Current densities beyond j_c cause the flux to flow with a dissipation determined by the flux flow resistivity $\rho_{ff} = dv/dj$ (v being the electric field). The "true" critical current of a superconducting device is the product of j_c and the cross section. The problem under discussion here deals with instabilities in the V-I diagram which make a superconductor revert to the resistive state before the true critical current is reached. If such a degraded critical current occurs in a short sample it may show "training" i.e., increasing values for successive transitions.

This paper was presented at the Europhys Applied Superconductivity Colloquium in Smolenice, June 23-27, 1969, and published in E. techn. J. of the Slovak Academy of Sciences, April 1970.

III. AC LOSSES OF SUPERCONDUCTING COILS

S. L. Wipf and C. A. Guderjahn

ABSTRACT

The ac losses of superconducting coils have been measured over a frequency range from 1 to 2500 Hz. The conductor was a composite composed of Nb, Nb_3-Sn and Cu in the form of tape which was wound into a pancake coil. The loss/cycle is approximately proportional to the peak field cubed when the applied field is less than 1000 gauss and is proportional to the peak field to the 3.5 power when the peak field is over 1000 gauss.

I. INTRODUCTION

Superconductors when wound onto a coil do not carry currents as high as that observed in tests on short samples. This degradation severely limits the application of superconductivity to large magnet systems and has been the subject of much research. Several mechanisms leading to degradation are possible such as (a) imperfections in the conductor which show up when long lengths are used, (b) shifting of conductors under the influence of magnetic forces, and (c) generation of persistent eddy currents in the conductor which locally exceed the current density limitation of the superconductors. Remedies for the degradation usually involve the division of the superconductor into multiple strands and the use of normal material such as copper in parallel with the superconductor. These remedies are compromises since the current density is decreased from short sample current density and cost is increased.

It is hoped that increased understanding of the mechanisms causing degradation will lead to new methods of stabilization. In particular, it is believed that if the pinning sites which resist the Lorentz forces become stronger as the temperature increases, the superconductor will be inherently stable.

Investigation of superconducting coils excited by alternating current is a promising approach to a better understanding of the mechanisms of degradation. If a coil is excited with alternating current, flux lines must pass into and out of the superconductor. This results in the generation of eddy currents in the superconductor which at times exceed the allowable current density and are therefore dissipative. A measure of the heat dissipated should make it possible to calculate the maximum rate at which the coil may be changed. Any method of reducing ac losses should also increase direct current carrying capacity of the coil.

We have constructed a calorimeter to measure the heat generated in a coil. This report concerns the results obtained from the calorimetric measurements and a theory which correlates the measured losses.

II. ALTERNATING CURRENT LOSSES

A. Alternating Current Losses in Tape Coils

A superconductor carries direct current without loss but unfortunately some heat is generated if alternating current is used. The loss is associated with the passage of magnetic flux through the conductor. When a flux line impinges on the surface of the superconductor eddy currents are generated which oppose the flux motion. The eddy currents can and do become large enough to exceed the local current carrying capacity of the superconductor. When this occurs the conductor becomes resistive, heat is generated and the flux penetrates further into the superconductor. Usually normal material, e.g., copper, is bonded in parallel so as to provide an alternative path for the current to flow around regions which become normal in order to stabilize the conductor. In such a stabilized conductor, eddy currents are generated in the normal material also and the resulting losses are usually more severe than those occurring in the superconductor.

It is evident that the generation of eddy currents is geometry dependant, particularly when the conductor is wound into a coil. Coil losses may be minimized by first minimizing the amount of conductor present and secondly by arranging the conductor in such a way that the eddy currents which do flow are self shielding.

The eddy currents are induced by the magnetic field of the coil intersecting the coil conductor. The collective eddy current paths have an effective self inductance ℓ, resistance ρ, and a mutual inductance M with the primary, which is the coil itself. The coil resistance R_{eff} when alternating currents of angular frequency ω flow is approximately given by[1]

$$R_{eff} = R_o + \frac{M^2 \rho \omega^2}{\rho^2 + \ell^2 \omega^2} , \quad (1)$$

if the conductor is composed of a single normal material.

This expression is usually derived in elementary texts for transformers to give the effective primary resistance.

B. Loss in Normal Coils

Examination of Eq. (1) aids in understanding the behavior of more complicated systems where the eddy current path resistance is current dependent as in a superconductor. At low frequency, $\ell^2 \omega^2$ is small compared with ρ^2 and the magnetic wave penetrates the conductor since the shielding currents on the surface are limited by resistance rather than inductance. Then

$$R_{eff} = R_o + \frac{M^2 \omega^2}{\rho} . \quad (2)$$

At higher frequency, $\ell^2 \omega^2$ is large compared with ρ^2. In this case, the shielding currents build up to the extent required to exclude flux from within the conductor. Then:

$$R_{eff} = R_o + \frac{M^2 \rho}{\ell^2} , \quad (3)$$

and the resistance is independent of frequency. We see the above behavior actually illustrated by an example of a copper coil. A pancake coil was wound from 34 turns copper tape 1.27 cm wide x 0.081 cm thick. The coil had an ID of 16.5 cm and an OD of 24.0 cm. Insulation was provided by glass fiber tape having a thickness of about 0.015 cm. The resistance of the coil was measured at various frequencies using an impedance bridge at room temperature and at liquid nitrogen (LN_2) boiling temperature (78°K). The bridge used (General Radio Type 1632-A) gives the conductance and inductance of the coil. The dc resistance of copper is reduced by about a factor of 4.5 when cooled to 78°K. Higher purity copper should reduce in resistance by a factor of 7. The data are given in Table 1.

TABLE 1

Conductance and Inductance of a Copper Pancake Coil

	Room Temperature		80°K	
Frequency (Hz)	Conductance* (Mho)	Inductance (μ Henry)	Conductance* (Mho)	Inductance (μ Henry)
50	10.25	342.2	48.62	301.3
100	10.15	340.5	42.52	299.9
200	9.91	338.5	33.9	295.99
400			24.99	291.34
500	8.60	334.3	22.5	290.4
1000	6.52	329.7	16.39	286.8
2000	3.90	325.6	10.8	283.7
5000	1.20	319.9	5.88	278.9
10000	0.382	310.2	12.1	274.55
Direct Current	10.00		45.5	

*Measurements include lead resistance of 0.008 Ω

We subtract the dc resistance of the coil, R_o, and plot $(R_{eff} - R_o)$ vs frequency in Fig. 1. At low frequency the resistance is approximately proportional to ω^2. At higher frequency the slope should approach zero according to Eq. (2). Actually the slope approaches one at about 300 Hz for the coil cooled to LN_2 temperature. The loss in the coil at room temperature remains nearly proportional to ω^2 up to 10,000 Hz indicating that little self-shielding occurs.

Another point of view is to consider that the current tends to be excluded from the interior of a conductor, i.e., the current is confined to the conductor skin. In the case of a tape coil, the current tends to flow at the coil edges. This is due to the flow of eddy currents within the tape. At the tape center, the eddy currents flow in opposite direction to the primary current and tend to cancel it. At the edges, the eddy currents flow in the same direction as the primary current, and increase it. Since there is a decrease in cross section available for current flow, there is an increase in resistance.

The heat generated in a coil by alternating current is the $I^2 R_{eff}$, where I is the rms current. Part of this heat is due to the resistance of the conductor to the transport current $(I^2 R_o)$. We see, however, that the heat generated by eddy currents $I^2 (R_{eff} - R_o)$ can greatly exceed the direct losses particularly when the coil is cooled so that its resistance is low. If the magnetic wave which generates the eddy currents penetrates the coil the loss is proportional to ω^2. If self shielding occurs so as to prevent complete magnetic wave penetration, then the loss becomes approximately proportional to ω. This indicates that each cycle of current generates an amount of heat independent of frequency, i.e., the loss is hysteretic in

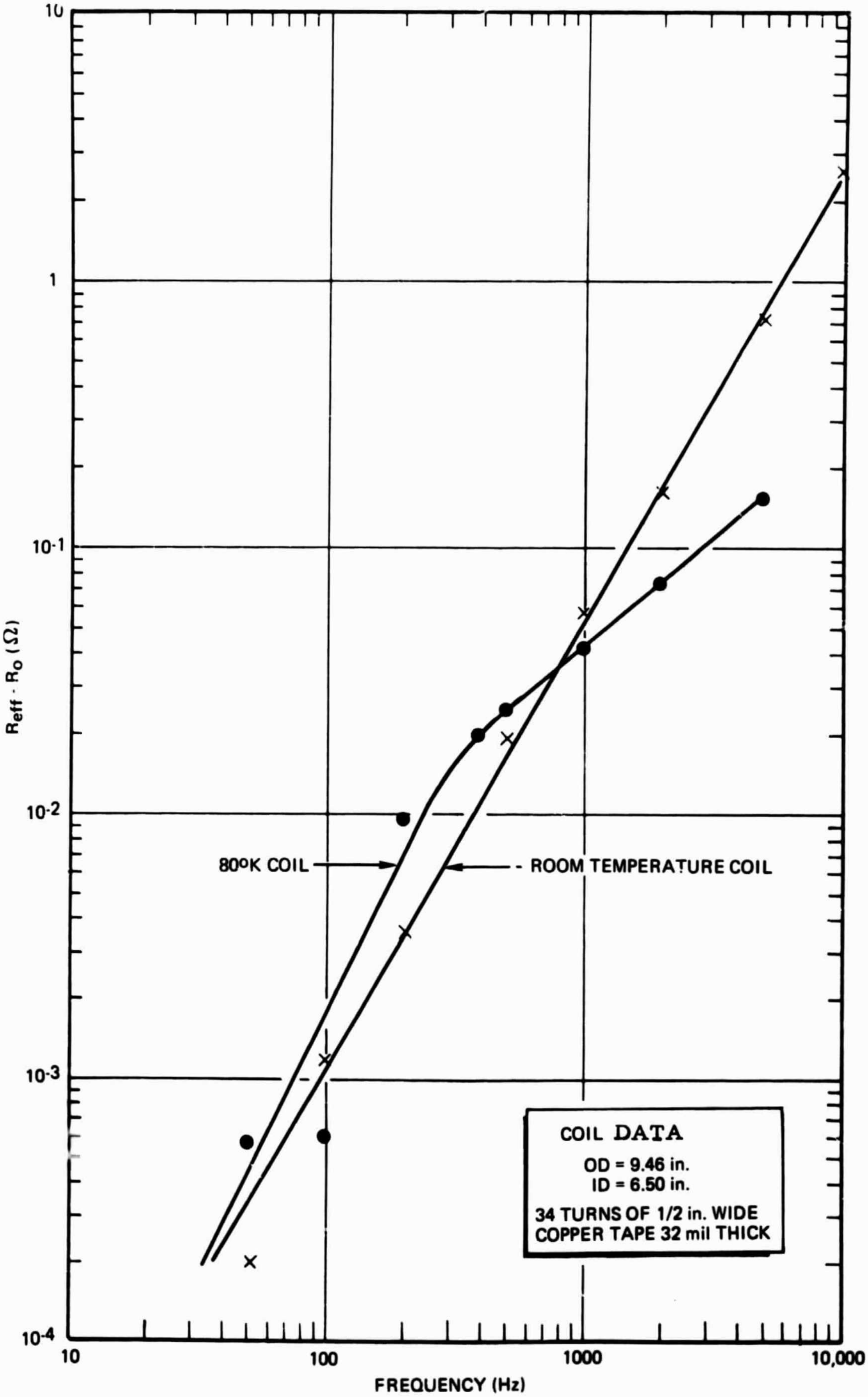

FIGURE 1. Alternating Current Resistance of a Coil vs Frequency

nature. The loss/cycle of a superconductor is hysteretic also because the superconductor is even more self shielding than is copper. However, the loss/cycle of a superconductor depends approximately on I^3 rather than on I^2 as for a normal material.

C. Loss Measurements

Loss measurements of ac coils at liquid helium temperature are complicated by several factors. Generally, the amount of heat produced is fairly small and heat is generated by eddy currents in the metal dewar surrounding the coil which is properly not part of the coil loss.

The measurements can be made in several ways. The easiest method is to measure the ac impedance of a coil while immersed in a cryogen. The losses of the copper coil described above was measured in this way. The resistance, which is the real part of the impedance, is multiplied by current squared to compute the loss. The principal difficulty with this method is that the coil must be isolated from conducting objects, such as a metal dewar wall, since any eddy currents induced in these objects show up as decreased measured coil conductance. Also, available bridges operate at currents too low to be of interest.

The direct method of loss measurement is to measure the heat given off when the coil is excited. This is most easily done by measuring the amount of liquid cryogen which is evaporated. The coil is placed in a non-electrically conducting box to collect gas bubbles. The gas is conducted from the dewar, heated to room temperature and the total volume measured, using a gas volume meter (wet test). A resistor is also placed in the box, so that the calorimeter can be electrically calibrated. The best results were obtained by calibrating with a pulse of the same duration and power as the pulse applied to the coil. A diagram of the experimental set-up is shown in Fig. 2. Several precautions must be observed to obtain accurate results. If boiling is too rapid, film boiling (rather than nucleate boiling) occurs, and the vapor is superheated. Also, very rapid boiling results in lowering of the liquid level inside the box, and possible uncovering of the coil.

The capacitor shown in Fig. 2 is of the proper capacity to compensate for the coil inductance at the frequency of operation, i.e., $C = (2\pi f)^{-2} L^{-1}$.

We have measured the loss calorimetrically for several types of coils. The coil dimensions and other data are given in Table II. All coils are pan-cake type coils (i.e., a single width of tape wound in a spiral coil).

The superconducting tape used is a commercially available product. The tape is made (from the center outwards) of a ribbon of pure niobium, covered on each side with Nb_3Sn which is then covered with pure copper. The tapes were obtained from the General Electric Co., and the Kawecki Chemical Co. In the case of the General Electric Tape, the outer surface of the copper was tinned with solder.

We compare the losses for four different coils in Fig. 3 where the loss in $w/(amp\text{-}m)^2$ is plotted as a function of frequency. The losses are divided by current squared and length of tape squared in this plot as this figure is of practical interest and seems to correlate the data. There is no theoretical foundation for this correlation.

Coil No. 4 was the last tested and was more carefully wound than the other three coils, which accounts at least in part for its lower losses. It was believed important to have the coil edges as even as possible because

TABLE II

COIL DIMENSIONS AND SPECIFICATIONS

Coil Ident. No.	Coil ID (cm)	Coil OD (cm)	Tape Width (cm)	Tape Length (m)	No. of Turns	Winding Density (turns/cm)	Tape Manu-facture
1	18.45	22.28	1.27	62.5	98	51.6	GE 22CY030
2	5.61	8.74	1.27	18.0	80	51.0	GE 22CY030
3	16.5	24.1	0.50	131.3	206	54.2	GE 22CY015
4	16.5	24.0	0.635	147.5	232	62.	Kawecki H1210-1

AC LOSS MEASUREMENT ON TAPEWOUND COILS

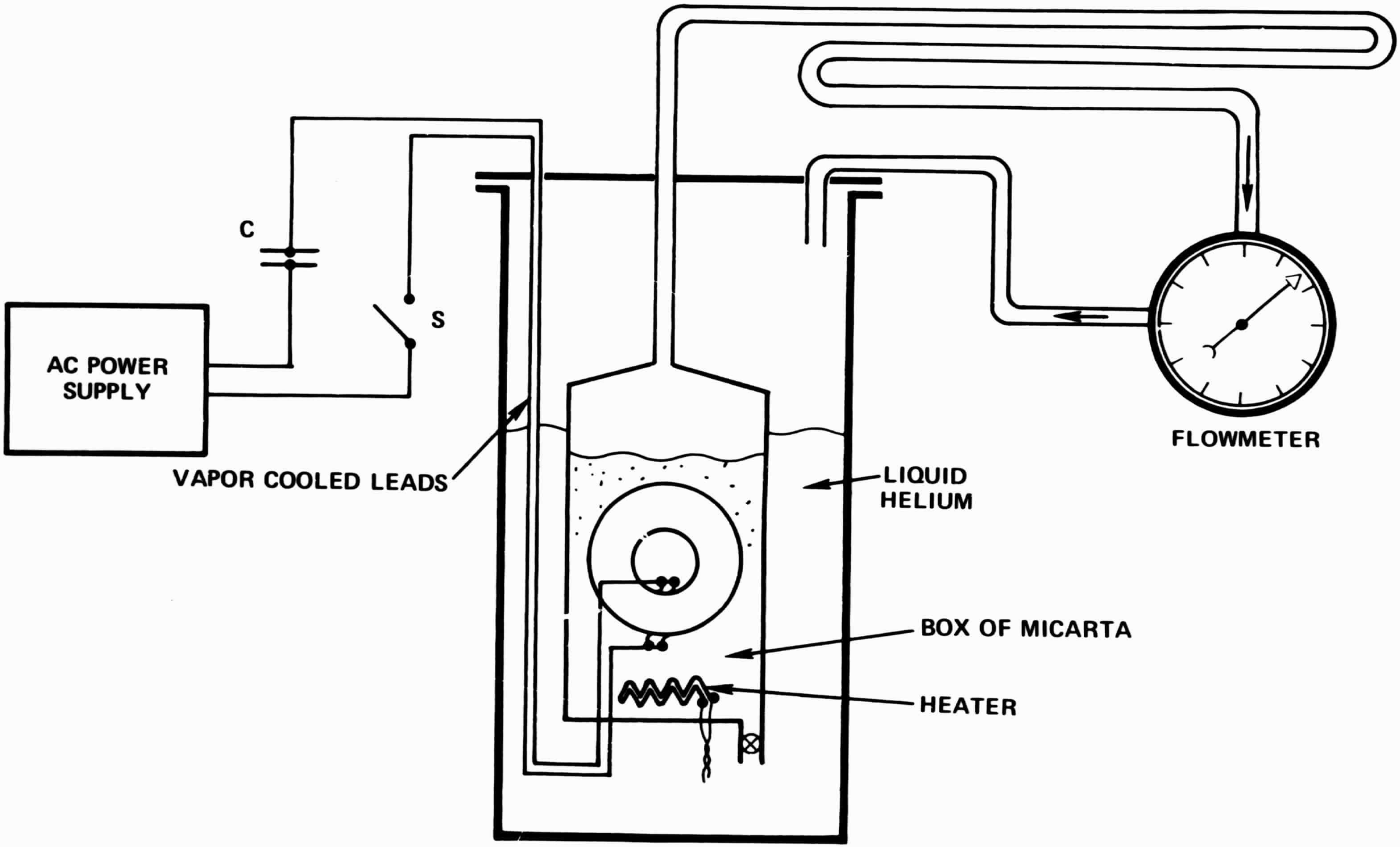

FIGURE 2. AC Loss Measurements on Tape Wound Coils

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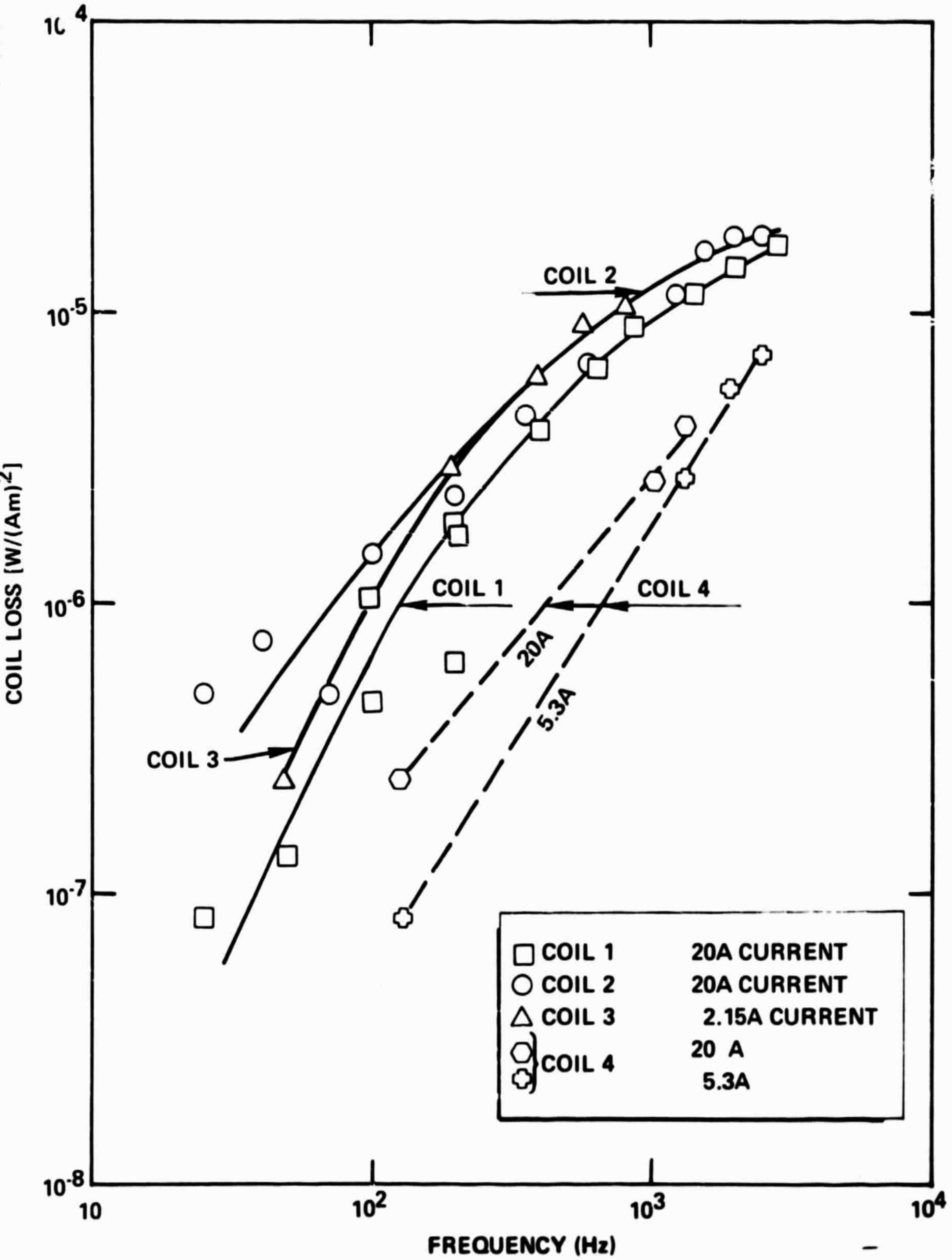

COIL LOSS vs FREQUENCY

a protruding edge is subject to much greater loss since flux lines easily penetrate it. The coil was wound in bifilar fashion (that is two parallel tapes were simultaneously wound) in order to make the detection of shorts between turns easy. It was necessary to rewind the coil several times to eliminate shorts. Also coil 4 was wound using tape which was not tinned on the outside with solder. Ordinary solder is a lead tin alloy which is a superconductor with a low critical current and is consequently more lossy than the bare copper substrate. As a consequence of the above precautions it is believed that losses in coil 4 are nearly minimal for a copper covered superconductor tape wound into a pancake coil.

D. Calculation of Coil Losses

We first consider what occurs as magnetic flux penetrates a superconductor and generates heat. Moving flux lines as they approach the surface of a superconductor generate an emf which produce surface eddy currents. The eddy currents rise to a magnitude to prevent the penetration of flux or to the critical current of the superconductor. If the critical current is exceeded, the eddy currents in excess of the critical current meet resistance to their flow and tend to die out. The flux which is not shielded by the persistent currents may then penetrate the superconductor to deeper and deeper levels as the same process occurs. Eventually the magnetic flux is completely shielded by persistent eddy currents which are just at the critical current level throughout the shielding layer. If the superconductor is of inadequate thickness to completely shield the interior, then the flux will penetrate.

There are several complications to the above process. In particular, heat is generated by the eddy currents which exceed the critical current. (There is some loss associated with establishment of supercurrents below critical current but this is negligible for our purposes.) Should the heat produced increase the superconductor temperature, the critical current will be reduced and the heat produced will increase. Thus a thermal runaway process occurs leading to total loss of superconductivity since the critical temperature is exceeded. This process is commonly called a flux jump.

Commonly a normal type conductor such as copper is bonded to the superconductor so that it may temporarily carry current and prevent propagation of a normal region through the coil. The method of bonding the superconductor to the normal material usually involves having the normal conductor on the outside of the superconductor. That is eddy currents are also induced in the normal material and the losses in the normal material can be expected to be more than in the superconductor.

Thus in calculating the stability and losses of a composite superconductor we must consider several factors. These are: (1) Losses in normal material, (2) losses in superconductor, (3) temperature dependance of the above, and (4) temperature heat capacity and method of refrigeration of the coil. The problem is very difficult to solve if a substantial temperature change is involved.

We have attempted a calculation of the ac losses of the pancake coil No. 4 described in Table II. The coil was assumed to remain at the helium bath temperature.

FIELD OF TAPEWOUND COIL

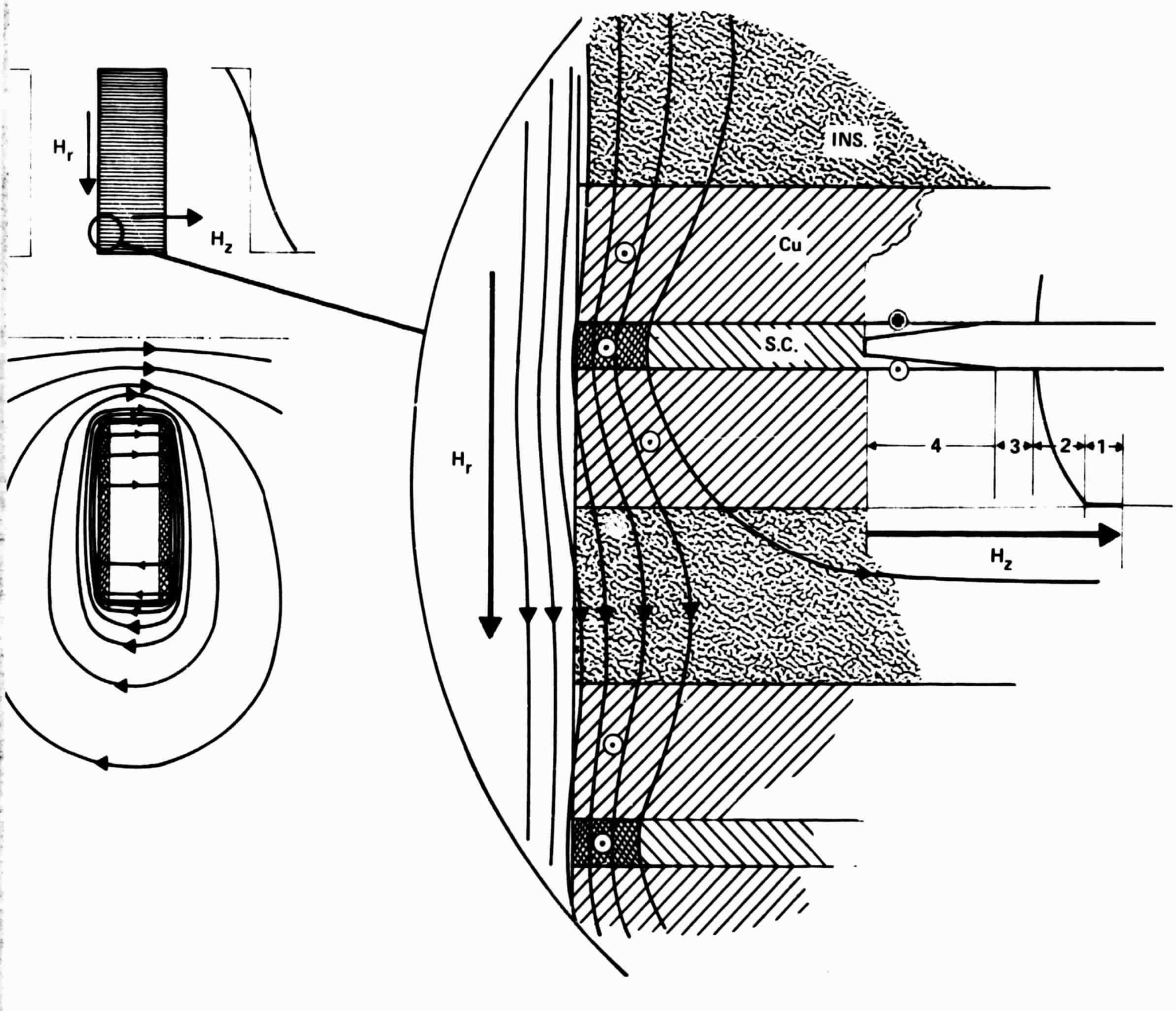

FIGURE 4

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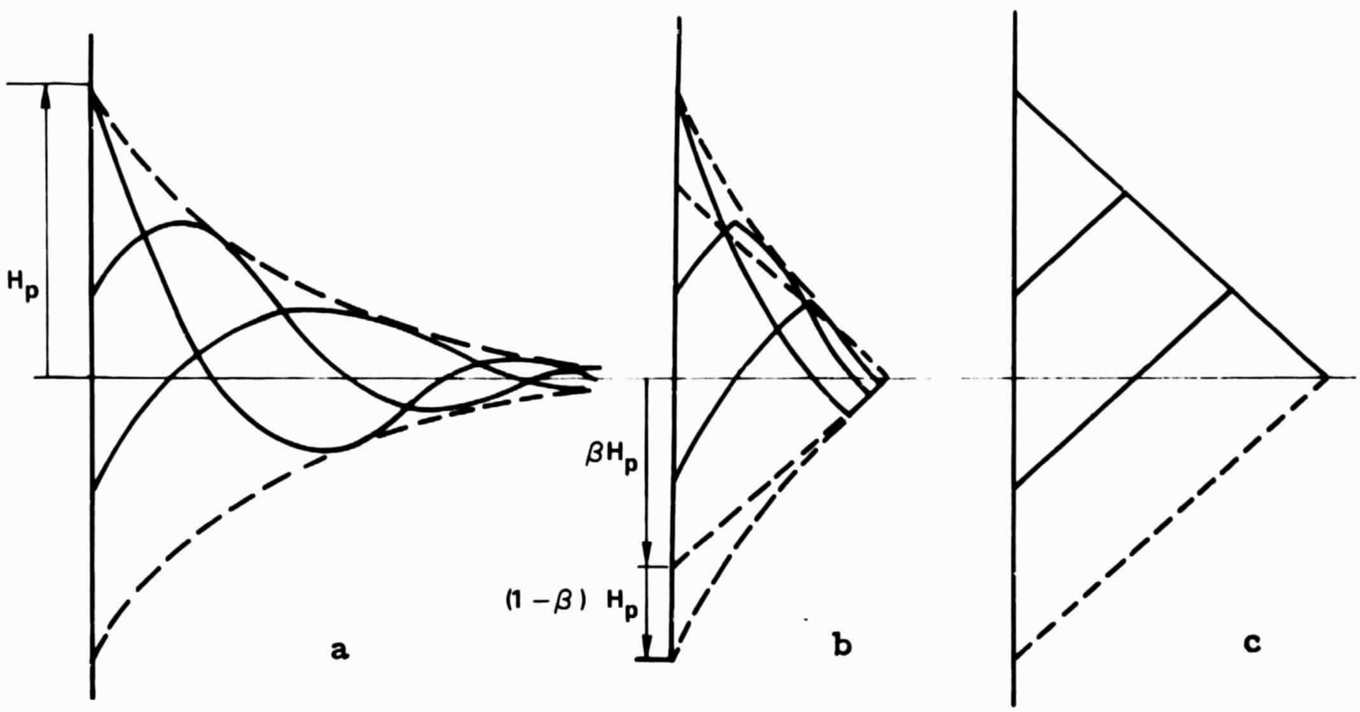
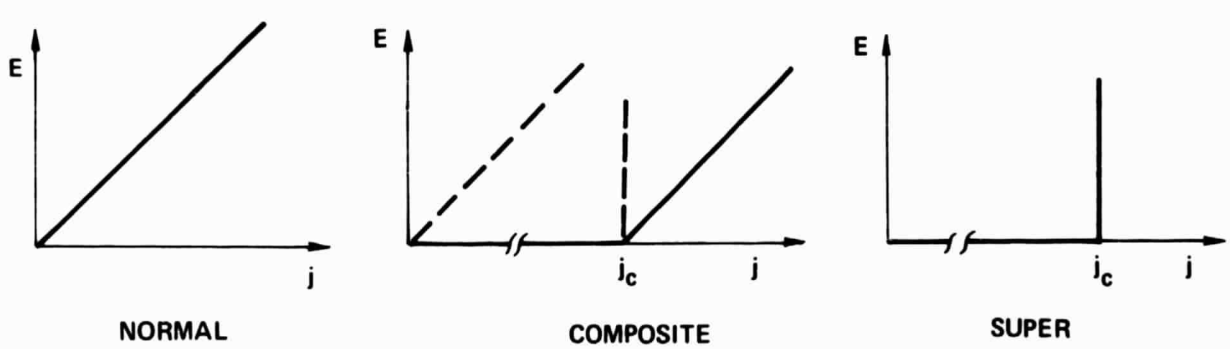
COMPARISON OF CONDUCTORS





	NORMAL	COMPOSITE	SUPER
LOSS:	$B\sqrt{\rho\nu}\ H_p^2$	$B\sqrt{\rho\nu}\ H_p^2\ (1-\beta)^2 + A\frac{\nu}{j_c} H_p^3 \beta^3$	$A\frac{\nu}{j_c} H_p^3$

$$\beta = \frac{1}{X}\ \ell n\,(X+1)\ ; \qquad \text{WITH}\ \ X = \frac{H_p}{j_c}\sqrt{\frac{\nu}{4\rho}}$$

FIGURE 5

Figure 4 shows the flux distribution around a pancake coil, - overall on the left and in detail on the right. The flux may be resolved into a radial component Hr and an axial component Hz. The magnitude of each component as obtained by computer calculations is shown also. In the detailed illustration the radial flux is shown to penetrate more deeply into the insulation and copper region, because the eddy currents which repel the flux are concentrated in the superconductor.

For making the loss calculation, it is assumed that the material is homogeneous with an effective critical current density $j_c = j_c\ (d_{sc}/d_{total})$, where j_c and d_{sc} are the actual critical current density and thickness of the superconductor layer and d_{total} is the thickness of one layer including insulation. Also, the effective resistivity for current in excess of j_c is $\rho_{eff} = \rho_{Cu}\ (d_{tot}/d_{Cu})$ where ρ_{Cu} is the resistivity of copper at 4.2°K and d_{Cu} is the thickness of the copper layer.

In general, the loss due to Hz is negligible compared to the loss due to Hr. Both losses were calculated. To the extreme right in Fig. 4 is an illustration of how the Hz component decreases as it penetrates the conductor. Step 1 is due to a critical current density of the solder on the copper surface. The tape used in coil 4 did not have this coating. Step 2 is due to eddy currents in copper, Step 3 is due to surface current density at the superconductor. Step 4 is due to the critical current in the superconductor. Each step represents a loss with Step 1 contributing the largest loss particularly at low fields.

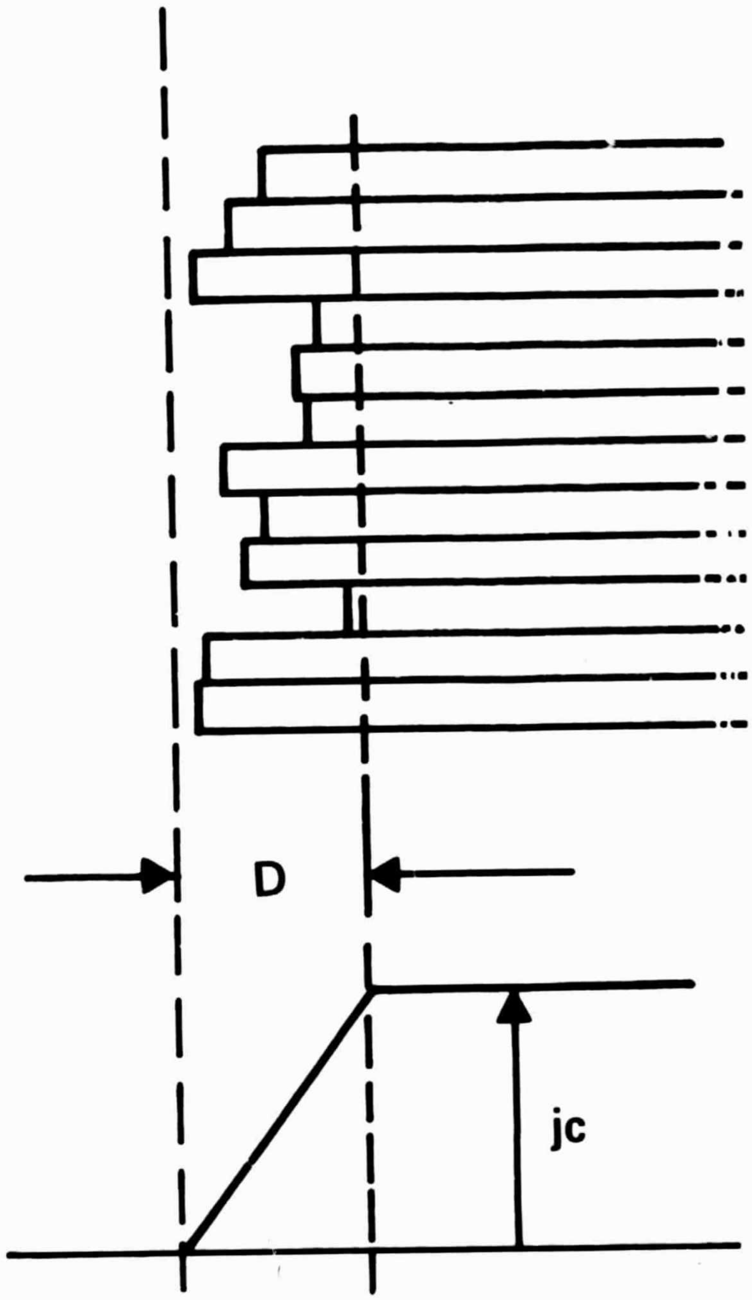
Figure 5 shows the penetration of magnetic field lines into the normal and superconducting material. The current in normal material and induced voltage are related by ohm's law and losses are proportional to the square of the peak field H_p. In the case of the superconductor, the magnetic field penetrates so as to leave the current at just its critical value and losses are proportional to H_p^3. A discussion of the penetration of a magnetic field into normal and superconductors is given elsewhere[2]. The loss in the composite conductor are obtained by weighing the contribution of each material type according to a factor β as shown in Fig. 5.

Figure 6 illustrates the effect of uneven edges on the losses. An uneven edge reduces the self shielding of the coil and increases losses. In winding coil 4 great care was taken to reduce the effect of uneven edges by winding each turn on top of the previous turn within 1 mil tolerance.

Figure 7 gives the loss/cycle for coil 4 vs applied field compared with calculation. At low frequencies the loss/cycle is proportional to H_p^3 as expected. At higher field, the losses are proportional to $H_p^{3.5}$. The deviation from H_p^3 may be due to the reduction of critical current with increasing field but is more likely due to flux jumps. The present study did not pursue this in detail.

According to the formula in Fig. 5, for sufficiently high amplitude, the loss should asymptotically approach the losses for normal material with the same resistivity. These losses are given by the dashed lines. That is, the losses at high frequency can only be lower or equal to the losses at low frequency. This could not be tested due to the limitations of the available power supply. The limit was about 3000 v peak at the coil terminals.

At low amplitudes, the high frequency losses are somewhat greater than calculated. This is due to the shielding of the copper between the superconducting layers. That is, the assumption of a homogeneous material no longer applies.



EDGE EFFECTS

FIGURE 6

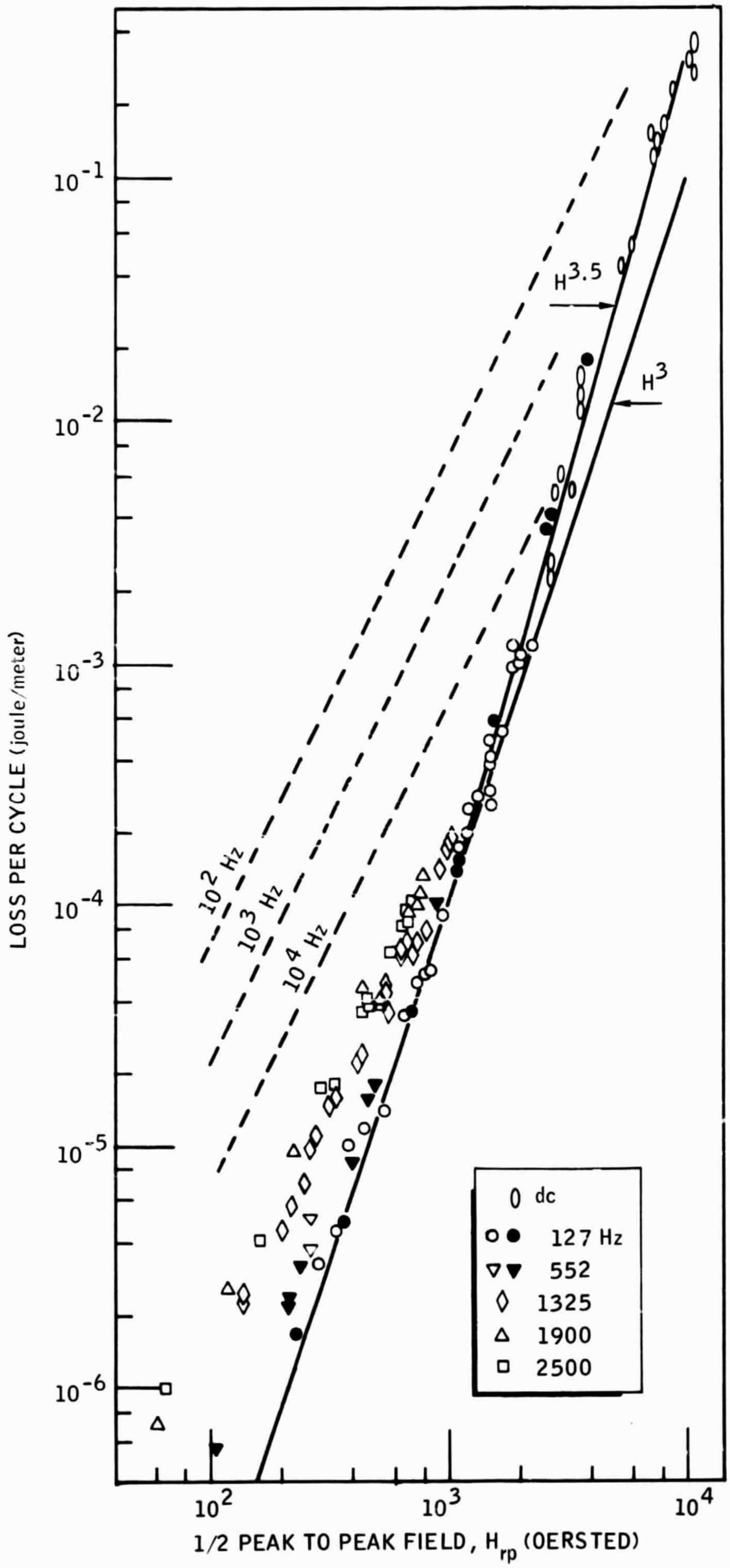


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FIGURE 7. Loss Per Cycle vs Peak Field for Coil 4

III. CONCLUSIONS

The ac losses in pancake coils wound from composite superconductor tape have been measured and correlated with calculations. As expected the losses are proportional to H^3 in lower fields but increase to a dependance of $H^{3.5}$ at higher fields. The increased losses are believed due to flux jumps. More experimental work is needed to determine if this is actually the case.

The results of this study are applicable to the design of a dc coil. The coils should be wound with good insulation and with smooth edges. The use of solder on the outside of the tape will increase the charging losses.

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