INTRINSICALLY STABLE CONDUCTORS

P.F. Smith, M.N. Wilson, C.R. Walters, and J.D. Lewin
Rutherford Laboratory
Chilton, Berks., England

It is generally believed that flux jumps are the only real obstacle to obtaining reliable short sample performance in superconducting coils. The sudden local release of energy results in a premature transition to the resistive state and prevents the reliable attainment of high current densities. Even in large, fully-stabilized coils, the flux jumps which could occur in wide conductors might in some cases release sufficient energy to cause an undesirably large temperature rise, perhaps of the order of 15-25°. This is discussed in a separate paper.

During the last few years, the development of realistic theoretical models for the electrical and thermal processes which occur during a flux jump has led to some remarkably simple criteria which indicate that flux jumping should be absent in superconducting wires typically less than about 0.002 in. in diameter, and in certain arrangements of superconducting filaments and normal metal.

There is, therefore, an obvious incentive to try to develop conductors using these criteria. With this objective, theoretical and experimental work has been in progress at the Rutherford Laboratory since early 1967, and was reported briefly last year.[1] Closely related to this is the possibility of developing a conductor with an ac loss small enough for use in pulsed synchrotron magnets, which could also be achieved by the use of finer filaments.

Since the beginning of 1968 the scale of this work has increased, and experiments are being carried out on samples and small coils of a wide variety of filamentary composites developed in collaboration with Imperial Metal Industries, Ltd. (U.K.). Although the initial tests are encouraging in many respects, much still remains to be done and we would not normally publish any results at this stage. However, in view of the growing interest in this possibility, we have agreed to set down the essential features and principal conclusions of the theory, and to summarize the experimental results obtained so far, as a guide to those planning similar programs, but with the reservation that some of our statements may turn out to require modification in the light of further experimental data.

We discuss the subject under the following headings:

- Theory of single filaments of superconductor.
- Theory of composites of superconductor and normal metal.
- Conductor configurations being tested.
- Description of the four types of test being used.
- Main results so far.

More detailed accounts of both theoretical and experimental work will be published at a later date.

1. P.F. Smith, in Proc. 2nd Magnet Technology Conference, Oxford, 1967, p. 543.

I. THEORY OF SINGLE FILAMENTS

An external field applied to a piece of superconductor induces loops of current at the critical current density $\pm J_c$ (A/cm^2). These are known as magnetization currents and, in typical 0.010 in. diameter wires, are observed to be unstable and may suddenly decay rapidly with release of energy. A simple integration of $H^2 dV$ for the field associated with these currents [for the case, say, of an infinite slab of thickness d (cm)] shows that the energy released is about $(2\pi/3)(J_c^2 d^2)/10^9$ joules/cm^3. This is enough to cause, for example, a temperature rise of 10°K in 0.010 in. wire, but only 0.1°K in 0.002 in. wire; this calculation by itself indicates the use of finer wires.

Several authors have analyzed this instability in more detail and have shown that the flux jump should not occur provided that

$$d \leq (10^9 \; S \; T_o \; f)^{\frac{1}{2}}/J_c \quad , \qquad (1)$$

where S is the heat capacity (joules/cm^3 °K), T_o (°K $\equiv J_c/(-dJ_c/dT)$ and is usually of order $T_c/2$, and f is a numerical factor in the region 0.6 to 0.9, depending on detailed assumptions.

The right-hand side of (1) is typically of order $1500/J_c$, so if, for example, the maximum (low field) value of J_c is 300 000 A/cm^2, flux jumping should not occur provided that $d < 5 \times 10^{-3}$ cm (0.002 in.).

Among the authors who have derived and discussed this result are Hancox, Carden, Swartz and Bean, Neuringer and Shapira, Wipf, Kim, Lange, etc. It is probably most well known from the papers by Hancox,[2-4] who has also extended the theory to include the effect of the temperature rise on the transport current,[3] and has shown that undegraded performance should in general be possible under somewhat less stringent conditions than suggested by Eq. (1) (see Fig. 1).

This was all done in 1965 and 1966, but at that time reliable ways of manufacturing filaments below 0.005 in. diameter were not available. By 1967, however, it became possible to make finer superconducting filaments provided they were embedded in a matrix of normal metal.

II. THEORY OF COMPOSITES

We thus want to know what happens when a number of parallel superconducting filaments are joined together by normal metal.

Consider the simplest (two-dimensional) case of two parallel sheets of superconductor (Fig. 2). If they are separated by an insulator, then obviously the magnetization current loops flow separately in each (Fig. 2a). But if they are connected by a low resistance metal, then in general the voltage associated with the finite rate of rise of field $\dot{H}$ (G/sec) is sufficient to drive the current from one strand to the other

---

2. R. Hancox, Phys. Letters 16, 208 (1965).

3. R. Hancox, Culham Laboratory Report CLM-P121 (1966).

4. R. Hancox, in Proc. 10th Intern. Conf. Low Temperature Physics, Moscow 1966, Vol. 2B, p. 45.

through the normal metal, forming one large loop occupying the full width of the composite (Fig. 2b). It can then be shown that phenomena such as stability and ac losses are governed by the full width and not the strand width.

We find, theoretically, that the transverse currents occupy a finite length of conductor ℓ_c (cm), given by

$$\ell_c^2 \simeq 10^8 \lambda J_c d \rho/\dot{H} \quad , \tag{2}$$

where d (cm) is the superconductor thickness, J_c (A/cm^2) its current density, ρ ($\Omega\cdot$cm) is the matrix resistivity, and λ is a space factor, discussed later. (Note that transient and steady-state derivations of this formula only differ by a factor of 2 in the right-hand side.)

Therefore, if the conductor length is less than ℓ_c, only part of the magnetization current will cross the matrix and the rest will be confined to the separate filaments. (Fig. 2c). As an example, taking J_c (at low field) = 300 000, d = 0.003, $\rho \sim 2 \times 10^{-8}$, $\dot{H} \sim$ G/sec (and ignoring λ for the moment), we find $\ell_c \sim 14$ cm. So for a length > 28 cm the sample behaves as a conductor of width w, but for a length ≪ 28 cm it behaves as two strands of width d.

Considering now the three-dimensional situation, we can in fact achieve the latter condition in an arbitrarily long length of wire, simply by twisting with a pitch $\leqslant \ell_c$. The local emf's cancel in adjacent segments of wire, each loop acts independently, and the system is effectively cut into lengths equal to one-half the twist pitch. How much less than ℓ_c the twist must be is not known. By simple arguments, it need only be typically in the region 0.3 ℓ_c, but we have some theoretical and experimental evidence that, owing to an additional heating effect resulting from the localized penetration of flux at the cross-over points, the twist pitch may possibly have to be as small as 0.01 ℓ_c for stability. However, in dc coils this should usually present no problem since one can increase ℓ_c by lowering $\dot{H}$.

We have also examined the theory for more complicated systems containing many filaments. Some useful features to note are the following:

1) ℓ_c is independent of w, the strand separation.

2) ℓ_c is unaffected by intervening superconducting filaments.

3) In a composite containing several values of ρ in a path connecting two filaments, it is, to a good approximation, the highest value of ρ which governs ℓ_c, and not the average value.

4) In a three-dimensional system, only some fraction λ of the direction parallel to the field is occupied by superconducting filaments, so that in any particular case some guess must be made at an effective value of λ for insertion into Eq. (2).

5) When the radial or axial field gradients become appreciable, one must transpose rather than simply twist the filaments. Approximate criteria are:

$$\frac{\Delta\dot{H} \text{ across composite}}{\text{Mean (mod } \dot{H}) \text{ across composite}} > \frac{d}{w}$$

and

$$\frac{\Delta\dot{H} \text{ along one twist}}{\text{Mean (mod } \dot{H}) \text{ along twist}} > \frac{d}{w} \quad .$$

This usually seems to suggest that it is sufficient to twist a basic 0.010 in. composite, but multistrand cables formed from this may have to be transposed. Even with mutually insulated filaments, of course, some degree of transposition or twist is necessary, in view of the fact that all the filaments are connected together at the end of the conductor.

In the case of pulsed synchrotron magnets, where $\dot{H}$ may be as high as 60 000 G/sec, ℓ_c in the preceding calculation reduces to ~ 0.2 cm, presumably making it difficult to achieve the necessary rate of twist. However, by using a higher resistance alloy, with $\rho \sim 2 \times 10^{-5}\ \Omega\cdot$cm, ℓ_c increases to the more manageable value of 5 cm. Alternately, it has been suggested that it may be possible to create a high resistivity layer around each filament.

Recently, it has been found that there is a second, independent, criterion for absence of flux jumping in a composite. This requires the assistance of the normal metal itself to slow down the flux motion, and has been discussed by Chester.[5] Using this approach for the case of filaments of thermal conductivity k (W/cm °K) embedded in a matrix of resistivity ρ ($\Omega\cdot$cm), we obtain the approximate criterion:

$$d^2 < (T_o k/\rho)(1/J_m J_c) \quad , \qquad (3)$$

where T_o is the same as in (1), J_c is the critical current density in the filament, and J_m is the mean current density in the composite; J_m and J_c apply to the magnetization currents, so that values appropriate at low fields must be used. k is of order 10^{-3} for NbTi. Note that (3) is identical to the criterion given in the paper by Stekly at this Summer Study,[6] which was derived independently using a different approach. Note also that the derivation assumes the normal metal to be a perfect heat sink, so that it may not be valid for perturbations above a certain level.

At the time of writing, the numerical factors in the derivation are somewhat uncertain and the right-hand side of (3) could, for example, be greater by a factor of four. This new criterion tends to lead to similar values of d ($\sim$ 2 mil), but in this case a low resistance matrix is essential, and a twist is no longer necessary except to reduce ac heating effects during charging.

To summarize, the theory in its present stage suggests two distinct ways of achieving an intrinsically stable conductor:

Method 1:	$d < 1500/J_c$ Twist $\ll \ell_c$	Low ρ suitable for dc coils, but high ρ necessary for pulsed magnets
Method 2:	$d < (T_o k/\rho\ J_m J_c)^{\frac{1}{2}}$ No twist necessary	Low ρ essential; not suitable for pulsed magnets

5. P.F. Chester, Rep. Prog. Phys. <u>30</u>, Part 2, 361 (1967).

6. Z.J.J. Stekly, these Proceedings, p. 748.

A conductor satisfying both criteria, for example composed of 0.002 in. filaments in copper with a twist pitch of a few centimeters, looks particularly attractive, and initial coil tests with conductors of this type are giving encouraging results. Whether it is actually necessary, in Method 2, to also satisfy criterion (1), is not clear at the present time.

III. RANGE OF SAMPLES

For the initial stages of this work, quantities of the order of 2 lb of each configuration (e.g., 8000 ft of 0.010 in. diameter composite) are being produced. The range of parameters being covered is as follows:

Filament diameter	- 0.0005 in. to 0.004 in.
Composite diameter	- 0.005 in. to 0.020 in.
Number of filaments	- in range 10 to 100
Ratio NbTi/normal metal	- approximately 1/1.3
Resistivity	- 2×10^{-8} (copper) or 2×10^{-5} (cupronickel)
Twist	- 0 or 1/in.

Three-component composites, containing both Cu and CuNi, are also being designed (mainly for protection reasons).

IV. EXPERIMENTAL PROGRAM

Four types of test are being used, summarized in Fig. 3:

1) Swept field. Using a small single-layer coil, the external field is increased with a fixed transport current, enabling the intrinsic stability to be determined as a function of sweep rate and current density.

2) Magnetization. Using the same coil as in the swept field test, the M-H curve for the material is determined as a function of sweep rate, showing the relative contribution of matrix and filament.

3) Ac losses. Loss measurements as a function of frequency provide confirmation of the results of the magnetization tests.

4) Coil degradation. The transport current in small coils wound from about ½ lb material is determined for various values of an externally applied field.

V. INITIAL RESULTS

Results so far on short samples are in very good agreement with theory. The onset of instability has been determined as a function of filament diameter, and is consistent with the relation $J_c d$ = const, the constant being in the region 10^3 as predicted by (1).

The effect of twisting is also clearly shown in these tests, the samples without a twist being highly unstable down to much lower values of J_c. An experiment was also carried out in which a single sample, initially without a twist and unstable, was subsequently twisted and found to be stable below a certain value of $\dot{H}$.

A few magnetization and ac loss results are available which approximately confirm the formula for ℓ_c. Further experiments to determine ℓ_c and its effect on stability are in progress.

Coil tests using cupronickel composites with no twist show considerable degradation, as expected, the currents obtained being similar to those obtained from coils of unstabilized 10 and 20 mil wire.

Coils of the twisted cupronickel composites reached much higher currents, often approaching short sample, but still show some degradation and variability of performance at all field levels. This effect is independent of filament diameter, and is at present believed to be caused by internal heating due to wire movement; the effect of impregnation of the coil with, for example, grease or oil, is being investigated.*

Initial coil tests using copper composites are giving short sample performance. For example, a small (½ lb) coil of 0.020 in. composite containing 0.002 in. filaments reached its short sample current of about 120 A at 50 kG, corresponding to a current density in the region 40 000 A/cm^2. Larger coils wound from the filamentary copper composites will be tested in the near future.

---

*Note added in proof: We have now confirmed this; a coil of cupronickel composite, previously showing some residual degradation, reliably went to short sample current after impregnation with oil.

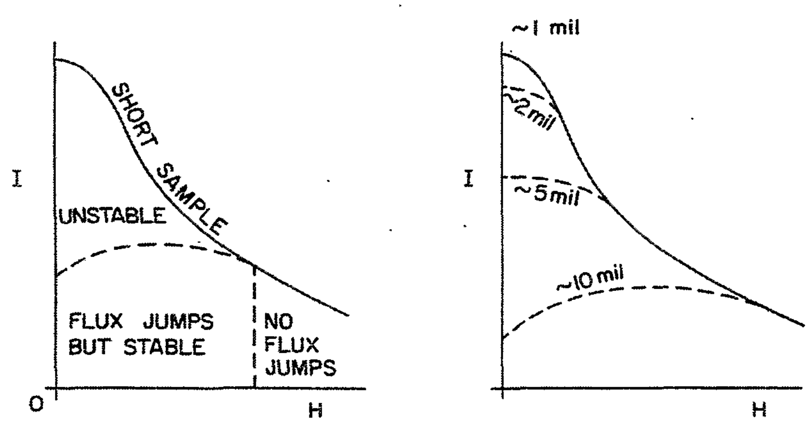

Fig. 1. Stability of transport current predicted by Hancox' theory.

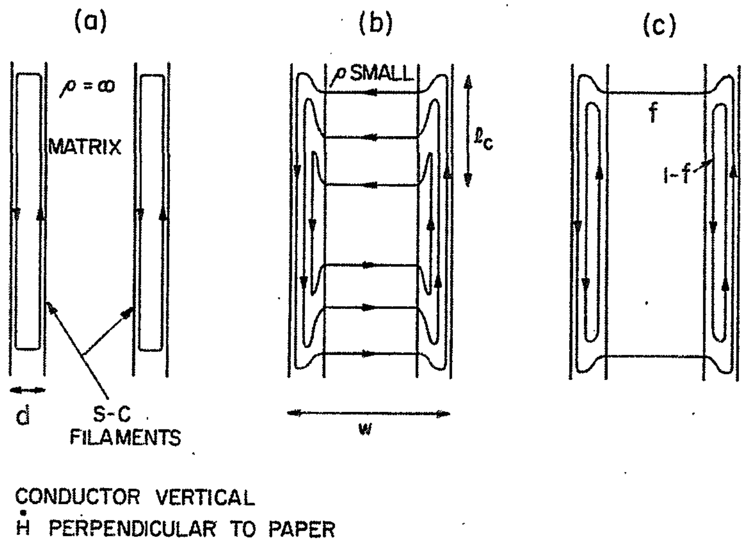

Fig. 2. Current distribution in composite conductors.

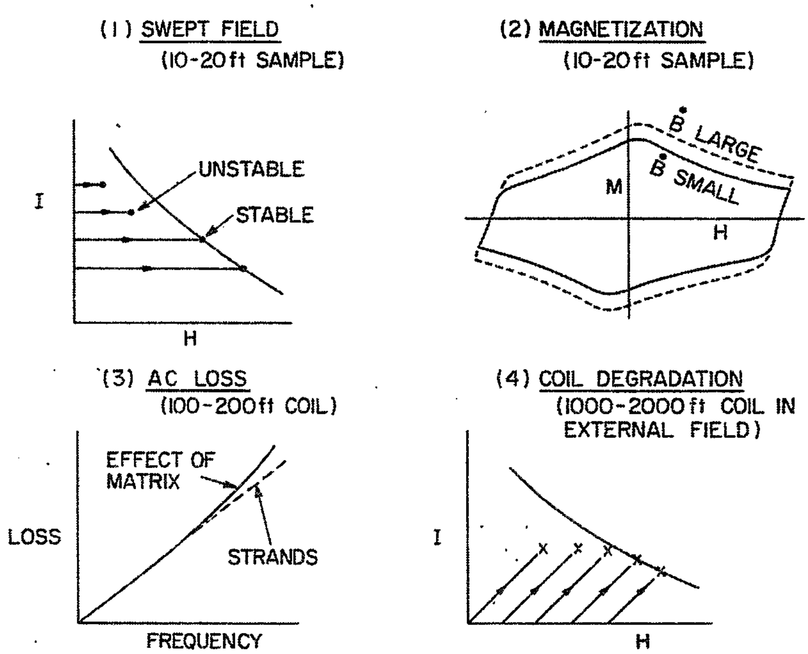

Fig. 3. Experimental program on filamentary composites.