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Stability of Cable-in-Conduit, Force-Cooled Conductors: Elementary Theory

Lawrence Dresner

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1. INTRODUCTION AND HISTORICAL REVIEW

The main problems facing the designer of high current, high field superconductors for toroidal field coils are stability and ac losses. Both of these problems may be eased by subdividing the conductor: the cooling surface is increased by subdividing, and the eddy current and coupling losses are decreased. However, finer and finer subdivision of the metal makes the helium channels smaller and smaller and increases the danger of vapor locking. This danger can be avoided by using supercritical helium rather than two-phase helium as the coolant. But, if we suppress the large density changes that cause vapor locking by use of supercritical helium, we suppress at the same time the natural convection in boiling helium that is responsible for the high heat transfer to it. To guarantee adequate heat transfer, it was thought necessary to make the interstitial helium turbulent (more will be said on this point later). The reasoning above thus led to the concept of the cable-in-conduit conductor cooled by supercritical helium in forced convection.¹⁻⁴

Offsetting the advantages of such force-cooled conductors (FCCs) is the large pumping power they consume. This power is dissipated at cryogenic temperatures and may add substantially to the refrigeration load. A step was taken toward reducing these losses by recognizing the existence of stability-optimized FCCs, i.e., FCCs whose stability was maximized by simultaneous variation of the matrix-to-superconductor ratio and the helium volume fraction.⁵ Stability-optimized FCCs turn out to have minimal pumping requirements, and based on this, a systematic method of design of FCCs with low pumping requirements has been proposed.^{5,6}

Lately, it has been observed that FCCs recover from heat pulses at much lower flow rates than expected on the basis of steady-state heat transfer coefficients. Indeed, they recover after substantial heat pulses even at zero flow.^{4,7,8,9} Several authors have suggested that good recovery at very low flow is due to enhanced heat transfer caused by transient flow induced by heating of the helium.^{7,10,11} This is a heartening development and suggests that the steady flow may

be reduced below the levels previously calculated on the basis of steady-state heat transfer coefficients.

Nevertheless, a word of caution is necessary here. If a short section of conductor is pulse-heated, the helium it contains will begin to flow in a time of the order of half the heated length divided by the speed of sound in helium (~ 200 m/s). Thus, flow will start in a 40-cm-long normal zone in about 1 ms, but, in a 5-m-long normal zone (created, for example, by a plasma disruption), flow will not start near the center of the zone for about 12.5 ms. The pulse energy per unit volume which the conductor can stand should be much less for long normal zones than for short ones. There is corroborative evidence that this is so from experiments carried out with boiling liquid rather than supercritical helium as coolant.¹² In these experiments, the pulse energy per unit volume of composite from which the conductor can still recover (hereafter called the stability margin) was reduced by an order of magnitude by sealing the ends of the conductor and thus suppressing induced flow.

Early calculations of the recovery of pulse-heated FCCs did not take into account the flow induced in the helium by heating, but did take into account the complicated variation of the material properties with temperature. Lately, calculations have been described that include the hydrodynamics.¹⁰ Even the early, simple calculations required lengthy runs on high speed computers, and more recent calculations including the hydrodynamics are likely to require even longer runs. While such elaborate numerical calculations are useful for confirming a particular design, they are not convenient for surveying a large number of designs and picking out the best one. It is for this latter purpose that we want simple, approximate formulas.

If we ignore the temperature dependence of all the material properties and take them to be constants, we can solve the stability problem analytically and get simple formulas for such things as the stability margin and the composition of stability-optimized conductors. The formulas can be used to get rough values useful for estimation (but not for comparison with experiment) to reveal useful trends, to

get starting values for a numerical optimizing search, and to achieve a good general understanding of the overall system.

2. ASSUMPTIONS AND BASIC EQUATIONS

The problem we consider in this paper is the following: What temperature rise can be *uniformly* and *suddenly* imposed on the conductor over its *entire length* and still allow it to recover the superconducting state? The problem is *space independent* because the conductor is very long, so that during recovery (which occurs in tens of milliseconds) we can neglect both conduction out the ends of the normal zone and the entrance of cold helium into the channel. Since the initial perturbation is the same at every point, the temperature history is also the same at every point. As the helium moves along the channel, each volume element of helium replaces one whose temperature and flow velocity are identical to its own. Hence, in the calculation of the temperature history of the conductor and the helium, the motion of the helium may be neglected, except insofar as it may be needed to guarantee a prescribed heat transfer coefficient between the copper and the helium.

This problem is only the first in a series of related problems that need to be dealt with in studying the stability of FCCs. Other problems are those of recovery from an external heat input that varies in space, time, or both. At least some of these other problems are space dependent, and their solution will require more complex treatment than the simple problem being considered here.

The sweeping assumption made in this paper is that all thermophysical properties are independent of temperature.

With these preliminary remarks, let us make a heat balance over a unit length of conductor:

$$S_{co} A_{co} \frac{dT_{co}}{dt} = -h(T_{co} - T_{He}) P + Q_J A_{co} \quad (1a)$$

$$S_{He} A_{He} \frac{dT_{He}}{dt} = h(T_{co} - T_{He}) P, \quad (1b)$$

where S_{co} and S_{He} are the heat capacity per unit volume of the superconducting composite and the helium, respectively; A_{co} and A_{He} are the cross-sectional areas occupied by the composite and the helium, respectively; T_{co} and T_{He} are the temperatures of the composite and the helium, respectively (assumed uniform in each material); t is time; h is the heat transfer coefficient; P is the cooled perimeter of the composite; and Q_J is the Joule power density in the composite.

Below the threshold temperature for current sharing T_{cs} , $Q_J = 0$. Above the critical temperature $T_{cr} > T_{cs}$

$$Q_J = \frac{I^2 \rho}{f A_{co}^2} \quad (T > T_{cr}) , \quad (2)$$

where I is the current in the conductor, ρ is the resistivity of the copper (including magnetoresistance), and f is the volume fraction of copper *in the composite*. Between T_{cs} and T_{cr} , Q_J varies linearly with temperature, from zero at T_{cs} to the value given in Eq. (2) at T_{cr} . This linear variation is a consequence of the assumption of a linear relation between critical current I_{cr} and temperature:

$$\frac{I_{cr}(T)}{I_{cr}(T_b)} = \frac{T_{cr} - T}{T_{cr} - T_b} \quad (3)$$

where T_b is the ambient helium temperature. The current-sharing threshold temperature (T_{cs}) can be found from Eq. (3) as the temperature at which $I = I_{cr}(T)$:

$$T_{cs} = T_b + (1 - i)(T_{cr} - T_b) ; \quad i = \frac{I}{I_{cr}(T_b)} . \quad (4)$$

3. INTRODUCTION OF DIMENSIONLESS VARIABLES

In the following, it will be useful to introduce dimensionless variables. We have already defined a dimensionless current [$i = I/I_{cr}(T_b)$], and now we introduce a dimensionless temperature defined by

$$\theta = \frac{T - T_b}{T_{cr} - T_b} . \quad (5)$$

At $T = T_b$, $\theta = 0$; at $T = T_{cs}$, $\theta = 1 - i$; and at $T = T_{cr}$, $\theta = 1$. For simplicity in what follows,

$$y = \theta_{He} \quad (6a)$$

and

$$x = \theta_{Co} . \quad (6b)$$

Finally, we introduce Stekly's parameter

$$\alpha = \frac{I^2 \rho}{f A_{co} P h (T_{cr} - T_b)} . \quad (7)$$

If we divide Eq. (1b) by (1a) to eliminate explicit reference to the time t , we obtain the following equation in terms of the dimensionless variables just introduced:

$$\beta \frac{dy}{dx} = \frac{x - y}{\alpha F(x) - (x - y)} \quad (8a)$$

where

$$\beta = \frac{S_{He} A_{He}}{S_{co} A_{co}} \quad (8b)$$

and

$$F(x) = \begin{cases} 0 & x < 1 - i \quad (\text{superconducting state}) \\ \frac{x + i - 1}{i} & 1 - i < x < 1 \quad (\text{current-sharing state}) \\ 1 & x > 1 \quad (\text{normal state}) . \end{cases} \quad (8c)$$

4. TRAJECTORIES IN THE (x,y) PLANE

In order to decide on the further treatment of Eq. (8a), we need to consider the nature of the trajectories it describes in the (x,y) plane (see Fig. 1).

Consider the trajectory beginning at the point x_6 on the x-axis. Its initial point $(x_6, 0)$ corresponds to a composite dimensionless temperature $x_6 > 1$ and therefore to a state of the composite in which the superconductor is normal. The helium temperature ($y = 0$) is initially T_b . As time advances, we traverse the trajectory to the left; the composite temperature falls and the helium temperature rises, with x always remaining greater than y . On trajectory 6, y eventually becomes greater than $1 - i$ so that both x and y are greater than $1 - i$. This means that Joule power production never stops, and the helium and composite temperatures ultimately increase without bound. In this case, the conductor does not recover.

On the other hand, on trajectory 1, x eventually reaches the value $1 - i$, at which point Joule power production stops. The helium and composite then equilibrate, ultimately reaching some point on the segment OP of the line $x = y$. In this case, the conductor recovers.

There is a trajectory originating at the point $(x_m, 0)$ on the x-axis that just passes through the point P. It describes the history of a conductor that just barely recovers: for any initial composite dimensionless temperature greater than x_m , the conductor fails to recover; for any initial dimensionless temperature less than x_m , the conductor recovers. Thus, x_m is the largest initial dimensionless temperature from which recovery is still possible, and that is what we seek to calculate.

5. CURRENT-SHARING REGION

In the current-sharing region, $1 - i < x < 1$, Eq. (8a) takes the form

$$\beta \frac{dy}{dx} = \frac{x - y}{\alpha \frac{x + i - 1}{i} - (x - y)} . \quad (9)$$

The point P is a critical point of Eq. (9), and the trajectory stretching from P to M: $(x_m, 0)$ is the separatrix between two families of integral curves of Eq. (9), those which reach the line $x = 1 - i$ and those which do not.

We can find the separatrix algebraically without the necessity of integrating Eq. (9) by making use of the fact that Eq. (9) is invariant to the one-parameter continuous group of transformations¹³

$$\begin{aligned} x' &= \mu x + (1 - \mu)(1 - i) \\ y' &= \mu y + (1 - \mu)(1 - i) \end{aligned} \quad 0 < \mu < \infty \quad (10)$$

It is easy to prove that the value $x = 1 - i$ always maps into the value $x' = 1 - i$ and that if $x > 1 - i$ then $x' > 1 - i$ also. Hence, under the mapping in Eq. (10), trajectories which correspond to recovery are interchanged among themselves, and trajectories which correspond to non-recovery are interchanged among themselves, but no member of one family is mapped into the other family. Since the point $(1 - i, 1 - i)$ is mapped into itself, the separatrix must be mapped into itself. The separatrix is thus an invariant curve of the group in Eq. (10).

The invariant curves of Eq. (10) satisfy the equation

$$\frac{dy}{dx} = \frac{y - (1 - i)}{x - (1 - i)} \quad (11)$$

But, since the separatrix must also satisfy Eq. (9), if we substitute Eq. (11) into Eq. (9) we get an *algebraic* equation for the separatrix. After a little computation, we find the following equation for the separatrix

$$y = \lambda x + (1 - \lambda)(1 - i) \quad (12a)$$

where λ is a root of the quadratic equation

$$\lambda^2 + \lambda(\alpha/i - 1 + 1/\beta) - 1/\beta = 0 \quad (12b)$$

Eq. (12b) has two real roots, one positive and one negative. [Thus we see that P is a saddle point of Eq. (9).] The negative root, which we want, is given by

$$\lambda = -C - \sqrt{C^2 + \beta^{-1}} \quad ; \quad C = \frac{1}{2} (\alpha/i - 1 + 1/\beta) . \quad (13)$$

The coordinates of the point Q, which we need to continue our integration, are then

$$y_Q = 1 - (1 - \lambda)i \quad (14a)$$

and

$$x_Q = 1 . \quad (14b)$$

6. NORMAL REGION

In the normal region $x > 1$, Eq. (8a) takes the form

$$\beta \frac{dy}{dx} = \frac{x - y}{\alpha - (x - y)} . \quad (15)$$

The portion QM of the trajectory PQM is not a separatrix of Eq. (15) [which is *different* from the differential Eq. (9)]. Hence, to go from Q to M, we must integrate Eq. (15). This is facilitated by Lie's theory.¹³ Equation (15) is invariant under the translation group

$$\begin{aligned} y' &= y + \mu \\ 0 &< \mu < \infty \\ x' &= x + \mu \end{aligned} \quad (16)$$

from which it can be shown that

$$[(\beta + 1)(x - y) - \beta\alpha]^{-1} \quad (17)$$

is an integrating factor. With this factor, Eq. (15) can be integrated to give

$$x + \beta y + \frac{\beta\alpha}{\beta + 1} \ln[(\beta + 1)(x - y) - \beta\alpha] = \text{constant}. \quad (18)$$

Since both M and Q lie on Eq. (18), we find

$$x_m + \frac{\beta\alpha}{\beta + 1} \ln[(\beta + 1)x_m - \beta\alpha] = 1 + \beta[1 - (1 - \lambda)i] + \frac{\beta\alpha}{\beta + 1} \ln[(\beta + 1)(1 - \lambda)i - \beta\alpha] \quad (19)$$

where λ is given by Eq. (13).

7. STABILITY AS A FUNCTION OF HEAT TRANSFER

To study stability as a function of heat transfer, we need to study how x_m varies with α for fixed i and β . First, let us consider the value of x_m when $\alpha \rightarrow 0$, i.e., when $h \rightarrow \infty$. When h is very large, recovery is nearly instantaneous, and the Joule heat produced during recovery is so small that it can be neglected. Then, the maximum heat addition following which recovery is still possible is the heat that just raises the conductor (helium and composite together) to the current-sharing threshold:

$$A_{co} S_{co} (T_m - T_b) = (A_{co} S_{co} + A_{He} S_{He}) (T_{cs} - T_b) \quad (\alpha = 0) \quad (20a)$$

or rewritten

$$x_m = (\beta + 1)(1 - i) \text{ when } \alpha = 0. \quad (20b)$$

This same value follows from Eqs. (13) and (19), which give, respectively, $\lambda = -\beta^{-1}$ and $x_m = 1 + \beta[1 - (1 - \lambda)i]$ when $\alpha = 0$.

Secondly, when $x_m = 1$, it follows at once from Eq. (19) that $(1 - \lambda)i = 1$. Inserting this value in Eq. (13), we find

$$\alpha = \frac{1 - \frac{\beta + 1}{\beta} i}{1 - i} \quad \text{when } x_m = 1. \quad (21)$$

Because the specific heat of supercritical helium is much larger than that of the composite, β is a large number (of the order of several hundred). This means that as α varies from 0 to 1, x_m falls from the high value given in Eq. (20b) to 1.

If $\beta \gg 1$, λ as given by Eq. (13) has an interesting behavior when considered as a function of C : to leading order,

$$\lambda = -\frac{1}{2\beta|C|} + \dots \quad \text{when } C < 0 \quad (22a)$$

$$\text{and } C^2 \gg \beta^{-1}$$

$$= -2|C| + \dots \quad \text{when } C > 0. \quad (22b)$$

Thus, near $C = 0$, λ switches rapidly from very small negative values to much larger negative values. This leads us to conjecture that the small negative values ($C < 0$) will be associated with large values of x_m near that given by Eq. (20b), and the larger negative values ($C > 0$) will be associated with the rapid decrease toward $x_m = 1$. The break between these two regions of behavior comes near $C = 0$ or $\alpha = i(\beta - 1)/\beta \sim i$. If $C > 0$ and $C^2 \gg \beta^{-1}$,

$$\lambda = -2|C| \sim 1 - \frac{\alpha}{i}. \quad (23a)$$

If the second term on the right-hand side of Eq. (19) dominates because of the large value of β , then the logarithmic terms can be neglected and

$$x_m \sim 1 + \beta(1 - \alpha) \quad \text{for } \alpha > i(\beta - 1)/\beta. \quad (23b)$$

Figure 2 shows the results of calculating x_m as a function of α for $\beta = 250$ and $i = 0.6$ using Eqs. (13) and (19). The curve shows the

qualitative features mentioned above, namely, a value close to that of Eq. (20b) for $\alpha < 1$ and a value close to that of Eq. (23b) for $\alpha > 1$, with a relatively sharp change in behavior near $\alpha = 1$. Customarily, the stability margin x_m is plotted against a quantity proportional to the heat transfer coefficient which is itself proportional to α^{-1} . Shown in Fig. 3 is x_m plotted against α^{-1} . The S-shaped curve strongly resembles the curves produced by computer calculations.⁵ The stability margin thus increases rapidly with increasing heat transfer until the "knee" of the curve is reached, after which little is gained by further increasing the heat transfer.

8. STABILITY-OPTIMIZED CONDUCTORS

As mentioned earlier, a stability-optimized conductor is one for which x_m has been maximized by the best choice of f and $f_{co} = A_{co}/A$, where $A = A_{co} + A_{He}$, with everything else held constant. We want to know the coordinates (f_{co}, f) of stability-optimized conductors in terms of the other parameters, e.g., current, field, heat transfer coefficient.

We begin our calculations by subtracting $\beta\alpha \ln(\beta + 1)/(\beta + 1)$ from both sides of Eq. (19), which can then be written as

$$x_m + \gamma \ln(x_m - \gamma) = 1 + \beta(1 - w) + \gamma \ln(w - \gamma), \quad (24a)$$

where

$$\gamma = \frac{\beta\alpha}{\beta + 1} \text{ and } w = (1 - \lambda)i. \quad (24b)$$

Since x_m increases when the right-hand side of Eq. (24a) increases, we should make the right-hand side of Eq. (24a) as large as possible. Let us consider how the right-hand side of Eq. (24a) varies with w . Plotted in Fig. 4 are the sum of the first two terms, the last term, and the entire right-hand side. The first two terms represent a straight line with the steep slope $-\beta$ through the point $(1,1)$. The third term is monotone increasing, with a negative infinite asymptote at $w = \lambda$ and a

zero at $w = 1 + \lambda$. Thus, the right-hand side of Eq. (24a) has a maximum, which turns out to be at $w = \alpha$.

Now, according to Eq. (13),

$$1 - \lambda = \frac{1}{2} \left(\frac{\alpha}{i} + 1 + \frac{1}{\beta} \right) + \left\{ \left[\frac{1}{2} \left(\frac{\alpha}{i} - 1 + \frac{1}{\beta} \right) \right]^2 + \frac{1}{\beta} \right\}^{1/2} \quad (25a)$$

$$> \frac{1}{2} \left(\frac{\alpha}{i} + 1 + \frac{1}{\beta} \right) + \frac{1}{2} \left| \frac{\alpha}{i} - 1 + \frac{1}{\beta} \right| \quad (25b)$$

$$> \begin{cases} \frac{\alpha}{i} + \frac{1}{\beta} > \frac{\alpha}{i} & \text{if } \alpha > i \left(\frac{\beta - 1}{\beta} \right) \\ 1 & \text{if } \alpha < i \left(\frac{\beta - 1}{\beta} \right) \end{cases} \quad (25c)$$

so that $(1 - \lambda)i = w > \alpha$ if $\alpha > i(\beta - 1)/\beta$ and $(1 - \lambda)i = w > i$ if $\alpha < i(\beta - 1)/\beta < i$. Hence, in all cases, $w > \alpha$, and we can never attain the maximum at $w = \alpha$. Because the left-hand side of Eq. (24a) increases with increasing x_m , we see that we must make w as close to α as possible in order to make the right-hand side as large as possible. This conclusion is the first step in finding the coordinates (f_{co}, f) of the stability-optimized conductor.

The maximum value of the right-hand side of Eq. (24a) at the point $w = \alpha$ is

$$1 + \beta(1 - \alpha) + \beta\alpha \frac{\ln[\alpha/(\beta + 1)]}{\beta + 1} \quad (26)$$

This quantity has a negative derivative with respect to α for $\alpha < (\beta + 1)e^\beta$. Since $(\beta + 1)e^\beta$ is very large, Eq. (26) is monotone decreasing for all practical purposes. It appears then that we should make α as small as possible (while keeping w as close to α as we can). But since the left-hand side of Eq. (24a) also contains α , we must calculate $dx_m/d\alpha$ to be sure. When $w = \alpha$, we have

$$\frac{\beta + 1}{\beta} \frac{dx_m}{d\alpha} = \frac{dx_m}{d\gamma} < [\gamma - (x_m - \gamma) \ln(x_m - \gamma)]/x_m \quad (27)$$

if $x_m > \gamma$. Now $\gamma \sim \alpha \lesssim 1$, while $x_m \sim \beta(1 - \alpha) \sim$ several hundred; thus, $dx_m/d\alpha < 0$, in general, and we really want to make α as small as possible.

Let us return now to Eq. (25c) and use it to prepare a sketch of $w = (1 - \lambda)i$ vs α . According to Eq. (25c), if $\beta \gg 1$, $w = \alpha$ when $\alpha > i$ and $w = i$ when $\alpha < i$ (see Fig. 5). The smallest value of α for which w is very close to α is clearly $\alpha = i$. Hence, *stability-optimized conductors are characterized by $\alpha = i$.*

The condition $\alpha = i$ gives us the value of f , the volume fraction of copper, for the stability-optimized conductor. Written out fully, $\alpha = i$ is

$$\frac{I^2 \rho}{f A_{co} Ph (T_{cr} - T_b)} = \frac{I}{I_{cr}}. \quad (28)$$

If we set $J = I/A$ (overall current density) and note that

$$I_{cr} = J_{cr} A_{co} (1 - f), \quad (29)$$

where J_{cr} is the *critical current density of the pure superconductor*, then Eq. (28) becomes

$$\frac{a_1}{f} = \frac{a_2}{1 - f}, \quad (30a)$$

where

$$a_1 = \frac{J^2 \rho / (T_{cr} - T_b)}{Ph/A} \quad (30b)$$

and

$$a_2 = J/J_{cr}. \quad (30c)$$

Then

$$f = \frac{a_1}{a_1 + a_2}. \quad (31)$$

When $\alpha \sim i < 1$, we find from Eq. (24a) that

$$x_m \sim \beta(1 - \alpha) = a_3 \frac{1 - f_{co}}{f_{co}} \left(1 - \frac{a_1 + a_2}{f_{co}} \right), \quad (32a)$$

where

$$a_3 = S_{He}/S_{co}. \quad (32b)$$

Maximizing x_m with respect to f_{co} , we find

$$f_{co} = \frac{2(a_1 + a_2)}{a_1 + a_2 + 1} \quad (33)$$

and

$$x_m = a_3 \frac{[1 - (a_1 + a_2)]^2}{4(a_1 + a_2)}. \quad (34)$$

Equations (31), (33), and (34) are the central results of this paper.

In addition to using Eqs. (31), (33), and (34) for estimating the location (f_{co}, f) and stability margin x_m/a_3 of optimized conductors, we can also use Eqs. (20b) and (23b) to draw contours of constant x_m/a_3 in the (f_{co}, f) plane around the optimized conductor. Such contours are shown in Fig. 6 for $a_1 = 0.1$ and $a_2 = 0.05$. The coordinates of the optimized conductor calculated from Eqs. (31) and (33) are $f_{co} = 0.26$ and $f = 0.67$.

If we ignore quantities of the order of unity when compared with quantities of the order of β , then Eqs. (20b) and (23b) can be written, respectively,

$$1 - f = \frac{a_2}{f_{co} \left(1 - \frac{x_m}{a_3} \frac{f_{co}}{1 - f_{co}} \right)} \quad (\alpha < i) \quad (36a)$$

$$f = \frac{a_1}{f_{co} \left(1 - \frac{x_m}{a_3} \frac{f_{co}}{1 - f_{co}} \right)} \quad (\alpha > i). \quad (36b)$$

Contours plotted with Eqs. (36a) and (36b) are shown in Fig. 6. The dark point in Fig. 6 is the location of the optimized conductor. The horizontal line through this point is the line $\alpha = i$. Above this line $\alpha < i$ and below the line $\alpha > i$; Eqs. (36a) and (36b) intersect on the line. Also shown are three contours for which x_m/a_3 is 83%, 67%, and 27.5% of the value of x_m/a_3 at the optimum. The contours bear a strong qualitative resemblance to those shown in Ref. 5. Especially noteworthy is the much closer spacing of the contours on the low f_{co} side of the optimum than on the high f_{co} side. *If the calculated location of the optimum is felt to be uncertain, conservative design requires f_{co} to be increased slightly.*

9. DISCUSSION AND EXAMPLE

As an example of the application of these formulas, let us consider the design of a 15-kA NbTi/Cu FCC operating at 4.0 K and 8.0 T using a superconductor of which the critical current density is $6.4 \times 10^8 \text{ A-m}^{-2}$. We shall strive for an operating current density of $3.75 \times 10^7 \text{ A-m}^{-2}$ over the cable space, which then has an area of 4.0 cm^2 . Let us further suppose that the residual resistance ratio of the copper matrix is 160 at zero field; then, at 8.0 T the resistivity of the copper including magnetoresistance is $5.35 \times 10^{-10} \Omega\text{-m}$.

With these parameters fixed, $a_1 = 4.77 \times 10^5 \times (\text{Ph/A})^{-1}$ (with Ph/A expressed in mks units) and $a_2 = 0.0586$. We can estimate the range of values Ph/A must have in order for the conductor to be reasonably stable as follows. In Sect. 8 we have seen that α should be $\leq i$ for good stability. Now,

$$\frac{\text{Ph}}{A} = \frac{J^2 \rho / (T_{cr} - T_b)}{f f_{co} \alpha} \quad (37)$$

If we guess $f \sim 0.8$, $f_{co} \sim 0.5$, and $\alpha = i \sim 0.6$, we find $\text{Ph/A} \sim 2.0 \times 10^6 \text{ Wm}^{-3}\text{K}^{-1}$. Now, $P/A = 4 f_{co}/D$, where D is the diameter of the individual strands. For $D \sim 1 \text{ mm}$, $P/A \sim 2000 \text{ m}^{-1}$; thus, $h \sim 1000 \text{ Wm}^{-2}\text{K}^{-1}$. Using the Giarratano correlation¹⁴ (with $T_w = T_b$, $k = 0.02 \text{ Wm}^{-1}\text{K}^{-1}$,

$D = 10^{-3}$ m, and $Pr = 0.65$), we find that this value of h corresponds to a Reynolds number of about 16,000. Both Arp¹⁰ and Krauth¹¹ have reported obtaining local, instantaneous Reynolds numbers as high as 100,000 in machine calculations of the recovery of the FCC. The corresponding heat transfer coefficient for 1-mm wires would be $4300 \text{ Wm}^{-2}\text{K}^{-1}$, and Ph/A would be $8.6 \times 10^6 \text{ Wm}^{-3}\text{K}^{-1}$. The interesting range of Ph/A then appears to be 10^6 - $10^7 \text{ Wm}^{-3}\text{K}^{-1}$.

Table 1 shows f , f_{co} , and $(x_m/a_3)f_{co}$ calculated from Eqs. (31), (33), and (34) as functions of Ph/A . The quantity x_m/a_3 in the last

Table 1. Parameters of stability-optimized conductors

$Ph/A (\text{MW m}^{-3}\text{K}^{-1})$	f	f_{co}	(x_m/a_3)
1	0.89	0.70	0.10
2	0.80	0.46	0.42
3	0.73	0.36	0.70
5	0.62	0.27	1.16
7	0.54	0.22	1.50
10	0.45	0.19	1.88

column is related to the stability margin ΔH as follows:

$$\frac{x_m}{a_3} = \frac{\Delta H}{S_{He} (T_{cr} - T_b)} \quad , \quad (38)$$

where ΔH is the maximum heat pulse *per unit volume of metal* from which recovery is still possible. [For the problem at hand, $S_{He}(T_{cr} - T_b) \sim 500 \text{ mJ cm}_{He}^{-3}$, the precise value depending on the choice of average specific heat in the interval T_b, T_{cs} .]

Suppose we choose a particular conductor from Table 1, e.g., the one for which $f = 0.8$ and $f_{co} = 0.46$. This conductor is optimized for $Ph/A = 2 \text{ MW m}^{-3}\text{K}^{-1}$; for this value of Ph/A , $\alpha = i$. For larger Ph/A , $\alpha < i$, and (x_m/a_3) remains fixed at the value in Table 1 [cf. Eq. (36a) or Fig. 2]. For smaller Ph/A , (x_m/a_3) will fall rapidly, as expected from Fig. 3 or Eq. (36b). These considerations then lead to the following

rule of design:^{5,6} *If there is a smallest stability margin ΔH that we deem tolerable, we choose the conductor that is optimized for this margin. This conductor will have the smallest value of Ph/A for which the prescribed margin ΔH is attainable.*

Earlier, it was thought that steady turbulent flow was necessary to provide enough heat transfer for good stability. In this case, using a stability-optimized conductor would have enabled us to achieve a given stability margin at a given Reynolds number with the least pumping power. Recently, however, it has been shown that steady turbulent flow is not necessary and that substantial flow is induced by the heat transferred from the FCC. At present, we know very little about these induced flows and the heat transfer associated with them. In the absence of such knowledge, use of stability-optimized conductors is advantageous because a stability-optimized conductor would require the smallest induced flow for a given stability margin and therefore would have the best chance of achieving the desired stability. If in the future we find that the heat transfer during the transient period of induced flow can be described by some known effective value of h , then use of a stability-optimized conductor will permit us to minimize P/A , i.e., to maximize the wire diameter, for a given stability margin. A larger wire diameter means fewer drawing operations and therefore cheaper and stronger strands. For all these reasons, the easy identification of stability-optimized conductors as described in this paper appears useful.

10. COMPARISON WITH EXPERIMENT

Miller et al.⁷ have performed an experiment in which they measured the "zero-flow" stability margin of a short length of a single triplex inserted into a sleeve and heated by an embedded heater. At the outset of each experiment, the sample was immersed in *stationary* supercritical helium. The test conductor parameters are as follows: strand diameter = 1.0 mm (conductor only); strand diameter = 1.05 mm (with insulation); Cu/NbTi ratio = 4.5; tube inside diameter = 2.41 mm; helium volume fraction = 0.394; critical current (at 7 T) = 404 A; and copper resistivity (at 7.0 T) = 4.7×10^{-10} Ω -m. The test results are as follows:

at zero flow the stability margin is 200, 50, and 33 mJ cm⁻³ for transport currents of 200, 250, and 300 A, respectively.

Let us analyze these stability results in order to find the effective heat transfer coefficient h for each of these three cases. When the transport current is 200 A, $i = 200/404 = 0.495$. Furthermore,

$$\alpha = \frac{J^2 \rho / (T_{cr} - T_b)}{f f_{co} (Ph/A)} = \frac{1.00 \times 10^6 \text{ Wm}^{-3} \text{ K}^{-1}}{Ph/A} \quad (39)$$

Now, when $Ph/A > 2.03 \times 10^6 \text{ Wm}^{-3} \text{ K}^{-1}$, $\alpha < i$. Then,

$$\frac{x_m}{a_3} = \frac{1 - f_{co}}{f_{co}} (1 - i) = 0.328 \quad (40)$$

We can now evaluate ΔH from Eq. (38). Since the sample is short, pressure relief is almost instantaneous and, accordingly, we use the specific heat at constant pressure: $S_{He} = 540 \text{ mJ cm}^{-3}$ at 5.0 atm in the interval 4.0–5.0 K. Then, $\Delta H = 322 \text{ mJ cm}^{-3}$ which is larger than the measured result (200 mJ cm^{-3}). Thus α must be greater than i and

$$\frac{x_m}{a_3} = \frac{1 - f_{co}}{f_{co}} (1 - \alpha) \quad (41)$$

To fit the measured value of ΔH , x_m/a_3 must be 0.204, so that α must be 0.686 and $Ph/A = 1.46 \text{ MW m}^{-3} \text{ K}^{-1}$. Using 5/6 of the geometric perimeter of the wires as the cooled perimeter, we find $P/A = 1722 \text{ m}^{-1}$; thus, $h = 847 \text{ Wm}^{-2} \text{ K}^{-1}$. These results and similar ones for the other two transport currents are summarized in Table 2.

Since the theory on which these computations are based is at best schematic, it is safe only to conclude that the period of induced flow is described by an effective heat transfer coefficient $h \sim 1000 \text{ Wm}^{-2} \text{ K}^{-1}$ and that h appears to increase as the transport current increases.

Table 2. Analysis of experiments of Miller et al. for the heat transfer coefficient

I (A)	i	$(x_m/a_3)_{as}$	$(\Delta H)_{as} \left(\frac{mJ}{cm^3} \right)$	$(\Delta H)_{exp} \left(\frac{mJ}{cm^3} \right)$	$(x_m/a_3)_{exp}$	α	$h(Wm^{-2}K^{-1})$
200	0.495	0.328	322	200	0.204	0.686	847
250	0.619	0.248	243	50	0.0510	0.922	985
300	0.743	0.167	164	33	0.0336	0.948	1378

11. SUMMARY AND CONCLUSIONS

The recovery of cable-in-conduit conductors cooled by supercritical helium has been studied. The initial perturbation is a sudden, uniform deposition of heat. The problem has been solved, and answers have been obtained in the form of simple closed formulas under the simplifying assumption of constant thermophysical properties. Stability-optimized conductors have been identified and simple formulas for their material composition are given. A rule of design of cable-in-conduit conductors based on the existence of stability-optimized conductors is suggested. Some "zero-flow" experiments of Miller et al. have been analyzed, and it has been determined that for these experiments the effective heat transfer coefficient during the period of recovery is approximately $1000 Wm^{-2}K^{-1}$.

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Fig. 1. Trajectories of Eq. (8) (cf. Sect. 4).

Fig. 2. Dimensionless maximum conductor temperature vs Stekly parameter.

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Fig. 3. Dimensionless maximum conductor temperature vs reciprocal Stekly parameter.

Fig. 4. Sketch of the right-hand side of Eq. (24a).

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Fig. 5. Sketch of $w = (1 - \lambda)i$ vs α .

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Fig. 6. Contours of x_m in the $f - f_{co}$ plane. The dark point shows the location of the stability-optimized conductor (cf. Sect. 8).

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