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SUPERCONDUCTING FAULT CURRENT LIMITER

Fifth Quarterly Technical Progress Report for
August 8–November 7, 1979

MASTER

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Work Performed Under Contract No. ET-78-C-01-3015

Gould-Brown Boveri
Chalfont, Pennsylvania

U. S. DEPARTMENT OF ENERGY

Division of Electric Energy Systems

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Fifth Quarterly Technical Progress Report

August 8, 1979 - November 7, 1979

Prepared By

GOULD - BROWN BOVERI

Prepared For

DEPARTMENT OF ENERGY
ELECTRICAL ENERGY SYSTEMS

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1.1 INTRODUCTION, SUMMARY AND FORECAST

This program can be considered to be made up of six elements:

1. Performance objectives
2. Ranking of device design concepts
3. Analysis and design: magnetically switched resistive device
4. Experimental program
5. Evaluation of SCFCL device and definition of on-going program
6. Literature search

Items 1, 3 and 6 were studied in the earlier months of this program, and no further time was devoted to these tasks during this quarter. Activities 3 and 4 received major emphasis this quarter and are described respectively in Sections 3 and 4 of this Fifth Quarterly Report.

A transient heat transfer model was developed during this quarter. This model indicates the parameters which are important in determining the thermal heating and recovery of the superconducting film. "Best guess" ranges for these material characteristics are assumed in order to carry out calculations, and these results, which are plotted in Section 3, give an approximate picture of the thermal behavior of the SCFCL. High accuracy is not claimed for these results, because of the uncertainty of the input data, but the model is more important as a guide to understanding and interpretation of the experiments.

Designs for the switching coil and the S/C element were also carried out during this quarter and are reported in Section 3. A four-pole magnetic coil is recommended; this generates a magnetic field which is nearly perpendicular to spiral or helical S/C film geometrics. A spirally-designed, 3000 Ω limiter is shown to be able to fit within a .5 to 1m inner radius, .05 to .03 m wide, 1.3 to 3.9 m long annular region.

The experimental program has included work on materials development and on preparation of the switching and thermal recovery experimental facility. The material development program has uncovered several serious shortcomings of NbN as the S/C film material. Macroscopic holes and surface debris, and microscopic imperfections reduce the critical current density below the expected value and, in addition, cause nonuniform switching. Reasons for these effects are postulated, and a continuing, vigorous materials program is suggested in hopes of alleviating these problems.

Virtually all of the experimental equipment had been installed by the end of this Fifth Quarter, and so the magnetic switching and thermal recovery experiments can begin and progress during the next quarter.

1.0 PERFORMANCE OBJECTIVES

No further progress was made this Quarter; see Second and Fourth Quarterly Reports for results to date.

2.0 RANKING OF DEVICE DESIGN CONCEPTS

No further effort was devoted to this task during this Quarter; see the Second Quarterly Report for results to date.

3.0 MAGNETICALLY-SWITCHED RESISTIVE DEVICE: ANALYSIS AND DESIGN

3.1 Transient Circuit Analysis

No further progress this Quarter; see Fourth Quarterly Report for results to date.

3.2 Transient Heat Transfer

3.2.1 Objectives and Constraints.

Analysis of transient heat transfer from the film to its plastic substrate and helium bath is of controlling importance in the design of our superconducting fault current limiter (SCFCL). The primary objective of this analysis is to determine the thermal stability of the device.

The optimum amount of heat to be transferred from the film to its coolants (helium bath and plastic substrate) must be determined. Too much heat transfer reduces film's temperature abruptly and may take it back to its superconducting state before the isolation switch is opened (see figure 3.2.1). The film's low resistance in the superconducting state will drain the fault current into the film and heat it up into its normal state again. This may cause very undesirable temperature and current oscillations in the device and power system respectively.

A slow heat transfer, on the other hand, may result in a high steady state film temperature before the isolation switch is opened. Film's temperature is expected to drop to helium bath temperature ($T_b = 4.2^\circ\text{K}$) after this switch is opened. If the film's final temperature is too high before the switch is opened, it may take an excessively long time before it is reset for another operation ($T = T_b$). This increases the response time of the current limiting device.

FIGURE 3.2.1 Sketch Of A Faulted System Protected With An SCFCL

Heat transfer should be so controlled that film's final temperature would significantly exceed $T_c \approx 10 - 18\text{K}$ but would not exceed $T \approx 100^\circ\text{K}$ before the isolation switch is opened.

3.2.2. Method of Analysis

To perform the required transient heat analysis, general numerical method of Dusenberre for one dimensional transient heat conduction is considered¹. Heat transfer by radiation and helium convection is believed to be negligible and is ignored.

Figure 3.2.2 shows a cross section of the film with its plastic substrate and helium bath divided into a number of slices of thicknesses Δx_2 and Δx_1 , respectively. The interface of any two neighboring slices is a temperature-reference plane as shown in the Figure. Equation (3.2.1) expresses the heat balance for the crosshatched zone between planes P_1 and P_2 in helium. The slope $-dT/dx$ at plane P_1 is approximated by the cord slope $(T_{n-1} - T_n)/\Delta x_1$; similarly the slope $-dT/dx$ at plane P_2 is replaced by $(T_n - T_{n+1})/\Delta x_1$. T_n is approximately the average temperature of the crosshatched slice. Equation of the heat balance is

$$\frac{kA(T_{n-1} - T_n)}{\Delta x_1} - \frac{kA(T_n - T_{n+1})}{\Delta x_1} = \frac{(A\Delta x_1)(\rho C_p)(T'_n - T_n)}{\Delta t} \quad (3.2.1)$$

Where T'_n is the new temperature at plane n , after the time increment Δt ; k, ρ and C_p are thermal conductivity, density and specific heat of the coolant (He). A is the uniform cross-sectional area for heat conduction. By defining the thermal diffusivity as

$$\alpha = \frac{k}{\rho C_p} \quad (3.2.2)$$

and the dimensionless modulus M as

$$M = \frac{(\Delta x_1)^2}{\alpha \Delta t} \quad (3.2.3)$$

Figure 3.2.2 Diagram of one-dimensional transients in the plastic substrate and helium bath covering the superconducting film.

3.2.2 Method Of Analysis - (Cont'd)

Equation (3.2.1) becomes

$$T_n' = \frac{T_{n-1} + (M-2) T_n + T_{n+1}}{M} \quad (3.2.4)$$

A similar equation can be written for the plastic substrate

$$T_{n'}' = \frac{T_{(n-1)'} + (M'-2) T_{n'} + T_{(n+1)'}}{M'} \quad (3.2.5)$$

These equations indicate that at any time interval, the temperature of each plane is a weighed average of the old values of its own temperature and the temperature of its neighboring planes at the previous time interval.

Equations (3.2.4) and (3.2.5) can be used to find the temperature distribution in helium and plastic substrate at any given time interval. Helium and plastic substrate are originally at the bath temperature $T_b = 4.2^\circ K$. Film's initial temperature is determined by the transient circuit analysis explained in the previous section. Film's temperature changes with time as indicated by the following energy balance equation

$$\Delta T_f = \frac{(P_e - P_h - P_s) \Delta t}{d \times g \times C_f} \quad (3.2.6)$$

Where d , g and C_p are film's thickness, specific gravity and specific heat respectively. P_e , P_h and P_s are the powers absorbed from the electric circuit and lost to the coolants. These powers, expressed per unit area of cross section, are:

$$P_e = \frac{RI^2}{A} = d \rho_N J^2 \left[\frac{W}{cm^2} \right] \quad (3.2.7)$$

$$P_h = K_h \frac{T_o - T_l}{\Delta x_1} \left[\frac{W}{cm^2} \right] \quad (3.2.8)$$

$$P_s = K_p \frac{T_o' - T_l'}{\Delta x_2} \left[\frac{W}{cm^2} \right] \quad (3.2.9)$$

3.2.2 Method Of Analysis - (Cont'd)

Where ρ_N is film's resistivity in normal state and J is its current density. The cord slopes $\frac{T_o - T_1}{\Delta x_1}$ and $\frac{T_o' - T_1'}{\Delta x_2}$ are used to approx-

imate the slope $\frac{dT}{dx}$ at film's surfaces. The film temperature T_f is assumed to be the same at both surfaces because of high value of film's thermal conductivity and small thickness d .

So far, it has been assumed that helium and plastic temperatures at film's surfaces (T_o and T_o') are equal to the film temperature T_f . This is acceptable as long as the surface resistance between the film and its coolants is negligible. The coefficient of heat transfer at helium/film surface is approximately $0.8 \text{ W/cm}^2\text{°K}$ at the bath temperature of $T_b = 4.2^\circ\text{K}$.^{2,3,4}

This coefficient increases with the third power of the temperature that is³

$$h = 0.8 \left(\frac{T^\circ\text{K}}{4.2^\circ\text{K}} \right)^3 \frac{\text{W}}{\text{cm}^2\text{°K}} \quad (3.2.10)$$

Now the heat balance for the first half slice of helium in contact with the film can be written as

$$hA(T_f - T_o) - kA \frac{(T_o - T_1)}{\Delta x_1} = \frac{(A \cdot \frac{\Delta x}{2}) (\rho C_p) (T_o' - T_o)}{\Delta t} \quad (3.2.11)$$

By using equations (3.2.2) and (3.2.3), and the dimensionless Nusselt modulus N defined as

$$N = h \frac{\Delta x}{k} \quad (3.2.12)$$

equation (3.2.11) can be rearranged to give T_o' ;

$$T_o' = \frac{2NT_f + (M-2N-2) T_o + 2T_1}{M} \quad (3.2.13)$$

3.2.2 Method Of Analysis - (Cont'd)

This indicates that, at any time interval, helium temperature at film's surface T_o is a weighed average of the old values of its own temperature T_o , film's temperature T_f , and the temperature of the first slice T_1 at the previous time interval.

When the modulus N is large, helium temperature at the film's surface T_o follows film's temperature T_f very closely. If we assume that film temperature would not go below its critical value of $T_c \approx 15^\circ K$, the coefficient of heat transfer will always be larger than

$$h = 0.8 \left(\frac{15}{4.2} \right)^3 = 36 \frac{W}{cm^2 K} \quad (3.2.10)$$

and for a typical helium slice thickness of 2×10^{-4} cm and helium conductivity of 6×10^{-4} W/cmK, Nusselt modulus would be larger than

$$N = 36 \left(\frac{W}{cm^2 K} \right) \times \frac{2 \times 10^{-4} (cm)}{6 \times 10^{-4} \left(\frac{W}{cmK} \right)} = 12 \quad (3.2.11)$$

This indicates that the surface resistance between the film and helium is negligible and, T_o is practically equal to the film's temperature T_f .

The surface resistance between the film and its plastic substrate depends on the plastic material and the process by which they are joined together. It is important that the metal be in good contact with its substrate.

3.2.3 Numerical Analysis Of Transient Heat Conduction

Based on the method explained in the last section, a computer program is developed that also considers the nonlinear variation of film's specific heat and current density during the heat transfer. Table 3.2.I has a list of some constants used in the program. Specific heat of the film is a function of its temperature and is given in Figure 3.1.3 in the last section. Figure 3.2.3 shows a simplified flowchart of the program. A list of the program is given in Appendix 3.2.A. Transient heat transfer analysis is done per unit area of the film. Note that the modulus M is chosen equal for both helium and plastic. This results in different

3.2.3 Numerical Analysis Of Transient Heat Conduction - (Cont'd)

slice thicknesses ($\Delta x_1 \neq \Delta x_2$) but the temperature distribution in the two media will be similar, that is $T_n' = T_n$ for any given n (see equations 3.2.4 and 3.2.5). The larger the value of M , the more stable is the iterative solution. The problem with choosing high value of M , as indicated in equation 3.2.3, is small Δt or large Δx . Small time intervals increase the required time and cost of running the program while large Δx reduces its accuracy. Values of M smaller than 2 will result in unstable solution. In the specific heat transfer problem that we are dealing with, values of M larger than 4 did not improve the stability of the iteration. Values of $M = 3$ and $M = 4$ proved to be good choices for our specific problem.

TABLE 3.2-I
Constants Used In The Transient Heat Analysis^{5,6}

Thermal Constant	Symbol	Value	Unit
Helium density	ρ	0.125	gm/cm ³
Helium specific heat	C_p	5.19	J/gm°K
Helium thermal conductivity	K_h	6×10^{-4}	W/cm°K
Helium thermal diffusivity	α_h	10^{-3}	cm ² /sec
Helium bath temperature	T_b	4.2	°K
Plastic (bakelite) thermal conductivity	K_p	3.3×10^{-3}	W/cm°K
Plastic thermal diffusivity	α_p	1.56×10^{-3}	cm ² /sec
Film's specific gravity	g	8.4	gm/cm ³
Film resistivity (normal state)	ρ_N	3×10^{-4}	Ω -cm
Heat transfer modulus (same for helium and plastic)	M	3	Dimensionless
Initial time interval	Δt	10^{-7}	sec
Maxium permitted time interval	Δt	1×10^{-4}	sec

At the beginning of iterations, a time interval of $\Delta t = 0.1 \mu\text{sec}$ is chosen. Choice of initial time intervals larger than $10 \mu\text{sec}$ leads to unstable iterations. Time intervals smaller than $0.1 \mu\text{sec}$ do not improve

Figure 3.2.3 Flowchart of a Program to Analyse Transient Heat Transfer from Superconducting Film to its Plastic Substrate and Helium Bath.

3.2.3 Numerical Analysis Of Transient Heat Conduction - (Cont'd)

The convergence of iterations. As the iteration goes on, variation of the film temperature during one time interval decreases. Whenever this temperature change drops to less than 0.9%, time interval is doubled and the thickness of helium and plastic slices are calculated again. These constants are determined by trial and error based on the stability of the iterations.

When film's temperature drops down close to the temperature of its coolants, the term $T_f - T_1$ (equivalent to $T_o - T_1$ or $T_o' - T_1$ in equations 3.2.8 and 3.2.9) gradually reach 0^+ . But, due to discrete time intervals and roundoff errors, the value of $T_f - T_1$ may become negative and its absolute value becomes much larger than it should be.

Large negative values of $T_f - T_1$ causes a back flow of energy from the coolants into the film. This is not physically true, but happens in the numerical iterations and, falsely, raises up film's temperature T_f . This, in the next time interval, causes another sharp drop of film's temperature and the above process repeats itself. This results in temperature oscillations that may or may not converge.

Large values of modulus M helps to reduce the amplitude of these oscillations but does not eliminate the problem. Reducing the time intervals may help to eliminate these oscillations but computation time and cost become excessively large. A rather simpler method is to control the rate of change of film's temperature dT_f/dt . This rate of change, or or slope, can be limited to a factor of its value in the previous time interval, that is

$$\left|dT_f/dt\right|_n \leq k \left|dT_f/dt\right|_{n-1} \quad (3.2.12)$$

Where k is a factor to be determined by trial and error.

Figure 3.2.4 shows a plot of the film's temperature determined by the above iterative method. Film is initially at 111°K with a d.c. current density of 15.54 kA/cm^2 passing through it. This film is $5 \times 10^{-4} \text{ cm}$ thick. Film temperature drops to its minimum value in about 0.4ms and then is raised up again due to its resistive heating. Up to about 0.1ms, film

Figure 3.2.4 Effect of Controlling Film's Temperature under DC Current.

3.2.3 Numerical Analysis Of Transient Heat Conduction - (Cont'd)

temperature is at least 1°K above the temperature of its coolants. Figure 3.2.5 shows a plot of film and coolants temperatures. After $t \approx 0.1\text{ms}$, temperature fluctuation due to discrete iterations overrides the decreasing temperature difference between the film and the coolant slices in its immediate neighborhood. This, as explained before, will lead to temperature oscillations. The shaded area in Figure 3.2.4 indicates the maximum amplitude of these oscillations. This Figure also shows the effect of applying relation (3.2.12) to the film's temperature slope dT_f/dt . By reducing the slope factor $k(K>1)$, the amplitude of temperature oscillation decrease. There are no oscillations when k is less than 5. Slope factors smaller than 2 have too much effect on the temperature profile and may lead to erroneous results. A typical value of $k = 2$ proved to be effective in eliminating the unwanted temperature oscillations without too much effect on the results.

There is one problem with the slope control relation (3.2.12). The temperature slope at the previous interval $(dT_f/dt)_{n-1}$ maybe zero. To eliminate the problem, this slope is checked at each interval and its absolute value is kept above 5.0 °K/sec. Variation of this arbitrary number from 1 to 50°K/sec would not affect the computed temperature profile.

Appendix 3.2.B shows a typical output of the program with limited film temperature ($k = 3$). As is indicated in this output, slope control is not applied before $t = 0.15\text{ms}$. To ensure that slope control has no appreciable effect on the output, film and coolant energies are calculated and compared to the total input energy. Figure 3.2.6 shows the variation of film and coolants energies. As indicated, film's energy drops to its minimum in about 0.4ms (cooling period) and then increases proportional to the square of the film's current density (heating period). Controlling the temperature has no effect during the cooling period but eliminates the oscillations during the heating period.

The total energy absorbed by the coolants increases while the film energy decreases. Coolants absorb most of the electric energy received from the circuit (see Figure 3.2.1). Total energy of the film and its

Figure 3.2.5 Variation of Film and Coolant Temperatures with Time. Coolant Temperatures are given at Different Multiples of their Slice Thickness Δx . Helium Slice Thickness is $\Delta x_h = 1.73 \times 10^{-5}$ cm and Plastic Slice Thickness is $\Delta x_p = 2.16 \times 10^{-5}$ cm.

Figure 3.2.6 Energy Distribution between the Film and its Coolants (He and Plastic substrate).

3.2.3 Numerical Analysis Of Transient Heat Conduction - (Cont'd)

coolants, at any time, should be equal to the film's initial energy plus the total electric energy delivered to the films. This energy balance law is violated in the numerical iteration. This is partly due to iterative solution and partly due to numerical integration of energy. This unbalance is not related to film temperature control and can be observed even in simple classic examples of Dusinger numerical method of transient heat conduction.¹

Film's temperature control can also be applied to the cases where the input current is alternating. Figure 3.2.7 shows the effect of controlling film temperature when the input current is a 60Hz 15.54kA-rms/cm². Here undesirable oscillations are eliminated without much effect on the temperature itself. Figure 3.2.8 compares film temperature for the cases when the input current is 15.54kA/cm² and 60Hz 15.54kA-rms/cm².

Figure 3.2.9 shows the effect of temperature control when there is no input current into the film. In this case, computation results are completely erroneous without temperature control.

3.2.4 Effect Of Parameters

Parameters considered in this section can be listed as:

Film's resistivity	ρ	(Ω -cm)
Film's initial temperature	T_{f_0}	(°K)
Film's thickness	d	(cm)
Film's current density	J	(kA/cm ²)
Helium thermal conductivity	K_h	(W/cm°K)
Helium thermal diffusivity	α_h	(cm ² /sec)
Plastic thermal conductivity	K_p	(W/cm°K)
Plastic thermal diffusivity	α_p	(cm ² /sec)
Opening time of the isolation switch	t_s	(sec)

In addition to the above parameters, effect of covering the film with plastic (imbedding) is also explored.

Figure 3.2.7 Effect of Controlling Film's Temperature Under AC Input Current.

Figure 3.2.8 Comparison of Film Temperature for DC ($15.54 \text{ kA}/\text{cm}^2$) and 60 Hz AC ($15.54 \text{ kA-rms}/\text{cm}^2$) Input Current Densities.

Figure 3.2.9 Effect of Controlling Film's Temperature in Complete Cool-down (Current density $J = 0$).

3.2.4 Effect Of Parameters - (Cont'd)

Figure 3.2.10 shows the effect of reducing film's resistivity. This effect is not considerable before $t = 0.1\text{msec}$. Film's temperature, after 1.0ms , is more or less proportional to its resistivity (for the same current density). This indicates that variation of resistivity with temperature should be considered for more accurate studies.

Figure 3.2.11 shows the effect of film's initial temperature. This effect decreases with time and gradually perishes during the heating period.

Figure 3.2.12 indicates the effect of film's thickness on its temperature. This effect becomes more important during the heating period. Electric power into the film is directly proportional to its thickness (for constant current density).

Figure 3.2.13 shows the effect of current density on film's temperature. This effect is apparent during the heat up period. Electric power into the film is proportional to the square of its current density. Film's temperature, more or less, follows the same proportion. The curve with $J = 7.9\text{kA/cm}^2$ represents the base case studied in section 3.2 for transient circuit analysis.

Figure 3.2.14 shows the effect of helium thermal constants on film's temperature. As expected, reducing helium's thermal conductivity increases film's temperature. This effect is more apparent during the heating period ($t > 0.1\text{ms}$). Reducing helium's thermal diffusivity decreases film's temperature. This effect is apparent during cooldown as well as heating period.

Figure 3.2.15 shows the effect of plastic substrate's thermal constants on film's temperature. This is very similar to Figure 3.2.14. Comparison of these two Figures indicate that plastic substrate absorbs more heat than helium. Energy stored in one slice of helium is:

$$\Delta E_h = mc\Delta T = \frac{K_h \Delta x_h}{\alpha_h} (T_h - T_b) \quad (3.2.13)$$

Figure 3.2.10 Effect of Film's Resistivity on its Temperature Profile.

Figure 3.2.11 Effect Film's Initial Temperature

Figure 3.2.12 Effect of film thickness on its temperature.

Figure 3.2.13 Effect of current density on film's temperature

Figure 3.2.14 Effect of Helium Thermal Constants on the Film's Temperature.

Figure 3.2.15 Effect of Plastic Substrate's Thermal Constants on the Film's Temperature.

3.2.4 Effect Of Parameters - (Cont'd)

Whereas the energy stored in one slice of plastic substrate is

$$\Delta E_P = mC\Delta T = \frac{K_P \Delta x_P}{\alpha_P} (T_P - T_b) \quad (3.2.14)$$

Assuming the same temperature for helium and plastic, the ratio of plastic to helium heat capacities can be written as:

$$\frac{\Delta E_P}{\Delta E_h} = \frac{K_P \alpha_h}{K_h \alpha_P} \frac{\Delta x_P}{\Delta x_h} \quad (3.2.15)$$

Thickness of a helium or plastic slice can be found from equation (3.2.3), that is

$$\Delta x = \sqrt{M\alpha\Delta t} \quad (3.2.3)$$

so,

$$\frac{\Delta x_P}{\Delta x_h} = \frac{\sqrt{M_P \alpha_P \Delta t}}{\sqrt{M_h \alpha_h \Delta t}} = \sqrt{\alpha_P / \alpha_h} \quad (3.2.16)$$

Substituting equation (3.2.16) in (3.2.15) gives:

$$\frac{\Delta E_P}{\Delta E_h} = \frac{K_P}{K_h} \sqrt{\frac{\alpha_h}{\alpha_P}} \quad (3.2.17)$$

Upon using the numerical values of K's and α 's from Table 3.2.I, we get

$$\frac{\Delta E_P}{\Delta E_h} = \frac{3.3 \times 10^{-3}}{6 \times 10^{-4}} \sqrt{\frac{10^{-3}}{1.56 \times 10^{-3}}} = 4.4 \quad (3.2.18)$$

This indicates that plastic substrate, compared to helium, is 4.4 times more effective in cooling the film. In other words, 81% of the absorbed energy is stored in the plastic substrate. This energy will be later transferred to the helium bath. Depending on the substrate thickness, heat transfer from plastic to helium may take a long time. For the cases indicated in Figures 3.2.4 to 3.2.15, heat did not penetrate more than about 0.001 cm in the plastic substrate before 20ms.

3.2.4 Effect Of Parameters - (Cont'd)

The above analysis indicates that covering the film with plastic will help to cool down the film faster. This is clearly shown in Figure 3.2.16. Imbedding the film into plastic has other advantages such as higher dielectric capability and less chance of helium boiling.

Switching time of the isolation switch is another important factor in the thermal performance of the fault current limiter. Location of this switch is shown in Figure 3.2.1. Its purpose is to isolate the superconducting film from the rest of the electric circuit and to stop it from being heated up by its residual current. Figure 3.2.17 shows the effect of switching time on film's temperature. The best time for opening the switch is about 0.5ms when the film and its coolants are at their lowest temperature. It is practically difficult to open a high voltage switch faster than 0.5ms and there is no thermal advantage in doing so. But, opening the isolation switch much later than 0.5ms will cause higher film temperature and longer cooling time constants.

System studies on the 242kV system of "Philadelphia Electric" and transient circuit analysis on the superconducting film have indicated that the isolation switch does not need to interrupt more than 100 amperes or withstand more than 200kV when its contacts are open.

3.2.5 Correlation Between Heat Transfer And Circuit Analyses

The transient heat transfer analysis presented in this section and the computer program developed to do it numerically are based on the assumption that transient heat transfer and circuit analyses can be done separately. This assumption is valid due to the following reasons:

- 1) After the film is switched from superconducting to normal state, its temperature reaches its maximum value within a few nanoseconds whereas it takes more than one μ sec to drop its temperature by 10% (cooldown)

Figure 3.2.16 Effect of Complete Plastic Cover on Film's Temperature.

Figure 3.2.17 Effect of Switching Time on Cool-down of the Device.

3.2.5 Correlation Between Heat Transfer And Circuit Analyses - (Cont'd)

- 2). Current in the film (normal state) reaches its steady state value in less than 20 μ sec whereas the effect of RI^2 heating on film's temperature is negligible before 50 μ sec.

The results of these two analyses and the computer programs developed for them can now be used to analyze and design a superconducting fault current limiter that is thermally stable and electrically effective in limiting the fault current.

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APPENDIX 3.2.A

COMPUTER PROGRAM TO CALCULATE TRANSIENT HEAT TRANSFER FROM SUPERCONDUCTING FILM TO ITS PLASTIC SUBSTRATE AND HELIUM BATH

LISTING

```

00100 PROGRAM HEAT(INPUT,OUTPUT)
00110
00120 THIS PROGRAM DETERMINES FILM'S TEMPERATURE AND ENERGY AS A
00130 FUNCTION OF ITS THICKNESS, CURRENT DENSITY AND INITIAL TEMP.
00140
00150 COMMON /FIX/ ROWD,SGD,FJ,FJM,OMGA,PHI,HK,HM,PK,TB,LIM,LIM1
00160 COMMON /VAR/ M,T,SLP0,IT,CONT,NDX,HDX,PDX,CONT2,TS,IP
00170 COMMON /VAR2/ NPRT,NP1,TMIN,TRATIO,DTPRT,HEC,PEC
00180
00190 DIMENSION HLM(2,36)
00200 ARRAY LENGTH SHOULD BE EQUAL OR LARGE THAN LIM+1
00210 LIM=35
00220
00230 SET UP INITIAL CONDITIONS ...
00240 T IS TIME (SEC) ROW IS FILM RESISTIVITY (OHM-CM)
00250 TF IS FILM TEMPERATURE (K) SG IS FILM SPECIFIC GRAVITY (GM/CM3)
00260 FD IS FILM THICKNESS (CM) CP IS FILM SPECIFIC HEAT (J/GM-K)
00270 FJ IS FILM CURRENT DENSITY (KA/CM2)
00280 DTPRT IS MINIMUM TEMPERATURE CHANGE (P.U.) BEFORE IT IS PRINTED
00290 TMIN IS MINIMUM TEMP. CHANGE (P.U.) BEFORE INCREASING TIME INTERVAL
00300 TRATIO IS RATIO OF NEW TO OLD TIME INTERVALS
00310 NDX IS NUMBER OF HELIUM OR PLASTIC SLICES (SPACE INTERVALS)
00320
00330 TMIN=0.009
00340 TRATIO=2.0
00350 DTPRT=0.02
00360 NDX=2000
00370 T=0
00380 PRINT, * FILM TEMPERATURE TF(K) *,
00390 READ, TF
00400 PRINT, * FILM THICKNESS FD(CM) *,
00410 READ, FD
00420 ROW=0.0003
00430 SG=8.4
00440 SGD=FD*SG
00450 ROWD=ROW*FD
00460 PRINT, * INITIAL FILM CURRENT DENSITY FJ(KA/CM2) *,
00470 READ, FJ
00480 PRINT, * FREQUENCY (CPS) *,
00490 READ, F
00500 OMGA=6.283*F
00510 FJM=FJ
00520 IF (OMGA.LT.1) GO TO 12
00530 PRINT, * MAX. FILM CURRENT DENSITY FJM(KA/CM2) *,
00540 READ, FJM
00550 12 IF (FJM.LT.FJ) FJM=FJ
00560 PRINT, * TIME WHEN ISOLATION SWITCH IS OPENED TS(SEC)*,
00570 READ, TS
00580 PHI=0.0
00590 IF (FJM.NE.0.0) PHI=ASIN(FJ/FJM)

```

```

006000
006100 HK AND PK ARE HELIUM AND PLASTIC THERMAL CONDUCTIVITIES (W/CM-K)
006200 HA AND PA ARE HELIUM AND PLASTIC THERMAL DIFFUSIVITIES (CM2/SEC)
006300 TB IS HELIUM BATH TEMPERATURE (K)
006400
00650 HK=0.0006
00660 HA=0.001
00670 TB=4.2
00680 PK=0.0003
00690 PA=0.00156
007000
007100 FIND INITIAL FILM ENERGY
007200
00730 CALL CFF(TF,CP)
00740 FILMEN=(TF-TB)*SGD*CP
007500
007600 DETERMINE OTHER ITERATION CONSTANTS
007700
00780 M=0
00790 DT=1.0E-07
00800 SLP0=0
00810 NPRT=6
00820 HM=3.0
00830 CONT=0
00840 CONT2=0
00850 HDX=SQRT(HM*HA*DT)
00860 PDX=SQRT(HM*PA*DT)
008700
008800 CALCULATE HELIUM AND PLASTIC ENERGY CONSTANTS.
008900
00900 HEC=HDX*HK/HA
00910 PEC=PDX*PK/PA
009200
009300 PRINT OUT INITIAL INPUT DATA.
009400
00950 PRINT 900, FD,TF,FJM,OMGA,PHI,NDX,HDX,PDX
00960 900 FORMAT(///**FILM THICKNESS*,14X,*FD =*,E9.2,* CM*,/* FILM *,
00970+*INITIAL TEMPERATURE*,4X,*TF =*,F6.1,5X,*K*,/* FILM'S CURRENT *,
00980+*DENSITY      FJ =*,F6.1,* SIN(*,F4.0,* T+*,F5.2,*) (KA/CM2)*,/*
00990+*NUMBER OF SPACE INTERVALS*,3X,*NDX=*,I5,/* HELIUM SPACE *,
01000+*INTERVAL*,6X,* HDX=*,E10.3,* CM*,/* PLASTIC SPACE INTERVAL*,
01010+5X,* PDX=*,E10.3,* CM*)

```

```

010200
010300 SET UP INITIAL TEMPERATURE DISTRIBUTION IN
010400 HELIUM AND PLASTIC ... PRINT THEM OUT.
010500
010600 HLM(1,1)=TF
010700 LIM1=LIM+1
010800 DO 100 I=2,LIM1
010900 100 HLM(1,I)=TF
011000 PRINT 910
011100 910 FORMAT(///*.TIME . . . FILM - FILM . . . HELIUM (OR PLASTIC) *,
011200+*TEMP. (K) AT*,4%,*FILM . . . HE+PL*,/9%,*CURRENT TEMP . . . *,
011300+*MULTIPLES OF HDX (OR PDH) FROM FILM*,2%,*ENERGY . . . ENERGY*,/
011400+* (SEC) (KA/CM2) (K) 1 2 3 4 5 6*,
011500+* (J/CM2) (J/CM2)*
011600 NP1=NPRT + 1
011700 COOLEN=0
011800 PRINT 920, T,FJ,TF,(HLM(1,J),J=2,NP1), FILMEN,COOLEN
011900 920 FORMAT(E8.2,F6.1,F7.1,6F6.1,1X,2E9.1)
012000
012100 ASK FOR THE NUMBER OF ITERATIONS
012200
012300 IF=0
012400 200 PRINT, * ENTER NUMBER OF TIME ITERATIONS NT*
012500 READ, ST
012600 NT=ST+0.1
012700 IF(NT.L1.1) STOP
012800 CALL ITER(NT,HLM)
012900
013000 GO TO 200
013100 END
013200-----
013300

```

```

01340 SUBROUTINE ITER(NT,HLM)
01350C
01360C   THIS ROUTINE EVALUATES FILM, HELIUM AND PLASTIC
01370C   TEMPERATURE DISTRIBUTION THROUGH TIME AND SPACE
01380C
01390 COMMON /FIX/ ROWD,SGD,FJ,FJM,OMGA,PHI,HK,HM,PK,TB,LIM,LIM1
01400 COMMON /VAR/ M,T,SLP0,DT,CONT,NIX,HDX,PDX,CONT2,TS,IF
01410 COMMON /VAR2/ NFRT,NP1,TMIN,TRATIO,DTPRT,HEC,PEC
01420 DIMENSION HLM(2,36)
01430C
01440 TFO=HLM(1,1)
01450 T0=T
01460 DO 400 N=1,NT
01470 M=M+1
01480 T=T+DT
01490 IF (T.GT.TS) FJM=0
01500 CALL CPF(HLM(1,1),CP)
01510 PHASE=OMGA*T+PHI
01520 FJ=FJM*SIN(PHASE)
01530C
01540C   FIND FILM'S POWER FLOW AND TEMPERATURE DROP
01550C
01560 PE=ROWD*FJ**2 * 1.0E+06
01570C
01580 PH=HK*(HLM(1,1)-HLM(1,2))/HDX
01590 PP=PK*(HLM(1,1)-HLM(1,2))/PDX
01600 DTF=(PE-PH-PP)*DT/SGD/CP
01610C
01620C   CHECK TEMPERATURE GRADIENT (DTEMP/DTIME)
01630 SLP=DTF/DT
01640 IF (ABS(SLP).LE.2.0*ABS(SLP0).OR.M.LT.10) GO TO 97
01650 SLP=SIGN(ABS(2.0*SLP0), SLP)
01660 DTF=SLP*DT
01670 CONT2=CONT2+1
01680 97 HLM(2,1)=HLM(1,1)+DTF
01690 SLP0=0.5*(SLP+SLP0)
01700 IF (ABS(SLP0).LT.5) SLP0=SIGN(5.0,SLP0)
01710C
01720C   FIND TEMPERATURE DISTRIBUTION IN HELIUM AND PLASTIC
01730C
01740 DO 300 I=2,LIM
01750 IF (HLM(2,I-1).LE.TB) GO TO 310
01760 300 HLM(2,I)=(HLM(1,I-1)+(HM-2)*HLM(1,I)+HLM(1,I+1))/HM
01770C
01780C   REPLACE THE OLD TEMPERATURE DISTRIBUTION BY THE NEW ONE
01790C
01800 310 DO 350 I=1,LIM
01810 HLM(1,I)=HLM(2,I)
01820 IF ((HLM(1,I)-TB).LT.0.005) GO TO 311
01830 350 CONTINUE
01840C
01850 311 IF (T.GT.0.001 .AND. T-T0.LT.7.0E-04) GO TO 352
01860 IF (T.LT.0.001.AND.T.GT.0.0001.AND.T0/T.GT.0.7) GO TO 352
01870 IF (ABS(TFO-HLM(1,1))/HLM(1,1).LT.DTPRT .AND.
01880+      T-T0.LT.7E-4) GO TO 352

```

```

018900
019000  CALCULATE ENERGIES IN THE FILM AND ITS COOLANTS (HE+PL),
019100  PRINT ENERGY AND TEMPERATURE DISTRIBUTIONS
019200
019300 FILMEN=(HLM(1,1)-TB)*SGD*CF
019400 SUM=0
019500 LIM2=LIM/2
019600 DO 121 JJ=1,LIM2
019700 JD=2*JJ
019800 IF (ABS(HLM(1,JD)-TB).LT.0.01) GO TO 122
019900 121 SUM=SUM+HLM(1,JD-1)+HLM(1,JD)*4+HLM(1,JD+1)
020000 122 COOLEN=(SUM/3.0-JD*TB)*(HEC+PEC)
020100 IF (CONT2.GT.0.5) PRINT 919, CONT2
020200 CONT2=0
020300 PRINT 920, T,FJ, (HLM(1,J),J=1,NP1),FILMEN,COOLEN
020400 TFO=HLM(1,1)
020500 T0=T
020600 IF (T.GT.1.0E-6) DTFRT=0.08
020700 IF (T.GT.0.001) DTFRT=0.13
020800 IP=IP+1
020900
021000  CHECK TEMPERATURE GRADIENT*(DT/DX) AT THE BOUNDARY POINTS
021100 352 IF (NDX.GT.LIM.OR.CONT.GT.0.5) GO TO 600
021200 IF ((HLM(1,NDX)-HLM(1,NDX+1)).GE.(HLM(1,NDX+1)-TB)) GO TO 600
021300 PRINT,* WARNING ... BOUNDARY COND. VIOLATION. CHECK TEMP. DIST.*
021400 CONT=1
021500
021600  IF FILM TEMPERATURE DROP IS TOO SMALL, INCREASE THE TIME INTERVAL
021700
021800 600 IF (IP.LT.3) GO TO 400
021900 IF (ABS(DTF)/HLM(1,1).GT.TMIN .AND. DT.GT.0.008*T) GO TO 400
022000 IF (DT*TRATIO.GE.0.5*T.OR. DT.GT.1.0E-04) GO TO 400
022100 CALL SCALE(HLM)
022200 TFO=HLM(1,1)
022300 T0=T
022400 IP=0
022500 400 CONTINUE
022600 IF (ABS(HLM(1,1)-TFO).LT.0.01) RETURN
022700 PRINT 920, T,FJ, (HLM(1,J),J=1,NP1), FILMEN,COOLEN
022800 920 FORMAT(E8.2,F6.1,F7.1,6F6.1,1X,2E9.1)
022900 919 FORMAT(* FILM TEMP. IS LIMITED*,F6.0,* TIMES.*)
023000 IP=IP+1
023100 RETURN
023200 END
023300-----

```

```

02240 SUBROUTINE SCALE(HLM)
02350C
02360 COMMON /FIX/ ROWD,SGD,FJ,FJM,OMGA,PHI,HK,HM,PK,TB,LIM,LIM1
02370 COMMON /VAR/ M,T,SLP0,DT,CONT,NDX,HDX,PIX,CONT2,TS,IP
02380 COMMON /VAR2/ NPRT,NP1,TMIN,TRATIO,DTPRT,HEC,PEC
02390C
02400 DIMENSION HLM(2,36)
02410C
02420C THIS ROUTINE INCREASES TIME AND SPACE INTERVALS, SETS UP NEW
02430C TEMPERATURE DISTRIBUTION IN HELIUM AND PLASTIC (PRINTS THEM OUT).
02440C
02450 DT=DT*TRATIO
02460 RH0=SQRT(TRATIO)
02470 HDX=HDX*RH0
02480 PIX=PIX*RH0
02490 HEC=HEC*RH0
02500 PEC=PEC*RH0
02510 NSH=1
02520 10 RH=NSH*RH0
02530 IRH=RH
02540 NSH1=NSH+1
02550 IF((2+IRH).GT.LIM) GO TO 20
02560 IF((HLM(1,NSH)-TB).GT.0.01) GO TO 40
02570 20 DO 30 K=NSH1,LIM1
02580 30 HLM(1,K)=TB
02590 NSH=NDX/RH0
02600 GO TO 100
02610 40 S=RH-IRH
02620 HLM(1,NSH1)=(1-S)*HLM(1,IRH+1)+S*HLM(1,IRH+2)
02630 NSH=NSH+1
02640 GO TO 10
02650C
02660 100 NDX=NSH
02670 IF(NDX.GE.6) GO TO 110
02680 PRINT,* THERE ARE NOT ENOUGH PLASTIC AND HELIUM LAYERS LEFT*
02690 PRINT,* NDX IS LESS THAN 6 LAYERS..... EXECUTION STOPS*
02700 STOP
02710C
02720 110 NDX1=NDX+1
02730 PRINT 900, DT,NDX,HDX,PIX
02740 900 FORMAT(/'DT =*,E9.2,* SEC.*,3X,*NDX=*,I4,3X,*HDX=*,E10.3,
02750+ * CM*,3X,*PIX=*,E10.3,* CM*)
02760 PRINT 920, T,FJ,(HLM(1,J),J=1,NP1)
02770 920 FORMAT(E8.2,F6.1,F7.1,6F6.1)
02780 930 FORMAT(21X,9F6.1)
02790 RETURN
02800 END
02810C-----
02820C

```



```

02830 SUBROUTINE CPF(TF,CP)
02840
02850 THIS ROUTINE FINDS FILM'S SPECIFIC HEAT CP (J/GM-K)
02860 AT ANY GIVEN TEMPERATURE TF (K).
02870
02880 IF (TF.GT.100) CP=27*TF**0.18
02890 IF (TF.GT.30.AND.TF.LE.100) CP=0.141*TF**1.58
02900 IF (TF.GT.4.2.AND.TF.LE.30) CP=0.00686*TF**2.46
02910 IF (TF.LE.4.2) GO TO 10
02920 CP=CP*0.001
02930 RETURN
02940 10 PRINT, * FILM'S TEMPERATURE IS MUCH BELOW ITS CRITICAL TEMP. TC*
02950 STOP
02960 END
*RDY*

```

APPENDIX 3.2.B

TYPICAL OUTPUT OF TRANSIENT HEAT TRANSFER PROGRAM

RUN

03/19/80. 08.31.15.
PROGRAM HEAT

FILM TEMPERATURE TF(K) ? 111
FILM THICKNESS FD(CM) ? 5E-4
INITIAL FILM CURRENT DENSITY FJ(KA/CM2) ? 15.54
FREQUENCY (CPS) ? 0
TIME WHEN ISOLATION SWITCH IS OPENED TS(SEC) ? 1

FILM THICKNESS FD = 5.00E-04 CM
FILM INITIAL TEMPERATURE TF = 111.0 K
FILM'S CURRENT DENSITY FJ = 15.5 SIN(0 T+ 1.57) (KA/CM2)

NUMBER OF SPACE INTERVALS NDX= 8000
HELIUM SPACE INTERVAL HDX= 1.732E-05 CM
PLASTIC SPACE INTERVAL PDX= 2.163E-05 CM

TIME (SEC)	FILM CURRENT (KA/CM2)	FILM TEMP (K)	HELIUM (OR PLASTIC) TEMP.(K) AT MULTIPLES OF HDX (OR PDX) FROM FILM						FILM ENERGY (J/CM2)	HE+PL ENERGY (J/CM2)
			1	2	3	4	5	6		
0.	15.5	111.0	4.2	4.2	4.2	4.2	4.2	4.2	9.1E-02	0.
ENTER NUMBER OF TIME ITERATIONS NT										
? 800										
1.00E-07	15.5	108.7	39.8	4.2	4.2	4.2	4.2	4.2	8.9E-02	4.1E-03
3.00E-07	15.5	105.9	58.0	23.7	8.2	4.2	4.2	4.2	8.6E-02	6.5E-03
6.00E-07	15.5	103.1	68.2	38.8	19.3	9.2	5.4	4.3	8.3E-02	8.9E-03
DT = 2.00E-07 SEC. NDX=5656 HDX= 2.449E-05 CM PDX= 3.059E-05 CM										
6.00E-07	15.5	103.1	56.0	22.7	8.3	4.7	4.2	4.2		
1.00E-06	15.5	100.3	63.7	33.8	15.5	7.3	4.8	4.3	8.1E-02	1.1E-02
1.40E-06	15.5	98.1	67.6	40.9	21.9	11.2	6.4	4.7	7.9E-02	1.3E-02
3.40E-06	15.5	90.3	72.7	55.2	39.7	27.1	17.9	11.7	6.3E-02	1.9E-02
DT = 4.00E-07 SEC. NDX=3999 HDX= 3.464E-05 CM PDX= 4.327E-05 CM										
3.40E-06	15.5	90.3	65.5	42.3	24.8	13.8	7.8	5.4		
6.20E-06	15.5	82.7	66.8	50.4	35.8	24.1	15.6	10.2	5.1E-02	2.4E-02
9.40E-06	15.5	76.1	65.0	53.0	41.4	31.0	22.4	15.9	4.1E-02	2.8E-02
1.30E-05	15.5	70.2	62.2	53.2	43.9	35.2	27.4	20.8	3.3E-02	3.0E-02

DT = 8.00E-07 SEC. NDX=2827 HDX= 4.899E-05 CM PDX= 6.119E-05 CM

1.30E-05	15.5	70.2	58.4	45.5	33.3	23.1	15.4	10.4		
1.70E-05	15.5	64.7	56.1	46.1	35.9	26.7	19.2	13.6	2.7E-02	3.3E-02
2.18E-05	15.5	59.3	53.1	45.4	37.2	29.4	22.4	16.7	2.1E-02	3.4E-02
2.66E-05	15.5	54.9	50.2	44.2	37.5	30.8	24.5	19.1	1.7E-02	3.6E-02
3.22E-05	15.5	50.7	47.2	42.6	37.2	31.5	26.1	21.1	1.4E-02	3.7E-02
3.86E-05	15.5	46.8	44.3	40.7	36.4	31.7	27.0	22.6	1.1E-02	3.8E-02

DT = 1.60E-06 SEC. NDX=1998 HDX= 6.928E-05 CM PDX= 8.653E-05 CM

4.02E-05	15.5	46.0	42.2	36.8	30.6	24.3	18.7	14.1		
4.82E-05	15.5	42.1	39.5	35.4	30.4	25.1	20.1	15.7	8.5E-03	3.9E-02
5.78E-05	15.5	38.8	36.8	33.7	29.7	25.4	21.1	17.1	6.8E-03	3.9E-02
7.06E-05	15.5	35.6	34.1	31.7	28.6	25.2	21.7	18.2	5.3E-03	4.0E-02

DT = 3.20E-06 SEC. NDX=1412 HDX= 9.798E-05 CM PDX= 1.224E-04 CM

7.54E-05	15.5	34.6	32.3	28.7	24.3	19.6	15.3	11.7		
9.14E-05	15.5	31.8	30.1	27.4	23.8	20.0	16.3	12.9	3.9E-03	4.0E-02
1.33E-04	15.5	27.9	26.6	24.8	22.5	19.9	17.2	14.6	2.5E-03	4.1E-02
1.91E-04	15.5	25.4	24.2	22.8	21.1	19.3	17.3	15.4	1.8E-03	4.3E-02

DT = 6.40E-06 SEC. NDX= 998 HDX= 1.386E-04 CM PDX= 1.731E-04 CM

1.91E-04	15.5	25.4	23.6	21.4	18.8	16.1	13.4	11.0		
LIMIT	5 TIMES.									
2.93E-04	15.5	23.5	21.9	20.1	18.2	16.2	14.2	12.4	1.3E-03	4.6E-02
LIMIT	41 TIMES.									
9.97E-04	15.5	23.6	22.1	20.6	19.2	17.8	16.5	15.3	1.3E-03	7.1E-02
LIMIT	29 TIMES.									
1.70E-03	15.5	26.0	24.4	23.0	21.6	20.2	18.9	17.7	1.9E-03	1.0E-01

DT = 1.28E-05 SEC. NDX= 705 HDX= 1.960E-04 CM PDX= 2.448E-04 CM

1.70E-03	15.5	26.0	23.8	21.8	19.9	18.1	16.5	15.0		
LIMIT	13 TIMES.									
2.40E-03	15.5	28.4	26.2	24.2	22.2	20.5	18.8	17.2	2.6E-03	1.2E-01
LIMIT	14 TIMES.									
3.11E-03	15.5	30.6	28.4	26.3	24.4	22.6	20.9	19.3	3.5E-03	1.5E-01
LIMIT	4 TIMES.									
3.81E-03	15.5	32.6	30.4	28.4	26.4	24.6	22.8	21.2	4.1E-03	1.8E-01

DT = 2.56E-05 SEC. NDX= 498 HDX= 2.771E-04 CM PDX= 3.461E-04 CM

3.81E-03	15.5	32.6	29.6	26.8	24.2	21.8	19.6	17.6		
LIMIT	7 TIMES.									
4.53E-03	15.5	34.7	31.6	28.7	26.1	23.7	21.4	19.3	4.9E-03	2.0E-01
LIMIT	9 TIMES.									
5.25E-03	15.5	36.5	33.4	30.6	27.9	25.4	23.1	21.0	5.6E-03	2.2E-01
LIMIT	10 TIMES.									
5.96E-03	15.5	38.3	35.2	32.3	29.6	27.1	24.8	22.6	6.4E-03	2.5E-01

DT = 5.12E-05 SEC. NDX= 352 HDX= 3.919E-04 CM PDX= 4.895E-04 CM

5.96E-03	15.5	38.3	34.0	30.1	26.6	23.4	20.5	18.0		
LIMIT	4 TIMES.									
6.68E-03	15.5	40.1	35.7	31.8	28.2	24.9	22.0	19.4	7.2E-03	2.7E-01
LIMIT	3 TIMES.									
7.40E-03	15.5	41.7	37.4	33.4	29.7	26.4	23.4	20.7	8.0E-03	3.0E-01
LIMIT	2 TIMES.									
8.11E-03	15.5	43.2	38.9	34.9	31.2	27.9	24.8	22.1	8.8E-03	3.3E-01

DT = 1.02E-04 SEC. NDX= 218 HDX= 5.543E-04 CM PDX= 6.923E-04 CM

8.11E-03	15.5	43.2	37.3	31.9	27.1	23.0	19.4	16.4		
LIMIT	4 TIMES.									
8.83E-03	15.5	44.8	38.7	33.3	28.5	24.3	20.7	17.5	9.7E-03	3.5E-01
LIMIT	2 TIMES.									
9.55E-03	15.5	46.2	40.2	34.7	29.9	25.6	21.9	18.6	1.1E-02	3.8E-01
LIMIT	3 TIMES.									
1.03E-02	15.5	47.7	41.6	36.1	31.2	26.9	23.1	19.7	1.1E-02	4.0E-01
LIMIT	2 TIMES.									
1.10E-02	15.5	49.2	43.0	37.5	32.5	28.1	24.2	20.8	1.2E-02	4.3E-01
LIMIT	2 TIMES.									
1.17E-02	15.5	50.3	44.3	38.8	33.8	29.3	25.3	21.9	1.3E-02	4.6E-01
LIMIT	1 TIMES.									
1.24E-02	15.5	51.7	45.6	40.0	35.0	30.5	26.5	22.9	1.4E-02	4.8E-01
LIMIT	2 TIMES.									
1.31E-02	15.5	52.9	46.8	41.2	36.2	31.6	27.5	23.9	1.5E-02	5.1E-01
LIMIT	1 TIMES.									
1.38E-02	15.5	54.2	48.0	42.4	37.3	32.7	28.6	24.9	1.6E-02	5.4E-01
LIMIT	2 TIMES.									
1.44E-02	15.5	55.2	49.2	43.6	38.5	33.8	29.7	25.9	1.7E-02	5.6E-01
LIMIT	2 TIMES.									
1.53E-02	15.5	56.5	50.3	44.7	39.6	34.9	30.7	26.9	1.8E-02	5.9E-01
LIMIT	3 TIMES.									
1.60E-02	15.5	57.5	51.4	45.8	40.7	36.0	31.7	27.9	1.9E-02	6.2E-01
LIMIT	3 TIMES.									
1.67E-02	15.5	58.7	52.5	46.9	41.7	37.0	32.7	28.8	2.0E-02	6.4E-01
LIMIT	2 TIMES.									
1.74E-02	15.5	59.6	53.6	47.9	42.8	38.0	33.7	29.8	2.1E-02	6.7E-01
LIMIT	1 TIMES.									
1.81E-02	15.5	60.8	54.6	49.0	43.8	39.0	34.6	30.7	2.2E-02	7.0E-01
1.89E-02	15.5	61.7	55.7	50.0	44.8	40.0	35.6	31.6	2.3E-02	7.2E-01
1.96E-02	15.5	62.8	56.7	51.0	45.8	40.9	36.5	32.5	2.4E-02	7.5E-01
2.03E-02	15.5	63.7	57.7	52.0	46.7	41.9	37.4	33.4	2.5E-02	7.8E-01
2.10E-02	15.5	64.7	58.6	52.9	47.7	42.8	38.3	34.2	2.6E-02	8.0E-01
2.17E-02	15.5	65.7	59.6	53.9	48.6	43.7	39.2	35.1	2.7E-02	8.3E-01
2.21E-02	15.5	66.2	60.1	54.4	49.1	44.2	39.7	35.6	2.7E-02	8.3E-01
ENTER NUMBER OF TIME ITERATIONS NT										
? 80										
2.29E-02	15.5	67.1	61.0	55.3	50.0	45.1	40.6	36.4	2.9E-02	8.7E-01
2.36E-02	15.5	68.0	62.0	56.3	50.9	46.0	41.4	37.2	3.0E-02	9.0E-01
2.43E-02	15.5	68.9	62.9	57.1	51.8	46.9	42.3	38.1	3.1E-02	9.2E-01
2.50E-02	15.5	69.8	63.7	58.0	52.7	47.7	43.1	38.9	3.2E-02	9.6E-01
2.57E-02	15.5	70.7	64.6	58.9	53.5	48.6	43.9	39.7	3.3E-02	9.9E-01
2.64E-02	15.5	71.6	65.5	59.8	54.4	49.4	44.8	40.5	3.4E-02	1.0E+00
2.72E-02	15.5	72.4	66.3	60.6	55.2	50.2	45.6	41.2	3.5E-02	1.0E+00
2.79E-02	15.5	73.3	67.2	61.4	56.1	51.0	46.4	42.0	3.6E-02	1.1E+00
2.86E-02	15.5	74.1	68.0	62.3	56.9	51.8	47.1	42.8	3.7E-02	1.1E+00
2.93E-02	15.5	74.9	68.8	63.1	57.7	52.6	47.9	43.5	3.8E-02	1.1E+00
3.00E-02	15.5	75.7	69.6	63.9	58.5	53.4	48.7	44.3	3.9E-02	1.1E+00
3.03E-02	15.5	76.1	70.0	64.2	58.8	53.7	49.0	44.6	3.9E-02	1.1E+00
ENTER NUMBER OF TIME ITERATIONS NT										
? 0										
STOP.										
RDY										

3.3 Superconducting Element and Switching Coil; Configurations, Inductance and Field

3.3.1 Design Objectives and Constraints

The superconducting element and switching coil (items # 1 and # 6 in Figure 1.1) are closely related in their functions and geometries and the designs of these two components are therefore carried out together. These designs must satisfy the following criteria:

1. Length, width and thickness of the superconducting element are determined by circuit and heat transfer requirements, as described in Sections 3.1 and 3.2. The nominal design objectives chosen for illustration are:

Length	1000 m
Width	10 cm
Thickness	5 - 10 μ m
Substrate Thickness	1 mm

2. Substrate material should maintain its strength at liquid helium temperatures and should be nonconducting. Mylar^R is a suitable choice for the substrate.

3. Electric fields during current - limiting operations should be below corona-start and flashover values. Adjacent conducting films will be separated by mylar and/or helium; some dielectric properties of these materials are:

<u>Material</u>	<u>Dielectric Strength</u>	<u>Relative Permittivity</u> (60 Hz)
mylar ¹	~ 100 kV/mm	3.3
liquid helium (boiling)	~ 6 kV/mm ²	1.05 ³

1. "Mylar^R" Polyester film; Dupont technical information bulletin M-4D
2. "Cryogenic Power Transmission Technology - Cryogenic Dielectrics", ORNL/TM-5941, for ERDA, July 1977.
3. American Institute of Physics Handbook, Table 5d - 8, McGraw-Hill, New York, 1957.

4. The switching coil should generate a magnetic field normal to the superconducting film surface. For maximum coil efficiency, this normal component will be nearly uniform over the entire film and will have minimal tangential component. We assume that the normal component of field must be at least 200 gauss (H_{C1}) for the design worked out in this section. Experimental measurements (see Section 4) will determine the exact required value for this parameter. Small sections where the field does not reach the switching level can be tolerated since it merely means that that area remains superconducting. This will result in a longer, more costly device.

3.3.1 (Continued)

5. The configuration of the superconducting film should have low inductance, for minimum system disturbance while conducting, for rapid switching into the limiting state, and in order to keep film heating low (see section 3.1).
6. There should be minimal mutual inductive coupling between the switching coil and the superconducting element. This is to avoid high induced voltages in the film when the switching coil is pulsed.

3.3.2 Superconducting element configuration

The superconducting element (the "element") will be a flat thin film of length l , width w and thickness d , supported on a plastic substrate of thickness d_s . The substrate length and width are taken to be l and w , although there may be some small extra substrate edge required for fastening and separation from adjacent film. The film might be on one side of the substrate but it probably will have to be on both sides ("double sided") in order to keep the inductance low. There must be an adequate depth of liquid helium directly against the superconducting film to receive heat during switching and to cause the film to rapidly recover its superconducting state after an operation.

The element must be located in an insulated container (dewar), and this requirement rules out excessively complicated geometries. As a result, three basic configurations have been considered:

1. Folded ("accordion" style).

The long flat ribbon is folded many times, so that a long ribbon can fit in a relatively short dewar cylinder. The film would be laid on both sides of the substrate ("double-sided"), series connected at one end of the ribbon, with both terminals at the same end of the dewar. This design is shown in Figure 3.3.1.

Advantage: A simple solenoidal coil surrounding the cylindrical dewar can be used to generate the switching field.

Disadvantages: There is concern that folding will weaken the film. There is also no electrical shielding and strong, corona-producing electric fields are therefore liable to exist at the sharp edges of the film. Unless an oval cross-section dewar is used, the length of the folded element will still be quite long.

2. Radial Spirals

The long, flat, double-sided substrate ribbon is wound into spirals which are then inserted into an annular dewar, as shown in Figure 3.3.2. Adjacent spirals are electrically connected in series so that the element finally ends up as a set of series-connected film sections. A four-pole magnetic field winding is used to generate the switching field (This field is analysed in a subsequent section of this report).

Figure 3.3.1 Folded ("accordian") element design

Figure 3.3.2 Radial spiral element design

FIGURE 3.3.2b RADIAL SPIRAL ELEMENT DESIGN - HIGH VOLTAGE BUSHINGS AT EACH END. (SEE FIGURE 3.3.5 FOR S/C ELEMENT DETAIL)

3.3.2 (Continued)

Advantages: The double-sided substrate could be free-standing inside the dewar. There is very little inductive coupling between the element and the coil.

Disadvantages: If the "top" and "bottom" films of all spirals are connected in series, then two bushings can be at the same end of the dewar, but the substrate must support the full FCL voltage during operation. If the two sides are short-circuited at the end of each spiral, then the substrate need only support a fraction of the total limiting voltage, but the input and output terminals must be located at opposite ends of the dewar.

3. Coaxial helical spirals

Long, flat, single-sided substrate ribbons are wound as helices on the inside and outside surfaces of rigid coaxial plastic cylinders (Figure 3.3.3). (A helix made from a double-sided substrate ribbon would have to be self-supporting, and it was felt that proper clearances could not be maintained between adjacent layers.) Helices are wound on both the inside and outside of the supporting cylinder to keep very close spacing, and these two helices are then connected in series (current traveling in one direction in the "top" helix and the other direction in the "lower" helix) so that the self inductance is minimized. All double helices are also connected in series to produce the desired high resistance during limiting operation. A four pole magnetic field coil is used for this element configuration (Section 3.3.4).

Advantages: The substrate (and support cylinder) need only withstand a portion of the full limiting voltage, and both bushings can still be at the same end of the dewar. The film edges on adjacent helix-turns face each other, so there is very little voltage and little likelihood of corona. There is very little inductive coupling between the element and the coil.

Disadvantages: Requiring the additional plastic cylinder for support, with windings inside and outside, adds somewhat to the self-inductance of the element and makes assembly more difficult.

3.3.3 Typical dimensions for the coaxial helical spiral design

The helical spiral geometry appears to have sufficient advantages to deserve further study. We seek dimensions which will approximate the parameters used in the circuit and heat transfer analyses (see section 3.3.1, "Design Objectives and Constraints").

Consider a coaxial helical element which has film (and substrate) width w helix axial length, ℓ , p coaxial layers, d radial spacing between adjacent layers and R , inner layer radius. The length of each helix will be,

$$\text{helix length} \approx \frac{\ell}{w} \times 2 \pi R + \ell$$

and each layer ("top" plus "bottom") will contribute twice this length.

Figure 3.3.3 Coaxial helical spiral element design

3.3.3 (Continued)

The total element length therefore is:

$$L \cong \sum_{n=1}^p \left(2 \left(\frac{\ell}{w} \times 2 \pi R_n + \ell \right) \right)$$

$$\text{where } R_n = R_1 + (n-1) d$$

$$\text{or } L \cong \ell \sum_{n=1}^p \left(\frac{4\pi}{w} (R_1 + (n-1) d) + 2 \right)$$

A suitable solution which meets the design objectives for purposes of illustration is:

$$\begin{aligned} w &= .10 \text{ m} \\ \ell &= 3.0 \text{ m} \\ p &= 3 \\ d &= .031 \text{ m} \\ R_1 &= .875 \text{ m} \\ L &= 1013 \text{ m} \end{aligned}$$

3.3.4 Typical dimensions, inductances and assembly designs for the radial spiral concept (Figure 3.3.2)

The following parameters are defined for analysis of the radial spiral superconducting current limiter:

number of spiral sections	n_s
number of turns per spiral	p
inner radius	r_1
spacing between adjacent turns	d
element width	w_e
spacing between adjacent spirals	w_s
element thickness	t_e
substrate thickness	t_s

The total length of the superconducting element (ℓ_e) will be the length per spiral times the number of spirals:

$$\ell_e \cong n_s \times (2p) \times 2\pi \bar{r},$$

where the $(2p)$ factor indicates that the S/C element is on each side of the spiraled substrate, and $\bar{r}$ is the mean radius:

$$\bar{r} = r_1 + (p/2) d,$$

The axial length (ℓ_a) of the structure will be determined by the width per spiral, spacing between spirals* and the number of spirals:

$$\ell_a = n_s (w_e + w_s)$$

The normal resistance of the S/C element is:

$$R = \rho \ell_e / w_e t_e$$

where ρ is the normal resistivity.

*Note that the spacing between adjacent windings of the helical spiral (section 3.3.3) was small and therefore neglected. The spacing between adjacent spirals in the radial spiral design must include the support and spacing structure for each spiral and must therefore be considered.

Figure 3.3.4 DESIGN CHART FOR RADIAL SPIRAL SUPERCONDUCTING FAULT CURRENT LIMITER

The inductance per unit length of double-sided substrate is given by:

$$L^1 = \mu_0 t_s / w_e$$

Figure 3.3.4 shows plots of element length, normal resistance and element inductance versus number of spiral sections (and therefore axial length) for different spiral designs. Any required current limiting resistance can be obtained by several combinations of spiral design and number of spirals. The choice would depend on manufacture, assembly, operating cost and reliability considerations.

The "base case" design ($R = 3.0k \Omega$) used in the analyses of sections 3.1 and 3.2 is indicated on Figure 3.3.4. This normal resistance could be achieved using eight one-meter (radius) by five-turn spirals, 27 .75-meter by two-turn spirals or any of several intermediate designs. The cryogenic surface area might be the determining factor since cost of helium refrigeration will be a major operating cost.

Note that the "base case" design will have only about $3\mu H$ internal inductance. The external inductance of the connectors and leads must be added to this value to obtain the full inductance L_{SC} of Figure 3.1.1.

A conceptual design for a radial spiral SCFCL is shown in Figure 3.3.5. This shows each turn of each spiral being supported so that the S/C films always stay in contact with helium and do not sag against each other. Cryogenics engineering principles must be applied to the final design of the cryostat and high voltage bushing, in order to minimize helium refrigeration cost.

Figure 3.3.5 Conceptual Design for a Radial Spiral Superconducting Fault Current Limiter

3.3.5 Four-pole switching field analysis.

A four-pole, air-core field has been recommended for use with the two spiral element designs (Figure 3.3.2, 3.3.3). This field and coil arrangement will now be analysed to show to what extent it satisfies the switching field design requirements (Objective # 4). Brief comments will then be made on advantages and disadvantages of using iron and of going to a larger number of poles.

The four-pole coil arrangement is shown in Figure 3.3.6, with dimensions and currents defined. The field will be analysed along the central annular cross section shown in Figure 3.3.6. The following parameters must be defined.

element inside radius R_1
element outside radius R_2
Field point: radius R ($R_1 < R < R_2$)
 azimuth angle θ ($0 < \theta < \pi/2$)
 (The field repeats itself each quadrant)

(coil designations:

LC large coil, close to field point
SC small coil, close to field point
LF large coil, far from field point
SF small coil, far from field point)

coil dimensions

half length A (all coils have the same length)
large coil half width Y_L
small coil half width Y_S
large coil axial position Z_L
small coil axial position Z_S

magnetic field components

transverse $BY_{LC}, BY_{SC} \dots$
axial $BZ_{LC}, BZ_{SC} \dots$

Figure 3.3.6 Four-pole (four-coil) field winding, shown with coaxial helical spiral element

In Appendix A3.1, the magnetic field generated by a single rectangular coil is derived in terms of the length (2A) width (2B), field position (Y, Z), and current I. The four pole (four coil) field is found as an algebraic sum of the fields from each of the four coils taking proper account for directions of the field components from each coil at each field point. Appendix A3.2 shows the computer program which was used to calculate this total field.

The typical dimensions derived in Section 3.3.3 were used in the A3.2 computer program, and the results are plotted in Figures 3.3.7 and 3.3.8. Note that the coil length, 3.4 m, is chosen longer than the element length (3.0m) to diminish the end effects. In Figure 3.3.7, the radial component of the field (per ampere of coil current) is shown for the inner, center and outer layers, for angles from 0 to 45°. From 45° to 90°, the pattern is a mirror image of 3.3.7, with negative values for the field. The pattern repeats itself for each of the other three quadrants.

The usefulness of this coil design can be evaluated by assuming that the switch will occur when the lowest field at the pole ($\theta = 0^\circ$) (6.7×10^{-7} T/A) reaches the switching field magnitude. All of the coil from 0° to 38.4° will also have switched, and so, if the coil current is maintained at this level, about 85% of the coil ($38.4/45 = .853$) will switch.

The remaining 15%, in the vicinity of the coil locations, will remain superconducting. Thus, if the limiting resistance requires film length of 1000 m, then the actual film length must be 1150 m, knowing that 150 m may not switch.

The field sketch shown in Figure 3.3.8 gives a semi quantitative indication of the field shape at the poles and at the coil locations. The "dead spot" near the coils and the nearly totally radial field elsewhere are clearly seen from this sketch. All things considered, this would appear to be a reasonably efficient method for generating the necessary switching field normal to the film.

Figure 3.3.7 Radial magnetic field produced by the four-pole (four-coil) winding at the inner, center and outer superconducting film helices (see Figure 3.3.6.)

ΔY

Figure 3.3.8 Sketch of magnetic field produced by four-pole (four-coil) field winding. Arrows show direction and approximate magnitude of field.

The improvement which can be gained by using iron can be estimated. Let us imagine that all space except an annular air-gap region between $R = .825$ and $R = 1.05$ m is filled with high permeability iron. This air gap width is chosen to allow 5 cm outside and inside the superconducting film for the dewar walls. Essentially all of the mmf of any magnetic circuit will be in this air gap, and so the air gap field will be

$$H_a = \frac{2I \text{ (two coils per loop)}}{2\ell_a \text{ (two air gap lengths per loop)}}$$

$$\text{or } \frac{B}{I} = \frac{\mu_0}{\ell_a} = \frac{4\pi \times 10^{-7}}{1.05 - .825} = 55.9 \times 10^{-7} \text{ T/A}$$

A factor of about 8 times ($55.9/6.7 = 8.34$) improvement has been achieved by use of iron. The uniformity of the radial component and the extent of the "dead spot" are probably also improved by iron. A thorough economic analysis would have to be made to determine whether the benefit (lower current) is worth the cost (large amount of iron and higher coil inductance so more difficult to pulse).

Our preliminary guess is that the benefits gained by using iron are not worth the cost.

More coils, and more poles, can be used to make the field more uniform over a greater percentage of the full element circumference. Again, no quantitative evaluation has been made, but it is assumed that the extra coils do not contribute enough gain in field characteristics to warrant the extra cost.

Four-pole air-core switching-field coil designs will now be considered for the radial spiral current limiter analysed in Section 3.3.4. Consider the "base case" in Figure 3.3.4. The following dimensions are taken for that case from Figure 3.3.4:

normal resistance	3k Ω
number of sections	17
axial length	2.25 m
number of turns per spiral	3
inner turn radius	.75 m
spacing between turns	.01 m

Assume that the field coil extends 20 cm beyond each end of the S/C coils:

$$A = (2.25 + .40)/2 = 1.325 \text{ m}$$

The outer S/C turn will be at radius = .77 m.

We will calculate the radial component of the magnetic field (i.e., the component normal to the S/C film) for a 4-pole coil as shown in Figure 3.3.6. Calculations are made for angular positions 0 to 45° (the field reverses sign but repeats in magnitude each 45°), at the inner ($R = .75 \text{ m}$) and outer ($R = .77 \text{ m}$) S/C films, for three field coil positions, close to the cryostat wall, 10 cm out from the cryostat and 20 cm out from the cryostat and 20 cm out from the cryostat. (The reader is referred to Figure 3.3.5 for a drawing showing the cryostat and S/C coils.)

The results of these calculations are shown in Figure 3.3.9. Three facts are evident from these curves:

1. There is only a small percentage difference between the field strengths at the inner and outer S/C films.
2. The angular uniformity of the field improves as the field coils recede away from the S/C windings.
3. The "dead-space", that is, the angular extent of the film in which the magnetic field is below the $\theta = 0^\circ$ value, increases as the field coils reced away from the S/C windings.

These factors indicate the constraints on optimum specification of the field coils. Excessive non-uniformity of the field will cause non-uniformity in the instances at which different sections of the coil become normal. This would cause localized heating of the film sections which first convert. A large "dead-space", where the film never becomes normal, will require that the film, cryostat, etc., be made considerably larger and costlier than desired.

Figure 3.3.9 Radial magnetic field; base case radial spiral SCFL design

4×10^{-6}

CURVE

YS

ZS

YL

ZL

1

.488

.488

.587

.587

2

.452

.452

.622

.622

3

.417

.417

.658

.658

A = 1.325m (field coil length)

3

Inner: S/C film R = .75

Outer: S/C film R = .77

RADIAL MAGNETIC FIELD (TESLA/AMPERE)

2

1

1

2

3

10

20

30

40

50°

ANGULAR POSITION

3-60

Possibly a compromise strategy should be adapted, in which non uniformity is kept down to an acceptable level, as perhaps shown in curves 2 or 3, and "dead-space" is reduced by using higher current than required for switching at $\theta = 0^\circ$.

Appendix 3.3.A Derivation of the magnetic field produced by a single-turn rectangular loop - in the central plane normal to the plane of the loop

$$r_1 = \sqrt{x_1^2 + (y-b)^2 + z^2}$$

$$r_{14} = \sqrt{a^2 + (y-b)^2 + z^2}$$

$$r_3 = \sqrt{x_3^2 + (y+b)^2 + z^2}$$

$$r_{34} = \sqrt{a^2 + (y+b)^2 + z^2}$$

Calculate magnetic vector potential at the field point $(0, y, z)$:

$$\vec{A} = \frac{\mu_0}{4\pi} \int \frac{I d\vec{s}}{r}$$

Integrals from sides 2 and 4 cancel

$$\begin{aligned} A_x &= \frac{\mu_0 I}{4\pi} \left\{ \int_a^{-a} \frac{dx (-\hat{a}_1)}{\sqrt{x_1^2 + (y-b)^2 + z^2}} + \int_{-a}^a \frac{dx (+\hat{a}_1)}{\sqrt{x_3^2 + (y+b)^2 + z^2}} \right\} \\ &= \frac{\mu_0 I}{4\pi} \left\{ \ln(-a + r_{14}) - \ln(a + r_{14}) \right. \\ &\quad \left. + \ln(a + r_{34}) - \ln(-a + r_{34}) \right\} \end{aligned}$$

$$A_y, A_z = 0$$

Calculate magnetic field from magnetic vector potential:

$$B_y = \frac{\partial A_x}{\partial z}$$

$$B_z = -\frac{\partial A_x}{\partial y}$$

$$B_x = 0$$

$$B_y = \frac{\mu_0 I}{4\pi} \left\{ \frac{1}{-a + r_{14}} \left(\frac{1}{2} \right) - \frac{2z}{r_{14}} \right\}$$

$$B_y = \frac{\mu_0 I}{4\pi} \left\{ \frac{z}{r_{14}(r_{14}-a)} - \frac{z}{r_{14}(r_{14}+a)} + \frac{z}{r_{34}(r_{34}+a)} - \frac{z}{r_{34}(r_{34}-a)} \right\}$$

$$B_z = -\frac{\mu_0 I}{4\pi} \left\{ \frac{(y-b)}{r_{14}(r_{14}-a)} - \frac{(y-b)}{r_{14}(r_{14}+a)} + \frac{(y+b)}{r_{34}(r_{34}+a)} - \frac{(y+b)}{r_{34}(r_{34}-a)} \right\}$$

Listing

LIST OF COLFLD

```

00100      PROGRAM COLFLD (INPUT,OUTPUT)
00110C     THIS PROGRAM CALCULATES THE MAGNETIC FIELD
00111C     FROM A FOUR COIL COAXIAL ARRAY, A HALF WIDTH,
00112C     BS, BL HALF HEIGHTS, ZS, ZL AXIAL POSITIONS.
00113C     UNITS OF B ARE TESLA PER AMPERE, LENGTHS
00114C     ARE IN METERS, ANGLES ARE IN RADIANS
00120      A=1.7
00130      R=1.
00140      BS=.5
00150      BL=.825
00160      ZS=.5
00170      ZL=.825
00180      PRINT,*A,R*,
00190      PRINT, A,R
00200      PRINT, *BS,BL*,
00210      PRINT, BS,BL
00220      PRINT,*ZS,ZL*,
00230      PRINT, ZS,ZL
00240      10 CONTINUE
00250      THETA=.471
00260      20 CONTINUE
00270      Y=R*SIN(THETA)
00280      Z=R*COS(THETA)
00290      PRINT, *R,THETA*,
00300      PRINT, R,THETA
00310C     CALCULATE LARGE CLOSE COIL FIELD
00320      B=BL
00340      ZUS=ZL-Z
00350      ZU=ABS(ZUS)
00360      CALL CALCFLD(A,Y,B,ZU,BY,BZ)
00370      IF(Z.GT.ZL) BYLC=BY
00380      IF(Z.LE.ZL) BYLC=(-1)*BY
00390      BZLC=BZ
00400      PRINT,*BYLC,BZLC*,
00410      PRINT, BYLC,BZLC
00420C     CALCULATE SMALL CLOSE COIL FIELD
00430      B=BS
00440      ZUS=ZS-Z
00450      ZU=ABS(ZUS)
00460      CALL CALCFLD(A,Y,B,ZU,BY,BZ)
00470      IF(Z.GT.ZS) BYSC=BY
00480      IF(Z.LE.ZS) BYSC=(-1)*BY
00490      BZSC=BZ
00500      PRINT, *BYSC,BZSC*,
00510      PRINT, BYSC,BZSC

```

Listing (continued)

```

005600 CALCULATE LARGE FAR FIELD
00570     B=BL
00580     ZU=ZL+Z
00590     CALL CALCFLD(A,Y,B,ZU,BY,BZ)
00600     BYLF=(-1)*BY
00610     BZLF=(-1)*BZ
00620     PRINT,*BYLF,BZLF*,
00630     PRINT, BYLF,BZLF
006400 CALCULATE SMALL FAR FIELD
00650     B=BS
00660     ZU=ZS+Z
00670     CALL CALCFLD(A,Y,B,ZU,BY,BZ)
00680     BYSF=(-1)*BY
00690     BZSF=(-1)*BZ
00700     PRINT, *BYSF,BZSF*,
00710     PRINT, BYSF,BZSF
007200 CALCULATE TOTAL FIELDS AT P, THETA
00730     BYT=BYLC+BYSC+BYLF+BYSF
00740     BZT=BZLC+BZSC+BZLF+BZSF
00750     RATE=BYT/BZT
00760     THETAB=ATAN(RATE)
00770     BMAG=((BYT**2)+(BZT**2))**.5
00780     PRINT, *BYT,BZT*,
00790     PRINT, BYT,BZT
00800     PRINT, *ANGLE B, MAGNITUDE B*,
00810     PRINT, THETAB,BMAG
00812     THETA=THETA+.0524
00814     IF (THETA.LE.1.10) 20,30
00816 30 CONTINUE
00820     STOP
00830     END
00840     SUBROUTINE CALCFLD(A,Y,B,ZU,BY,BZ)
00850     R14=((A)**2+(Y-B)**2+(ZU)**2)**.5
00860     R34=((A)**2+(Y+B)**2+ZU**2)**.5
00870     BY=(10.**(-7))*((ZU/(R14*(R14-A)))-
00880+      (ZU/(R14*(R14+A)))+(ZU/(R34*(R34+A)))-
00890+      (ZU/(R34*(R34-A))))
00900     BZ=(-1)*(10.**(-7))*(((Y-B)/(R14*(R14-A)))-
00910+      ((Y-B)/(R14*(R14+A)))+((Y+B)/(R34*(R34+A)))-
00920+      ((Y+B)/(R34*(R34-A))))
01000     RETURN
01010     END
*FIY*

```


Typical Output

RUN

07/30/79. 15.11.24.
PROGRAM 4COLFLD

A,P	1.70	8.75000E-01	
BS,BL	5.00000E-01	8.25000E-01	
ZS,ZL	5.00000E-01	8.25000E-01	
R,THETA	8.75000E-01	4.71000E-01	
BYLC,BZLC	-4.24857E-08	5.80719E-07	
BYSB,BZSB	5.64785E-07	4.06096E-07	
BYLF,BZLF	-3.23937E-08	-6.09098E-08	
BYSF,BZSF	-4.67658E-08	-6.40456E-08	
BYT,BZT	4.43140E-07	8.61859E-07	
ANGLE B, MAGNITUDE B		4.74917E-01	9.69110E-07
R,THETA	8.75000E-01	5.23400E-01	
BYLC,BZLC	-7.77791E-08	6.14783E-07	
BYSB,BZSB	6.76252E-07	3.48004E-07	
BYLF,BZLF	-3.63881E-08	-6.06821E-08	
BYSF,BZSF	-5.23132E-08	-6.23347E-08	
BYT,BZT	5.09772E-07	8.39770E-07	
ANGLE B, MAGNITUDE B		5.45578E-01	9.82385E-07
R,THETA	8.75000E-01	5.75000E-01	
BYLC,BZLC	-1.28822E-07	6.46763E-07	
BYSB,BZSB	7.98501E-07	2.51230E-07	
BYLF,BZLF	-4.05145E-08	-6.04236E-08	
BYSF,BZSF	-5.79726E-08	-6.03867E-08	
BYT,BZT	5.71192E-07	7.77183E-07	
ANGLE B, MAGNITUDE B		6.33801E-01	9.64507E-07
R,THETA	8.75000E-01	6.28200E-01	
BYLC,BZLC	-1.98179E-07	6.69403E-07	
BYSB,BZSB	9.17031E-07	9.66132E-08	
BYLF,BZLF	-4.47905E-08	-6.01324E-08	
BYSF,BZSF	-6.37567E-08	-5.81823E-08	
BYT,BZT	6.10304E-07	6.47702E-07	
ANGLE B, MAGNITUDE B		7.55679E-01	8.89938E-07
R,THETA	8.75000E-01	6.80600E-01	
BYLC,BZLC	-2.84381E-07	6.72120E-07	
BYSB,BZSB	9.96482E-07	-1.30925E-07	
BYLF,BZLF	-4.92355E-08	-5.98066E-08	
BYSF,BZSF	-6.96788E-08	-5.56992E-08	
BYT,BZT	5.93187E-07	4.25689E-07	
ANGLE B, MAGNITUDE B		9.48335E-01	7.30124E-07
R,THETA	8.75000E-01	7.33000E-01	
BYLC,BZLC	-3.78343E-07	6.44018E-07	
BYSB,BZSB	9.79436E-07	-4.17038E-07	
BYLF,BZLF	-5.38705E-08	-5.94442E-08	
BYSF,BZSF	-7.57525E-08	-5.29117E-08	
BYT,BZT	4.71470E-07	1.14624E-07	
ANGLE B, MAGNITUDE B		1.33	4.85204E-07
R,THETA	8.75000E-01	7.85400E-01	
BYLC,BZLC	-4.63071E-07	5.80827E-07	
BYSB,BZSB	8.22598E-07	-6.90832E-07	
BYLF,BZLF	-5.87188E-08	-5.90431E-08	
BYSF,BZSF	-8.19920E-08	-4.97900E-08	
BYT,BZT	2.18817E-07	-2.18839E-07	
ANGLE B, MAGNITUDE B		-7.85349E-01	3.09469E-07

4.0 EXPERIMENTAL PROGRAM

4.1 MATERIALS DEVELOPMENT

In the second quarterly report, an expression was derived for the volume of the superconducting element in a resistive SCFCL. Using reasonable, if slightly optimistic, estimates of the parameters a volume of about 1/4 meter cubed was calculated. Since the complexity of construction and ultimate cost will increase for significantly larger volumes, we must endeavor to achieve the parameters used in that estimate. The two materials parameters used were the normal state resistivity ρ_N ($300 \mu\Omega\text{cm}$) and the critical current density J_c ($3 \times 10^6 \text{ A/cm}^2$), and enter the expression for the volume Ω as

$$\Omega \propto (\rho_N J_c^2)^{-1/2}$$

Using the above estimates, we require $J_c \rho_N^{1/2} \approx 5 \times 10^4 (\text{W/cm}^3)^{1/2}$, and the aim of the materials development program is to achieve this result.

Based on our previous experience with high T_c superconductors and the existing literature, NbN is clearly the most promising material. Reported values of ρ_N up to $1000 \mu\Omega\text{cm}$ and J_c up to $2 \times 10^7 \text{ A/cm}^2$ were far in excess of our needs. Also it appeared possible to fabricate this material at relatively low temperatures which are comparable with flexible plastic substrates.

Unfortunately, our preliminary attempts to fabricate NbN films have had limited success. Although the values of $J_c \rho_N^{1/2}$ are close to the above goal (see Table 4.1.1), problems have occurred with macroscopic inhomogeneities (holes and debris), microscopic inhomogeneities (grains which may be partially insulated from one another), and a drop off of J_c with increasing film thickness and width. In the next subsection we discuss NbN preparation and characterization while the following subsections describe the above problems which were encountered in our preliminary NbN samples.

Table 4.1.1 Properties of some NbN samples.

Sample #	Width (mm)	Thickness (μm)	R_{300}/R_{20}	ρ_{20} ($\mu\Omega\text{cm}$)	J_c ($10^6 \text{A}/\text{cm}^2$)		$J_c \rho_{20}^{1/2}$ ($10^4 (\text{W}/\text{cm}^3)^{1/2}$)	
					dc	pulsed	dc	pulsed
7902N	0.08	3.07	0.84	242	1.35	1.4	2.1	2.2
7902W	0.165	3.07	0.82	288		1.2		2.0
7903W	0.16	3.3	0.90	224		1.0		1.5

4.1.1 NbN Film Preparation and Characterization

The previous quarterly report described the vacuum system and the reactive sputtering process. To fabricate NbN films, a mixture of nitrogen and argon gas and a niobium target are used. There are a large number of sputtering parameters involved: nitrogen and argon partial pressure, impurity gases, substrate material and temperature, film thickness and width and sputtering rate. Therefore, in order to systematically proceed to an acceptable material, we must correlate a variety of intermediate microscopic parameters with the desirable superconducting properties on the one hand, and also with the sputtering conditions. The superconducting properties are T_c , J_c and ρ_N , while the intermediate parameters include grain size, stoichiometry, crystal structure and structural disorder. The intermediate probes included optical microscope, scanning electron microscope, energy dispersive X-rays, microprobe and Rutherford backscattering for compositional analysis, film thickness profiler and X-ray analysis for crystal structure.

In all samples made so far (see Table 4.1.2), the argon partial pressure was fixed at 6 mTorr and the deposition rate at 11-14 Å/sec. The stoichiometry, structural phase and film morphology all depend on the nitrogen partial pressure, the substrate temperature and quite possibly the impurity gases. The transition temperature T_c is very sensitive to these properties since only the cubic phase of NbN has a high T_c (16.1 K) and interstitial nitrogen or structural disorder will reduce T_c . Thus the data shown in Fig. 4.1.1 is a preliminary indication of the quality of the films as a function of substrate temperature and nitrogen partial pressure. The fact that the optimum T_c shifts to higher nitrogen partial pressure for the higher temperature substrate is presumably because of the lower sticking coefficient for N_2 .

Table 4.1.2 Summary of NbN samples

Sample #	Substrate Type	N ₂ PP (mTorr)	Substrate Temp. (°C)	Deposition Rate (Å/sec)	Width (mm)	Thickness (μm)	T _c (K)	R ₃₀₀ /R ₂₀	(10 ⁶ A/cm ²) dc pulsed	
7902	SiO ₂	0.6	250	12.6	6.4	3.07	~15		>0.9	
7902	Glass	0.6	250	12.6	12.7	3.07	14.6	0.77		
7902N	Glass	0.6	250	12.6	0.08	3.07	~14.5	0.84	1.35	1.4
7902W	Glass	0.6	250	12.6	0.165	3.07	~14.5	0.82		1.2
7903	Glass	0.6	250	14.5	12.7	3.3	14.9	0.94		
7903W	Glass	0.6	250	14.5	0.16	3.3	14.7	0.90		1.0
7904	Glass	0.6	250	14.7	12.7	3.25	14.8	0.88		
7905	Glass	1.0	250	11.0	12.7	3.5	12.7	0.84		
7905	Glass	1.0	250	11.0	0.43	3.5			0.49	0.52
7905	Al ₂ O ₃	1.0	250	11.0	12.7	3.5	13.3	0.91		
7906	Glass	1.1	250	10.8	12.7	1.1	12.5			
7906	Glass	1.1	250	10.8	0.5	1.1			1.0	1.03
7906	Al ₂ O ₃	1.1	250	10.8	12.7	1.1	13.0	0.85		
7907	Glass	1.1	250	10.8	12.7	0.39	12.8	0.91		
7907	Glass	1.1	250	10.8	0.47	0.39			1.36	0.97
7908	Glass	0.2	250	16.5	12.7	4.8	14.8			
7908-1	Glass	0.2	250	16.5	0.45	4.8			0.22	0.23
7908-2	Glass	0.2	250	16.5	0.50	4.8				0.08
7909	Glass	0.4	250	13.3	12.7	4.0	14.6			
7909	Al ₂ O ₃	0.4	250	13.3	12.7	4.0	15.4			
7909-1	Glass	0.4	250	13.3	0.5	4.0				1.28
7909-2	Glass	0.4	250	13.3	0.5	4.0			1.34	1.2
7909	Glass	0.4	250	13.3	6.3	4.0			>0.81	0.18
7909	Glass	0.4	250	13.3	22.0	4.0			0.27	0.11
7910	Glass	0.7	250	11.0	12.7	3.3	13.9			
7910	Al ₂ O ₃	0.7	250	11.0	12.7	3.3	14.6			
7910-1	Glass	0.7	250	11.0	0.52	3.3			1.0	1.0
7910	Glass	0.7	250	11.0	22.0	3.3				0.08
7911-1	Al ₂ O ₃	0.5	500		12.7		15.3	1.23		
7911-2	Al ₂ O ₃	0.5	500		12.7		14.8	1.47		
7912-1	Al ₂ O ₃	1.0	500		12.7		15.8	0.86		
7912-2	Al ₂ O ₃	1.0	500		12.7		16.3	1.17		
7912	Al ₂ O ₃	1.0	500	11.5	1.0	3.1				0.69
7913	Al ₂ O ₃	0.2	500		12.7		12.5

Fig. 4.1.1. Superconducting transition temperature (T_c) as a function of nitrogen partial pressure, substrate temperature, and type.

A microprobe analysis of two samples made at a nitrogen pressure of ≈ 0.6 mTorr showed about 15% nitrogen, minimal trace impurities and the remainder Nb. The low nitrogen content (50% = correct stoichiometry) along with the high T_c (~ 15 K) is somewhat surprising. Further work is anticipated using Rutherford backscattering to clear up this discrepancy.

4.1.2 Macroscopic Imperfections.

Visual observations of the NbN samples revealed a macroscopic graininess to the surfaces. Further observation with optical and scanning electron microscopy showed a series of surface imperfections whose number density increased with film thickness and N_2 partial pressure. Figure 4.1.2 is an SEM of 3 samples made at N_2 partial pressures of 0.2, 0.4, and 0.7 mTorr respectively. As can be seen, not only does the number density increase, but the size of these imperfections also increases. The origin is not clear but seems related to the presence of N_2 in the system; e.g., films of pure Nb ($N_2 = 0$) were completely free of imperfections. Observations indicated most of the imperfections to be debris sticking above the surface. Energy dispersive X-ray analysis of the debris showed significant Nb content, but is unfortunately insensitive to nitrogen. This debris was also indicated in surface scans with a Dektak stylus deflection profiler as shown in the upper part of Fig. 4.1.3. Similar measurements on another film (lower part of Fig. 4.1.3) revealed the existence of surface depressions (holes) as well.

It was found that these imperfections provide nucleation points for driving the sample normal. Evidence for this was found in one of the samples being tested for critical current density. This sample, shown in Figure 4.1.4 was repeatedly driven normal with current pulses, which resulted in structural transformations of the film along well defined paths approximately perpen-

Fig. 4.1.2.a. SEM of sample 7908 at 200x magnification showing surface debris. $N_{2pp} = 0.2$ mTorr, thickness = $4.8 \mu\text{m}$, $T_C = 14.8$ K

Fig. 4.1.2.b. SEM of sample 7909 at 200x magnification showing surface debris. $N_{2pp} = 0.4$ mTorr, thickness = $4.0 \mu\text{m}$, $T_C = 14.6$ K

Fig. 4.1.2.c. SEM of sample 7910 at 200x magnification showing surface debris. $N_{2pp} = 0.7$ mTorr, thickness = $3.8 \mu\text{m}$, $T_C = 13.9$ K

Fig. 4.1.3.a. Cross section of sample 7912 made by a Dektak surface profiler.

Fig. 4.1.3.b. Cross section of sample 7903W made by a Dektak surface profiler.

Fig. 4.1.4. Optical micrographs of sample 7902W at different magnifications, showing transformation paths perpendicular to length of film.

dicular to the current. Closer examination reveals that surface depressions are always associated with these paths, although the nature of the transformation is not known. Presumably some annealing occurs due to the large energy density dumped into these narrow regions upon breakdown. However, since there are many of these paths, the transformation must improve the breakdown properties of the local region so that subsequent breakdown occurs elsewhere. After many current pulses exceeding the critical current, the sample's resistance discontinuously increased to 300 ohms and was not superconducting at 4.2 K, indicating a catastrophic transformation.

The effect of the holes is much more serious on these narrow samples (165 μm wide). Wider samples never showed evidence of these transformations. Although these imperfections may not greatly reduce J_c , they preclude uniform switching, and open the possibility of sample damage after repeated switching.

4.1.3 Critical Current Density: Thickness Dependence.

In addition to the macroscopic imperfections, a second shortcoming of the NbN films produced to date is the decrease in critical current density J_c with increasing thickness d . Pulsed and dc results on 0.5 mm wide strips are shown in Fig. 4.1.5. The total volume Ω is proportional to $d^{-1/2}$ and since we have used 5 microns in our calculation of volume, significantly smaller values of d cannot be tolerated, and high J_c must be maintained for such thicknesses.

Three possible causes of the decrease of J_c with d have been considered. Two of these involve mechanisms associated with NbN grain size which may vary as a function of film thickness. The third possible cause is related to the increase in the self-magnetic field due to increase in total current with film thickness. In order to quantitatively check these possibilities, specific predictions must be made for each model.

Fig. 4.1.5.

Critical current density for ≈ 0.5 mm wide NbN films of different thicknesses under pulsed and dc conditions. Sample 7907 is $0.39 \mu\text{m}$ thick, with a $T_c \sim 12.8$ K. Sample 7906 is $1.1 \mu\text{m}$ thick with a $T_c \sim 12.5$ K. Sample 7905 is $3.5 \mu\text{m}$ thick with a $T_c \sim 12.7$ K. All samples were prepared at an $N_2\text{pp} \sim 1.0$ mTorr on glass substrates, with strips widths defined by in situ masking.

Self-field: Assuming the current distribution across the film width w is independent of current density J , and that the film is much thinner than its width ($d \ll w$), then to a good approximation, the self-magnetic field B at any point only depends on the total current. Hence for constant film width, $B \propto Jd$. Breakdown occurs via flux flow at a critical value of the product of $J \times B$, which implies that $J_c^2 d$ is constant. For the data shown in Fig. 4.1.5, the product $J_c^2 d$ has the values 0.68, 1.1, and 0.82 (in units of $10^{12} \text{ A}^2 \mu\text{m}/\text{cm}^4$) instead of being constant. This is not in good agreement with the model.

Grain boundary pinning. The motivation for considering grain boundary pinning is our experience with Nb_3Sn films in which the grain size is related to thickness. This is shown graphically in Fig. 4.1.6. Systematic studies have not yet been carried out for the NbN samples, however, Fig. 4.1.7 shows scanning electron micrographs for NbN samples with thicknesses of 3 to 5 microns made at different partial pressures of nitrogen. Grain sizes are in the range of 0.12 to 0.5 microns.

The above self-field model can readily be extended to include grain boundary pinning. Here the critical value of the product $J \times B$ is not constant, but is proportional to the grain boundary area per unit volume, which is just the reciprocal of the average grain diameter a_0 . This model predicts that $J_c^2 d a_0$ is a constant. Unfortunately, the model cannot be checked until grain sizes are measured in films with significantly different thicknesses.

Josephson coupling of grains. This is a totally different mechanism, but one which depends on the grain size. It is assumed that the NbN grains of diameter a_0 are partially insulated from each other. Normal conductivity is by thermally activated hopping from grain to grain and superconductivity is due

Fig. 4.1.6. SEM's of fracture edges of Nb₃Ge samples made by magnetron sputtering at a substrate deposition temperature of 740°C. These growth patterns demonstrate how column diameter (grain size) increases with increasing thickness and are typical of both Nb₃Ge and Nb₃Sn.

Fig. 4.1.7. SEM's of the surface structure grains of NbN films shown at 2000 x magnification.

to Josephson tunnel junctions between grains. Supporting evidence is found in the typical temperature dependent resistivity shown in Fig. 4.1.8 which indicates that the normal state conductivity in our NbN films is thermally activated. In fact the resistivity is higher than the maximum metallic resistivity ($\sim 150 \mu\Omega\text{cm}$) associated with an electron mean free path of one atomic spacing. This in itself implies another, non-metallic conductivity mechanism, usually associated with hopping between grains.

The model is simplified by assuming a three dimensional grid of grains of diameter a_0 on a cubic lattice and by neglecting current flow lateral to the net current flow. The critical current density can be calculated by lumping together all the junctions in a plane (any plane) perpendicular to the current flow. For this lumped Josephson junction (consisting of dw/a_0^2 grain to grain junctions in parallel, the critical current I_c is given by the well-known expression

$$I_c = \frac{\pi}{2} \frac{\Delta(T)}{R_0} \tanh \frac{\Delta(T)}{2kT} \quad 4.1.1$$

where $\Delta(T)$ is the temperature (T) dependent energy gap, k is Boltzman's constant and R_0 is the total parallel resistance of the junctions in the plane. At the low temperatures where J_c is measured $\Delta(T) = \Delta(T=0)$ and $\tanh \frac{\Delta(T)}{2kT} \approx 1$, so that

$$J_c = \frac{I_c}{dw} = \frac{\pi}{2} \frac{\Delta(0)}{R_0 dw}$$

Now the total normal resistance of such a film of length ℓ will be given by the series sum of $\frac{\ell}{a_0}$ of these junctions, that is

Fig. 4.1.8. Resistance ratio of sample 7903W as a function of temperature.

$$R = R_o \frac{\ell}{a_o}$$

Since by definition

$$R = \frac{\rho_N \ell}{dw}$$

the final expression for J_c becomes simply

$$J_c = \frac{\pi \Delta(o)}{2 \rho_N a_o}$$

The T_c of our NbN films implies $\Delta(o) \approx 2.7$ mV, $\rho_N \approx 230 \mu\Omega\text{cm}$ and choosing $a_o \approx 2500 \text{ \AA}$, we calculate $J_c \approx 8 \times 10^5 \text{ A/cm}^2$. This grain size corresponds to the measured value for the sample in the lower part of Fig. 4.1.6 for which the measured critical current density was $\approx 10^6 \text{ A/cm}^2$. Thus the agreement is quite reasonable.

As final evidence for Josephson coupling, the temperature dependence of J_c near T_c is shown in Fig. 4.1.9. Near T_c , Eq. 4.1.1 predicts $J_c \propto (T_c - T)$ and this is reasonably well in agreement. Flux flow in high T_c films is characterized by a $(T_c - T)^2$ dependence, and is a much poorer fit to the data.

4.1.4 Critical Current Density: Width Dependence.

In a series of 4 micron thick NbN films made at the same time, the critical current density is shown to fall off with increasing width in Fig. 4.1.10. This is similar to the decrease in J_c with thickness except that in the wider films the pulsed results are substantially lower than the dc critical current densities. Models for this effect do exist, and a detailed comparison will be done next quarter.

Fig. 4.1.9. Critical current density vs. sample temperature for two NbN samples. Sample 7902 was made at $N_2 = 0.6$ mTorr, with a thickness of $3.07 \mu\text{m}$, etched width of $80 \mu\text{m}$, and $T_c \sim 14.5$ K. Sample 7903W was also made at $N_2 = 0.6$ mTorr with a thickness of $3.3 \mu\text{m}$, width of $160 \mu\text{m}$ and $T_c \sim 14.7$ K.

Fig. 4.1.10. Width dependence of the critical current density for 3 different widths of sample 7909. These samples were made simultaneously but on different substrates and should reflect similar conditions. $N_{2pp} = 0.4$ mTorr and $T_c \sim 14.6$ K.

4.1.5 Conclusions.

The main result of the materials development program during the 5th quarter has been to throw into question the use of NbN as a material for the SCFCL. Based on this work it appears that the problem of materials development will be a formidable task and spread into the next contract period. Because of this switching tests will commence in the next quarter with the present NbN films, but at the same time, a vigorous materials development program will be pursued to improve the NbN and also study alternatives such as Nb₃Sn.

4.2 FACILITIES AND EQUIPMENT

Virtually all the equipment and installations are in place and operating, so experiments will begin in the next quarter (mid-November). Figure 4.2.1 shows an overview of the setup with most of the equipment in place. The following subsections describe the equipment and facilities in detail.

4.2.1 Laboratory Installations.

A new laboratory has been made available for the experimental program connected with the Superconducting Fault Current Limiter (SCFCL). There is approximately 900 sq. ft. of floor space of which 300 sq. ft. are set aside for a sputtering system not involved in the SCFCL effort. This area was previously used for miscellaneous storage, so a considerable effort involved clearing the room. After this, electrical supplies were installed for the high power equipment needed in the SCFCL project--essentially 2 circuits of 50 amps, 208 volts, three phase and 100 amps of 115 volt single phase. The three phase circuits are used for the 500 amp pulsed power supply and a 600 amp, 60 Hz source respectively. At the same time, chilled water, helium,

Fig. 4.2.1. View of the experimental area for the SCFCL with some of the equipment in place.

and nitrogen gas supplies were installed. The recirculating chilled water is used with the 500 amp pulsed supply and the nitrogen and helium gas are necessary for the cryogenics. An overhead rack was installed for moving the cryostat insert.

The new laboratory has sufficient bench and drawer space as well as tables for sample mounting. There is a sink and chemical hood also available. The laboratory has been supplied with tools required for installations and further experiments.

4.2.2 Cryogenic Equipment.

The following cryogenic equipment necessary for the experiments is installed and ready for operation.

(A) CRYOSTAT. This cryostat, built by Minnesota Valley Engineering (MVE), is stainless steel with a 6 inch inner diameter by 42" height for the experiment and liquid helium. The vacuum insulation space is common for the liquid helium and liquid nitrogen and has an evacuation port with valve. The cryostat will withstand 1 to 2 atmospheres over pressure within the code ratings according to the MVE engineer. These code ratings have a factor of 4 safety margin, so that supercritical helium studies at about 2 atm can be conducted in this cryostat with no modification.

(B) PORTABLE VACUUM PUMPING STATION. This system consists of an Acatel direct drive mechanical pump and a Veeco 2" air cooled diffusion pump (liquid nitrogen trapped) and is used to evacuate the insulation space in the cryostat (A).

(C) VACUUM MANIFOLD AND GAUGE. This manifold allows pumping out of insulation vacuum space and/or helium space. A Phillip's gauge reads pressure from 0.5 torr to 10^{-7} torr.

(D) LN SYSTEM. Liquid nitrogen (LN) is filled into the outer and inner cryostat from a pressurized MVE 50 liter dewar through an automatic discharge valve. The LN level in the outer space is automatically controlled during experiments. LN is filled into the helium space before transfer of liquid helium (LHe) to precool the cryostat and insert thereby avoiding excessive LHe consumption. The helium inner space is then pressurized so that the LN is blown out before LHe is transferred and the experiment begun.

(E) LIQUID HELIUM LEVEL INDICATOR. This device measures the level of liquid helium during the experiment. It is necessary when filling and also to determine when the level drops below the sample.

(F) VACUUM PUMP. A Welch 1397B mechanical pump provides sufficient pumping speed to reduce the pressure and temperature of the liquid helium so that studies in superfluid helium are possible.

4.2.3 Cryostat Insert.

The cryostat insert for the switching experiments is shown in Fig. 4.2.2. The details of the relevant components are described in the following.

(I) HIGH CURRENT FEEDTHROUGHS. Two high current (500 amp, American Magnetics) feedthroughs are attached to the top plate and have solid copper extensions down to the sample holder (shown in an exploded view in Fig. 4.2.3). The liquid helium boiloff is forced through channels in these feedthroughs to provide extra cooling and reduce the LHe consumption to 1.4 liters/hour for both. The measured resistance of the pair of feedthroughs at room temperature is $\sim 2 \text{ m}\Omega$ and with LHe is $\sim 0.3 \text{ m}\Omega$. When a low inductance shunt is placed across these at the top of the cryostat and a sample at the bottom, the calculated inductance is $1.0 \text{ }\mu\text{Hy}$. This could be reduced if necessary to about $0.2 \text{ }\mu\text{Hy}$ by moving them closer together.

Fig. 4.2.2. Cryostat insert for switching tests. Note the 500 amp feed-throughs, the stripline for the pulsed magnet, the helium level detector and the sample holder at the bottom.

(II) PULSE MAGNET FEEDTHROUGH. The low inductance strip lines to the pulsed magnet come through a specially fabricated seal at the top of the insert. Connectors at the bottom allow the two pulsed field coils to be run in series or parallel and to have each coil's field direction parallel or antiparallel.

(III) SAMPLE HOLDER AND PULSED MAGNET. An exploded view of the sample holder and pulsed magnet is shown in Fig. 4.2.3. The pulsed magnet consists of two ten turn coils of #24 copper wire, approximately three inches long and one inch wide. The wires are potted in Emerson and Cummings 1266 Stycast epoxy inside a plate made of G-10 fiberglass. These are attached to a G-10 frame which can rotate with respect to the plane of the sample to determine the effect of field orientation on switching. Detents are provided at angles of 0° , 30° , 45° , 60° , and 90° .

The samples lie on a piece of G-10 fiberglass inside a three by one inch depression. On each end of the sample holder is attached a gold plated copper plug into which is soldered two 1/2 inch wide pieces of commercial superconducting tape (tinned Nb_3Sn on Copper). Samples are soldered to the flexible tapes with indium. The gold plated copper plugs are attached with stainless steel bolts and washer to mating pieces of gold plated copper which have been soldered to the solid copper extensions of the high current feedthroughs (see Fig. 4.2.2). This arrangement allows the sample to be rotated with respect to gravity to determine the effect of helium bubbles on the switching. The high current pressure contact between gold plated copper parts has optically polished flats, and the resistance at room temperature is measured to be $\approx 5 \mu\Omega$, and less than $1 \mu\Omega$ at liquid helium temperatures.

(IV) SAMPLE VOLTAGE LEADS. The voltage leads to the sample (not shown) are a twisted pair of #26 copper wire which run along the vertical support

Fig. 4.2.3. Sample holder for pulsed magnetic field switching of the SCFCL.

just left of center. These precautions greatly reduce the pickup from the pulses in the other feedthroughs (I) and (II). They are connected to the copper plugs in such a way that the inductive loop is as small as possible.

(V) HELIUM LEVEL DETECTOR. The helium level detector is shown on the support just left of center. The holes (at one inch intervals) allow liquid into the superconducting wire sensor. The sensor reads up to 20 inches of liquid helium measured from 1/2" below the axis of the sample holder. This corresponds to about ten liters of helium in the cryostat, which lasts for about three to four hours during normal conditions.

(VI) LN EXTRACTION. A vertical tube running the length of the cryostat (not shown) and open at the bottom is used to extract the liquid nitrogen from the sample space after precooling and prior to transferring liquid helium.

4.2.4 Electrical Equipment.

A host of electronic equipment is necessary for properly conducting the experiments outlined in our proposal. These are all in operation at this time, and are listed below along with their description and function. A block diagram schematic is shown at the end.

(a) 500 AMP PULSED POWER SUPPLY. This is the key device for all the switching experiments and was very recently installed. This device is not available commercially, so it was constructed in the Electronics Division at Argonne. Its function is to supply a simulated fault current to the test sample at a repetition rate up to 100 Hz. In order to measure recovery times this supply must turn off faster than expected recovery times; thus a fast pass transistor circuit is used. It is supplied from switching capacitors and a three phase transformer diode package (see Fig. 4.2.4). Although the transistors turn off in a few microseconds, the inherent inductance in the

Fig. 4.2.4.b. Schematic diagram of 500 amp pulsed supply.

Fig. 4.2.4.c. Schematic diagram of 500 amp pulsed supply.

Fig. 4.2.4.d. Schematic diagram of 500 amp pulsed supply.

- 1- " ∇ " IS GATE COMMON
- 2- " ∇ " IS REG. COMMON
- 3- ALL OP AMP & I.C. SUPPLY LINES ARE BYPASSED WITH .22M.F.
- 4- 6PC383
- 5- ALL OP AMPS HAVE OFFSET TRIM POTS

ELECTRONICS DIVISION	TITLE	100 AMP. PULSED CURRENT SUPPLY INTERNAL GEN & D.F. MONITOR	DRAWING NO.	L4686 - 7901 - D8-00
	DESIGN BY	E A JUNG	BUILT FOR	KEN GRAY
			DATE	1-1-79
			SHEET	5 OF 6
			MODEL NO.	CR 93

Fig. 4.2.4.e. Schematic diagram of 500 amp pulsed supply.

Fig. 4.2.4.f. Schematic diagram of 500 amp pulsed supply.

circuit extends the decay of the current to about 30 μ sec. However, the operation of the SCFCL is unaffected unless the recovery time is sufficiently greater than 1 millisecond, so the supply is adequate in this respect.

On the other hand, the rise of the current should mimic a fault which has about 1 millisecond rise time. The supply is therefore designed to regulate the current to follow an input voltage waveform which can be ramped up in any desired time (minimum of 30 μ seconds). Switching the SCFCL is initiated by a magnetic field pulse synchronized to a specified current level in this ramp. Shortly afterwards the simulated fault current is dropped to zero by turning off the pass transistors. This conserves helium loss and allows recovery time measurements. In an actual device, an isolation switch or circuit breaker would operate much later (1-50 milliseconds).

The supply utilizes a specially designed current shunt, split into two parts for current regulation. There is an amplifier installed on the zero magnetic field symmetry axis of the shunt to avoid inductive pickup in the current measuring feedback circuit. This was found to be a simple yet essential solution to the problems of inductive pickup and supply oscillation. See Fig. 4.2.5. The shunt resistance is 0.25 milliohms.

Duty factors of up to 10% are possible, but it is found that water cooling is necessary for the transistors during conditions of peak power dissipation. For lower duty cycles water cooling is unnecessary, and fans are installed which operate when the heat sink temperature exceeds some prescribed temperature. Safety interlocks shut off the supply if: the duty factor exceeds 10%; circulating water fails; transistor power dissipation is excessive; temperature rise in heat sink is excessive; current called for is too great; or the pulse width is too long.

Fig. 4.2.5. Current shunt for 500 amp pulsed supply composed of commercial shunts in parallel with sensing amplifier mounted in the field free region in between.

(b) RAMP GENERATOR. This device, built in the Solid State Science Division at Argonne provides the reference signal to control the current delivered by the 500 amp pulsed supply (a) to the SCFCL. It also provides a trigger pulse (TPI) at the beginning of a variable rise time ramp, as shown in Fig. 4.2.6. The circuit diagram is shown in Fig. 4.2.7.

(c) OSCILLOSCOPE MONITER I. This two channel oscilloscope monitors the signal from the ramp generator (b) to the 500 amp pulsed supply (a) as well as the output current of that supply (a) as measured across its current shunt. It is triggered by the ramp generator trigger pulse (TPI).

(d) MAGNET TRIGGER PULSE GENERATOR. This is a Hewlett-Packard 214A pulse generator which provides a trigger pulse (TPII) for the pulsed switching magnet supply (e) at an adjustable delay time after the initiation of the current ramp [i.e., trigger pulse (TPI) from ramp generator]. It provides enough current for the transformer coupled input of the magnet pulse supply.

(e) MAGNET PULSE SUPPLY. This supply was built previously by the Accelerator Research Facilities Division at Argonne for our switching studies supported by the Electric Power Research Institute (EPRI). The device discharges a high voltage switching capacitor into an inductance (the switching magnet in the cryostat) using an SCR. Peak currents of 300 amps and minimum rise times of $\approx 7 \mu$ seconds are possible. Low inductance strip lines are used throughout the current path to the magnet. The maximum pulsed field using our 20 turn magnet is about 1200 gauss, which is adequate. The input trigger (TPII) is transformer coupled to provide isolation from the output. The current is measured with a low inductance shunt resistor (2.875 milliohms). The circuit diagram is shown in Fig. 4.2.8, but note that the low voltage circuit, using the SCR's labeled CR2 and CR3, is not used for this application.

Fig. 4.2.6. Voltage ramp to control simulated fault in sample (below).
Trigger pulse (TPI) is shown in upper trace.

Fig. 4.2.7. Schematic of ramp generator. The trigger pulse (TPI) is obtained at the output of the first operational amplifier.

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Fig. 4.2.8. Schematic of the power supply for the pulsed magnet. For present purposes the 7.5 volt capacitors and SCR's labeled CR2 and CR3 are not used.

(f) CURRENT MONITOR. An inductively coupled current monitor (Bell Inc., Model IA-5023P) measures the sample current going into the cryostat. The sensitivity is 40 mvolts per amp.

(g) SHUNT RESISTOR. A specially designed low inductance shunt resistor (5.9 milliohms) was fabricated and attached to the high current feedthroughs at the top of the cryostat. The voltage is proportional to the current in the shunt. Thus we can independently measure the total current from the 500 amp supply (a) as well as the components going into the sample and shunt.

(h) SAMPLE VOLTAGE AMPLIFIER. The voltage across the sample is amplified by a Princeton Applied Research Model 113 preamplifier. In order to avoid voltage drops across the high current feedthroughs into the cryostat (inductive as well as resistive drops), the voltage leads must be attached at the sample. In order to reduce the inductive pickup from the two pulse power supplies (a) and (e), the two voltage leads are tightly twisted along their entire length and the inductive loop where the leads connect to the sample is minimized by careful layout. The leads are attached so as to also measure the voltage drop across the contact resistance of the high current leads to the sample. This facilitates measurement of the contact resistance, so we can reject data from experiments where the contact resistance is high (causing undue heating), however, on good samples this resistance is small enough (a few micro ohms) that the voltage is negligible.

(i) OSCILLOSCOPE MONITOR II. This three channel oscilloscope monitors: the current pulse to the switching magnet (e); the sample current (f); the sample voltage (h); and the shunt resistor (g). It is triggered by the magnet trigger pulse (TPII).

(j) DC SAMPLE CURRENT. A Kepko 5 amp power supply provides a constant current through the sample to provide recovery time measurements after the 500 amp pulsed supply (a) turns off. This supply is connected to the high current feedthroughs at the top of the cryostat and is protected from the current pulse (a) by an 8 ohm 250 watt resistor in series with the output. This dc current gives rise to a voltage drop across the sample until the superconductivity is recovered, allowing a direct measure of the recovery time of the sample.

(k) 200 AMP AC/DC SUPPLY. This supply is similar to the 500 amp supply (a) except for a lower current rating and a slower recovery time. On the other hand, it can be operated in the dc mode, facilitating measurements of dc critical currents and very small contact resistances. The supply uses 56 PNP germanium power transistors, driver transistors, and a feedback loop to regulate the output current to 1 part in 10^4 at 200 amps. See Fig. 4.2.9. Power is supplied by two 12 volt, 125 amp-hour car batteries. An external ramp generator can increase the current to 200 amps in ramp times from about 1 sec to 10^4 sec. If the feedback loop is bypassed, pulses can be fed directly into the driver transistors. The supply then provides a constant voltage source with a minimum rise time of 150 μ sec and a maximum current of 320 amps.

(l) AC CURRENT SOURCE. This module consists of a high power double variac feeding three 200 amp stepdown transformers in parallel. Thus a 208 volt input will give 600 amps at 15 volts at line frequency of 60 Hz. This is used to measure the critical current density at 60 Hz and for an eventual demonstration experiment.

Finally we show in Fig. 4.2.10 a block diagram of all the electrical equipment used in the switching experiments.

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$\beta = 100$, $B = 40$ to 100

Fig. 4.2.9. Schematic of the 200 amp power supply. This can be used with pulses if the slow control circuitry is bypassed and the control signal is fed directly into the driver transistors at TP-4.

Fig. 4.2.10. Overall block diagram of electrical apparatus for the switching experiment. The labels correspond to the paragraphs in the text: (a) 500 amp pulsed power supply; (b) ramp generator; (c) oscilloscope monitor I; (d) magnet trigger pulse generator; (e) magnet pulse supply; (f) current monitor; (g) shunt resistor; (h) sample voltage amplifier, (i) oscilloscope monitor II; (j) dc sample current.

4.3 FUTURE PROGRAM

This section outlines the proposed experimental program for the last quarter of the present contract period. Due to inevitable delays in obtaining some of the equipment for experimental tests, a majority of the experimental effort will be concentrated in this period. However, exactly for this reason, it may be difficult to accurately summarize all out intended accomplishments, as work during the first part of this period will no doubt influence the final stages. The major efforts will involve pulsed magnetic field switching tests and materials development. Preliminary experiments using a pulsed laser to switch will be conducted. In addition, depending on available time any or all of the following tests will be started: high voltage breakdown tests at 10 KV; film temperature measurements using niobium films; samples on flexible substrates; and the effect of plastic overlays on switching.

4.3.1 Materials Development.

Because of uncertainties in NbN as the best choice for the SCFCL, the program will divide into two parts. In the first part, improvements in NbN will be pursued. Macroscopic imperfections must be eliminated and high critical currents must be maintained in thick, wide samples. X-ray analysis will provide the film structure which should be predominantly the high T_c cubic phase of NbN. Cavalier of Westinghouse has suggested using small amounts of O_2 to stabilize the cubic phase in the first atomic layers of the film. Substrate temperature and nitrogen partial pressure will be varied.

The second part of the materials development program involves addressing alternatives to NbN such as Nb_3Sn . These have the disadvantage that ρ_N is smaller, but they compensate with much larger J_c and do not have intergrain tunneling as the conductivity mechanism. Table 4.3.1 shows results we have

Table 4.3.1 Properties of Nb₃Sn films made at ANL by Magnetron Sputtering.

Substrate deposition temperature ranges from 650-800°C, all

substrates are Al₂O₃ and sample widths are 100-200 μm.

Sample #	T _c	Thickness	ρ ₃₀₀	ρ ₂₀	J _c	J _c ρ ₂₀ ^{1/2}
	(K)	(μm)	(cm)	(cm)	(10 ⁶ A/cm ²)	(10 ⁴ (W)cm ³) ^{1/2}
15	17.9	1.8	77.7	46.5	2.5	1.7
13	17.7	1.9	58.7	12.7	4.6	1.6
19-1	17.7	1.2	71.3	18.7	9.1	3.9
16-2	18.0	2.4	80.1	16.2	7.5	3.0
17-3	17.7	0.5	82.4	22.7	14.9	7.1
14-1	17.9	3.1	73.0	13.6	6.5	2.4

obtained for Nb_3Sn including ρ_N , J_c and $\rho_N^{1/2} J_c$ for comparison with our nominal value of $5 \times 10^4 \text{ (W/cm}^3\text{)}^{1/2}$ (see Section 4.1). Note that these include films up to 3 microns thick, but also that the substrate temperature is high. This latter fact precludes the use of flexible plastic substrates which would melt. Therefore alternative substrates would also have to be investigated.

4.3.2 Pulsed Magnetic Field Switching Tests.

These tests are to verify that the switching is uniform, without thermal propagation and to measure the recovery time for superconductivity after opening the circuit. They require precise measurements of the voltage rise time in the superconducting film after switching and decay time after the current is turned off. The system for measurements on existing NbN films is operational and described in Section 4.2. Certain modifications of the electronics may be necessary for very short decay times (less than 30 μsec).

There is particular interest in measurements as a function of the form of helium coolant used---superfluid, pool boiling, or supercritical. The existing cryostat can accomodate all three, using a mechanical pump to decrease the helium pressure and therefore temperature, to below the λ point (2.17 K) for superfluid studies. The cryostat can be pressured to 2-3 atmospheres for supercritical studies above the critical temperature (5.2 K) and pressure. Minor modifications on the top plate of the cryostat may be necessary.

4.3.3 Pulsed Laser Switching Tests.

These tests will be performed using a GaAs semiconductor diode laser capable of 100 watts peak optical flux with short pulse times (~ 20 n seconds). As such the laser power per unit area needed to adiabatically heat the superconductor above its T_c can be determined, and hence scaled to larger systems.

The power supply is ordered and expected to be delivered in January 1980. Appropriate samples of area $\approx 1 \text{ cm}^2$ must be fabricated as well as a fiber optic light pipe into the cryostat.

4.3.4 Miscellaneous Tests.

The following preliminary tests will be performed as time permits.

High voltage tests. These preliminary measurements would test the dielectric strength of the helium during conditions of switching when bubbles may be present. We plan to test at the maximum turn to turn voltage ($\sim 10 \text{ KV}$), not the line voltage (200 KV peak). This requires a HVDC supply to be located and the installation of a HV feedthrough into the cryostat and an insulated metal plate close to the sample. Although, because of the bubbles, it is of interest to test various forms of helium, this will await the next contract period.

Film temperature measurements. In order to model the thermal switching of the superconductor, measurements of the time evolution of the film temperature are needed. As a preliminary to these measurements we would make a clean Nb film with a large temperature dependent resistivity and calibrate it against a standard germanium resistance thermometer. Measurements of switching would commence during the followup contract period.

Flexible substrates. Both mylar and flexible edge drawn sapphire substrates will be considered. Preliminary results on superconducting properties, T_c and J_c will be measured.

Plastic overlay. Switching and recovery tests may include a thin plastic overlay (sprayed on Krylon?) to see what changes occur.

4.4 Proposed Research for Next Contract Period.

The proposed experimental research at Argonne for the 18 month continuation program includes further development of the previous work culminating in a demonstration test using a 60 Hz source, but low voltage (6 V). If the laser switching appears to be most attractive, a significant expense will be a Q switched laser for these experiments. The effort costs will be greater than the previous contract: 24 man months (MM) for a total of \$144 K. Travel shopwork, and materials would be an additional \$24 K and major equipment about \$30 K (not including a Q switched laser \$45-\$50 K).

a. Materials development. The goal of this area of research during this contract period is to establish which substrate and superconductor will be used, as well as the method of fabrication. This information is essential to the construction of a full sized prototype which should culminate the third 18 month contract period. Special attention will be paid to substrates and maximizing J_c .

Effort: 6 MM; Materials: \$10 K; Equipment: <\$5 K.

b. Film temperature measurements. These would measure the film temperature as a function of time after switching. Clean Nb films (in a field of 2 KG to quench superconductivity) will act as heaters and thermometers. The temperature dependent resistance of Nb will be used, and a pulse of current will be used to simulate actual switching. Extensive measurements will be conducted on various substrates, for the various states of helium, and with plastic covers, etc. To adequately simulate the heat transfer coefficient, thin NbN films will be deposited onto the Nb.

Effort: 4 MM; Materials: \$2 K; Equipment: Biomation Transient Recorder \$12 K; x-y recorder \$6 K.

c. Bubble formation. It is desired to know if bubbles are formed in the various forms of helium during or after switching. These will be detrimental to recovery time (especially subsequent reclosure of the circuit) and to high voltage strength. In these experiments bubbles will be detected optically using a pair of fibre optic light pipes into the cryostat. An existing HeNe laser will provide a light ray which is shined from one bundle to the other just above the superconducting film. Bubbles will scatter the light reducing the light detected in an existing photomultiplier tube.

Effort: 2 MM; Materials: \$2 K; Equipment: Storage Oscilloscope \$7 K.

d. Pulsed laser. The preliminary measurements of the previous contract period will be continued more completely. Design analysis of light distribution, conductor placement and resistivity will be initiated. A Q switched laser will be required for large scale tests including the demonstration tests at 60 Hz.

Effort: 6 MM; Materials: \$5 K; Equipment: Laser \$45-\$50 K.

e. High voltage tests. The preliminary measurements made during the last contract period will be extended to the various forms of helium. Also the conditions of film size, distance to high voltage plate and orientation with respect to gravity may be varied.

Effort: 2 MM; Materials: \$1 K; Equipment: none.

f. Demonstration. This test would culminate the 18 month contract period with a demonstration of a fault on a 60 Hz line (low voltage, but $\approx$ 600 amps). We require a shorting switch (SCR's) to simulate the fault and a circuit breaker to clear the fault. Early in this contract period a decision regarding method of switching (laser or pulsed field) must be made.

Effort: 4 MM; Materials: \$4 K; Equipment: Storage oscilloscope (above); circuit breakers, shorting switch, misc: <\$5 K.