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SUPERCONDUCTING FAULT CURRENT LIMITER

Fourth Quarterly Technical Progress Report, May 8—July 7, 1979

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

Gould-Brown Boveri
Spring House, Pennsylvania

U. S. DEPARTMENT OF ENERGY

Division of Electric Energy Systems

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Fourth Quarterly Technical Progress Report

May 8, 1979 - July 7, 1979

Prepared by

GOULD - BROWN BOVERI

Prepared for

DEPARTMENT OF ENERGY
ELECTRICAL ENERGY SYSTEMS

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1.0 SUMMARY AND FORECAST

Up until now, this project has established performance objectives for the SCFCL in terms of the limitations of circuit breakers and strategies for locating the SCFCLs within the system. During this fourth quarter, the possibility has also been explored of using SCFCLs to protect specific machines, namely superconducting alternators and transformers. Unique characteristics and requirements of these machines are identified in section 2 of this report and the possible benefits to be gained by using SCFCLs are suggested. It is concluded that no further specific design work, either on the SCFCL or on the machines be done toward this goal until these superconducting devices have proved themselves further.

The most promising SCFCL device is the resistive type of limiter (see the Second Quarterly Report for this project). This is shown schematically in Figure 1.1. The detailed analysis and design of this device have proceeded in the following aspects this quarter:

1. Transient circuit analysis. A transient circuit analysis program has been developed and applied to the Figure 1.1 device. The speed of switching ultimate temperature attained by the film and transient voltage occurring across the film are calculated for different values of key parameters including: Film size (length, width, thickness), film inductance, critical temperature, shunt resistance and its inductance, shunt capacitor. Analytical and empirical relations have been prepared to evaluate some of these results.
2. Transient heat transfer analysis. The analytical technique for calculating the heat transfer from the film to the liquid helium and substrate has been established, and the appropriate equations are being programmed for digital computer solution. It is clear that the time constant for heat transfer is much longer than for the transient electrical heating of the film and so the two transient analyses can be separated.
3. Switching field and film geometry. Configurations are suggested by which the long ribbon of superconducting film (typically 10 cm wide by 1000 m long) can be installed within reasonably sized dewars. A four-pole coil configuration is shown to be suitable for producing the switching field.
4. Shunt resistance and shunt capacitance. Some preliminary exploration of these components has been started.

Components

1. Superconducting Film (R_{SC})
2. Shunt Resistor (R_{SH})
3. Shunt Capacitor
4. Isolation Switch
5. Cryostat
6. Coil
7. Refrigerator
8. Fault Sensor
9. Relay & Trigger
10. Field Drive Circuit

Figure 1.1

Complete Diagram for Magnetically switched, Resistive superconducting
Fault Current Limiter

2.0 SUPERCONDUCTING FCL - SUPERCONDUCTING MACHINES AND TRANSFORMER INTERACTION

2.1 Introduction

Research programs have been carried out over the last decade to evaluate the technical feasibility and economic potential of generators and transformers utilizing superconducting field windings. These programs have been carried out at MIT, Westinghouse and General Electric. MIT has demonstrated the technical feasibility by building a small generator (ratings up to 5MVA) and by paper studies on the design of large machines and their system performance. For machines of much larger capacity, conceptual designs for both 300MVA and 1200MVA have been completed. The development of large superconducting generators will require a substantial effort to produce a machine with performance and reliability equal to, or greater than that of conventional generators.

The major objective of this study is to evaluate current progress and problems of superconducting machines and transformers and to consider the benefits resulting from use of SCFCL with these machines. The concept of incorporating superconducting fault current limiters in superconducting machines and transformers was proposed during our visit to MIT (March 1979) and Westinghouse (May 1979) in order to explore the potential benefits, including improved transient stability, reduced size and weight, and reduce short circuit requirements. It is recognized that the electromagnetic shielding and structure of superconducting machines are very difficult problems because of the high short circuit currents and forces (very low reactance, and possibly direct high voltage tie to system).

The 1st and 2nd Quarterly reports discussed the possibility of having SCFCLS at bus ties, transmission lines, and machine terminals (high voltage side). These studies concentrated on evaluating SCFCL ability to limiting the available fault current to circuit breaker interruption capability. In this section a new evaluation of the possible use of superconducting fault current limiters in association with superconducting machines and transformers is presented.

2.2 SCFCL Impact On Superconducting Machine Design

2.2.1 Introduction

The electrical network cannot economically change configuration (with the exception of new components to be added at the same time as cables and generators), nor can it significantly alter operating policy to accommodate a new unit. The enormity of the interconnected electric power system dictates that any generator be capable of being connected to and operated with the system as the system has presently evolved. Therefore, the addition of a superconducting generator will have to satisfy these requirements at least as well as conventional machines.

2.2.2 Transient Stability

Transient stability is concerned with the ability of the generator to remain in synchronism with the system after a severe system disturbance. The parameter that can be used to quantify the performance under these conditions is the critical fault clearing time t_C . This time is the longest time that the fault can be sustained and the generator still remain in synchronism with the system after the fault is cleared.

The critical fault clearing time t_C is related to the synchronous reactance (X_d) and the transient reactance (X'_d) in the following expression⁽¹⁾

$$t_C \propto \sqrt{\frac{H}{X'_d X_d}}$$

The critical clearing times for a close in (i.e. on the alternator terminals) three-phase symmetrical fault on 10 MVA and 2000 MVA superconducting alternators along with a 907 MVA conventional generator are listed in Table 2-1⁽²⁾..

The transient reactance of superconducting and conventional machines X'_d will be comparable to each other. This is due to changes in the characteristics which define X'_d , offsetting one another, thereby resulting in small differences in X'_d .⁽¹⁾ The synchronous reactance (X_d) decreases* and the critical fault clearing time increases, hence enhancing system stability. However, because of the large increase in the power density of the generator, the inertia of the shaft system decreases, tending to produce a tradeoff between a very "stiff" tie with the electrical system and a "light" (easily accelerated) shaft system.

It should be noted that in most of the transient stability studies reported in the literature, for the sake of efficient computing either the stator transient terms or the stator circuit resistance or the rotor circuit resistance or all of them are neglected. While this does not appear to present any substantial difficulties for the study of transient stability in conventional machines, it appears as if it will result in a substantial underestimation of critical fault clearing time in superconducting machines.⁽²⁾

- * The increased reluctance of the magnetic flux path through the armature windings due to the absence of iron as a flux path, and the significantly higher flux density produced by the superconducting field windings in the machine are principally responsible for the reduction in synchronous reactance (X_d); typically $X_d = 40\%$, $X'_d = 29\%$, $X''_d = 16\%$, $t_C = 13$ cycle.

2.2.2 Transient Stability - (Cont'd)

Three mechanisms often ignored in transient stability studies are important here:

1. The heat dissipation in the armature due to high fault current.
2. The heat dissipation on the rotor surface due to trapped armature flux.
3. The increase in stored energy in the machine due to field concentration.

Each of these effects becomes more important as sub-transient reactance is reduced. The end result of the three effects is a tendency toward backswing at the instant of a fault. For machines with high reactance this is not actually a backswing, but rather a slight "hesitation" in acceleration due to loss of load. For very low reactance machines an actual backswing occurs.

2.2.3 Short-Circuit Requirements

ANSI C50.13 1965, specifies the requirements for abnormal conditions as follows:

1. Armature Winding Short-Term Thermal Requirements:

The generator armature should be capable of operating at 130 percent of rated armature current for at least one minute, starting from stabilized temperatures at rated conditions.

The permissible armature currents at time up to 120 seconds will be:

Time (seconds)	10	30	60	120
Armature Current (percent)	226	154	130	116

2. Rotor Short-Time Thermal Requirements For Unbalanced Faults:

The generator rotor should be capable of withstanding the effects of unbalanced short circuits at the armature terminal for times up to 120 seconds, provided the integrated product ($I_2^2 t$) of generator negative - phase sequence current (I_2) and time (t) does not exceed 30. (Note: negative - phase sequence current would be expressed in per unit stator current at rated power, and time should be expressed in seconds).

It should be noted that the damper shield, incorporated into the rotor structure to prevent as much of a time varying flux from penetrating into the superconducting winding as possible, should have thermal capability sufficient to absorb continuous unbalanced currents (I_2 , negative - sequence) and transient unbalanced currents ($I_2^2 t$) in excess of conventional rotors.

2.2.4 Short Circuit Fault At Generator Terminals

We must assume for now that superconductor generator design has to satisfy short circuit requirements as indicated by ANSI C50.13 1965. These requirements are more severe for superconducting machine than conventional machine because of high power density and lower synchronous reactance. Table 2-2 shows a comparison of a conventional generator with a specific low and high voltage superconducting machine for 1200 MVA⁽³⁾

It is clear from Table 2-2 that transient reactance X'_d is the same for both conventional and superconducting, but synchronous reactance of conventional machine is approximately 4.5 times higher than superconducting synchronous reactance.

2.2.5 Short Circuit Fault Current (Low Voltage S.C. Machine)

$$I_{s.c. \text{ rated}} = \frac{1200 \text{ MVA}}{\sqrt{3} \text{ 30kV}} = 23 \text{ kA rms}$$

$I'' \equiv$ sub-transient current

$$= \frac{I_{\text{rated}}}{X''_d} = \frac{23}{.16}$$

$$= 144 \text{ kA rms}$$

$I' \equiv$ transient current

$$= \frac{I_{\text{rated}}}{X'_d} = \frac{23}{.29}$$

$$= 79 \text{ kA rms}$$

2.2.5 Short Circuit Fault Current (Low Voltage S.C. Machine) - (Cont'd)

$I \equiv$ steady state fault current

$$= \frac{I_{\text{rated}}}{X_d} = \frac{23}{.41}$$

$$= 56\text{kA rms}$$

$T'_d \equiv$ the short circuit transient time constant

$$= \frac{X'_d}{X_d} T'_{do}$$

Where

$$\begin{aligned} T'_{do} &\equiv \text{open circuit transient time constant of the machine} \\ &= 12.2 \text{ seconds (1)} \end{aligned}$$

then

$$T'_d = \frac{.29}{.41} 12.2 = 8.6 \text{ seconds}$$

The currents on the low side of the transformer (at generator terminal) are very high, which requires the following:

1. Strong mechanical shaft; during a terminal fault, the rotor is subjected to a non-uniform magnetic pressure, which tends to crush the rotor into an oval shape.
2. Good damper shield; negative sequence currents in the stator produce a magnetic field distribution which rotates in a sense opposite that of the rotor. The frequency of the negative sequence field, as seen by the rotor, is consequently twice rotational frequency. Since the damper is a good shield at that frequency, negative sequence magnetic field is excluded from the rotor (shield the superconducting winding from ac magnetic fields).

2.2.6 Conclusions and Recommendations

Based on superconducting machine design, several problem areas have been identified as a key to the rapid and successful development of superconducting machines. FCL will have a great influence on the following areas:

2.2.6 Conclusions and Recommendations - (Cont'd)

1. A reliable rotor shielding scheme, since the shield must satisfy a variety of conflicting requirements.
 - a. Absorb transient mechanical torques with acceptable stress levels.
 - b. Support transient magnetic crushing loads under faults with acceptable stress levels.
 - c. Incorporate adequate cooling capacity for steady-state and transient electrical dissipation.
 - d. Minimize cryogenic refrigeration requirements
 - e. Operate at a maximum surface speed for maximum power density.
 - f. Minimize radial gap between armature and field windings for low reactance and high power density.
 - g. Provide adequate machine damping.
 - h. Shield the superconducting winding from ac magnetic fields.

FCL will influence the development and optimization of a scheme which will best meet these conflicting requirements.

2. The full potential of the application of superconductors will be achieved by rotors employing the highest magnetic fields with optimized mechanical and thermal designs. The proper balancing of the following conflicting requirements is required in the development of superconducting machines.
 - a. Thermal isolation and mechanical support with adequate strength, with maximum rigidity and with minimum refrigeration requirements.
 - b. Superconducting winding structure with enough strength to restrain the superconducting wire against inertial and magnetic forces, adequate cooling by liquid helium, and with sufficient electrical insulation for rapid changes in magnetic field.
3. Optimizing the superconducting generator design entails the definition of a single number describing the "cost" of a machine design. Typically, this "cost" contains elements not only of the price of materials used in the machine, but also penalties for inefficiency and severe penalties for design parameters outside of an acceptable range. For example, critical clearing time shorter than an acceptable number would impose a large cost.

2.2.6 Conclusions and Recommendations - (Cont'd)

It is clear that fault current limiters will decrease the size of thermal, mechanical, and electrical problems associated with short circuit and transient stability for superconducting machine, and allow increased flexibility in the design. Further analysis will be required to fully explain the substantial impact of fault current limiters on superconducting machine design.

2.3 SCFCL Impact On Superconducting Transformer

Westinghouse indicated that their superconducting transformer will have a higher efficiency than a conventional transformer by one or two tenth of a percent. The design of superconducting transformer is sufficiently flexible that leakage reactance can fall in the range of 10-15% for 1000MVA. This leakage reactance is approximately the same as conventional transformers. This transformer is designed to have an auxiliary winding in parallel with each main winding. Under fault conditions, the main windings go normal, and current is transferred in approximately 10 microseconds into the more loosely coupled auxiliary windings. The resulting large leakage reactance ($x = 40\%$) causes the device to be inherently current limiting. The current limiting by this inductive effect may lead to the following problems:

1. Because of large fault leakage reactance ($x = 40\%$), the total impedance (source and transformer) ratio X/R increases significantly; therefore, the d.c. component becomes significant compared to sinusoidal component and the current waveform becomes asymmetrical (poor circuit breaker operation).
2. A large energy will be stored in the magnetic field.
3. Poor transient stability; because of high reactance impedance of the transformer during the fault, the total reactance impedance of the system will increase. An increase in the reactance impedance reduce the power angle curve "after fault" (see 1st Quarterly Report Appendix B) and thus allows a shorter time for breaker operation (shorter critical clearing time) to isolate the fault before the system becomes unstable.

Employing SCFCL (resistive) will provide the following advantages:

1. Decrease the impedance ratio X/R .
2. Dissipate the stored energy in superconducting machine and transformer during the fault.

TABLE 2-1

Transient Stability Limits

Generator	Armature Time Constant (seconds)	Critical Clearing Time (seconds)		X''_d	X'_d	H
		With Transmission Line	Without Transmission Line			
10 MVA	.035	.43	.48	.161	.249	2.69
10 MVA	.35	.25	.31	.161	.249	2.69
2000 MVA	.34	.27	.31	.149	.174	2.96
907 MVA Conventional	.2	.3	.36	.175	.235	3.14
907 MVA With Transformer .133 p.u.	.2	0.24	.29	-	-	-

TABLE 2-2

Comparison Between Conventional
And Superconducting Machines Reactances

	Conventional	Low S.C.	High S.C.
Voltage kV	26	30	500
X_d^*	180	41	50
X'_d	32	29	30
X''_d	26	16	27

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1. James S. Edmonds, "Superconducting Generator Technology - An Overview" Department of Energy, Washington, DC 20545
2. "Demonstration Of An Advanced Superconducting Generator" MIT Reports Prepared for the United States Department Of Energy, 1978, Under Contract No. E(49-18)-2295, Task Order No. 11
3. Westinghouse Electric Corporation Report "Superconducting Generator Design", Report 1977
4. "Demonstration of An Advanced Superconducting Generator" MIT Reports Prepared for the United States Energy Research and Development Administration, 1977, Under Contract No. E(49018)-2285, Task Order No. 11

3.0 ANALYTICAL STUDY OF MOST PROMISING DESIGN

3.1 Transient Circuit Analysis

The equivalent circuit of a faulted system protected with a resistive superconducting fault current limiter (SCFCL) is shown in Figure 3.1.1. The fault current can be switched from the superconducting film into the shunt resistor R_S by increasing the film resistance R_{SC} . Due to the inductances of the superconducting film and the shunt resistor (L_{SC} & L_S), this current commutation does not happen instantly. If the film resistance reaches its full normal value before its current has dropped, generated heat due to its resistive loss may burn it up. The amount and duration of this input power must be determined before a S/C film is designed.

Another important factor that affects the design of the S/C film is the transient voltage developed across the film during the current commutation. The amplitude of this voltage depends on the speed of commutation.

To determine the above two factors and also other parameters that affect the design of the S/C film, a transient circuit analysis has been done on this system.

Figure 3.1.1 - Equivalent circuit of a faulted system protected with a resistive SCFCL

3.1.1 Mathematical Model

The circuit of figure 3.1.1 can be represented by the following differential equations:

$$\frac{d I}{d t} = \frac{1}{L} (E - V_C - R I) \quad (3.1.1)$$

$$\frac{d I_s}{d t} = \frac{1}{L_s} (V_C - R_s I_s) \quad (3.1.2)$$

$$\frac{d I_{sc}}{d t} = \frac{1}{L_{sc}} (V_C - R_{sc} I_{sc}) \quad (3.1.3)$$

$$\frac{d V_C}{d t} = \frac{1}{C} (I - I_s - I_{sc}) \quad (3.1.4)$$

I , I_s , I_{sc} and V_C can be determined by solving the above four differential equations of the first order. Equations 3.1.1, 3.1.2 and 3.1.4 are linear. R_{sc} in equation 3.1.3 is a function of temperature which varies with time.

If we indicate the length, width and thickness of the S/C film with letters ℓ , w and d , its resistance can be written as:

$$R_{sc} = \rho(T) \frac{\ell}{d.w} \quad (3.1.5)$$

Where T is the film temperature and ρ is its resistivity. At the Helium bath temperature T_b , the resistivity of the S/C film is virtually zero. After a magnetic field has been applied to the film, ρ jumps up to a very small value of ρ_0 which is responsible for the lossy state of type II superconductors. The resistive loss inside the film raises its temperature. Film resistivity increases with temperature and accelerates film heating. This chain reaction continues until it reaches a critical temperature T_c where the S/C film enters a normal state and its resistivity stays constant at $\rho = \rho_N$. The variation of $\rho(T)$ with temperature between T_b and T_c is not known and will be determined by experiment. In order to do some primary analysis on the circuit at this time, a linear relationship between ρ and T for $T_b \leq T \leq T_c$ has been considered. Figure 3.1.2 shows the resistivity model used in this analysis.

Figure 3.1.2 - Model for Superconducting Film Resistivity as a function of its temperature

Figure 3.1.3 - Specific heat of niobium film as a function of its temperature.

3.1.1 Mathematical Model (continued)

The value of ρ_0 has been chosen arbitrarily. It was observed that as long as ρ_0 is at least a few orders of magnitude less than ρ_N , its value has no effect on the current commutation, temperature or total input energy (decreasing ρ_0 by one order of magnitude reduces the film temperature by 0.9%).

To determine the variation of temperature with time, we assume that all of the input energy into the films is used to raise its enthalpy. This assumption is valid for the time $t < 0.1$ msec when the transient heat transfer to helium has not started yet. In this case, we have:

$$\frac{dT}{dt} = \frac{P}{M.C} \quad (3.1.6)$$

where

P	= input power	(watts)
M	= S/C film mass	(grams)
C	= specific heat of the film	($\frac{\text{Joule}}{\text{gram} \times K^{\circ}}$)

The specific heat of the S/C film varies with temperature. Figure 3.1.3 shows C (T) for Niobium film.

The amount of input power is:

$$P = R_{SC} I_{SC}^2 \quad (3.1.7)$$

By solving equations 3.1.1 to 3.1.7 and using the graphs of Figures 3.1.2 and 3.1.3, we can find the circuit currents, voltage across the S/C film, its temperature and the input power as a function of time. The computer program that was developed for this purpose is given in appendix 3.1.A. This program takes the circuit parameters and S/C film dimensions as input data and does a transient analysis on the circuit. Its outputs are total current, S/C film current and voltage, current in the shunt resistor, input power to the S/C film, film temperature and total heat generated.

3.1.2 Transient Analysis - Base Case

The system studied here is "Philadelphia Electric" system taken from Reference 1.1 of the First Quarterly Report. In our previous short circuit analysis we determined three cases where resistive S/C fault current limiters could be used to limit the fault current (see table 1.1 in the Second Quarterly Report).

In case IR, each S/C fault current limiter sees the rest of the system as a 140 kV-rms 60 Hz voltage source behind an impedance of $Z = 0.08 + j 1.5$ ohms. The S/C film should be shunted with $R_s = 2.75 \Omega$ to limit the fault current to 43kA - rms.

To study the effect of the S/C film size and other circuit parameters, a base case has been defined. The parameters used for this case are given in figure 3.1.1. Graph # 1 gives a plot of the voltage and current transients with film power density and temperature. For this case the time origin ($t = 0$) is considered at the instant when the S/C fault current limiter is activated, that is when the applied magnetic field has put the S/C film into a lossy state. Film's initial current I_0 is 43kA at $t=0$.

Results of the transient analysis on this base case can be summarized as follows:

1. At about $t = 0.26$ nsec. temperature reaches the critical value of $T_c = 10^{\circ}\text{K}$. At this time the S/C film becomes normal and $R_{sc} = R_N = 3k\Omega$.
2. It takes more than 2 nsec for the film current to drop to 50% of its initial value. The fast rise of resistance and relatively slow decrease of current causes a power impulse of 5.5 GW that lasts less than 4 nsec. The total energy of this impulse is about 9.2kJ. This power impulse raises the film temperature from 4.2°K to 111°K in 4 nsec.
3. Until about $t = 1\mu\text{sec.}$, when the shunt resistor starts to pick up the fault current, shunt capacitor temporarily carries the fault current and is charged up.
4. All of the circuit transients are damped out in about 20 $\mu\text{sec.}$
5. Total current supplied by the source is constant until about 20 μsec after the S/C film is activated. At this time, the source current starts to follow the relation

$$I = \frac{E}{Z} \quad (3.1.8)$$

where E is the source voltage and

$$Z = 0.08 + j 1.5 + R_s = 2.83 + j 1.5 \text{ Ohms} \quad (3.1.9)$$

As the total current starts to change, S/C film current varies too. This affects the generated power in the film and, consequently, changes the film temperature.

Graph # 1 Base Case

3.1.3 Effects of the S/C Film Size and other Circuit Parameters on the current Commutation.

For a feasible and economical design of a resistive S/C fault current limiter, it is necessary to know the effects of different circuit elements as well as the S/C film size on the performance of the fault current limiter. Effects of these parameters are studied for the case IR and are summarized below:

a. Effects of S/C Film Size.

The size of the S/C film affects the performance of the fault current limiter by controlling film's resistivity and thermal capacity.

Graph #2 shows the device performance with the S/C film length increased to twice its size in the base case. Following changes are observed:

1. The peak of the input power impulse is proportional to the film length but its density and energy are independent of the film length (assuming that the total film inductance is constant).
2. Film temperature drops by 20%.
3. Steady state power density (after 20 μ sec.) drops by a factor of 4 (see equation 3.1.15 in the next section).
4. Steady state film current drops by a factor of 2 (see equation 3.1.12 in the next section).

Graph #3 shows the effect of increasing film width ($w = 15$ cm). Film width has been increased by 50% compared to the base case and the following changes are observed:

1. The peak of the input power impulse and its density are decreased but its energy is not changed (energy = 9.2kJ)
2. Film Temperature drops to 92.7°K (16% reduction).
3. Steady state film current is increased by 50% (see equation 3.1.12 in the next section).

Graph # 2 Effect of the S/C Film Size (Film length)

Graph # 3 Effect of S/C Film Size (Film Width)

3.1.3 (Continued)

Graph # 4 shows the effect of increasing film thickness ($d = 10^{-5}\text{m}$). The effects of doubling the film thickness can be summarized as:

1. The peak of the input power impulse and its density are decreased but its energy is not changed (energy = 9.2 kJ).
2. Film temperature drops to 82.7°K (25% reduction).
3. Steady state power density is doubled (see equation 3.1.15 in the next section).
4. Steady state film current is doubled (see equation 3.1.12 in the next section).

b. Effects of the S/C Film Inductance (L_{SC}).

This inductance is one of the key parameters in the design of the S/C element. The high voltage developed across the S/C film and its dielectric requirements urge a minimum inductance of few micro-Henries for the film. The inductances of the electrical connections to the film are also added to the total film inductance.

In the base case, a total S/C film inductance of $L_{\text{SC}} = 10 \mu\text{H}$ was considered. When this inductance was doubled, the following changes were observed in the performance of the fault current limiter (see graph # 5):

1. Current commutation was slowed down.
2. Energy of the input power impulse is doubled (see equation 3.1.16 in the next section).
3. Film temperature was increased to 147°K (32% increase).

c. Effects of the Film's Critical Temperature (T_{C}).

The critical temperature of a S/C film is the temperature at which film enters its normal state. In our model, we assumed that the film resistivity is constant and equal to ρ_{N} for $T \geq T_{\text{C}}$. A Niobium Nitrate film (NbN), with variable density of nitrogen in it, can have a critical temperature ranging from 10 to 15°K . This temperature can be controlled by changing the density of the nitrogen in the film.

To determine the effect of T_{C} on the performance of the fault current limiter, T_{C} was changed from 10°K (in the base case) to $T_{\text{C}} = 15^{\circ}\text{K}$ in the case shown in graph # 6. A comparison with the base case indicates that T_{C} has no appreciable effect on the device performance.

Graph # 4 Effect of S/C Film Size (Film Thickness)

Graph # 5. Effect of the S/C Film Inductance (L_{SC})

Graph # 6 Effect of Critical Temperature (T_c)

3.1.3 (Continued)

d. Effects of the Shunt Resistor (R_S).

Shunt resistor is used to limit the fault current. Its value also limits the voltage developed across the S/C element. In the Short Circuit Study presented in the first and second Quarterly Reports, the value of this resistor was determined to be $R_S = 2.75$ ohms for case IR. This resistor limits the fault current to 43kA rms (for case IR only).

Graph # 7 shows the effect of doubling the shunt resistance. Note that the total input energy into the film and its temperature are unaffected. The main changes in the device performance caused by doubling the shunt resistance are:

1. The voltage across the film is doubled. This increases the dielectric requirements of the S/C film and the shunt capacitor across it. Price of the storage capacitors is proportional to the square of their nominal voltage ($\text{cost} = K \times cv^2$).
2. Circuit voltage and currents are damped faster.
3. Steady state current in the S/C film is almost doubled (see eq. 3.1.12 in the next section).
4. Density of the input power into the S/C film is increased by a factor of 4.0 (see eq. 3.1.15 in the next section).

e. Effect of the Inductance of Shunt Resistor (L_S).

This inductance is one of the least effective parameters in the performance of the fault current limiter. Generally, the higher the value of L_S , the smaller is the damping of the circuit voltage and current oscillations. By doubling the value of L_S in the base case, the overvoltage across the shunt capacitor increased from 10% to 50%.

Graph # 8 shows the performance of the fault current limiter with $L_S = 20 \mu\text{H}$ ($L_S = 10 \mu\text{H}$ in the base case).

f. Effect of the Shunt Capacitor.

The main duty of this capacitor is to limit the overvoltages developed across the S/C film during the current commutation. This reduces the dielectric requirements of the film. Shunt capacitor carries the fault current in the time interval between few nSec to few μSec after the film is activated.

Graph # 7 Effect of the Shunt Resistance (R_S)

Graph # 8 Effect of the Inductance of Shunt Resistor (L_S)

3.1.3 (Continued)

Graph # 9 shows the effect of reducing this capacitance. C was $0.5 \mu\text{F}$ in the base case and the overvoltages were limited to 10%. In this case (graph # 9) $C = 0.2 \mu\text{F}$ and the overvoltages are as high as 70% ($\frac{1}{2} CV^2$ is constant).

Table 3.1 - I shows a summary of the above analysis.

Graph # 9 Effect of the Shunt Capacitor

Table 3.1 - I Summary of the SCFCL Circuit Analysis

Case	Graph #	Parameter Studied	SOURCE (Case IR)				SHUNT BRANCHES			FILM PARAMETERS									Maximum Value of $\frac{V_C}{E}$
			E kV	I _O kA	R Ω	L mH	C μF	R _S Ω	L _S μH	L _{sc} μH	ℓ m	w m	d 10 ⁻⁶ m	mass kg	T _c °K	R _N Ω	Energy kJ	Temp. °K	
1	1	Base Case	200	43	0.08	4.0	0.5	2.75	10	10	500	0.1	5	2.1	10	3000	9.2	111	1.1
2	2	Film Length	200	43	0.08	4.0	0.5	2.75	10	10	1000	0.1	5	4.2	10	6000	9.3	88.5	1.1
3	3	Film Width	200	43	0.08	4.0	0.5	2.75	10	10	500	0.15	5	3.15	10	2000	9.2	92.7	1.1
4	4	Film Thickness	200	43	0.08	4.0	0.5	2.75	10	10	500	0.1	10	4.2	10	1500	9.2	82.7	1.1
5	5	Film Inductance	200	43	0.08	4.0	0.5	2.75	10	20	500	0.1	5	2.1	10	3000	19	147	1.1
6	6	Film Critical Temperature	200	43	0.08	4.0	0.5	2.75	10	10	500	0.1	5	2.1	15	3000	9.2	108	1.1
7	7	Shunt Resistance	200	43	0.08	4.0	0.5	5.5	10	10	500	0.1	5	2.1	10	3000	9.2	111	1.3
8	8	Shunt Inductance	200	43	0.08	4.0	0.5	2.75	20	10	500	0.1	5	2.1	10	3000	9.2	111	1.5
9	9	Shunt Capacitor	200	43	0.08	4.0	0.2	2.75	10	10	500	0.1	5	2.1	10	3000	9.2	111	1.7

3.1.4 Results of the Transient Circuit Analysis after 20 μ Sec.

Regardless of the circuit and film parameters, the superconducting film becomes normal in 0.26 to 0.36 μ Sec. In about 20 μ Sec. after the S/C film is activated, all of the circuit transients are damped out and the variable parameters reach steady state values. As the heat transfer to helium starts after 20 μ Sec., the film's thermal stability analysis can be done independently. The steady state values of the device parameters found from the transient analysis can be used as the initial conditions to study the heat transfer and thermal stability of the S/C film.

Most of the steady state circuit parameters can be evaluated without actually doing the transient analysis. Some of them can be evaluated from the empirical relations based on the results of this analysis. Following is a list of equations that can be used to evaluate or estimate the steady state values of the device variables:

a. Current in the S/C Film (I_{sc})

After the initial transients, current splits resistively, that is

$$I_{sc} = I \frac{R_s}{R_s + R_{sc}} \approx I \frac{R_s}{R_{sc}} \quad (3.1.10)$$

Where I is the current supplied by the source (constant in the 20 μ Sec time interval), and

$$R_{sc} = \rho_N \frac{\ell}{d \cdot w} \quad (3.1.11)$$

so,

$$I_{sc} = \frac{IR_s}{\rho_N} \cdot \frac{dw}{\ell} \quad (3.1.12)$$

ρ_N is the resistivity of the S/C film in its normal state.

b. Current in the Shunt Resistor (I_s)

$$I_s = I \frac{R_{sc}}{R_{sc} + R_s} \approx I \quad (3.1.13)$$

c. Voltage Across the S/C Film (capacitor voltage).

$$V_c = R_{sc} I_{sc} = IR_s \quad (3.1.14)$$

d. Input Power density on the S/C film surface

$$H = \frac{R_{sc} (I_{sc})^2}{\ell w} = \frac{(IR_s)^2}{\rho_N} \cdot \frac{d}{\ell^2} \quad (3.1.15)$$

e. Energy Dissipated in the S/C Film.

Based on the results of the transient circuit analysis, it was found that the total film energy (generated heat) is equal to the energy stored in its inductance before the fault. In other words:

$$W = \int_0^{20 \mu \text{ Sec.}} R_{sc} I_{sc}^2 dt = \frac{1}{2} L_{sc} I_o^2 \quad (3.1.16)$$

3.1.4 (Continued)

Here we may conclude that all of the energy supplied by the external source in the first 20 μ S time interval is used to charge up the capacitor.

f. S/C Film Temperature

Film temperature, at about 20 μ S after it is activated, can be given by the following empirical relation:

$$T = 65 \left(\frac{W}{M} \right)^{0.36} \quad (3.1.17)$$

for the temperature range of $30^\circ \text{K} \leq T \leq 150^\circ \text{K}$.

In this relation, W is the film energy (kj) and M is its mass (kg) that can be written as:

$$M = S_g \times l \times w \times d \quad (3.1.18)$$

where S_g is film's specific gravity ($S_g = 8400 \text{ kg/m}^3$ for Niobium). Substituting equation 3.1.18 in 3.1.17, we get:

$$T = 2.5 \left(\frac{W}{lwd} \right)^{0.36} \quad (3.1.19)$$

Here, W is in kilojoules and film dimensions are in meters.

Now, at $t = 20 \mu\text{S}$, all of the device parameters necessary for a heat transfer analysis are known. At this time, variation of the source voltage and current should be considered too.

Appendix 3.1.A

Program List for Transient Circuit Analysis of Resistive Superconducting Fault Current Limiter

```

00100 PROGRAM CIRCUIT(INPUT,OUTPUT)
00110C THIS PROGRAM CALCULATES THE TRANSIENT CURRENTS AND VOLTAGES
00120C OF THE CIRCUIT WHERE A RESISTIVE SUPERCONDUCTING FAULT CURRENT
00130C LIMITER (SCFCL) IS USED. THE PROGRAM ALSO EVALUATES THE GENE-
00140C RATED HEAT AND TEMPERATURE OF THE SUPERCONDUCTING FILM WITHIN
00150C 0.1 MILISEC. WHEN HEAT TRANSFER TO HELIUM HAS NOT STARTED YET.
00160C
00170 REAL I0,I,I2,I3,L,LS,LSC
00180 COMMON /PAR/ E,R,RS,RSC,CAP,L,LS,LSC
00190C
00200C SET UP THE INITIAL CONDITIONS..... T IS TIME (SEC), TM IS
00210C TEMPERATURE (K), SGH IS THE SPECIFIC GRAVITY OF THE FILM
00220C (KG/M3), AND RES IS FILM RESISTIVITY (OHM-METER).
00230C
00240 SGH=8.4E+03
00250 RES=3.0E-06
00260 DTM=0
00270C
00280C SET UP INITIAL CONDITIONS
00290C
00300 TM=4.2
00310 T=0
00320 TP=T
00330 I2=0
00340 U=0
00350 K=0
00360 POWER=0
00370 HEAT=0
00380 DT=5.0E-11
00390 SL=0.
00400 RB=1.0E-06
00410 TC=10
00420C
00430C ASK FOR THE INPUT DATA
00440C
00450 PRINT, *ENTER CIRCUIT PARAMETERS: R, L, C*
00460 READ, R,L,CAP
00470 PRINT , * RS, LS, LSC*
00480 READ, RS,LS,LSC
00490 PRINT , * E, I(0)*
00500 READ, E,I0
00510 PRINT , *ENTER S/C FILM SIZE: FL, FW, FD*
00520 READ, FL,FW,FD
00530 RN=RES*FL/FW/FD

```

```

005400
005500 PRINT OUT INPUT DATA
005600
005700 PRINT 99, E, I0, R, L, CAP, RS, LS, LSC, FL, FW, FD, RN
005800 99 FORMAT(///1X,*CIRCUIT MODEL FOR S/C FAULT CURRENT LIMITER*,/
005900+/*E      =*,E8.1,* VOLTS*,/* I(0) =*,E8.1,* AMPS*,/* R      =*,
006000+F6.2,* OHMS*,/* L      =*,E8.1,* HENRY*,/* C      =*,E8.1,
006100+* FARAD*,/* RS      =*,F6.2,* OHMS*,/* LS      =*,E8.1,* HENRY*,
006200+* LSC      =*,E8.1,* HENRY*,/* FL      =*,F6.0,* METERS*,/* FW      =*,
006300+F6.3,* METER*,/* FD      =*,E8.1,* METER*,/* RN      =*,F6.0,
006400+* OHMS*)
006500 FMASS=SGH*FL*FW*FD
006600 CT=0.35*FMASS
006700 RSC=RB
006800 I=I0
006900 I3=I0
007000 AREA=FL*FW*10000
007100 S=(RN-RB)/(TC-4.2)
007200
007300 PRINT OUT THE HEADINGS AND INITIAL CONDITIONS
007400
007500 PRINT 100
007600 100 FORMAT(//1X,*ITER TIME I/I(0) IS/I(0) ISC/I(0) UC/E*,4X,*RSC*
007700+/*RN POWER ENERGY TEMP*,/6X,*(SEC.)*,45X,*(W/CM2) (JOUL) (K*)
007800 P1=I/I0
007900 P2=I2/I0
008000 P3=I3/I0
008100 P4=U/E
008200 P5=RSC/RN
008300 PWR=0
008400 PRINT 200, K, T, P1, P2, P3, P4, P5, PWR, HEAT, TM
008500 200 FORMAT(1X, I3, E9.1, F6.2, 6E9.1, F6.1)
008600
008700 20 K=0
008800 KP=1
008900
009000 ASK FOR THE NUMBER OF THE DATA POINTS TO BE
009100 PRINTED AND THE TIME INTERVAL BETWEEN THEM.
009200
009300 PRINT 300
009400 300 FORMAT(1X,*ENTER NP,DTP*)
009500 READ, NP,DTP
009600 IF(NP.EQ.0) STOP
009700
009800 10 K=K+1
009900 R0=RSC
010000 CN=I3
010100 DT=DT*1.01
010200
010300 ITERATE THE CIRCUIT DIFFERENTIAL EQUATIONS FOR ONE STEP ONLY.
010400
010500 CALL DEQ(DT, I, I2, I3, U, SL)
010600 T=T+DT
010700 POWER= (R0+RSC)*(CN+I3)**2/12.0 + (R0*I3**2+RSC*CN**2)/6.0
010800 HEAT=HEAT+DT*POWER
010900 TM0=TM
011000 DTM0=DTM
011100 CT0=CT

```

```

011200
011300 ESTIMATE FILM TEMPERATURE (TM), CALCULATE ITS SPECIFIC
011400 HEAT (CT) AND THEN RE-EVALUATE THE TEMPERATURE.
011500
01160 DTM=POWER/CT
01170 DTM=0.5*(DTM+DTM0)
01180 TM=TM+DTM*DT
01190 IF (TM.LT.9) CT=0.00586*TM**2.84
01200 IF (TM.GE.9.AND.TM.LT.10) CT=14100*TM**-3.85
01210 IF (TM.GE.10.AND.TM.LT.30) CT=0.00686*TM**2.46
01220 IF (TM.GE.30.AND.TM.LT.100) CT=0.141*TM**1.58
01230 IF (TM.GE.100) CT=250
01240 CT=CT*FMAS
01250 DTM=POWER/CT
01260 DTM=0.5*(DTM+DTM0)
01270 TM=TM+DTM*DT
012800
012900 EVALUATE FILM RESISTANCE AS A FUNCTION OF TEMPERATURE
013000
01310 RSC=RN
01320 IF (TM.LT.TC) RSC=RB+S*(TM-4.2)
01330 SL=(RSC-R0)/DT
01340 IF (K.LT.500.AND.(T-TP).LT.DTP) GO TO 10
01350 P1=I/I0
01360 P2=I2/I0
01370 P3=I3/I0
01380 P4=U/E
01390 P5=RSC/RN
01400 PWR=RSC*I3**2/AREA
01410 PRINT 200,K,T,P1,P2,P3,P4,P5,PWR,HEAT,TM
01420 IF (KP.GE.NP) GO TO 20
01430 K=0
01440 TP=T
01450 KP=KP+1
01460 GO TO 10
01470 END

```

```

01490C
01500 SUBROUTINE DEQ(H,I,I2,I3,U,SL)
01510C   THIS SUBROUTINE ITERATES THE CIRCUIT DIFFERENTIAL EQUATIONS
01520C   USING MODIFIED EULER METHOD. THE VARIATION OF THE FILM
01530C   RESISTANCE DURING THE TIME INTERVAL OF ITERATION IS CONSIDERED.
01540C
01550 REAL I,I2,I3,L,LS,LSC
01560 COMMON /PAR/ E,R,RS,RSC,CAP,L,LS,LSC
01570C
01580C   SET UP CIRCUIT DIFFERENTIAL EQUATIONS (DERIVATIVE OF U AND I'S)
01590C
01600 F(I,U)=(E-U-R*I)/L
01610 G(I2,U)=(U-RS*I2)/LS
01620 Q(I3,U)=(U-RSC*I3)/LSC
01630 T(I,I2,I3)=(I-I2-I3)/CAP
01640C
01650 DT=H
01660 ERR=0.02
01670C
01680C   EVALUATE THE DERIVATIVES AT T=T0
01690C
01700 F0=F(I,U)
01710 G0=G(I2,U)
01720 Q0=Q(I3,U)
01730 T0=T(I,I2,I3)
01740C
01750 10 RSC=RSC+SL*H
01760C
01770C   EVALUATE THE DERIVATIVES AT T=T0+H
01780C
01790 F1=F(I+H*F0,U+H*T0)
01800 G1=G(I2+H*G0,U+H*T0)
01810 Q1=Q(I3+H*Q0,U+H*T0)
01820 T1=T(I+H*F0,I2+H*G0,I3+H*Q0)
01830C
01840C   IF THE TIME INTERVAL (H) IS TOO LONG, REDUCE IT
01850C
01860 IF(H/DT.LT.0.8) GO TO 20
01870 IF(Q0*Q1.GE.0.OR.ABS(H*Q0/I3).LT.ERR) GO TO 20
01880 RSC=RSC-SL*H
01890 H=H*0.9
01900 GO TO 10
01910C
01920C   CALCULATE CIRCUIT VOLTAGE AND CURRENTS AT TIME T=T0+H
01930C
01940 20 I=I+H*(F0+F1)/2.
01950 I2=I2+H*(G0+G1)/2.
01960 I3=I3+H*(Q0+Q1)/2.
01970 U=U+H*(T0+T1)/2.
01980 RETURN
01990 END

```

3.2 Transient Heat Transfer

This analysis 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 environments (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 very low superconducting film's resistance will drain the fault current and heat the film 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.

Heat transfer should be so controlled that film's final temperature would significantly exceed $T_c \approx 10 - 15 \text{ K}$ but would not exceed $T \approx 100^\circ \text{K}$ before the isolation switch is opened.

Figure 3.2.1 General sketch of a faulted system protected with an SCFCL.

To perform the required transient heat analysis, a computer program is being developed that considers the nonlinear variation of film's specific heat and current density during the heat transfer. General numerical method of Dusenberre is applied for the one-dimensional transient heat conduction.*

Heat transfer by radiation and helium convection is believed to be negligible and is ignored.

Some of the inputs to this program, such as film's initial conditions, are the results of the transient circuit analysis explained in section 3.1. Other set of program inputs are film's geometrical parameters, such as its thickness, which control its heat capacity and temperature.

The primary objective of transient electrical (circuit) and thermal (heat transfer) analyses, combined or separated from each other, is to determine the optimum dimensions of a S/C film that is thermally stable with fast response time, and electrically effective in limiting the fault current.

Transient circuit analysis is already done and reported in section 3.1. Results of the thermal analysis will be reported later.

* W.H. McAdams, "Heat Transmission", McGraw-Hill, New York, 1954

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).

Two film sides connected in series here.

Figure 3.3.1 Folded ("accordian") element design

Figure 3.3.2 Radial spiral element design

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:

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

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

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

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 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 3.3.4, with dimensions and currents defined. The field will be analysed along the central annular cross section shown in Figure 3.3.4. 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)

Figure 3.3.4 Four-pole (four-coil) field winding, shown with coaxial helical spiral element

3.3.4 (Continued)

coil dimensions

half length A (all coils have the same length)
large coil half width YL
small coil half width YS
large coil axial position ZL
small coil axial position ZS

magnetic field components

transverse BYLC, BYSC ...
axial BZLC, BZSC ...

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 3.3.5 and 3.3.6. Note that the coil length, 3.4 m, is chosen longer than the element length (3.0 m) to diminish the end effects. In Figure 3.3.5, 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 3.3.5, 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.

Figure 3.3.5 Radial magnetic field produced by the four-pole (four-coil) winding at the inner, center and outer superconducting film helices (see Figure 3.3.4)

Figure 3.3.6 Sketch of magnetic field produced by four-pole (four-coil) field winding. Arrows show direction and approximate magnitude of field.

3.3.4 (Continued)

The field sketch shown in Figure 3.3.6 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.

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 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.

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:

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

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

$$B_x = 0$$

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

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

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

Appendix 3.3B Computer Program to Calculate the Magnetic Field
of a Four - Coil, Four - Pole Winding

Listing

LIST OF 4COLFLD

```

00100      PROGRAM COLFLD (INPUT,OUTPUT)
001100     THIS PROGRAM CALCULATES THE MAGNETIC FIELD
001110     FROM A FOUR COIL COAXIAL ARRAY, A HALF WIDTH,
001120     BS, BL HALF HEIGHTS, ZS, ZL AXIAL POSITIONS.
001130     UNITS OF B ARE TESLA PER AMPERE, LENGTHS
001140     ARE IN METERS, ANGLES ARE IN RADIAN
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
003100     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
004200     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 R, THETA
00730     BYT=BYLC+BYSC+BYLF+BYSF
00740     BZT=BZLC+BZSC+BZLF+BZSF
00750     RATB=BYT/BZT
00760     THETAB=ATAN(RATB)
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 20 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
*RIY*

```

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	
BYSO,BZSO	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	
BYSO,BZSO	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	5.75800E-01	
BYLC,BZLC	-1.28822E-07	6.46763E-07	
BYSO,BZSO	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	
BYSO,BZSO	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	
BYSO,BZSO	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	
BYSO,BZSO	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	
BYSO,BZSO	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

3.4 Shunt Resistor

Shunt resistor is used in parallel with the superconducting film to limit the fault current. When the resistance of the S/C film is increased, fault current starts to go through the shunt resistor. The value of this resistance is determined by the maximum permissible fault current.

The physical size of the shunt resistor depends on its power rating. The base case considered in the transient circuit analysis of section 3.1 requires a shunt resistor of $R_s = 2.75 \Omega$. This resistor must dissipate 85 MJ in each cycle of current it is in service (limited fault current = 43kA rms).

To dissipate this much energy, shunt resistor should have a special structure. Nickel alloys such as Incoloy and Nicrome ($\rho \approx 10^{-6} \Omega\text{-m}$) are commonly used for this purpose. A tube of such material is usually filled with Magnesium oxide that serves as a heat sink. These tubes are shaped into some spirals. Two such spirals, wound in opposite directions, are put at the top of each other and connected in series to make a high power resistor unit with low inductance.*

These units can be connected in series and parallel to obtain the required resistance and power rating. This structure provides a good cooling action by the air flow through the spirals.

*P.S. Kroon and W. N. Rothenbuhler, "The Development and Application of a 69 kV Fault Current Limiter", Seventh IEEE/PES Conference and Exposition on Overhead and Underground Transmission and Distribution. April 4th, 1979.

3.5 Shunt Capacitor

This capacitor plays an important role in the performance of a SCFCL device. It carries the fault current and is charged up in the time interval between few nSec. to few μ Sec. after the S/C film is activated. This is a time interval when the S/C film has stopped carrying the fault current and the shunt resistor is still carrying only a negligible fraction of it.

The importance of the shunt capacitor is in limiting the overvoltages developed across the S/C film during the current commutation. These voltage transients determine the dielectric requirements of the film. This, indirectly, limits the minimum film inductance. As the amount of the heat developed in the S/C film is proportional to its inductance, one may realize the effect of the shunt capacitor in reducing this energy (heat).

The shunt capacitor used with the SCFCL device must also have a very low inductance to allow fast current commutation. This classifies the capacitor as low inductance energy storage type.

Another factor to be considered in choosing the size of the shunt capacitor is its price which is proportional to the amount of energy it can store. One supplier of such low inductance capacitors has quoted a price of \$ 1.00/Joule. This has to be pursued more thoroughly before the final design of the current limiting device.

4. EXPERIMENTAL PROGRAM

4.1 SAMPLE PREPARATION AND CHARACTERIZATION

The initial experimental effort of this quarter was to evaluate the resistance of high current contacts to thin film superconductors on insulating substrates. All previously reported high current contacts were for bulk superconductors or films on solid metallic (e.g. stainless steel) substrates. The niobium films used in this study also turned out to have a high residual resistivity ratio making them useful for self thermometers in our thermal recovery tests. Our efforts then pursued niobium nitride (NbN) in a program to achieve the high values of ρ_n and J_c required for the switch.

4.1.1 Clean Niobium Films for Thermal Recovery Measurements.

Niobium films were prepared using a Varian 5 inch S-gun sputtering source mounted in a 24 inch diameter stainless steel vacuum chamber pumped by a cryo-trapped 6 inch diffusion pump. Base pressure prior to introduction of the sputtering gas was typically 1.3×10^{-7} Torr. The films were sputtered at 80-100 A/sec in 6 mTorr of 99.9999% pure Argon. Power input to achieve these rates was about 3.5 KW. At the 6.5 cm target to substrate spacing used, substrates reached a temperature during deposition of $\sim 300^\circ\text{C}$ due to heating from the plasma.

Because of the low level of background impurities, particularly oxygen and the high deposition rate, high quality Nb films could be produced on a variety of substrates. Films of order $1 \mu\text{m}$ thick have a resistivity ratio of about 6, while films from 8 to $>25 \mu\text{m}$ thick were greater than 40. Since the room temperature resistivity of these films is relatively constant, the increasing resistivity ratio is a measure of the decreasing residual resistivity ρ_N which in turn is a measure of the decreasing impurity content. The large resistivity ratio indicates that these films can be useful as thermometers to measure the

thermal behavior of the film-substrate-helium combination when a current pulse drives the film from its superconducting to normal state. One needs only to tabulate $\rho(T)$ using a calibrated thermometer.

4.1.2 NbN Films for Switching Tests

As discussed in previous reports, it is desirable to have a superconducting material with high values of critical current density ($J_c \sim 3 \times 10^6 \text{ A/cm}^2$) and a normal state resistivity ($\rho_N \sim 300 \mu\Omega\text{cm}$). Although Nb and Nb₃Sn have high J_c , in order to obtain high enough ρ_N we found that T_c must be reduced substantially. Dirty Nb films which are superconducting at about 6K have a ρ_N of about $10 \mu\Omega\text{cm}$ and Nb₃Sn with reasonable T_c 's have a ρ_N of about $15\text{--}20 \mu\Omega\text{cm}$. Thus it was decided to look at the characteristics of NbN films which have been reported to have very high ρ_N and J_c simultaneously with T_c from 10–16 K.

NbN can be most readily formed by reactive sputtering using a Nb target and a gas mixture of Ar and N₂. To accomplish this the 24" sputtering system (described in 4.1.1) was modified by the addition of a regulated nitrogen feed line with variable leak valve and shut off valve. The nitrogen is obtained as blowoff from a large liquid nitrogen reservoir and should be free of impurities.

Initial attempts to make NbN consisted of establishing a N₂ partial pressure of 1.0 mTorr using an absolute pressure manometer accurate to ± 0.1 mTorr. This was followed by the introduction of 6 mTorr of Ar and establishment of the plasma discharge.

The plasma discharge caused the total pressure to drop by 1.0 mTorr, and since the plasma discharge is known to have no effect on the Ar pressure, it was concluded that N₂ was being gettered. Opening and closing the shutter above the target had little effect on the pressure reduction, indicating that most if not all the N₂

was being gettered at the target. Films made under the above conditions showed no superconductivity above 4.2 K. Because of the gettering by the target, it proved necessary to initially introduce larger amounts of N_2 (several mTorr) in order to maintain 0.1 to 1.0 mTorr during sputtering. A typical sequence of events is shown in Fig. 4-1. As can be seen, a starting pressure of 4 mTorr N_2 produces 0.7 to 0.8 mTorr during the deposition. As might be expected the N_2 partial pressure is very sensitive to target power (i.e. sputtering rate). A change from 1.1 to 1.2 KW causes N_2 to drop by 0.6 mTorr. Thus the rate and N_2 pressure were monitored and controlled carefully during sample preparation. All films were prepared on microscope slides either 1" x 3" or 7/8" diameter. These substrates reached measured temperatures between 200 and 300°C due to heating by the plasma.

To determine film quality, the superconducting properties of sample number NN7902 were measured. The film was 3 μ m thick, 0.63 cm wide and 1.2 cm long. Using a 4 probe resistive technique, T_c was determined to be 14.6 K with a transition width ΔT_c of 0.1 K. This compares favorably with the results of others and the narrow ΔT_c indicates the film is quite uniform in its properties. The upper critical field $H_{c2}(0)$ was determined by measuring T_c as a function of external magnetic field H as shown in Fig. 4.2. Using the non-paramagnetically limited form of the Werthamer, Helfand, Hohenberg relationship:

$$H_{c2}(0) = -0.693 T_c \left(\frac{dH}{dT} \right)_{T_c}$$

we get $H_c(0) = 346$ KG. This is within the range of values expected for NbN.

One of the most important parameters for the SCFCL is the normal state resistivity. The residual resistance ratio was measured to be 0.77, indicating that the conductivity is activated and not metallic. This is understandable because the low temperature resistivity (235 $\mu\Omega$ cm) is greater than the maximum

Fig. 4-1. Total pressure in sputtering system as a function of time during typical NbN deposition.

Fig. 4-2. Resistance of sample NbN 7902 as a function of temperature at various values of magnetic field (in kGauss).

theoretical metallic resistivity. The maximum metallic resistivity of 150-200 $\mu\Omega$ cm corresponds to an electron mean free path equal to the interatomic spacing of a few Ångströms. Therefore in this first attempt at a NbN film we have achieved a ρ_N which is close to that desired for the SCFCL.

The critical current density at 4.2 K in liquid helium was 9.3×10^5 A/cm². This is also a very respectable value relative to the requirements of the SCFCL. It is expected that by suitable adjustments of the sputtering conditions this value can be considerably improved (see section 4.4.1).

4.1.3 CONTACT LEAD RESISTANCE MEASUREMENTS

The resistance between the superconducting film and high current leads must be made small enough to preclude unacceptable helium boiloff. The guidelines for the preliminary work were a maximum resistance of 1.0 $\mu\Omega$ with one cm² of contact area and 500 Amps of current. These parameters result in a power dissipation of 0.25 watts per contact.

Two techniques of making the contact were considered: ultrasonic soldering and ultrasonic bonding.

To evaluate the ultrasonic bonding method we sent several samples of niobium films on various substrates to the manufacturer of these bonders. They bonded 0.020" diameter aluminum wires to these films. Preliminary evaluation showed the contacts to be very fragile and easily broken. Attempts to measure contact resistance were unsuccessful due to lead breakage and the non-superconducting properties of some of the Nb films.

Concurrently, a study to develop low resistance soldered indium contacts using an existing ultrasonic soldering iron were initiated. The ultrasonic agitation during the soldering process aids in breaking down the thin oxide layer which forms on the surface of niobium and its compounds. Pure indium proved very effective as a

solder because of its very low resistivity and ability to wet to other surfaces. Initial measurements were limited by the cryostat leads to currents below 20A, but the results were encouraging: contact resistance could be kept below $0.5\mu\Omega$ and was approximately independent of current.

To evaluate performance at higher current values, an existing cryostat was modified by the addition of low loss, vapor cooled 200 Amp current feed thrus. Connection to the samples was made with a 1/2 inch wide superconducting Nb_3Sn tape shunted with 0.030" thick Cu strips. The Nb_3Sn tape itself consisted of a $10\mu m$ thick layer of diffusion formed Nb_3Sn sandwiched between two 0.0015 inch thick layers of plated Cu coated with Pb/Sn solder. Manufacturers specifications rated the Nb_3Sn ribbon at 1000 Amps in liquid helium. Samples consisted of 1.9 cm long Nb films which were $\sim 25\mu m$ thick by 0.63 cm wide and deposited on 2.2 cm diameter microscope slides. Contact was made to each end of the Nb film using indium solder to bond the Nb_3Sn tape. Each contact had an area of $\sim 0.2\text{ cm}^2$. The current was supplied from an existing regulated battery, which will be discussed in section 4.2.3. The maximum d.c. current was 170 Amps. The current-voltage, $I(V)$, characteristics of the contacts showed only slight deviations from linearity up to 170 Amps; the resistance changed from $0.33\mu\Omega$ at 10 Amps to $0.36\mu\Omega$ at 170 Amps.

This resulted in a power dissipation of $\sim 10\text{ mW}$ per contact at 170 Amps. Projections to 500 Amps indicate contact resistance to be well under the $1\mu\Omega/\text{cm}^2$ guideline previously established.

Preliminary measurements on 1.9 cm long by 0.63 cm wide x $3.0\mu m$ thick NbN films were also made. The results are shown in Fig. 4.3. Here, the $I(V)$ characteristics are quite non-linear, with the contact resistance changing from $0.08\mu\Omega$ at 10 Amps to $0.2\mu\Omega$ at 170 Amps. There is, at present, no explanation

Fig. 4-3. Current-Voltage characteristic for indium solder contact to sample NbN 7902.

for the shape of the curve. In any event the $0.2\mu\Omega$ contact resistance at 170 Amps with 5.4 mW power dissipation is a very encouraging result. As a result, we feel that ultrasonic soldering, using indium, is adequate for our present needs, and we have abandoned further studies of the ultrasonic bonder.

4.2 FACILITIES AND EQUIPMENT

At this time, all the major equipment needed for the experiment has been ordered and is due between August 15, 1979 and October 1, 1979. The laboratory facilities are installed and the cryostat insert is nearing completion. It is expected that full scale tests can begin sometime in October.

4.2.1 Cryostat Insert

A sample holder, which has been designed and is nearing final assembly, offers a great deal of flexibility in its use. It is designed to fit in our existing 6" diameter stainless steel helium cryostat and is serviced with 500 Amp (RMS) feed-throughs and vapor-cooled leads. The holder can take samples up to 3" x 1" microscope slides, and has two Nb_3Sn ribbons to transmit the current to the sample. There is a 20 turn, split coil pulse magnet which can be rotated at any angle with respect to the plane of the sample. Using an existing power supply the magnitude of the field for a 5 μ sec rise time is about 400 Gauss.

The sample holder and magnet can also be rotated with respect to gravity. This orientation may be important to remove bubbles, although it is our intention to find a form of helium which does not produce bubbles during switching (section 4.3.1).

4.2.2 Laboratory Installations

A laboratory with approximately 1000 sq. ft. of floor space has been made

available for the experimental area. Most services were available (chemical hood, some electrical power, natural gas, compressed air, cabinets, etc.) but nitrogen gas, circulating chilled water and some electrical power had to be added. This work is completed and we are ready to move in the experimental apparatus.

4.2.3 D. C. Power Supply - 200 Amps

In order to expedite contact resistance testing and critical current measurements, while the 500 Amp pulsed power supply was being designed and constructed (see section 4.2.4), an existing 200 Amp d.c. supply was upgraded. This supply uses a series of 56 PNP Germanium power transistors, driver transistors and a feedback loop to regulate the current output from a 125 Amphour, 12 Volt car battery to better than 1 part in 10^4 at 200 Amps. Input circuits allow an external ramp generator to increase the current to 200 Amps in controlled times from ~ 1 sec to 10^4 sec.

Using this power supply to make high current contact resistance measurements revealed several shortcomings, for which modifications were required. A cooling fan was provided to keep the transistors within their operating temperature range, and an additional 12V, 125AH battery was placed in parallel.

It is desirable to start pulsed current measurements as soon as possible on the samples. Therefore we made additional modifications on this supply to improve its rise time to less than 1 msec. As a result, output currents up to 320 A were obtained into a typical load. The results are shown in a series of oscilloscope traces in Fig. 4 - 4. The output current was measured using a non-contact Hall probe current sensor with a risetime of $< 150\mu\text{s}$. This arrangement should prove quite useful in future experiments.

Fig. 4-4. Output current of the 200 Amp pulsed supply versus time (upper trace, 50 A/cm) and input pulse to transistor drivers (lower trace, 1 V/cm). Horizontal scale is 0.5 m sec/cm. The sequence shows different amplitudes.

4.2.4 Pulsed Power Supply - 500 Amps.

In testing samples there are compelling reasons to have a 500 Amp supply which can be switched on and off abruptly. All commercial units at this current rating use enormous capacitors (~ 1 Farad) to smooth the output, and these greatly impair the speed for switching on and off. We must be able to switch on in a millisecond to simulate 60Hz operation. However the real need for fast switching is at the end of the measurement where we must measure the recovery time by reducing the current very rapidly. Unfortunately the commercial supplies are even too slow (~ 0.1 sec) to reduce helium boiloff to an acceptable level during experiments.

The solution to this is a transistor bank controlling the current with response time of a few microseconds. Since these are not available commercially, we are instead having it built in the Electronics Division of Argonne, utilizing their experience with such supplies.

The supply will rectify 208 volt, 3 phase (4 wire Y) and transform it down to 20 volts. This output ($\sim 8\%$ ripple) will be controlled by a bank of 10 water cooled, matched transistors. Metering and several safety devices will be built in, as well as an internal pulsing circuit. External waveforms may also be applied as long as the average power stays below about 1KW.

The necessary parts have been ordered, and the supply is to be delivered by October 1, 1979.

4.2.5 Ultrasonic Bonder

Because of the success of bonding leads to films using indium solder reported in section 4.1.3, there is no longer a need for the ultrasonic bonder which was originally requested. We have therefore deleted that equipment purchase.

4.3 TRANSIENT HEAT TRANSFER

Within the context of the SCFCL development there is a need for an experimental program on transient heat transfer to liquid helium. The information required is twofold. We need to evaluate various states of liquid helium coolant (supercritical, 4.2 K pool boiling, superfluid and subcooled) with respect to bubble formation, recovery time and ability to interrupt a second fault immediately after system reclosure. Secondly, we need to know the time profile of the temperature of the superconducting film subjected to a pulse of heat which simulates switching, i.e., highly concentrated in the first microsecond but extending out to several milliseconds. This must include the recovery time after the pulse is turned off, and should also cover a range of representative values of heat dissipation per unit film area, film thickness and cooling channel width.

The National Bureau of Standards, Boulder, Colorado has significant experience in the area so a visit was arranged to evaluate possible participation by NBS in transient heat flow experiments required for the Superconducting Fault Current Limiter (SCFCL) Project. Whether or not this collaboration occurs, valuable suggestions and ideas were generated through discussions and a tour of experimental facilities. Ken Gray represented the Gould/ANL SCFCL project. W. G. (Gene) Steward was the principle contact at NBS but Vincent Arp, Pat Giarritano, Nolan Fredrick and D. Devaney also participated in discussions and tours.

4.3.1 DISCUSSIONS AT NBS.

The discussions began with my review of the SCFCL to better acquaint the NBS scientists with the concepts. This part of the discussion resulted in my realization of the need for additional electrical insulation between turns in

the spiral coil at the end supporting the large voltage gradient. This could be accomplished by a wider gap for helium (thus increasing the volume of the device) or by inserting a mylar sheet between turns. A second point involved the effect of impurities in liquid helium. These greatly reduce the dielectric breakdown strength. We should find out more about this possibility.

Gene Steward had prepared the following preliminary proposal for answering the questions outlined in my letter to him:

NBS PRELIMINARY PROPOSAL 7/27/79

Helium transient heat transfer for the superconducting fault current limiter project at Argonne National Laboratory. (K. E. Gray)

I. Operation of the device:

- A. Very large heat pulse drives a superconducting film normal in less than 1 microsecond. Temperature must exceed 10 or 15K.
- B. A much smaller heat pulse continues for a few milliseconds. Temperature must not exceed about 100K during this time.
- C. Heat load removed (or reduced) the temperature must return to the superconducting level in ____ s.

II. Experimental requirements and methods considered:

- A. Fluid conditions: subcritical and supercritical pressure. Superfluid or subcooled liquid are possible means to suppress boiling.
- B. Heat transfer surface: Since Kapitza resistance could be the most important factor for very short times, and R_K is very sensitive to the kind of material we should try to use the same kind of material as a test heater as in the actual device. The resistive characteristics of Nb above the transition might be used for thermometry. An extremely high current pulse would be required to drive a pure superconductor normal, and it would be difficult to control the heating after resistance occurred. Solutions considered:
 - 1. Laminated film with resistive heater-thermometer. This is undesirable because of the added heat capacity, necessity of electrical insulation between the heater-thermometer and the superconductor heat transfer surface. This type of film has proven very troublesome to fabricate.
 - 2. Laser heating with possible feedback to control temperature rise. Separate calorimeter experiments could be used to determine heat absorption.

3. The film might be held on the verge of transition with a steady magnetic field and then pulsed electrically, or the current or magnetic field could be raised slowly until the transition conditions occurred.

C. Verification of presence or absence of bubbles during millisecond pulse:

1. Fiber optic bundle with magnifying lenses.
2. High speed photography through does not look like a good idea:
 - a. Too much attenuation.
 - b. Interpretation is highly subjective.
 - c. Difficult to correlate occurrences of events with experimental data in heat transfer.
3. Solution suggested by Nolan Fredrick is to use a photocell to detect light scattering by bubbles. Photomultiplier might be used. Bubble events could be recorded along with heat transfer data. Fiber optic magnifier could be used to obtain characteristics of signals which indicate bubbles.

D. Cooling following heat pulses. A small measurement current would have to be maintained after the main pulse is stopped. Temperature recovery may have to be recorded in separate tests since measurement current would be much smaller than the pulse current.

E. Data recording. Our digital storage oscilloscope has minimum recording interval of 0.5 microsecond; therefore an analog storage scope might have to be used.

The scheme to detect bubbles proposed by NBS uses fibre optics with lenses to observe the bubbles and perhaps photograph them using high speed photography. In discussions before this meeting I proposed a simpler system in which a light pipe has a short gap just above the superconducting film. The transmitted light can be readily detected at room temperature with a photomultiplier tube. The presence of bubbles $> 1 \mu$ meter in diameter will scatter the light, reducing the transmitted intensity and exhibiting a noise spectrum representative of the bubble formation. The time at which bubbles form can be easily measured to verify the conjecture of earlier work by Steward on bubble formation.

The formation of bubbles has a very deleterious effect on the SCFCL in terms of high voltage breakdown, recovery time and difficulty and delay in removing the bubbles through narrow channels. Thus a high priority should be placed on finding

a form of helium coolant which does not produce bubbles. In either case, the cooling channel width will be important, but the presence of bubbles may also dictate a particular orientation for the channels with respect to gravity.

Knowing the form of helium which minimizes bubble formation, the temperature profile as a function of time is most easily obtained by the technique used previously by Steward. He used a carbon film which has a reasonably large temperature coefficient of resistivity - $\rho(T)$. Steward pointed out that the short term heat conductivity is primarily determined by the Kapitza boundary resistance, which varies with material and surface smoothness. Therefore, carbon films may be inappropriate to estimate the effects in our metal films. Fortunately pure metals can also exhibit a reasonably large temperature dependent resistivity and so can substitute for carbon. In order to adequately model our proposed NbN films, pure Nb films can be used. These have been made at ANL with residual resistivity ratios about 20. (See section 4.1.1).

However, it is desirable to separate these experiments from switching experiments, so the superconductivity of niobium is a nuisance. I suggested that this could easily be overcome by a constant magnetic field of 2-3 kG which would quench the superconductivity but leave the heating effects unaltered. Such a field is readily available from an easily wound small superconducting magnet.

It is not a simple matter to experimentally approximate the time dependent heat flux to the sample that is calculated for the actual SCFCL. This is partly because the resistance of the Nb film is temperature dependent, whereas in the actual device the NbN will be independent of temperature. This can be accounted for by measuring current and voltage, computing the power and using feedback to adjust the heater supply to keep the power following the prescribed waveform. Unfortunately, the bandwidth of such a feedback device is too slow for the initial heat surge occurring in less than one microsecond. Therefore, an additional fast

heat pulse will be applied by discharging a capacitor through the resistance of the sample to simulate the initial stages of switching. The most important parameter is the total energy per unit area, and the exact time profile in the sub microsecond range may be much less important. This can be checked by varying the fast pulse decay time.

The measured current and voltage can be stored in separate channels of a digital storage oscilloscope with time resolution of $0.5 \mu \text{ sec}$. This gives the temperature T from the temperature dependent resistivity $\rho(T)$, and has more than adequate time resolution.

After the slow pulse ($\sim 1 \text{ m sec.}$) is turned off (simulating the isolation switch), a small probe current must be sent through the sample to measure its temperature decrease back to the bath temperature.

As a check on short term multiple operation of the SCFCL, a second series of heat pulses can be dissipated after a short period of time to assure that the helium has adequately recovered from the first pulses, i.e., the temperature rise should be similar for both series of pulses.

4.3.2 Relevant Facilities and Experience at NBS.

Steward has already reported transient heat flow measurements for carbon films using the various forms of helium coolant. These facilities are still available as well as the electronics to produce and control the slow heat pulse, and to measure the temperature with $0.5 \mu \text{sec}$ resolution. A pulsed capacitor system is available which may be suitable for the fast heat pulse in these studies.

There is much experience at NBS in these and other measurements using supercritical, superfluid, sub-cooled and pool boiling helium. Cryostats and auxiliary equipment are available. This includes a facility in which the

various forms of flowing helium could be used.

There is additional experience looking at instabilities in supercritical helium cooling in a long flowing system. This study was performed for the Brookhaven superconducting A-C Transmission Line. A 600' tube, with constant heat input along the length showed oscillatory instabilities in flow, temperature and pressure. These instabilities became gradually larger as the fluid flow and heat flux increased. The period of oscillation was twice the transit time for the fluid through the tube (i.e. a few hours).

In a second study for BNL, they are looking at the cooldown time for long lengths of transmission line. They find times as long as 20 to 40 days for the proposed transmission line. The reason for this long time is because of the counter flow cooling cycle: liquid goes down the center and back the outer shield. There is significant thermal conductivity between these and the result is to greatly impare cooldown - for example a single run with a fully insulated return would take only two days. I suggested that initial cooldown be done that way, with the liquid helium from one refrigerator being recycled into the next refrigerator along the transmission line. Then the excess at the end of the line would have to be trucked back.

4.3.3 Conclusions and Recommendations

A proposal to subcontract work to NBS should be considered. NBS is certainly interested in the funding and Steward and others seem genuinely interested in the problems and proposed solutions. They are also adequately prepared and staffed for such work.

NBS would want a three man month effort as a minimum and would like some lead time to adjust their other programs. Therefore, we should keep them informed about the possibility of funding under the present contract or during the continuation

contract period. I suggested that such a subcontract would not likely start before March 1980. We should discuss this in more detail and make a recommendation to DOE, perhaps in the fifth quarterly report. At some stage a detailed work statement must be written, and NBS should be consulted during this process. An administrative point: NBS cannot be funded directly from Gould, but must get funding directly from DOE or Argonne.

4.4 PROJECTED PROGRAM

In this section we outline our major objectives for the upcoming quarter. However, in some cases the work may extend beyond the next quarter, and the work pursued may require changes in direction.

4.4.1 NbN Development

During the next quarter efforts will focus primarily on the development of NbN films with characteristics suitable for the superconducting switch. The relationship between sputtering process parameters and the superconducting properties such as J_c , T_c and ρ_N will be explored. The goal will be to maximize J_c and ρ_N without unduly lowering T_c .

An important consideration here is that the desired resistivity ρ_N is greater than the maximum metallic resistivity (150-200 $\mu\Omega\text{cm}$). The results we reported in section 4.1.2 may be indicative of a granular material in which the conductivity is limited by tunneling between grains. As such, it is perhaps surprising that such large critical current densities are possible ($\sim 1 \times 10^6 \text{ A/cm}^2$). We must determine if the usual procedures for increasing J_c in metallic films is applicable, since the breakdown of Josephson intergrain tunneling may control J_c and not flux pinning. A major portion of the next three month's effort will focus on this problem.

In addition preliminary experiments will begin on the film width and thickness dependence of J_c . These will be systematically varied and relationships developed as to their effect on J_c . Widths will be defined by insitu masking and photolithographic techniques, which should produce distinctly different film edges and help quantify edge effects on J_c . All measurements made using d.c. currents will be extended to equivalent rise times for 60 Hz currents using the power supplies described in sections 4.2.3 and 4.2.4. Pulse risetimes will be of order ~ 1 m sec with widths from 1-10 ms and at currents up to ~ 300 Amps.

4.4.2 Facilities and Equipment

All the major equipment anticipated for the experimental program should be delivered and operational in the next quarter. The film thickness monitor should be delivered by September 1 and the 500-1000 amp pulsed supply by October 1. Minor equipment items - liquid nitrogen dewars etc. are already operational.

The power supply for the pulsed magnet, the experimental cryostat and a.c. 500 amp source are items which we have on hand and are all operational. Installations in the laboratory should be completed by mid-August and equipment moved into place by September 1. During September, electrical power and water cooling will be connected along with miscellaneous installations for the experiments.

4.4.3 Thermal Propagation Experiment

Full scale thermal propagation experiments are planned to begin in October, however preliminary ones at lower current level are anticipated before that. Samples of NbN about 2" long carrying currents up to 500 Amps will be tested by switching in the pulsed magnetic field. The time response will be analyzed to determine if switching is uniform or by thermal propagation.

4.4.4 Transient Heat Transfer/Thermal Recovery

During the next quarter we shall determine when these experiments (see section 4.3) should be started and the advisability of subcontracting part of them to NBS rather than setting up at Argonne. Two crucial considerations are manpower and equipment availability. Apparently NBS has these readily available whereas the situations at Argonne must be given further consideration. There is a definite advantage in doing the thermal recovery and heat transfer studies at Argonne: we can establish "in house" experience and facilities which will become important for continuing studies. We expect to make a definite recommendation to DOE, possibly before the next quarterly report.