MASTER

**Report
for**

**RESEARCH
AND
DEVELOPMENT**

➔ GOULD-BROWN BOVERI

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D.O.E. CONTRACT ET-78-C-01-3015

SUPERCONDUCTING FAULT CURRENT LIMITER

Sixth Quarterly Technical Progress Report

November 8, 1979 - February 7, 1980

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TABLE OF CONTENTS

	<u>PAGE</u>
i. INTRODUCTION, SUMMARY AND FORECAST	i-1
1.0 PERFORMANCE OBJECTIVES	1-1
2.0 RANKING OF DEVICE DESIGN CONCEPTS	2-1
3.0 ANALYTICAL STUDY OF MOST PROMISING DESIGN	3-1
3.1 Transient Circuit Analysis	3-1
3.1.1 Mathematical Model	3-2
3.1.2 Transient Analysis - Base Case	3-6
3.1.3 Effects Of The S/C Film Size And Other Circuit Parameters On The Current Commutation	3-8
3.1.4 Modified Model For The Superconducting Film Resistance	3-20
3.1.5 Final Values Of The Electrical Transients	3-22
3.3.6 Effect Of The Magnetic Field Distribution On The S.C. Film's Resistance	3-95
3.4 Thermal Recovery Time Of The S.C. Fault Current Limiter	3-104
3.5 Shunt Resistor Evaluation Criteria	3-111
3.5.1 Resistor Element Types	3-111
3.5.2 Evaluation Of Resistor Element Types	3-113
3.5.3 Selection Of Resistor Element Type	3-116
3.5.4 Fault Current Limiter Resistor Design Concept	3-117
3.5.5 Analysis Of Resistor Dimensions (Computer (Computer Simulation)	3-123
3.5.6 Support Structure For The Shunt Resistor	3-124
3.5.7 Future Work	3-126
4.0 EXPERIMENTAL PROGRAM	4-1
4.1 Materials Development	4-1
4.1.1 Surface Defects In NbN Films	4-1
4.1.2 X-ray Analysis Of NbN Films	4-2
4.1.3 Nb ₃ Sn Evaluation	4-2
4.1.4 Metallic Stabilization Of NbN	4-4

i. INTRODUCTION, SUMMARY AND FORECAST

Principal effort during this quarter continued to focus on the experimental tests and on the analysis of the resistive device.

In Section 3.1, the transient circuit analysis is discussed. This has been changed in two ways since the report in the Fourth Quarterly Report. In the 4th Quarterly analysis, the S/C film was assumed to already be in the mixed, lossy state, and the resistivity of the film was then assumed to rise as the film temperature rises due to its own ohmic heating. In Section 3.1.1, a better analytical relation between enthalpy and temperature has now been included in this self heating model. Switching times are still in the nanosecond range, but final temperatures are less than predicted by the earlier model.

The second change in the transient circuit model is described in Section 3.1.4. In this new approach, the S/C film is assumed to remain in the superconducting, lossless state until the magnetic field rises to the critical value. After reaching the critical point, which may take up to a microsecond, the film is assumed to instantly (e.g., in nanoseconds) attain its fully normal resistivity. This model now depends on the detailed time and space analysis of the magnetic field, which is carried out in a new Section 3.3.6. Here, the rise of magnetic field along the S/C film is determined by two design parameters: 1) the spacial uniformity of the field (determined by the geometry of the field coils) and 2) the rate of rise of current in the coils.

With the space-time magnetic field model, different parts of the S/C film reach the critical switching field at different times. Thus, in all cases, one point on the film will switch first, and since it is in series with essentially the full fault current, it will be the "hot spot". The temperature to which this hot spot rises depends on how rapidly the remainder of the film is switched. Expected hot spot temperatures are calculated for different coil conditions; the lowest film temperatures will of course be reached when the coil rapidly and uniformly switches the entire film. The equations in these sections indicate the important criteria for coil design.

i. INTRODUCTION, SUMMARY AND FORECAST

Thermal recovery times for different hot spot temperatures are calculated in Section 3.4. This analysis assumes that the isolation switch opens on the second current zero after the fault, and that the film loses heat to the substrate on one side and the liquid helium on the other side. The desired goal is for the film to be cooled down and again superconducting in fourteen cycles after isolation.

The resistive device analysis in this Quarterly Report concludes with evaluation of the shunt resistor, Section 3.5.

Section 4 describes the progress made in the experimental tasks during this Quarter. The new low inductance feed through was being manufactured through this Quarter and so no new switching or thermal recovery tests have been performed. Several important advances have been made in material development, however.

Metal stabilizing layers adjacent to the S/C film have been studied. This greatly improves the pulse performance of NbN, although J_c 's never exceeded $1-2 \times 10^6$ A/cm². Nb₃Sn was also tested with and without a metal stabilizing layer. Although ρ_n for Nb₃Sn is lower than for NbN, the critical current density is higher, making Nb₃Sn an attractive alternate. This material is used on a sapphire substrate. The metal stabilizing layer in this case helped but was not essential. The stabilizing effect may therefore be due to high thermal conductivity of the stabilizer (and of the sapphire substrate) rather than due to local current sharing.

Surface defects in NbN samples were almost totally eliminated by changes in sputtering technique. This did not increase the critical current density, however, indicating that the surface irregularities do not cause the reduction of J_c . NbN film structure was also examined by X-ray diffractometry. Some irregularities in the crystal lattice structure were noted.

i. INTRODUCTION, SUMMARY AND FORECAST

During the next and final Quarter of this contract, the low inductance feed through will be completed and final switching and thermal recovery tests will be made. These tests will evaluate the comparative advantages of NbN and Nb₃Sn, on sapphire and glass substrates, with and without stabilization. Switching and recovery times will be measured. A final evaluation of the resistive device based on these experimental and analytical results will also be carried out.

1.0 PERFORMANCE OBJECTIVES

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

2.0 RANKING OF DEVICE DESIGN CONCEPTS

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

3.0 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:

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

$$\frac{dI_S}{dt} = \frac{1}{L_S} (V_C - R_S I_S) \quad (3.1.2)$$

$$\frac{dI_{SC}}{dt} = \frac{1}{L_{SC}} (V_C - R_{SC} I_{SC}) \quad (3.1.3)$$

$$\frac{dV_C}{dt} = \frac{1}{C} (I - I_S - I_{SC}) \quad (3.1.4)$$

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 and 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. This model will be later modified to approximate film's total resistance as a function of time.

FIGURE 3.1.2 Initial Model For Superconducting Film Resistivity As A Function Of Temperature

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 input energy into the films is used to raise its enthalpy. This assumption is valid for the time $t < 1.0 \mu\text{sec}$. when the transient heat transfer to helium has not effectively started yet. In this case, we have:

$$\frac{dT}{dt} = \frac{P}{Mxc} \quad (3.1.6)$$

or

$$Q = \int_{T_0}^T c dT = \int \frac{p dt}{M} = \frac{\text{Energy}}{\text{Mass}} \quad (3.1.7)$$

Where

P	=	input power	(watts)
M	=	S/C film mass	(grams)
c	=	specific heat of the film	(Joule/gram x °K)
Q	=	Film's enthalpy	(Joule/gram)

Equation 3.1.7 is preferred to equation 3.1.6 for finding film's temperature because it is less sensitive to the errors inherent in the iterative methods.

The specific heat and enthalpy of the S/C film varies with temperature. Figure 3.1.3 shows variation of Niobium enthalpy with temperature. Niobium enthalpy can be approximated with the following relations (Q is given in J/kg)

$$\begin{aligned} Q &= 1.53 \times 10^{-3} T^{3.84} - 0.38 & T < 9^\circ\text{K} \\ Q &= -4947/T^{2.85} + 16.12 & 9^\circ\text{K} < T < 10^\circ\text{K} \\ Q &= 1.98 \times 10^{-3} T^{3.46} + 3.42 & 10^\circ\text{K} < T < 30^\circ\text{K} \\ Q &= 0.0547 T^{2.85} - 95 & 30^\circ\text{K} < T < 100^\circ\text{K} \\ Q &= 30.15 T^{1.35} - 7298 & 100^\circ\text{K} < T < 300^\circ\text{K} \end{aligned} \quad (3.1.8)$$

which can be rearranged to give film's temperature as a function of its enthalpy (energy per unit mass):

$$\begin{aligned} T &= 5.39 (Q + 0.38)^{0.26} & Q < 6.7 \text{ J/kg} \\ T &= 19.78 / (16.12 - Q)^{0.35} & 6.7 < Q < 9.1 \\ T &= 6.04 (Q - 3.42)^{0.29} & 9.1 < Q < 259 \\ T &= 3.08 (Q + 95)^{0.39} & 259 < Q < 7812 \\ T &= 0.08 (Q + 7298)^{0.74} & 7812 < Q < 60,000 \end{aligned} \quad (3.1.9)$$

The amount of input power is:

$$P = R_{sc} I_{sc}^2 \quad (3.1.10)$$

By solving equations 3.1.1 to 3.1.10 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

FIGURE 3.1.3 Enthalpy of Niobium

3.1.1 Mathematical Model (Continued)

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

$$I = \frac{E}{Z} \quad (3.1.11)$$

where E is the source voltage and

$$Z = 0.08 + j 1.5 + R_s = 2.83 + j 1.5 \text{ Ohms} \quad (3.1.12)$$

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.

Case IR	Device:	S/C Film:
$E = 200\text{kV}$	$C = 0.5\mu\text{F}$	$L = 500\text{m}$
$I_o = 43\text{kA}$	$R_s = 2.75\Omega$	$w = 0.1\text{m}$
$R = 0.08\Omega$	$L_s = 10\mu\text{H}$	$d = 5 \times 10^{-6}\text{m}$
$L = 4.0\text{mH}$	$L_{sc} = 10\mu\text{H}$	$R_N = 3000\Omega$

GRAPH #1 Electrical Transients Of The 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 24%.
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 71.5°K (14% reduction).
3. Steady state film current is increased by 50% (see equation 3.1.12 in the next section).

Case IR	Device:	S/C Film:
$E = 200 \text{ kV}$	$C = 0.5 \text{ } \mu\text{F}$	$L = 1000\text{m}$
$I_o = 43 \text{ kA}$	$R_S = 2.75 \text{ } \Omega$	$w = 0.1\text{m}$
$R = 0.08 \text{ } \Omega$	$L_S = 10 \text{ } \mu\text{H}$	$d = 5 \times 10^{-6}\text{m}$
$L = 4.0 \text{ mH}$	$L_{SC} = 10 \text{ } \mu\text{H}$	$R_N = 6000\text{m}$

GRAPH #2 Effect Of S/C Film Size (Film Length)

Case IR

Device:

S/C Film:

 $E = 200 \text{ kV}$ $C = 0.5 \mu\text{F}$ $L = 500 \text{ m}$ $I_0 = 43 \text{ kA}$ $R_S = 2.75 \Omega$ $w = 0.15 \text{ m}$ $R = 0.08 \Omega$ $L_S = 10 \mu\text{H}$ $d = 5 \times 10^{-6} \text{ m}$ $L = 4.0 \text{ mH}$ $L_{SC} = 10 \mu\text{H}$ $R_N = 2000 \Omega$

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 64°K (23% 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 $L_{SC} = 10 \mu\text{H}$ 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 104°K (25% 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 $T \geq T_C$. 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 $T_C = 15^\circ\text{K}$ 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.

Case IR	Device:	S/C Film:
$E = 200\text{kV}$	$C = 0.5\ \mu\text{F}$	$L = 500\ \text{m}$
$I_0 = 43\text{kA}$	$R_S = 2.75\ \Omega$	$w = 0.1\ \text{m}$
$R = 0.08\ \Omega$	$L_S = 10\ \mu\text{H}$	$d = 10^{-5}\text{m}$
$L = 4.0\text{mH}$	$L_{SC} = 10\ \mu\text{H}$	$R_N = 150\ \Omega$

GRAPH #4 Effect Of S/C Film Size (Film Thickness)

Case IR

Device:

S/C Film:

 $E = 200 \text{ kV}$ $C = 0.5 \mu\text{F}$ $L = 500 \text{ m}$ $I_0 = 43 \text{ kA}$ $R_S = 2.75 \Omega$ $w = 0.1 \text{ m}$ $R = 0.08 \Omega$ $L_S = 10 \mu\text{H}$ $d = 5 \times 10^{-6} \text{ m}$ $L = 4.0 \text{ mH}$ $L_{SC} = 20 \mu\text{H}$ $R_N = 3000 \Omega$ GRAPH #5 Effect Of S/C Film Inductance (L_{SC})

Case IR	Device:	S/C Film:
$E = 200 \text{ kV}$	$C = 0.5 \mu\text{F}$	$L = 500 \text{ m}$
$I_0 = 43 \text{ kA}$	$R_S = 2.75 \Omega$	$w = 0.1 \text{ m}$
$R = 0.08 \Omega$	$L_S = 10 \mu\text{H}$	$d = 5 \times 10^{-6} \text{ m}$
$L = 4.0 \text{ mH}$	$L_{SC} = 10 \mu\text{H}$	$R_N = 3000 \Omega$
		$T_C = 15^\circ\text{K}$

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.

Case IR	Device:	S/C Film:
E = 200 kV	C = 0.5 μ F	L = 500 m
I ₀ = 43 kA	R _S = 5.5 Ω	w = 0.1 m
R = 0.08 Ω	L _S = 10 μ H	d = 5x10 ⁻⁶ m
L = 4.0 mH	L _{SC} = 10 μ H	R _N = 3000 Ω

GRAPH #7 Effect Of The Shunt Resistance (R_s)

Case IR	Device:	S/C Film:
$E = 200 \text{ kV}$	$C = 0.5 \mu\text{F}$	$L = 500 \text{ m}$
$I_0 = 43 \text{ kA}$	$R_S = 2.75 \Omega$	$w = 0.1 \text{ m}$
$R = 0.08 \Omega$	$L_S = 20 \mu\text{H}$	$d = 5 \times 10^{-6} \text{ m}$
$L = 4.0 \text{ mH}$	$L_{SC} = 10 \mu\text{H}$	$R_N = 3000 \Omega$

GRAPH #8 Effect Of The Inductance Of The Shunt Resistor (L_s)

3.1.3 (Continued)

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

Table 3.1-I shows a summary of the above analysis with the initial resistivity model for the superconducting film.

TABLE 3.1-I Effect Of Parameters On Circuit Transients

Case	Graph #	Parameter Studied	SOURCE (Case IR)				SHUNT BRANCHES			FILM PARAMETERS										Maximum Value of $\frac{V_c}{E}$
			E kV	I ₀ kA	R Ω	L mH	C μ F	R _s Ω	L _s μ H	L _{sc} μ H	l m	w m	d 10 ⁻⁶ m	mass kg	T _c $^{\circ}$ K	R _N Ω	Energy kJ	Temp. $^{\circ}$ 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	83	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	63	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	72	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	64	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	104	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	83	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	83	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	83	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	83	1.7	

Case IR

Device:

S/C Film:

 $E = 200 \text{ kV}$ $C = 0.2 \mu\text{F}$ $L = 500 \text{ m}$ $I_0 = 43 \text{ kA}$ $R_S = 2.75 \Omega$ $w = 0.1 \text{ m}$ $R = 0.08 \Omega$ $L_S = 10 \mu\text{H}$ $d = 5 \times 10^{-6} \text{ m}$ $L = 4 \text{ mH}$ $L_{SC} = 10 \mu\text{H}$ $R_N = 3000 \Omega$

GRAPH #9 Effect Of The Shunt Capacitor (C)

3.1.4 Modified Model For The Superconducting Film Resistance

Previously we assumed that film resistance increases linearly with its temperature up to a critical temperature T_c when it resumes its full normal-state resistance R_N . Use of this model in the circuit analysis gave temperature and resistance rise times of less than a nanosecond.

It is not easy to maintain a uniform magnetic flux density along the film during its resistance switching. Some parts of the film will be switched before the rest and the length of the switched part of the film will increase with time. This variation depends on the magnetic field distribution and its rise time.

Transition of the type II material from superconducting into normal state is made in two steps. Initially, a magnetic field is applied to put the superconducting film into its lossy state. This may take over a microsecond for the whole film. Then, the film will heat itself up into its normal state in less than a nanosecond. This indicates that the total resistance of the film, at any time, is proportional to the length of the part that is already switched into its normal state. So, the ratio of the instantaneous film's resistance $R(t)$ to its final (limit) resistance R_L can be written as:

$$\frac{R(t)}{R_L} = \frac{\ell_{\text{Switched}}}{\ell_{\text{Total}}} = \frac{\text{length of the switched part at time } t}{\text{total length of the film that will finally be switched.}} \quad (3.1.13)$$

Note that R_L is not equal to the total normal state resistance of the film R_N . This is due to the magnetic field distribution that cannot switch all of the film and always leaves a small fraction of the film's length in the superconducting state (see section 3.3.5). So, the effective length of the film, as well as its final resistance, is slightly reduced. To make R_L equal to R_N , the actual length of the film must be increased.

The ratio of the switched part to the total length of the film is determined by the distribution of the magnetic field along the film. This distribution depends on the geometry of the film and its magnetic circuit.

3.1.4 Modified Model For The Superconducting Film Resistance - (Cont'd)

Figure 3.1.4 shows the new film resistance model. The details of this model and its dependence on the magnetic field is explained in section 3.3.6.

FIGURE 3.1.4 New Model For S.C. Film Resistance

The rise time t_o is the key parameter in this model. It should be realized that in this model, initially, a very short section of the film will become normal with full resistivity whereas the current commutation has not actually started yet. Consequently, all of the fault current will pass through this small section which has a small effective mass. This will be a hot spot. If we show the length of the short switched section of the film with l' , its resistance and mass will be:

3.1.4 Modified Model For The Superconducting Film Resistance - (Cont'd)

$$R = \rho_N \frac{\ell'}{wd} \quad (3.1.14)$$

$$m = g \ell' w d \quad (3.1.15)$$

Where g is the specific density of the film. Consequently, the enthalpy of this section at time t will be:

$$Q(t) = \frac{\rho_N}{g w d^2} \int_0^t I_{s.c}^2(t) dt \quad (3.1.16)$$

Now the temperature of the hot spot can be determined by using the enthalpy characteristics of the Niobium film given in Figure 3.1.3. Electrical transients and temperature of the film's hot spots in the base case are shown in Graph #10. Here, the new resistance model with a rise time of $t_o = 1 \mu\text{sec}$ is used. Compared with the results of the initial resistance model, the only noticeable change in the electrical transients is the slower current commutation. Maximum overvoltage and film's energy are not changed. The main difference is that in this model, which is more realistic than the initial resistance model, there will be some hot spots on the film. The maximum temperature of these hot spots is limited by two factors; film's melting point and the thermal recovery time of the device. This is discussed in section 3.4 with more details.

Effect of the rise time t_o on the current commutation and hot spot temperature in the base case is clearly shown in Graph #11. The longer the rise time, the slower the current commutation and, consequently, the higher the temperature of the hot spots. The maximum permissible value of the resistance rise time t_o is discussed in section 3.4 on the thermal recovery of the S.C. fault current limiter.

3.1.5 Final Values Of The Electrical Transients

All of the circuit transients are damped out and reach their final values in few $\mu\text{seconds}$ after the S.C. film is activated. The final values of most of the circuit parameters can be evaluated without actually

Case IR

Device:

S/C Film:

 $E = 200 \text{ kV}$ $C = 0.5 \mu\text{F}$ $L = 500 \text{ m}$ $I_o = 43 \text{ kA}$ $R_s = 2.75 \Omega$ $w = 0.1 \text{ m}$ $R = 0.08 \Omega$ $L_s = 10 \mu\text{H}$ $d = 5 \times 10^{-6} \text{ m}$ $L = 4.0 \text{ mH}$ $L_{sc} = 10 \mu\text{H}$ $R_l = 3000 \Omega$ R_{sc} is equal to R_l after $t_o = 1.0 \mu\text{sec}$

GRAPH #10 Electrical Transients And Temperature Of Film Hot Spots In The Base Case With New Film Resistance Model.

* Film's effective length that will be switched to normal state.

Case IR	Device:	S/C Film:
$E = 300 \text{ kV}$	$C = 0.5 \mu\text{F}$	$L^* = 500 \text{ m}$
$I_0 = 43 \text{ kA}$	$R_S = 2.75 \Omega$	$w = 0.1 \text{ m}$
$R = 0.08 \Omega$	$L_S = 10 \mu\text{H}$	$d = 5 \times 10^{-6} \text{ m}$
$L = 4.0 \text{ mH}$	$L_{SC} = 10 \mu\text{H}$	$R_l = 3000 \Omega$

GRAPH #11 Effect Of Film Resistance Rise Time On The Current Commutation And Temperature Of The Hot Spots In The Base Case.

a- $t_0 = 0.01 \mu\text{sec}$. b- $t_0 = 0.1 \mu\text{sec}$. c- $t_0 = 1 \mu\text{sec}$. d- $t_0 = 2.5 \mu\text{sec}$.

* Film's effective length that will be switched to normal state.

3.1.5 Final Values Of The Electrical Transients - (Cont'd)

doing the transient analysis. Equations for evaluating the steady state values of the electrical transients are as follows:

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

After the initial transients fault current I_f splits resistively between the S.C. film and the shunt resistor R_s , that is:

$$I_{sc} = \frac{R_s}{R_s + R_{sc}} I_f \approx \frac{R_s}{R_{sc}} I_f \quad (3.1.17)$$

Where,

$$R_{sc} = \rho_N \frac{\ell}{d \cdot w} \quad (3.1.18)$$

So,

$$I_{sc} = \frac{R_s}{\rho_N} \cdot \frac{d \cdot w}{\ell} \cdot I_f \quad (3.1.17)$$

b. Current in the shunt resistor (I_s)

$$I_s = \frac{R_{sc}}{R_{sc} + R_s} I_f \approx I_f \quad (3.1.19)$$

c. Voltage across the S.C. film (capacitor voltage V_c)

$$V_c = R_{sc} I_{sc} = R_s I_f \quad (3.1.20)$$

d. Input power density on the S.C. film (H)

$$H = \frac{R_{sc} (I_{sc})^2}{\ell x w} = \frac{R_s^2}{\rho_N} \cdot \frac{d}{\ell^2} I_f^2 \quad (3.1.21)$$

e. Energy dissipated in the S.C. film (w)

This energy is a function of time and can be written as:

$$w(t) = \int_0^t R_{sc} I_{sc}^2 dt = w_1 + w_2(t) \quad (3.1.22)$$

3.1.5 Final Values Of The Electrical Transients - (Cont'd)

Where w_1 is the energy absorbed during the current commutation and, according to the results of the circuit analysis, is equal to the energy stored in the inductance of the film just before the current commutation started. That is:

$$w_1 = \int_0^{t_1} R_{sc} I_{sc}^2 dt = 1/2 L_{sc} I_f^2 \quad (3.1.23)$$

The time t_1 when the electrical transients are effectively over is about 1.5 to 2μseconds. Equation 3.1.23 has been found valid with either of the film resistance models and for any circuit parameter. Even the film resistance rise time t_0 was varied from 0.01 to 200μsec. and still the total film energy (heat) at $t_1 = 2\mu\text{sec}$ was equal to the energy it had stored in its inductance before the current commutation started.

The term $w_2(t)$ in equation 3.1.22 is the energy dissipated in the film after the transient are effectively damped. This energy is supplied by the external source (circuit):

$$w_2(t) = \int_{t_1}^t R_{sc} I_{sc}^2 dt \quad (3.1.24)$$

or,

$$w_2(t) = \frac{R_s^2}{\rho_N \ell / d.w} I_f^2 (t - t_1) \quad (3.1.25)$$

So equation 3.1.22 for film's energy can be re-written as:

$$w(t) = 1/2 L_{sc} I_f^2 + \frac{R_s^2}{\rho_N \ell / d.w} I_f^2 (t - t_1) \quad (3.1.26)$$

Where t_1 is approximately 2μseconds.

Note that ℓ is the effective length of the film which will be switched to normal state. The denominator of the second term in the above equation is actually the final value of the film's resistance.

APPENDIX 3.1.A

PROGRAM 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 MILLISEC. WHEN HEAT TRANSFER TO HELIUM HAS NOT STARTED YET.
00160C
00170 REAL IO,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), SGN IS THE SPECIFIC GRAVITY OF THE FILM
00220C (KG/M3), AND RES IS FILM RESISTIVITY (OHM-METER).
00230C
00240 SGN=8.4E+03
00250 RES=3.0E-06
00270C
00280C SET UP INITIAL CONDITIONS
00290C
00300 TM=4.2
00310 T=0
00320 TF=T
00330 I2=0
00340 V=0
00350 K=0
00360 POWER=0
00370 HEAT=0
00375 SI=0
00380 DT=1.0E-11
00390 SL=0.
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,IO
00510 PRINT, *ENTER S/C FILM SIZE: FL, FW, FD*,
00520 READ, FL,FW,FD
00525 RESD=RES/FD/FW**2.
00530 RN=RES*FL/FW/FD
00532 PRINT,*ENTER RESISTANCE RISE TIME: TRIS (SEC)*,
00534 READ,TRIS

```


APPENDIX 3.1.A - (Cont'd)

```

00540C
00550C PRINT OUT INPUT DATA
00560C
00570 PRINT 99, E, I0, R, L, CAP, RS, LS, LSC, FL, FW, FD, RN, TRIS
00580 99 FORMAT(///1X,*CIRCUIT MODEL FOR S/C FAULT CURRENT LIMITER*,/
00590+/* E      =*,E8.1,* VOLTS*,/* I(0) =*,E8.1,* AMPS*,/* R      =*,
00600+F6.2,* OHMS*,/* L      =*,E8.1,* HENRY*,/* C      =*,E8.1,
00610+* FARAD*,/* RS      =*,F6.2,* OHMS*,/* LS      =*,E8.1,* HENRY*,
00620+/* LSC      =*,E8.1,* HENRY*,/* FL      =*,F6.0,* METERS*,/* FW      =*,
00630+F6.3,* METER*,/* FD      =*,E8.1,* METER*,/* RN      =*,F6.0,
00640+* OHMS*,/* TRIS      =*,E8.1,* SEC.*)
00650 FMASS=SGN*FD
00670 RSC=0.0
00680 I=I0
00690 I3=I0
00710 S=(RN-RB)/(TC-4.2)
00720C
00730C PRINT OUT THE HEADINGS AND INITIAL CONDITIONS
00740C
00750 PRINT 100
00760 100 FORMAT(///1X,*ITER TIME I/I(0) IS/I(0) ISC/I(0) VC/E*,3X,*RSC*
00770+*/RN POWER ENERGY TEMP*,/6X,* (SEC.)*,41X,* (W/CM2) (JOUL) ---K*)
00780 P1=I/I0
00790 P2=I2/I0
00800 P3=I3/I0
00810 P4=V/E
00820 P5=RSC/RN
00830 FWR=0
00840 PRINT 200, K, T, P1, P2, P3, P4, P5, FWR, HEAT, TM
00850 200 FORMAT(1X, I3, E9.1, F5.2, E9.1, E8.1, E9.1, 3E8.1, F6.1)
00860C
00870 20 K=0
00880 KP=1
00890C
00900C ASK FOR THE NUMBER OF THE DATA POINTS TO BE
00910C PRINTED AND THE TIME INTERVAL BETWEEN THEM.
00920C
00930 PRINT 300
00940 300 FORMAT(1X,*ENTER NP,DTP*)
00950 READ, NP,DTP
00960 IF(NP.EQ.0) STOP
00970C
00980 10 K=K+1
00990 R0=RSC
01000 CN=I3
01010 DT=DT*1.01
01015 IF(T.GT.1.0E-05) DT=DT*1.1
01020C
01030C ITERATE THE CIRCUIT DIFFERENTIAL EQUATIONS FOR ONE STEP ONLY.
01040C
01050 CALL DEQ(DT,I,I2,I3,V,SL)
01060 T=T+DT

```

APPENDIX 3.1.A - (Cont'd)

```

01280C
01290C  EVALUATE FILM RESISTANCE AS A FUNCTION OF TIME
01300C
01310  RSC=RN
01315  IF(T.LT.TRIS) RSC=T/TRIS*RN
01330  SL=(RSC-R0)/DT
01070  POWER= (R0+RSC)*(CN+I3)**2/12.0 + (R0*I3**2+RSC*CN**2)/6.0
01080  HEAT=HEAT+DT*POWER
01085  SI=SI+DT*(I3**2+CN**2)/2.0
01340  IF(K.LT.999.AND.(T-TP).LT.DTF) GO TO 10
01350  P1=I/I0
01360  P2=I2/I0
01370  P3=I3/I0
01380  P4=V/E
01390  P5=RSC/RN
01400  PWR=RESID*I3**2/10000.
01405  Q=SI*RESID/FMASS
01403  IF(Q.LT.6.7) TM=5.39*(Q+0.38)**0.26
01404  IF(Q.GE.6.7.AND.Q.LT.9.1) TM=19.78/(16.12-Q)**0.35
01405  IF(Q.GE.9.1.AND.Q.LT.259) TM=6.04*(Q-3.42)**0.29
01406  IF(Q.GE.259.AND.Q.LT.7812) TM=3.08*(Q+95)**0.39
01407  IF(Q.GE.7812.AND.Q.LT.60000) TM=0.08*(Q+7298)**0.74
01408  IF(Q.GE.60000) TM=0.018*(Q+17586)**0.86
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
01480C

```

```

01490C
01500 SUBROUTINE DERQ(H,I,I2,I3,V,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 V AND I'S)
01590C
01600 F(I,V)=(E-V-R*I)/L
01610 G(I2,V)=(V-RS*I2)/LS
01620 Q(I3,V)=(V-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,V)
01710 G0=G(I2,V)
01720 Q0=Q(I3,V)
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,V+H*T0)
01800 G1=G(I2+H*G0,V+H*T0)
01810 Q1=Q(I3+H*Q0,V+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 V=V+H*(T0+T1)/2.
01980 RETURN
01990 END
*RDY*

```

3.3.6 Effect Of The Magnetic Field Distribution On The S.C. Film's Resistance

A complete cycle of the radial magnetic field along a section of the S.C. film is shown in Figure 3.3.10. There are two such cycles along each turn of the S.C. film in the cryostat. This distribution changes slightly with the location of the S.C. film.

A straight-line approximation of the first quarter-cycle of the radial magnetic field is shown in Figure 3.3.11. Here, flux distribution is given for a current I . If the critical flux density to switch the S.C. film into its normal state be B_c , the ratio of the switched length of the film to its total length is:

$$\frac{L_{sw}}{L_{Total}} = \frac{\theta_b - \theta_a}{\pi/4} \quad (3.3.1)$$

Where θ_a and θ_b are shown in Figure 3.3.11. The instantaneous resistance of the film, as explained before, is proportional to the length of the section that is already switched into its normal state. So, the ratio of the instantaneous film resistance to its maximum value can be written as:

$$\frac{R(t)}{R_N} = \frac{L_{sw}}{L_{Total}} = \frac{\theta_b - \theta_a}{\pi/4} \quad (3.3.2)$$

Equations of the two straight lines in Figure 3.3.11 are:

$$\theta_1(B, I) = \frac{\theta_o}{A_2 I} B \quad \text{for } 0 < \theta_1 < \theta_o \quad (3.3.3)$$

$$\theta_2(B, I) = \frac{\pi/4 A_2 - \theta_o A_1}{A_2 - A_1} - \frac{\pi/4 - \theta_o}{(A_2 - A_1) I} B \quad \text{for } \theta_o < \theta < \pi/4 \quad (3.3.4)$$

Where A_1 , A_2 and θ_o are shown in Figures 3.3.10 and 3.3.11. According to Figure 3.3.11, we can write:

FIGURE 3.3.10 Distribution Of The Radial Magnetic Flux Density Along A Section Of The S.C. Film

FIGURE 3.3.11 Approximate Distribution Of The Magnetic Field (1/4 cycle) Compared With The Critical Flux Density Of The S.C. Film

3.3.6 Effect Of The Magnetic Field Distribution On The S.C. Film's Resistance - Ctd

$$\theta_b - \theta_a = 0 \quad \text{for } I < B_c/A_2 \quad (3.3.5)$$

$$\theta_b - \theta_a = \theta_2(B_c, I) - \theta_1(B_c, I) \quad \text{for } B_c/A_2 < I < B_c/A_1 \quad (3.3.6)$$

$$\theta_b - \theta_a = \pi/4 - \theta_1(B_c, I) \quad \text{for } B_c/A_1 < I \quad (3.3.7)$$

Substituting equations (3.3.3) to (3.3.7) into equation (3.3.2) yields:

$$\frac{R}{R_N} = 0 \quad \text{for } I < B_c/A_2 \quad (3.3.8)$$

$$\frac{R}{R_N} = \frac{1 - \left(\frac{A_1}{A_2}\right) \left(\frac{\theta_0}{\pi/4}\right)}{1 - \left(\frac{1}{A_2}\right)} \left(1 - \frac{B_c}{A_2 I}\right) \quad \text{for } B_c/A_2 < I < B_c/A_1 \quad (3.3.9)$$

$$\frac{R}{R_N} = 1 - \left(\frac{\theta_0}{\pi/4}\right) \left(\frac{B_c}{A_2 I}\right) \quad \text{for } B_c/A_1 < I \quad (3.3.10)$$

The current I in the magnetic field coils is not an ideal step function and has a definite nonzero rise time. Figure 3.3.12 shows a typical current pulse. The front part of the current pulse may be approximated as:

$$I = I_{\max} (1 - e^{-t/\tau}) \quad (3.3.11)$$

Where τ is the overall rise time and $I_{\max}$ is the maximum value of the current.

Substituting equation (3.3.11) in equations (3.3.8) to (3.3.10) yields:

$$\frac{R(t)}{R_N} = 0 \quad \text{for } t < t_1 \quad (3.3.12)$$

3.3.6 Effect Of The Magnetic Field Distribution On The S.C. Film's Resistance - C

$$\frac{R(t)}{R_N} = \frac{1 - \left(\frac{A_1}{A_2}\right) \left(\frac{\theta_o}{\pi/4}\right)}{1 - \left(\frac{A_1}{A_2}\right)} \left[1 - \frac{B_c}{A_2 I_{\max}} \left(\frac{1}{1 - e^{-t/\tau}} \right) \right] \quad \text{for } t_1 < t < t_2 \quad (3.3.13)$$

$$\frac{R(t)}{R_N} = 1 - \left(\frac{\theta_o}{\pi/4}\right) \frac{B_c}{A_2 I_{\max}} \left(\frac{1}{1 - e^{-t/\tau}} \right) \quad \text{for } t_2 < t \quad (3.3.14)$$

Where:

$$t_1 = \tau \ln \left(\frac{1}{1 - \frac{B_c}{A_2 I_{\max}}} \right) \quad (3.3.15)$$

And

$$t_2 = \tau \ln \left(\frac{1}{1 - \frac{B_c}{A_1 I_{\max}}} \right) \quad (3.3.16)$$

Figure 3.3.13 shows a typical plot of the film's resistance $R(t)$. The maximum value of the film's resistance is R_ℓ and is always smaller than R_N due to the existence of the "dead-spaces" explained in the previous section.

The values of R_ℓ and R_1 in Figure 3.3.13 can be determined from the following equations:

$$\frac{R_1}{R_N} = 1 - \left(\frac{\theta_o}{\pi/4}\right) \left(\frac{A_1}{A_2}\right) \quad (3.3.17)$$

$$\frac{R_\ell}{R_N} = 1 - \left(\frac{\theta_o}{\pi/4}\right) \left(\frac{B_c}{A_2 I_{\max}}\right) \quad (3.3.18)$$

The difference between R_ℓ and R_1 diminishes as θ_o or $(A_1 - B_c/I_{\max})$ approach zero;

$$\frac{R_\ell - R_1}{R_N} = \left(\frac{\theta_o}{\pi/4}\right) \frac{A_1 - B_c/I_{\max}}{A_2} \quad (3.3.19)$$

FIGURE 3.3.12 Typical Shape For The Current Pulse In The Magnetic Coils

FIGURE 3.3.13 Typical Variation Of The S.C. Film's Resistance With Time

3.3.6 Effect Of The Magnetic Field Distribution On The S.C. Film's Resistance - C

During the time t_1 , in Figure 3.3.13, film's resistance is virtually zero and the current commutation will not start. This time delay can be added to the total relaying time of the S.C.F.C.L. So, the film resistance from the beginning of its activation is shown in Figure 3.3.14-a.

Here t_0 is:

$$t_0 = t_2 - t_1 = \tau \ln \left(\frac{A_2 I_{\max} - B_c}{A_1 I_{\max} - B_c} \cdot \frac{A_1}{A_2} \right) \quad (3.3.20)$$

Note that $I_{\max}$ must be larger than B_c/A_1 , otherwise a large section of the film will not be switched (see Figure 3.3.11). A plot of t_0 as a function of other magnetic field parameters is shown in Figure 3.3.14-b. The dashed line in Figure 3.3.14-a is a further simplification of the resistance model used in the transient circuit analysis of the S.C.F.C.L.

For a numerical example, consider the base case design shown in Figure 3.3.4. A four pole magnetic field circuit for this case is discussed in section 3.3.5. Figure 3.3.9 of this section gives the flux density distribution for three different magnetic coil arrangements. Parameters of these three distributions are summarized in Table 3.3.I. Here a critical magnetic field of $H_c = 300$ Oe or $B_c = 0.03$ Tesla is considered for switching the S.C. film into its lossy state. Figure 3.3.15 shows a plot of the film's resistance for the flux distribution curve #2. The film resistance is given for $I_{\max} = 50$ and 100kA. This is the total maximum current in a coil. Each coil can be composed of a few turns which will reduce the maximum current to be supplied to the magnetic circuit.

Figure 3.3.16 gives the films resistance rise time as a function of the magnet's maximum current $I_{\max}$ and its rise time τ for the above three flux distributions. This clearly indicates that a short resistance rise time t_0 requires a large coil current $I_{\max}$ with a short rise time τ .

FIGURE 3.3.14 Dependence Of Film Resistance Rise Time t_o On The Rise Time τ Of The Coil Current And Other Magnetic Field Parameters

TABLE 3.3.I

Parameters Of The Three Magnetic Field Curves
Of Figure 3.3.9 ($B_c = 0.03$ Tesla)

CURVE NUMBER	A_1 (TESLA/AMP)	A_2 (TESLA/AMP)	$\frac{\theta_o}{\pi/4}$	A_2/A_1	R_1/R_N	B_c/A_1 (kA)
1	1.0×10^{-6}	2.85×10^{-6}	0.13	2.85	0.95	30
2	0.95×10^{-6}	1.7×10^{-6}	0.20	1.79	0.89	32
3	0.9×10^{-6}	1.2×10^{-6}	0.31	1.33	0.77	33

FIGURE 3.3.15 S.C. Film Resistance For The Magnetic Field
Curve #2 In Table 3.3.I and Figure 3.3.9

FIGURE 3.3.16 Film's Resistance Rise Time For The Three Magnetic Field Curves Of Figure 3.3.9 And Table 3.3.I.

3.4 Thermal Recovery Time Of The S.C. Fault Current Limiter

Circuit breakers 121kV and above, are designed for 15 cycle reclosing time (ANSI C37.06-1971). This leaves 15 cycles for the supporting fault current limiters to reset.

If the isolation switch is opened on the second current zero after the fault (see Figures 3.2.1 and 3.2.17), there will be approximately 14 cycles left for the film to cool down completely and be ready for another possible fault current. If the film is given enough time, it will eventually cool down to helium bath temperature (4.2°K). The film will actually resume its superconductivity as soon as its temperature drops below a critical temperature of 6-9°K and will be ready for the next fault current. Altogether, since three time constants are needed for considerable cooling, the film should have a cooling time constant not longer than 5 cycles (80msec.).

The temperature profiles of film hot spots for the base case design of the S.C. fault current limiter are given in Figure 3.4.1 for different film resistance rise times (see sections 3.1 and 3.2). Curve d in Figure 3.4.1 is replotted in Figure 3.4.2 for $t > 12.5\text{msec}$ when the isolation switch is open. The cooling time constant of the film, in this case, is about $\tau_c = 79.5\text{ms}$ which is 4.8 cycles. This indicates that, for the base case design, film's resistance must reach its maximum normal-state-value in less than 2.5ms. Table 3.4.I has a summary of the rise time and temperature studies on the base case.

Figure 3.4.3 shows the effect of resistance rise time on film's hot point temperature and cooling time constant.

Limiting the cooling time constant to 5.0 cycles requires a relatively short resistance rise time. According to Figure 3.3.14 of section 3.3, a short resistance rise time requires satisfaction of one or a combination of the following conditions:

- a) Short rise time for the magnetic coil current
- b) Large magnetic coil current
- c) Relatively flat magnetic flux distribution along the S.C. film

FIGURE 3.4.1 S.C. Film's Hot Spot Temperature Profiles For The Base Case.
 Film Resistance Rise Times Are:
 a-0.01ms, b-0.1ms, c-1ms, d-2.5msec.

FIGURE 3.4.2 Cool-down Of The S.C. Film When The Isolation Switch Is Open (See Figure 3.4.1-d)

TABLE 3.4.I

Resistance Rise Times, Hot Point Temperatures And
Cooling Time Constants Of The Base Case Design

Film Resistance Rise Time (sec)	Hot Point Temperature (°K)	Film Temperature When Isolation Switch Is Opened $t = 0.0125\text{sec.}$ (°K)	Cooling Time Constant	
			(ms)	60Hz Cycles
3×10^{-10}	84	-	-	-
1×10^{-9}	90	-	-	-
-	100	10.6	52	2.5
1×10^{-8}	123	-	-	-
-	200	15	58.5	3.5
1×10^{-7}	239	-	-	-
-	500	29	67.5	4.0
1×10^{-6}	607	-	-	-
2.5×10^{-6}	924	51	79.5	4.8
-	1000	55	86	5.2
1×10^{-5}	1780	-	-	-

Figure 3.3.9 clearly indicates that a flat flux distribution requires longer wasted "dead-spaces" along the S.C. film. Briefly, satisfaction of any of the above three requirements is expensive.

An alternative to the above approaches is to change the parameters of the base case design to increase the film's resistance rise time without

a - Film Hot Point Temperature vs. Its Resistance Rise Time

b - Film Cooling Time Constant vs. Its Hot Point Temperature

FIGURE 3.4.3 Effect Of Resistance Rise Time On Film's Hot Point Temperature And Cooling Time Constant

3.4 Thermal Recovery Time Of The S.C. Fault Current Limiter - (Cont'd)

increasing its cooling time constant. Table 3.4-II summarizes the effect of film's dimensions on the maximum permissible resistance rise time that keeps its cooling time constant below 5.0 cycles.

TABLE 3.4.II

Effect Of Film Size On The Maximum Permissible Rise Time For Film Resistance. Cooling Time Constant is 5 Cycles.

CASE	FILM LENGTH l (m)	FILM WIDTH w (m)	FILM THICKNESS d (m)	STEADY STATE CURRENT DENSITY J (kA/cm ²)	MAXIMUM RESISTANCE RISE TIME t_o (μ sec)	MAXIMUM TEMPERATURE OF FILM HOT SPOTS (°K)	COMMENTS
BASE CASE	500	0.1	5×10^{-6}	8.0	2.5	924	-
EFFECT OF FILM THICKNESS	500	0.1	10^{-5}	8.0	2.5	400	Hot spot temperature is reduced but cooling is hampered too. Not effective in increasing resistance rise time.
EFFECT OF FILM WIDTH	500	0.15	5×10^{-6}	8.0	7.0	900	Film width does not effect cooling but decreases hot spot temperature. Resistance rise time can be increased to about 7.0 μ sec.
EFFECT OF FILM LENGTH	1000	0.1	5×10^{-6}	4.0	10.0	1300	Steady state film current density is decreased. Cooling is faster. Resistance rise time can be increased to about 10 μ sec.
EFFECT OF FILM LENGTH AND WIDTH TOGETHER	1000	0.1	5×10^{-6}	4.0	16.0	900	-

Still another more effective approach in increasing the resistance rise time is to decrease the limited fault current in the S.C. film. This requires a very fast fault current detection. It is estimated that reducing the fault current of the base case by a factor of 0.7 will let the resistance rise time be even larger than 100 μ sec. Resistance rise times larger than 100 μ sec will not let the film temperature reach its steady state value before a microsecond whereas film's heat transfer to

3.4 Thermal Recovery Time Of The S.C. Fault Current Limiter - (Cont'd)

helium starts in a fraction of a microsecond. So, a detailed study of the cases with resistance rise times larger than 100 μ sec may require combination of the two computer programs for transient circuit and thermal analyses of the S.C. fault current limiter.

In any event, each of the above variations of the base case design is expensive and a cost analysis of them is necessary to determine the optimum design.

3.5 Shunt Resistor Evaluation Criteria

The fault current limiter should perform its task reliably and successfully. In order to achieve these performances, the resistor used in this device should have the following salient features.

1. The resistor must dissipate maximum energy with a minimum amount of material.
2. The resistor must exhibit rapid thermal recovery.
3. The resistor must be consistent in its performance throughout a life-time of thermal cycles.
4. The resistor should lend itself well to production type standardization of shape for a range of system and energy levels.
5. The resistor should be cost effective WITHOUT sacrificing reliability.

Based upon these important features, several types of standard commercial resistors will be considered.

3.5.1 Resistor Element Types

In this section, three resistor materials have been considered, namely, ceramic-carbon, continuous strip resistor, and continuous tubular resistor.

1. Ceramic-Carbon Type Resistor

This type of resistor is formed by blending alumina, various clays, and carbon together in such a manner that an even distribution of the conductor throughout the mixture is ensured. This mixture is then formed into standard shapes and fired in high temperature and atmospherically controlled kilns. The flat faces of the resistors are normally sprayed with some form of metallic coating to provide the contact surfaces. The combination of ceramic with carbon results in a material that can withstand extremely high energy densities. Typical values for typical characteristics of the ceramic resistors are shown in Table 3.4-1. Standard shapes for this type of resistor include rods, rings, discs, and sleeves.

TABLE 3.5-1
TYPICAL PROPERTIES OF RESISTOR MATERIAL (1)

DESCRIPTION	CERAMIC-CARBON PROPERTY
Maximum Transient Energy Density	400-500 Joules/cc
Resistivity Range	2 ohm-cm to 10,000 ohm-cm
Maximum Operating Temperature	225° to 275°
Resistance Temperature Coefficient	-0.7% to -0.19% per °C
Resistance Voltage Coefficient	-4% to -8% per kV/cm
Specific Heat	2.2 Joules/cc/°C Change in Temperature
Specific Weight	2 to 2.4 grams/cc

2. Continuous Strip Resistors

This type resistor is usually formed by punching out a plate of resistor material and then forming the continuous lengths onto standard support frames. A variety of ratings is obtained by varying the thickness and stamped pattern. Some advantages of this type are as follows:

- i - The element is continuous on each frame and therefore, minimizes the number of joints or welds that can fail.
- ii - The standard size of resistor frame provides for easy series - parallel interconnection.
- iii - This type resistor element has a high surface area to volume ratio (a good cooling characteristic).
- iv - The material that can be used in this type resistor allows for a temperature excursion which provides for a high energy density

3. Continuous Tubular Resistor Element

This type of resistor design separates out the energy absorption and resistive functions. The embodiment of this design would be an Incoloy 800 (32.5% NI, .45% Cr + Al, 46% Fe)* or equivalent tube that is filled with magnesium oxide (e.g., Nichrome V, Nichrome, Inconel 600). Energy is absorbed in the magnesium oxide while the sheath material functions as the resistive element. Since the outer sheath is, in fact, the heat generator, its large surface area and high emissivity allow some percentage of energy to be instantly radiated away without having to be stored in the magnesium oxide core.

According to the Stefan-Boltzman law, the total emission of radiation per unit surface area per unit time from a blackbody is related to the fourth power of the absolute temperature. Thus, the very high temperature capability of this type of design promotes very rapid heat dissipation by radiation.

Variation of continuous tubular element resistor design (made necessary by different power system ratings) would be achieved through a change in the cross sectional area, or a change in the tube diameter, or even a change in the tube material (to utilize the various resistivities of the many high temperature metal alloys).

3.5.2 Evaluation Of Resistor Element Types

The following evaluation will be very helpful in selecting the proper materials for SCFCL resistor. The three types of resistor elements will be compared under each point of the resistor evaluation criteria set forth previously in this section:

1. The resistor must dissipate maximum energy with a minimum amount of material. The obvious measure of this ability would be the volume required of each resistor type for the given energy input. The continuous tubular resistor element has the most desirable material volume requirements while the ceramic-carbon type resistor element has the least desirable material volume requirements.

* Huntington Alloy

2. The resistor must exhibit rapid thermal recovery.

The heat transfer capability of the resistor both during energy input and during the time period immediately following energy input must be evaluated on the basis of both heat conduction and radiation. The thermal conductivity of each of the resistor element types can be simply evaluated by comparing the thermal conductivities of the actual materials used in each element. However, the evaluation of the ability of each resistor type to transmit heat by radiation will be made by assuming that each resistor type is acting like a black body. Thus, according to the Stefan-Boltzman law, the total emission of radiation from a black body is directly related to the fourth power of the absolute temperature of the material. In this evaluation, the maximum allowable temperature increase of each resistor type will be used as a measure of resistor element's radiant heat transfer ability.

The ceramic-carbon resistor element material has a typical thermal conductivity of $0.03 \text{ (cal./cm}^2\text{/sec./}^\circ\text{C/cm)}$ and a typical maximum operating temperature of 100°C to 240°C .

The rack mounted continuous strip resistor has a typical thermal conductivity of $0.039 \text{ (cal./cm}^2\text{/sec./}^\circ\text{C/cm)}$ for a stainless steel resistive element and allowable temperature excursion of 449°C .

A continuous tubular element has a thermal conductivity which can be attributed to the magnesium oxide core. Typical thermal conductivity for this material is $0.077 \text{ (cal./cm}^2\text{/sec./}^\circ\text{C/cm)}$. The maximum allowable temperature excursion of this resistor element is determined by the resistive material and ranges from 800°C to 1200°C .

3. The resistor must be consistent in its performance throughout a lifetime of thermal cycles.

Since all resistor types have been selected and designed with the temperature dependence of mechanical properties in mind, the only other major design parameter that affects consistent performance is the temperature dependence

of the resistance value. It is known that the typical temperature coefficient of each resistor type is used to measure performance consistency.

A typical temperature coefficient for ceramic-carbon resistor material is -0.13% per $^{\circ}\text{C}$.

A typical temperature coefficient for the stainless steel material used in the rack mounted continuous strip resistor is $+0.094\%$ per $^{\circ}\text{C}$.

A typical temperature coefficient for Nichrome V or equivalent material used in the continuous tubular resistor element is $+0.017\%$ per $^{\circ}\text{C}$.

4. The resistor should lend itself well to production type standardization of shape for a range of system and energy levels.

The evaluation of this characteristics must be based upon several factors: the ability to change the resistor rating without substantial change to its package size or configuration, a standardization of support structures, and the ease of assembly. The ability to standardize the package size and shape of each type resistor is evaluated on the basis of the number of design parameters that can be varied without substantially changing the resistors package size or shape. The ease of production type assembly will be evaluated on the basis of number of electrical connections necessary for a given input heat energy (choose 300 megajoules for comparison purpose).

The variable parameters in the ceramic-carbon resistor design are:

- Resistivity of mixture
- Disc cross sectional area (both the I.D. and the O.D.)

In the ceramic-carbon design between 60 and 7000 electrical connections would be necessary for 300 megajoules (2 ohms resistor).

In the rack mounted continuous strip resistor design, the variable parameters are:

- plate thickness
- stamped pattern

In the rack mounted continuous strip design, approximately 292 electrical connections would be necessary for 300 megajoules (2 ohms resistor).

In the continuous tubular element resistor design, the variable design parameters are:

- The cross sectional area of the magnesium oxide can be varied.
- The cross sectional area of the resistive material can be varied.
- The resistivity of the material can be varied by interchanging a relatively wide variety of equivalent high temperature materials.

In the continuous tubular element design, between 10 and 25 electrical connections would be necessary for 300 megajoules (2 ohms resistor).

5. The resistor should be cost effective WITHOUT sacrificing reliability.

For this evaluation a term that depicts joules per dollar should be considered. With the information available at this time, the continuous tubular resistor element is the most economical one.

3.5.3 Selection Of Resistor Element Type

As a result of the evaluation of resistor element types, it can be concluded that the use of a tubular element resistor design is best suited for use as the resistor in the superconducting fault current limiter. This type resistor design displayed outstanding characteristics for all five aspects of the resistor evaluation criteria.

3.5.4 Fault Current Limiter Resistor Design Concept

Primarily as a result of the circuit breaker reclosure problems associated with the temperature dependent resistors and the large masses of nonlinear resistor material needed to absorb the energies involved, the linear ohmic resistor is recommended for the insertion resistance in the current commutation type FCL.

1. Insertion Resistance Calculation

It is desirable to compute the value of a fixed resistor required to achieve a specified fault current limiter factor (based on given available fault current). Thus for a given power system with known voltage class, known available fault current, and by specifying the desired fault current limiting factor, F , the necessary value of insertion resistance can be calculated as follows:

$$R = \sqrt{x^2 (1/F^2 - 1)} \quad * \quad (3.5-1)$$

2. Temperature Increase Due To Heating

Current, $I(t)$ flowing in a resistor, R , delivers Q joules of energy as heat according to the relation:

$$Q = \int I(t)^2 R dt \quad \text{Joules} \quad (3.5-2)$$

It is assumed that no heat is lost from the material during the current limiting interval, the energy input can be related to the temperature increase by the equation

$$\Delta Q = \sigma \cdot v \cdot c \cdot \Delta T \quad (3.5-3)$$

Where

$$\begin{aligned} \sigma &\equiv \text{Density} && (\text{Kg/cm}^3) \\ v &\equiv \text{Volume} && (\text{cm}^3) \\ c &\equiv \text{Specific Heat} && (\text{Joules/Kg} - ^\circ\text{C}) \\ \Delta T &\equiv \text{Temperature Rise Above Ambient} && (25^\circ\text{C}) \end{aligned}$$

For this analysis, specific heat is assumed to be independent of T .

* (See Second Quarterly Report Chapter 2 For More Details)

When a material's temperature changes, there is often a corresponding change in resistance. For a given material, the characteristic temperature-resistance curve can be obtained from the manufacturer. A mathematical expression for these curves could be derived for each material to keep the analysis general. Limiting the analysis to ideal, fixed-value resistors which exhibit minimum resistance variation with temperature results in a tremendous simplification by eliminating the need for polynomial series approximations for the temperature-resistance curve. Furthermore, the temperature-independent resistance affords consistent current commutation requirements and consistent fault current factors during repetitive operations.

Equation 3.5-2 determines the heat energy for a given resistor value, and from this result, equation 3.4-3 can be solved for the required volume of a specified material:

$$v_{\text{required}} = \frac{Q}{\sigma \cdot c \cdot \Delta T} \quad \text{cm}^3 \quad (3.5-4)$$

In order to determine the cross-sectional area of the resistor wire, consider that for a given material,

$$R = \frac{\rho \cdot \ell}{A} \quad (3.5-5)$$

Where

$$\begin{aligned} \rho &\equiv \text{Resistivity} && (\text{ohm-cm}) \\ \ell &\equiv \text{Length} && (\text{cm}) \\ A &\equiv \text{Cross-Sectional Area} && (\text{cm}^2) \end{aligned}$$

Now, since volume is proportional to length and area, resistance can be expressed as a function of volume by the following:

$$\ell = v/A$$

$$R = \frac{\rho \cdot (v/A)}{A}$$

$$\therefore R = \frac{\rho \cdot v}{A^2}$$

Solving for area yields:

$$A = \sqrt{\rho \cdot v / R} \quad \text{cm}^2 \quad (3.5-6)$$

It can be observed from this development that once the energy absorbed by the resistor and the total temperature change involved is known, equation 3.5-4 can be used to determine the volume required of a given material. Once the volume requirement is known for a given material, equation 3.5-6 directly yields the necessary cross-sectional area.

3. Energy Dissipated In Resistor

The volume of resistance material required is dependent on the quantity of energy that will be dissipated in the resistor. It is desirable to determine this energy by using the heat duration (rated duty) of 3 cycles and 8 cycles which account for typical high voltage circuit breaker interrupting times. Of course other heating durations (rated duty) could be considered and corresponding different resistor dimensions would result.

In order to compute the heating, an expression for the fault current is needed. For worst case heating conditions, fault current commutation to the resistor is assumed to be instantaneous. A mathematical expression for a fully asymmetrical fault current can be expressed (with a good approximation) as shown in equations 3.5-7 and 3.5-8. In addition, the total energy absorbed by the resistor is assumed to be stored in the material during the fault current limiting action.

$$i(t) = I_{\text{peak}} (1 - \cos 377t) \quad 0 < t < 12.5 \text{m sec.} \quad (3.5-7)$$

$$i(t) = I_{\text{peak}} (-\sin 377t) \quad 12.5 \text{msec} < t < t_{\text{max}} \quad (3.5-8)$$

Where

$I_{\text{peak}} \equiv$ Peak fault current through FCL resistor

$t_{\text{max}} \equiv$ Continuous duration of the fully asymmetrical fault current defined above.

Substituting the approximate expression for current (equations 3.5-7 and 3.5-8) into equation 3.5-2 yields:

$$Q = \int_0^{12.5\text{msec}} I_{\text{peak}}^2 (1 - \cos 377t)^2 R dt + \int_{12.5\text{msec}}^{t_{\text{max}}} I_{\text{peak}}^2 (-\sin 377t)^2 R dt \quad (3.5-9)$$

For this integration, R is assumed to be ideal and constant valued for all temperatures. Obviously, actual materials have some temperature-resistance interaction. It is clear that some materials in Table 3.5-2 have such wide resistance variations with temperature that they can be immediately eliminated from further consideration for this fixed value resistance analysis. A limit to the percentage of allowable resistance variation must reflect the following concepts:

- a. Standard manufacturing tolerance for resistance values allows a three percent to eight percent deviation from the specified resistance value.
- b. The time-rate of increase in the actual temperature of the material (and the corresponding time-rate of increase in resistance) is reduced by the effect of large resistor material mass and heat loss to the environment during the fault current limiting time increment.
- c. Material costs increase with the degree of independence the material's resistance exhibits with respect to thermal variation.

4. Material Selection Concepts

With the magnitude of heating tabulated (see Figure 3.5-1), resistance material must now be selected in order to compute the volume required. For this linear resistance analysis, an interaction between the temperature dependence of resistance and fault current magnitude has been assumed to be negligible in the computation of energy dissipated. To maintain the validity of this assumption, materials which experience minimum variation in resistivity during large temperature change are desired. A good indicator of the temperature sensitivity of a material's resistance is provided by the material's temperature coefficient (supplied by the manufacturer). Lower values for temperature coefficients correspond to minimum resistance variation for large temperature changes.

Some representative materials have been chosen to illustrate the material selection procedure and are listed in Table 3.5-2 (material characteristics Tables are located at the end of this section). As a means of evaluating the materials shown in Table 3.5-2, the final material temperature is assumed to be limited to a value equal to the manufacturer's recommended maximum operating temperature. If a material's final temperature is specified, the corresponding total change of resistance can be determined from temperature-resistance curves furnished by the resistor material manufacturer. The total change in resistance corresponding to the material's final temperature is expressed as a percent of the resistance at ambient temperature in Table 3.5-2.

Since the ability of a substance to absorb energy is characterized by its specific heat, high levels of specific heat indicate that higher magnitudes of energy are required to effect a unit increase in temperature for a unit mass of a material. By minimizing the amount of material used to absorb a finite amount of energy, material usage efficiency is maximized. It can be reasoned, then, that higher levels of specific heat depict greater material usage efficiencies.

Nichrome V, Nichrome, and Incoloy 800 were chosen to compute the required volume (cross-sectional area and length). See section 6.0 for more details.

In Section 3.4.3, a tubular design was chosen. The Tables at the end of this chapter show material characteristics versus wire gauge size rather than tube size, however, so our design will be carried out in terms of the equivalent wire gauge. Conversion to the tube having the same cross-sectional area and resistance is then a simple calculation which must finally be done.

5. Optimum Wire Gauge Selection And Determination Of Required Wire Length

It is desirable to select the optimum wire gauge and to compute the required rank for the resistance values and the materials under consideration. The relation between resistance, volume, resistivity, and area, is given by equation 3.5-6. For a particular material, the weight per unit volume is given by the manufacturer (lb/in^3). In addition, the manufacturer supplies the resistance per unit weight (Ω/lb) for the various wire gauge sizes of each material. Multiplying the volume required of a particular material by the weight per unit volume yields the required weight of the material (for a particular resistance value). Dividing the desired resistance by the required weight, results in a value with the dimensions of ohms per pound.

Manufacturer specification sheets (see Tables 3.5-3, 3.5-4) provide the ohms per pound for each wire gauge size of a given material. By matching the required ohms per pound with those corresponding to various wire gauges, an optimum wire gauge can therefore be selected; thereby establishing the cross-sectional area and resistivity.

Knowing the resistivity and the desired resistance directly determines the length needed of a particular gauge size.

When choosing actual gauge sizes, there are cases where the ohms per pound value does not exactly correspond to a standard Brown & Sharp wire gauge. In this case, the next lowest gauge number is chosen. A lower gauge number results in a large cross-sectional area and volume than required, but this increased volume adds thermal capacity that serves as an additional safety margin.

6. Sample Resistor Dimensions

The resistor design computer program, developed by Gould-Brown Boveri, was used to examine the range of typical dimensions for resistor elements. Figure 3.5-2 shows the flow chart for resistor element design computer program. Nichrome V, Nichrome, and Incoloy 800 were used so that the physical properties of the materials can be compared with the resulting dimensions and the cost of the final design. The computer design was performed for both the three cycle and eight cycle rated duty levels.

Table 3.5-5 exhibits a comparison of material length and cost for 2.74 ohm resistor (4-10.98 Ω resistors in parallel) in a 242kV system with 93kA available fault current and an eight cycle duration. Since a longer length of wire can be assumed to increase the structural support costs, Table 3.5-5 shows that Nichrome V provides the more economically efficient design of the three materials. It is important to note that the basic material cost was determined by the simple dollars per pound price of the resistive material effective January 1980 and is provided by Hoskins Manufacturing Company, Detroit, Michigan.

5.5 Analysis Of Resistor Dimensions (Computer Simulation)

As a conclusion of previous sections, Nichrome V was selected as a resistor type element in the following analysis in order to determine the shunt resistor physical characteristics (dimensions).

It should be noted that the computer program for this study was developed assuming the heat dissipation during the duty cycle is ignored.

Case 1: SCFCL at Bus-Tie

The computer results for Nichrome V (resistor element type), show that the energy absorbed by 2.74 ohm shunt resistor is about 2340 Megajoules per operation based on a 15 cycle/operation insertion period. Several computer runs are performed to determine the physical size of the resistor and the cost. The resistor specification is shown in Table 3.5-6.

Case 2: SCFCL At Generator's Terminal

The computer results for Nichrome V show that the energy absorbed by 58 ohm shunt resistor is about 138 Megajoules per operation based on a 15 cycle/operation insertion period. The resistor specification is shown in Table 3.5-7.

Figure 3.5-3 shows the energy dissipated versus time per phase.

3.5.6 Support Structure For The Shunt Resistor

The resulting weight and length of resistor elements designed to dissipate moderate levels of fault current energy are considerable. The high temperature operation of these elements makes the spacing between wires, thermal expansion, sag, accelerated oxidation and corrosion rates, high temperature material tensile strength, high temperature strength of joints and welds, and the method of eventual heat dissipation important design considerations. The dielectric clearances and electromechanical forces also play an important role in determining the size and strength of the support structure.

The consideration of high voltage and high temperature effects in the design of a resistor element support structure dictates that a clear understanding of the design parameters that have a direct bearing on the reliability of this shunt resistor be investigated. Important design features for resistor element support are enumerated below:

1. Have adequate surface area upon which the resistor element's full length can be continuously formed.
2. Have adequate point-to-point dielectric clearance along the resistor's length. In the high temperature regions, the thermal expansion of the resistor material may cause a reduction in dielectric clearances for some structural configurations.
3. Have adequate freedom of motion at the point of resistor - support contact to prevent excessive thermal stress in the wire.
4. Have adequate dielectric clearance between any point along the resistor and ground potential.
5. Have adequate support strength to withstand sudden electromagnetic forces caused by the near proximity of high temperature radiating sources.

6. Have adequate capability of dissipating heat from the high temperature elements in a reasonable period of time.
7. Have adequate vertical clearance between any two sections of wire to avoid the heating of one section of wire by another. The hot spot created in this manner results in excessive local resistivity of the material and gives rise to an even greater I^2R heating condition. Higher temperatures are also accompanied by greater thermal expansion (sag) which serves to constrict the wire still further and again cause increased resistivity.
8. Have minimum inductance to provide for rapid change of current in the resistor branch.
9. Have a low temperature point of connection to the power system.
10. Have the ability to maintain all clearances and structural integrity during dynamic conditions such as wind, sudden electromagnetic forces, seismic disturbances.

A wide variety of resistor supports are used in industry today^(2,3). A great deal of insight can be gained by studying the design configurations of existing resistor support structures.

Since the length of a continuous resistor element is large to begin with, the geometry of its support should utilize volume efficiently to prevent the size of the overall structure from becoming unwieldy (the dielectric clearances required along the length of the wire tend to create very large geometrical shapes). The minimization of space required to support a long element with sufficient dielectric clearances resembles the mathematical problem of finding a three-dimensional shape that encloses the smallest volume yet has the largest amount of surface area. This shape is that of the frustum of a right circular cone. The general form of this shape resembles that of a simple funnel. Figure 3.5-4 shows a sketch of continuous winding design. This continuous winding technique provides for a minimum of critical high temperature connections and insures greater reliability.

It should be noted that this design is only a first attempt, taking advantage of Gould-Brown Boveri's experience in this field (72.5kV FCL resistor design). There are new techniques to improve the heat dissipation which will decrease the resistor size and cost. Further evaluation should be necessary.

3.5.7 Future Work

A. The design specifications for a support structure of the high temperature fault current resistor should be developed. The specifications should include the following:

1. Point - to - point dielectric clearances
2. Thermal stresses at support contact points
3. Point - to - ground clearances
4. Hot spot considerations
5. Minimum inductance
6. Temperature of connection to power system, and
7. Dynamic structural integrity.

These theoretical designs should be accompanied by experimental tests for verifications.

B. Resistor designed as subassembly for installation/removal.

C. Enclosure design (provides ample servicing room).

D. Investigate the use of different types of insulators for insulation and reinforcement.

FIGURE 3.5-1

Energy Dissipated Versus Time (Cycles)
242kV Systems 93kA Available Fault Current

FIGURE 3.542

FLOW CHART FOR RESISTOR ELEMENT DESIGN COMPUTER PROGRAM

FIGURE 3.5-3

Energy Dissipated Versus Time (Cycles)
242kV System, 11kA Available Fault Current

FIGURE 3.5-4

Layered Design Of Continuously Wound Resistor Element

TABLE 3.5-2

RESISTANCE MATERIAL CHARACTERISTICS

MATERIAL	TEMPERATURE COEFFICIENT ($\Omega/\Omega/^{\circ}\text{C}$)	TEMPERATURE MELT ($^{\circ}\text{C}$)	SPECIFIC HEAT (cal/g- $^{\circ}\text{C}$)	MAXIMUM DESIGNED TEMPERATURE OF A MATERIAL ($^{\circ}\text{C}$)	% CHANGE IN RESISTANCE
Advance (Ni-43% Cu-57%)	$\pm .00002$	1210	.094	847	1.69
Midohm (Ni-23% Cu-77%)	.00018	1100	.092	770	13.9
Nichrome V (Ni-80% Cr-20%) Def. 241	.00011	1400	.104	980	10.8
Chromax (Ni-35%, Cr-20%, Fe-45%)	.00036	1380	.110	966	34.8
Duranickel (Ni-94% Al-4.5%)	.001	1435	.125	1005	100.5
30 Alloy (Ni-2.25% Cu-97.75%)	.0015	1100	.092	770	115.5
Stainless Steel, Type Type 304 (Cr-18%, Ni-8%, Fe-74%)	.00094	1399	.117	979	92.0
Manganin (Mn-12% Ni-4%)	$\pm .000015$	1020	.095	714	-1.07
90 Alloy (Cu-89% Ni-11%)	.00049	1100	.092	770	37.7

TABLE 3.5-2 - Continued

MATERIAL	TEMPERATURE COEFFICIENT ($\Omega/\Omega/^\circ\text{C}$)	TEMPERATURE MELT ($^\circ\text{C}$)	SPECIFIC HEAT (cal/g- $^\circ\text{C}$)	MAXIMUM DESIGNED TEMPERATURE OF A MATERIAL ($^\circ\text{C}$)	% CHANGE IN RESISTANCE
Nichrome (Ni-60%, Cr-16%, Fe-24%)	.00015	1350	.107	945	14.2
Permanickel (Ni-99%)	.0036	1450	.130	1015	365.5
Gr.E Nickel Mn-2, Ni-98%	.0045	1435	.129	1004	451.8
Nilvar (Ni-36%, Fe-64%)	.00135	1425	.123	997	134.6
Incoloy 800 (Ni-35%, Cr-23% Iron-Balance	-	1357	.12	-	-

NICHROME V WIRE GAUGE TABLE (4.5)

B & S WIRE GAUGE	GAUGE DIAMETER (inches)	GAUGE AREA (in ²)	GAUGE AREA (circular inches)	GAUGE VOLUME PER FOOT LENGTH (in ³ /ft)	OHMS PER POUND - BARE WIRE (Ω /lb)
000000	.5800	.2642	.3363	3.1704	.0020
00000	.5165	.2095	.2667	2.5143	.0031
0000	.4599	.1661	.2115	1.9939	.0050
000	.4096	.1317	.1677	1.5813	.0080
00	.3647	.1045	.1330	1.2540	.0128
0	.3248	.0828	.1055	.9945	.0203
1	.2892	.0657	.0836	.7886	.0323
2	.2576	.0521	.0663	.6254	.0515
3	.2294	.0413	.0526	.4960	.0819
4	.2042	.0327	.0417	.3933	.1202
5	.1819	.0259	.0330	.3119	.2070
6	.1620	.0206	.0262	.2474	.3292
7	.1442	.0163	.0208	.1962	.5235
8	.1284	.0129	.0165	.1555	.8324
9	.1144	.0102	.0130	.1233	1.3236
10	.1018	.0081	.0103	.0978	2.1045
11	.0907	.0064	.0082	.0776	3.3462
12	.0808	.0051	.0065	.0615	5.3206
13	.0719	.0040	.0051	.0488	8.4600
14	.0640	.0032	.0041	.0387	13.4520
15	.0570	.0025	.0032	.0306	21.3890
16	.0508	.0020	.0025	.0243	34.0080
17	.0452	.0016	.0020	.0193	54.0750
18	.0403	.0012	.0016	.0153	85.9800

TABLE 3.5-4

NICHROME WIRE GAUGE TABLE

B & S WIRE GAUGE	GAUGE DIAMETER (inches)	GAUGE AREA (in ²)	GAUGE AREA (circular inches)	GAUGE VOLUME PER FOOT LENGTH (in ³ /ft)	OHMS PER POUND BARE WIRE (Ω /lb)
000000	.5800	.2642	.3363	3.1704	.0021
00000	.5165	.2095	.2667	2.5143	.0033
0000	.4599	.1661	.2115	1.9939	.0053
000	.4096	.1317	.1677	1.5813	.0085
00	.3647	.1045	.1330	1.2540	.0135
0	.3248	.0828	.1055	.9945	.0215
1	.2892	.0657	.0836	.7886	.0343
2	.2576	.0521	.0663	.6254	.0545
3	.2294	.0413	.0526	.4960	.0186
4	.2042	.0327	.0417	.3933	.1379
5	.1819	.0259	.0330	.3119	.2193
6	.1620	.0206	.0262	.2474	.3487
7	.1442	.0163	.0208	.1962	.5546
8	.1284	.0129	.0165	.1555	.8818
9	.1144	.0102	.0130	.1233	1.4021
10	.1018	.0081	.0103	.0978	2.2294
11	.0907	.0064	.0082	.0776	3.5449
12	.0808	.0051	.0065	.0615	5.6365
13	.0719	.0040	.0051	.0488	8.9623
14	.0640	.0032	.0041	.0387	14.2500
15	.0570	.0025	.0032	.0306	22.6580
16	.0508	.0020	.0025	.0243	36.0280
17	.0452	.0016	.0020	.0193	57.2850
18	.0403	.0012	.0016	.0153	91.0850

TABLE 3.5-5

Comparison Of Material Length And Cost For A 10.98 Ω Resistor
In A 242kV System With 23.25kA Available Fault Current
And 8 Cycle Duration

Material	R (Ω)	Designed Maximum Energy Absorption (Joules)	Length (Feet)	Resistive Material Cost (Dollars)
NICHROME V	10.98	312×10^6	3575	14,107
NICHROME	10.98	312×10^6	3443	-
INCOLOY 800	10.98	312×10^6	3905	14,548

TABLE 3.5-6

Resistor Specification (Case 1) SCFCL At Bus Tie

System Voltage L-L	kV	242
Fault Current Available	kA rms	93
Fault Current Let-Through	kA rms	45
Shunt Resistance/phase	ohms	2.74
Energy Absorption 45 Cycles/Phase	M Joules	6700
No of parallel resistor	#	6
Maximum voltage across the resistor	kV rms	V _{L-G} rms
Duty Cycle	operate 15 cycles, cool 20 cycles, operate 15 cycles, cool 10 seconds operate 15 cycles, cool to ambient temperature	

Physical characteristics for each 16.475 ohm resistor per phase; six of these are used in parallel.

Cross-section diameter	inches	.5165
Length	feet	6762
Resistor Weight	lbs	5170
Material cost per each 16.475 ohms	\$	33,646
The total length required for 6 resistors/phase	feet	40,572
Total resistor weight/phase	lbs	31020
The total material cost for 6 resistors/phase	\$	201,876

TABLE 3.5-7

Resistor Specification (Case 2) SCFCL At Generator Terminal

System Voltage L-L	kV	242
Fault Current Available	kA rms	11
Fault Current Let-Through	kA rms	2.33
Shunt Resistance/phase	ohm	58
Energy absorption 45 Cycles/phase	M Joules	412
No of parallel resistor	#	1
Maximum voltage across the resistor	kV rms	V_{L-G}^{rms}
Duty Cycle	operate 15 cycles, cool 20 cycles operate 15 cycles, cool 10 seconds operate 15 cycles, cool to ambient temperature	
Cross-Section Diameter	inches	.324
Length	feet	9412
Resistor Weight	lbs.	2846
Material Cost/phase	\$	18,525

REFERENCES (SECTION 3.5)

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4.0 EXPERIMENTAL PROGRAM

4.1 MATERIALS DEVELOPMENT

During this contract period we explored the effects of normal metal stabilization of NbN films, made an analysis of NbN X-ray diffraction patterns and looked for a solution to the surface imperfection problem prevalent in NbN films made by the reactive sputtering process. In addition, we looked at other superconducting materials besides NbN, settling on Nb₃Sn because it has been shown to have very high critical current density and we had an immediate capability to make it using existing facilities. We will discuss our results in the succeeding paragraphs.

4.1.1. Surface defects in NbN films.

We previously reported seeing a large number of surface defects in NbN films made by reactive sputtering. The preponderance of defects were bumps on the surface whose number density increased with increasing N₂ pressure. There was speculation that these bumps may lower J_c by acting as nucleation sites for flux jumping. Because of the dependence on N₂ pressure, the origin of the bumps was conjectured to be due to target spitting, i.e., the ejection of fine particles of Nb from the target surface during the sputtering process. To test this hypothesis, the target-substrate distance was increased from 7.1 cm to 14.2 cm. The result should be a reduction in the number density of bumps due to gravitational effects on the more massive particles.

Examination of films made at 14.2 cm showed almost total elimination of surface bumps. The critical current density of these samples, however, was no higher than samples with large number of surface defects, so we conclude that the bumps had no direct effect on J_c .

4.1.2. X-ray analysis of NbN films.

A majority of NbN films made to date were analyzed using X-ray diffractometry with the films still on their substrates. The results can be summarized as follows.

- a. The films exhibit the desired fcc structure over the entire range of N_2 content. The fcc structure forms over a narrow NbN_x range from $0.88 < x < 0.98$ and $1.015 < x < 1.062$. There was some evidence of the Nb_2N hexagonal phase forming in very small quantity at very large N_2 content.
- b. The NbN lattice constant varies from $< 4.36 \text{ \AA}$ to $4.393 \text{ \AA}$ as the N_2 content varies from 0.05 mTorr to 1.6 mTorr. Bulk NbN has a lattice constant of $4.390 \text{ \AA}$.
- c. The high angle diffraction peaks are very weak and quite broad, implying some inhomogeneity and strain. In addition, if the films are growing in a columnar fashion, the columns are probably quite short, certainly less than the film thickness.

4.1.3. Nb_3Sn evaluation.

A series of Nb_3Sn films were evaluated for their potential use in the SCFCL. Although ρ_N is much smaller than NbN, typical J_c values are much higher. These films were made on sapphire substrates 1/2" wide by either 1 or 2" length and all thicknesses were $1 \mu m$. Two sputtering parameters were varied; substrate temperature T_s and Ar sputtering pressure P_s . It was found that as T_s was decreased from $700^\circ C$ to $575^\circ C$, the transition temperature dropped from $\sim 17.9 \text{ K}$ to 15.3 K , the normal state resistivity at 20 K went up at least a factor of two from $\sim 17 \mu\Omega cm$ to $> 36 \mu\Omega cm$ and the unstabilized J_c dropped from $\sim 1.5 \times 10^6 \text{ A/cm}^2$ to as low as $5 \times 10^5 \text{ A/cm}^2$. Lowering

P_s from 30 to 10-15 mTorr did not affect the T_s trends just discussed but rather the magnitude of change. For example it was found that T_c was not as high at 700°C but did not fall off as rapidly with temperature as it had at 30 mTorr. ρ_{20} at $P_s = 10-15$ mTorr increased with increasing t_s but much less rapidly. J_c also fell off somewhat more slowly with decreasing T_s , however was somewhat higher at $T_s = 700^\circ\text{C}$ than was found at $P_s = 30$ mTorr.

As mentioned earlier, unstabilized J_c 's ranged from 0.5 to 1.35 x 10^6 A/cm² showing no difference between pulsed (4 ms wide, 0.5 ms rise time) and dc measurements for 1.27 cm wide samples. This is in sharp contrast to NbN samples which exhibited much lower unstabilized J_c 's under pulsed conditions than they did under dc conditions. The reasons for this are not clear, however, a possible explanation might be the improved thermal stability of the films on sapphire as opposed to glass, and/or the lower ρ_N in Nb₃Sn films.

A series of tests were also made on Nb₃Sn stabilized with a thin layer (30-60 μm thick) of indium applied by using an ultrasonic soldering iron and smearing the coating over the entire Nb₃Sn film as evenly as possible. Critical current densities measured on these samples increased by almost a factor of 7 over the same sample unstabilized. Thus a J_c of $\sim 7 \times 10^6$ Amps/cm² produced a $J_c \rho_N^{1/2}$ product of between 2.5 and 3 x 10⁴ which is as high as we have achieved in NbN.

Further work on Nb₃Sn will continue into the next quarter including switching tests.

4.1.4 Metallic stabilization of NbN.

The NbN samples previously reported always showed a decrease in J_c with increasing width and in addition, pulsed J_c 's were lower than dc values. It has been generally accepted that high conductivity normal metals adjacent to superconductors stabilize the superconductor against premature quenching due to thermal runaway from hot spots.

The addition of a normal metal in close proximity to a superconductor has two effects. The normal metal with its higher thermal conductivity greatly enhances the conduction of heat away from a hot spot and reduces the possibility of thermal runaway. Secondly, the normal conductor can slow down flux motion by eddy current damping again reducing the possibility of hot spots and thermal runaway.

We have coated several NbN samples with copper films 6 to 10 μm thick and compared the J_c with uncoated samples made at the same time. Measurements showed that the decrease in J_c with width was substantially reduced in the stabilized films and also that the difference in J_c between pulsed and dc was practically eliminated. It should be pointed out however that the highest J_c 's never exceeded $1-2 \times 10^6 \text{ A/cm}^2$ which we had previously measured in narrow unstabilized samples.

Measurements will continue into the next quarter and include the effects of high thermal conductivity substrates such as sapphire and whether stability can be achieved when the normal metal is electrically insulated from the superconductor.

Fig. 4.1. Sputtered Nb₃Sn film properties as a function of substrate temperature. The crosses (+) represent samples prepared at an Ar pressure of 30 mTorr. The solid circles (•) were samples prepared at 10-15 mTorr.

Fig. 4.2. NbN films about $3 \mu m$ thick and of varying widths deposited on glass substrates. The copper stabilized samples were made by sputtering $\sim 6-10 \mu m$ of Cu on fresh NbN films without breaking vacuum.