**Report
for**

MASTER

**RESEARCH
AND
DEVELOPMENT**

➔ GOULD-BROWN BOVERI

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

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

SUPERCONDUCTING FAULT CURRENT LIMITER

Second Quarterly Technical Progress Report

November 8, 1978 - February 7, 1979

Prepared by

GOULD-BROWN BOVERI (I-T-E IMPERIAL CORP.)

Prepared for

DEPARTMENT OF ENERGY
ELECTRICAL ENERGY SYSTEMS

PROJECT MANAGER

Russell Eaton, III

Contributors:

Gould-Brown Boveri, Research and Development Division
Spring House and Chalfont, PA

E. B. Khalafalla
D. B. Miller
A. Nourai
R. W. Reuther
E. M. Spencer

Gould Laboratory for Electrical and Electronics Research
Rolling Meadows, IL

A. J. Purdes

Argonne National Laboratories
Argonne, IL

K. E. Gray

D. B. Miller
Project Manager

"LEGAL NOTICE"

"This report was prepared by I-T-E Imperial Corporation as an account of work sponsored by the Department of Energy ("D.O.E."). Neither D.O.E., members of D.O.E., nor I-T-E Imperial Corporation, nor any person acting on behalf of either:

- "a. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- "b. Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report."

NOTICE

This report has not been reviewed to determine whether it contains patentable subject matter, nor has the accuracy of its information or conclusions been evaluated. Accordingly, the report is not available to the public and its distribution is limited to employees and advisors of D.O.E. for the sole purpose of evaluating the progress and future course of the project described in the report. Until the report has been reviewed and evaluated, it should be neither disclosed to others nor reproduced, wholly or partially.

TABLE OF CONTENTS

	Page No.
1. Introduction, Summary and Recommendation	1
2. Performance Objectives	5
2.1 Systems Parameters	6
2.2 Superconducting Fault Current Limiter Characteristics	8
2.3 The effect of Source Impedance on SCFCL Characteristics	17
2.4 References	19
Appendix I	
Superconducting Fault Current Limiter	21
Appendix II	
Equivalent Source Impedance Case 1	25
Appendix III	
Equivalent Source Impedance Case 2	26
Appendix IV	
Equivalent Impedance for T.L. Under Fault Conditions Case 2	27
Appendix V	
Equivalent Impedance for T.L. Case 3	28
3. Inductive Types of Superconducting Fault Current Limiters	55
3.1 Saturating Devices	56
3.2 Shielded SCFCL	68
4. Analysis of Resistive Superconducting Fault Current Limiters	72
4.1 Analysis of General Considerations	74
4.2 Switching Considerations	78
5. Proposed Experimental Program and Further Analysis	100
5.1 Experimental Program	101
5.2 Proposed Further Analysis	104

1. INTRODUCTION, SUMMARY AND RECOMMENDATION

1. INTRODUCTION, SUMMARY, RECOMMENDATIONS

This study has three basic objectives:

- A. Determine the performance characteristics of superconducting fault current limiters (SCFCL's) from analyses of electric power systems.
- B. Evaluate the comparative advantages and disadvantages of the various classes of SCFCL devices.
- C. Carryout key experiments which will determine the feasibility of the most promising type of SCFCL.

During this quarter, significant progress has been made on objectives A and B, and key experiments have been identified. Progress on these three objectives is described in the following four chapters of this report.

In Chapter 2, the performance objectives for SCFCL's are calculated for three modes of application in a particular, but typical system, the "Philadelphia Electric" system taken from Reference 1.1 of the First Quarter Report. The specifications for any SCFCL must finally be made for the exact system and location at which it will be employed. The objectives derived in Chapter 2 must be taken as typical but not necessarily suitable for any specific real application. Table 1.1 is therefore offered as a summary of performance objectives of SCFCL's used in three different configurations to limit a particular typical fault on a particular typical system.

Chapter 2 also indicates the relative desirability of resistive, rather than inductive, limiters, from a systems point of view.

Chapter 3 includes summaries of the two types of inductive SCFCL's, the saturating and shielding devices. Both are shown to be undesirable, the saturating device basically because of its massive iron requirement, and the shielding device, due to the high power loss in the shield during each limiting operation.

Resistive SCFCL's are treated in Chapter 4. The analyses of these devices do not reveal any obviously serious roadblocks. Two methods of switching, using a magnetic field and using a laser radiation beam, are described.

The resistive devices are therefore considered to be "most favored" from both the system and device analyses, and our recommendation is that work be continued on these SCFCL's.

Chapter 5 identifies those key experiments which we recommend to be done to establish feasibility of the resistive devices, and required experimental equipment is listed..

TABLE 1.1

PERFORMANCE OBJECTIVES OF SUPERCONDUCTING FAULT CURRENT LIMITERS
 ("Philadelphia Electric" Example System; Fault at the Generator Substation).

CASE IR	Two Resistive SCFCL's, one in each bus
CASE IL	Two inductive SCFCL's, one in each bus
CASE IIR	A resistive SCFCL in each of ten generator lines
CASE IIIR	Same as IIR with addition of a resistive SCFCL in each of three transmission lines

SUPERCONDUCTING GENERATORS AND LINES

Parameter per FCL	IR	IL	IIR	IIIR (GEN/TL)
R (Ω)	2.75		58	13.2 / 2
wL (Ω)	-	5.5	-	-
available current*	93	93	11	11/19
limited current*	43	43	2.3	7.8/13.4
Energy (MJ)	240	8.3	9.8	25.7/11.5
Voltage (kV, rms)	140	140	140	140
Number of FCL's	2	2	10	10/3

* kA, rms, symmetric

2. PERFORMANCE OBJECTIVES

2.0 SUPERCONDUCTING FAULT CURRENT LIMITER SYSTEM STUDY; PERFORMANCE OBJECTIVE

The purpose of this writeup is to present SC-FCL system studies in detail for the "Philadelphia Electric Company" example system (242kV) with three superconducting lines. Three different cases are studied to illustrate the required characteristics of SC-FCL's for various circumstances. These cases all apply to a fault at the generator substation, and SC-FCL's are employed in this same substation as follows:

Case 1: Using two SC-FCL's, one at each bus

Case 2: Utilizing ten SC-FCL's, one at each generator's terminal

Case 3: Employing ten SC-FCL's, one at each generator's terminal,
and three SC-FCL's, one at each transmission line.

2.1 SYSTEM PARAMETERS

Before these three cases are presented, it will be helpful to show the system parameters (see first Quarterly Report August 8, 1978-November 7, 1978).

a. Normal Operation

1. System Voltage: 242kVrms
2. Power Generated: 10GW
3. Number of Generators: 10
4. Number of Transformers: 10
5. Number of Superconducting T.L.: 3
6. Normal Current: 25kArms
7. Each T.L. carries normal load: 8.3kArms
8. Each T.L. carries under contingency: 12.5kArms

b. Short Circuit Conditions

From the previous short circuit studies, it was shown that the highest fault current would occur when the fault is located at or near the generation substation. Employing superconducting generators and transformers will produce more severe fault current than using conventional generators and transformers.

2.1 SYSTEM PARAMETERS - (Cont'd)

It would be proper to assume that SC-FCL's will be employed in a system utilizing superconducting elements such as T.L.'s, generators, and transformers. Therefore this study will be focused on a system with superconducting T.L.'s, generators, and transformers. Based on the previous short circuit studies utilizing 242kV superconducting system, a variety short circuit current conditions inside the generation substation are illustrated in Figures 2.1 - 2.10, and tabulated in Table I.

c. Circuit Breaker Rating

The circuit breaker interrupting capability, from ANSI standards for 242kV system, could reach up to 80kA, rms symmetrical and 104kA rms asymmetrical, for up to 4kA rms continuous current. The interrupting capability of the future circuit breaker could reach 100kA rms symmetrical and 130kA rms asymmetrical assuming two cycle breaker.

(Note: $I_s = S I_A$)

Where

$I_s \equiv$ asymmetrical fault interrupting capability

$S \equiv$ factor; depends on the speed of the breaker

$I_A \equiv$ symmetrical fault interrupting capability

From ANSI standards, $S = 1.3$ to 1.4 for a two cycle breaker; $S = 1.3$ represents the most difficult limitation requirement for a SC-FCL).

(Note: The S factor, and hence I_s , refers to the degree of asymmetry of the half cycle immediately prior to current zero interruption by the circuit breaker. The S factor does not specifically relate to the first loop and is a measure of breaker asymmetrical current interrupting capability only.)²

2.2 SUPERCONDUCTING FAULT CURRENT LIMITER CHARACTERISTICS

2.2.1 CASE 1: Two SC-FCL, one at each bus (Condition 4S, Figure 2.8)

Two different types of SC-FCL (resistive, inductive) will be investigated in order to illustrate the required characteristics of each one in order that the SC-FCL may perform its duty.

Determine The Required Resistance (Inductance) at Generation Substation

With reference to Figures 2.7 to 2.10, in order to limit the fault current at circuit breakers C12 or C8, C11, C13 to 100kA rms symmetrical, it is necessary to add a FCL at circuit breakers C1 and C3.

As an example of a worst case, consider condition 4S with superconducting machines, Figure 2.8. It is assumed that a FCL will be located at C1. For the case where the fault is at L3, the fault current limiter can only limit the current that passes through it i.e., the current coming from the right side of the substation Figure 2.8; the current that is coming from the left side cannot be limited in this case. Therefore, the addition of both currents from the left side and the right side should not exceed the circuit breaker (C8) capability. Knowing the circuit breaker capability and the current from the left side, one can easily determine to what value the current from the right side should be limited, therefore,

$$I_{\text{fault}} \text{ rms symmetrical from the right side} = 93\text{kA}$$

Since the circuit breaker capability is 100kA rms symmetrical then,

$$I_{\text{fault}} \text{ rms symmetrical (the limited value)} =$$

$$100 - I_{\text{fault}} \text{ (from the left side)}, = 100 - 55, = 45\text{kA}$$

2.2.1 CASE 1 - (Cont'd)

i.e., the fault current from the right side (93kA) should be limited to 45kA rms symmetrical.

Then,

$$F = \frac{I_{ss}}{I_F} = \frac{45}{93} = .48$$

Assume

$$F = .5$$

SC-FCL Characteristics (Case 1)

See Appendix II for derivation of equivalent source impedance used in this calculation.

A computer program has been developed using basic language (see the flow chart Figure 2-26), in order to predict the required switched resistance (inductance) to limit the fault current to a certain value. The equivalent source impedance for this case is derived in Appendix II.

1. Resistive FCL

The computer results, show that the required resistance R_L in order to limit the symmetrical fault current is approximately 2.75 ohms (Figure 2.11). Because the switched resistance is greater than the source inductive impedance ($x = 1.58$ ohms), the fault current after switching the resistance is symmetric even though the fault current before switching is fully offset (asymmetric).

The energy dissipated in the FCL can be easily calculated now as follows:

2.2.1 CASE 1 - (Cont'd)

$$I_{\text{rms}} \text{ after switching FCL} = \frac{I_{\text{max}} \text{ after switching}}{\sqrt{2}}$$

$$= \frac{60}{\sqrt{2}} \cong 43\text{kA}$$

$$\text{Energy (for 2 cycles)} = I_{\text{rms}}^2 R_t$$

$$= (43000)^2 (2.75) (32 \times 10^{-3})$$

$$\cong 163\text{M Joules/phase}$$

The voltage across the FCL is shown in Figure 2.12. Its rms value is:

$$\frac{V_{\text{max}}}{\sqrt{2}} = \frac{167}{\sqrt{2}} = 118\text{kV rms}$$

2. Inductive FCL

The computer results show (in Figure 2-13) that, if the FCL utilizes an inductance instead of resistance, the inductive impedance ωL_L must be 5.48 ohms in order to limit the fault current to 100kA, rms symmetric. (Note that inductive impedance is twice the resistive impedance which is calculated in the previous section).

Utilizing an inductive FCL, (Figure 2-13) notice that the current after switching is still asymmetric. This could cause an interrupting problem for a circuit breaker if the inductance exceeded certain values, because the current has a d.c. component, and current zero interruption opportunities will be missed. (This d.c. component is due to the exponential term which decays slowly, equation 11). Figure 2-14 shows the FCL currents for two other values of FCL inductance. Note that there is still no current zero even at the end of the second cycle, for $L_L = 25\text{mH}$. It is important to realize that the Figure 2.14 current is only through the FCL, not the circuit breaker. Figure 2.15 shows the two branch currents which add to give the total circuit breaker current.

2.2.1 CASE 1 - (Cont'd)

The two currents are then added in Figure 2-16.
Figure 2-17 plots the steady-state FCL and source voltages.

The rms voltage across the inductive FCL =

$$\frac{155}{\sqrt{2}} \cong 110\text{kVrms}$$

The required inductance = 14.5mH

$$\text{Assuming that } Q = \frac{\omega L}{r} = 100$$

Where

$r \equiv$ the internal resistance of the inductance L

The energy stored in FCL can be predicted as follows:

(See Figure 2-13)

For fully offset current

$$\begin{aligned} I_{ac \text{ rms}} &= \frac{I_{\text{peak to peak}}}{2\sqrt{2}} = \frac{55}{2\sqrt{2}} \\ &= 19.5\text{kA rms} \end{aligned}$$

$$I_{dc} = \sqrt{2} I_{ac \text{ rms}}$$

Then,

$$\begin{aligned} I_{\text{Total rms}} &= \sqrt{I_{ac \text{ rms}}^2 + I_{dc}^2} \\ &= \sqrt{(19.5)^2 + 2(19.5)^2} \\ &= 33.8\text{kA rms} \end{aligned}$$

2.2.1 CASE 1 - (Cont'd)

$$\begin{aligned}\text{Energy stored in magnetic field} &= \frac{1}{2} L_L I_{\text{Total rms}}^2 \\ &= \frac{1}{2} (14.5 \times 10^{-3})^2 \\ &\quad (33.8 \times 10^3)^2 \\ &= 8.3\text{M Joules/phase}\end{aligned}$$

Conclusions and Comments (Case 1)

1. Circuit Breaker Rating

The required asymmetrical interrupting capability is related to the required symmetrical interrupting current by the ratio S. The asymmetry capability ratio S is, for a 3 cycle breaker, a minimum of 1.2 (1.2 → 1.3), and for a 2 cycle breaker, a minimum of 1.3 (1.3 → 1.4). Therefore,

The required asymmetrical current interrupting capability

$$\begin{aligned}&= S \times \text{symmetrical interrupting capability} \\ &= 1.3 \times 100 \\ &= 130\text{kA rms asymmetrical} \\ &(\text{ANSI C37.04 - 1964})\end{aligned}$$

2. The peak voltage across a resistive FCL is approximately 85% of peak L-G system voltage; however, the peak voltage across an inductive FCL is approximately 78% of peak L-G system voltage (see Figures 2-12 and 2-15):

$$\begin{aligned}V_{\text{L-G peak}} &= \frac{\sqrt{2}}{\sqrt{3}} 242 = 197.6\text{kV} \\ V_R &\equiv \text{voltage across resistive FCL} \\ &= .85 \times 197.6 \cong 170\text{kV peak} \\ V_{L_L} &\equiv \text{voltage across inductive FCL} \\ &= .78 \times 197.6 \cong 155\text{kV peak}\end{aligned}$$

2.2.1 CASE 1 - (Cont'd)

3. A computer program using basic language has been developed in order to solve switching transients (see the flow chart, Figure 2-26).
4. Resistive FCL: choosing resistance equal to 2.75 ohms is satisfactory as far as circuit breaker capability is concern since this resistance could limit the fully offset fault current to circuit breaker limit after 2 cycles; clearly the 1st peak is limited within the circuit breaker capability for both electrical and mechanical modes (see Figure 2-19).
5. Inductive FCL: choosing reactive impedance equal to 5.5 ohms (twice the resistive FCL impedance) is satisfactory as far as circuit breaker capability is concern since this impedance could limit the fully offset fault current to circuit breaker limit after 2 cycles. The 1st peak is within the circuit breaker capability (see Figure 2-17).

Higher inductance is not recommended since the current passing through the FCL is fully offset and reaches zero after approximately 3 cycles (see Figure 2-14). This might cause a current interruption problem to a circuit breaker in series with a FCL, and also might cause instability problem.

6. It should be noted that in some cases two FCL's will be required in each tie bus, one on each side of the center branch. This case is beyond the scope of this project.

2.2.1 CASE 1 - (Cont'd)

7. The energy dissipated in a resistive FCL is approximately 163M Joules/phase. This is a very high energy to dissipate, and a non-linear resistance in parallel with the SC-FCL might be required to absorb some of this energy.

8. The energy stored in a inductive FCL is approximately 8.5M Joules/phase which is much lower than the energy dissipated in resistive FCL.

2.2.2 CASE 2: Ten SC-FCL; one at each generator's terminal

In this case only the resistive SC-FCL will be investigated. Similar calculations to Case 1 will be carried out.

Figure 2-21 shows the location of a fault at one of the generator's terminal. Referring to the previous short circuit study:

$$\begin{aligned}\text{The current delivered by 3 T.L.} &= 3 \times 10 \\ &= 57\text{kA rms symmetrical}\end{aligned}$$

Where

$$\text{T.L.} = \text{Transmission Line}$$

The limited current delivered by 9 generators

$$\begin{aligned}&= 100 - 57 \\ &= 43\text{kA rms symmetrical}\end{aligned}$$

Then,

The limited current delivered by one generator

$$= \frac{43}{9} = 4.8\text{kA rms symmetrical}$$

The available fault current from each generator equals 11kA rms symmetrical.

2.2.2 CASE 2 - (Cont'd)

Then, for steady state, in order to predict the inserted resistance for each SC-FCL,

$$F = \frac{I_{ss}}{I_F} = \frac{4.8}{11} \cong .44$$

A computer program was utilized in order to determine the required resistance to limit the first loop current. The equivalent source and T.L. impedance are derived in Appendices III and IV. The following calculations apply to the fault condition and current shown in Figure 2-20.

From the computer results, in order to allow 100kA rms symmetrical or 130kA rms asymmetrical through C5 circuit breaker at the 2nd loop, the inserted resistance at each SC-FCL is 58.0 ohms.

See Figures 2-21 to 2-23 for current and voltage waveforms.

The peak voltage across the SC-FCL (resistive) is 190kV peak (i.e., 139kV rms) i.e., approximately equal to V_{L-G} rms.

Each generator current must be limited to 2.3kA rms, so that C5 circuit breaker capability is not exceeded. Note that this is less than generator full load current (2.5kA rms).

The energy dissipated in SC-FCL within 2 cycles is

$$\begin{aligned} &= I^2 R t \\ &\cong (2.3 \times 10^3)^2 58.0 \times (32 \times 10^{-3}) \\ &= 9.8M \text{ Joules/phase} \end{aligned}$$

Total energy for 10 FCL

$$= 9.8 \times 10 = 98M \text{ Joules/phase}$$

2.2.3 CASE 3: Ten SC-FCL; one at each generator's terminal and three SC-FCL; one at each T.L.'s terminal.

Resistive SC-FCL will be investigated only. Calculations similar to Case 1 and Case 2 are carried out. Figure 2-20 circuit and fault conditions apply.

Figures 2-24 and 2-25 show the current waveforms for each SC-FCL at each generator and each T.L., so that the C5 circuit breaker (Figure 2-20) current does not exceed its capability. This total breaker current consists of nine generator currents (Figure 2-24) and three T.L. currents (Figure 2-25).

Computer Results

The required resistance for a SC-FCL at each generator is 13.2 ohms and the required resistance for the SC-FCL at each T.L. is 2 ohms. The limits the T.L. current to 16kA rms symmetric, which is twice the T.L. steady-state, full-load value (see Figure 1, First Quarterly Report, August 8 - November 7, 1978).

The energy dissipated in SC-FCL at each generator within 2 cycles is

$$\begin{aligned} &= I^2 R t \\ &\quad (7.8 \times 10^3)^2 \times 13.2 \times 32 \times 10^{-3} \\ &= 25.7 \text{M Joules/phase} \end{aligned}$$

The energy dissipated in SC-FCL at each T.L. within 2 cycles is

$$\begin{aligned} &= I^2 R t \\ &\quad (15.6 \times 10^3)^2 \times 2 \times (32 \times 10^{-3}) \\ &= 15.6 \text{M Joules/phase} \end{aligned}$$

Total energy for 13 SC-FCL

$$\begin{aligned} &= 25.7 \times 10 + 15.6 \times 3 \\ &\quad 304 \text{M Joules/phase} \end{aligned}$$

2.3 THE EFFECT OF SOURCE IMPEDANCE ON SC-FCL CHARACTERISTICS

The purpose of this section is to demonstrate the effect of different source impedance ratio X/R on the behavior of SC-FCL. Several computer runs for different impedance ratio X/R ($X/R = 20 \rightarrow 50$) were carried out for three cases which were previously discussed.

The computer results show that the current and voltage wave shapes after inserting FCL have the same forms as shown earlier for each separate case with a very little variation in the first peak currents and voltages as shown below:

Case 1:

FCL inserted resistance 2.75 ohms, source impedance Z ohms 1.58.

X/R	20 *	30	40	50
(source) X ohms	1.58	1.58	1.58	1.58
(source) R ohms	.08	.05	.04	.03
I_{peak} kA 1st loop	59.6	60.1	60.3	60.5
V_{peak} kV 1st loop	167.4	168.8	169.3	169.75

*See Fig. 2-11 and 2-12

Case 2:

FCL inserted resistance ohms 58.0, source impedance Z ohms 12.9

X/R	20 *	30	40	50
X ohms	12.9	12.9	12.9	12.9
R ohms	.645	.43	.32	.26
I_{peak} kA 1st loop	3.27	3.28	3.288	3.29
V_{peak} kV 1st loop	189.345	190.0	190.35	190.54

*See Fig. 2-21 and 2-22

2.3 THE EFFECT OF SOURCE IMPEDANCE ON SC-FCL CHARACTERISTICS - (Cont'd)

Case 3:

Similarly has a very small variation.

It should be noted that for Case 1, the left side current (the unlimited current) is assumed coming from a source with a very high source impedance ratio X/R ; R is negligible. Also Case 2, the currents which come from T.L.'s are considered coming from an inductive source; source impedance resistance is ignored.

2.3.1 ANALYSIS OF THE RESULTS

Increasing the source impedance ratio will increase the fault current and voltage, however, this increase is not significant because of the following reasons:

1. The source impedance is very small compared to the inserted resistance (FCL); after inserting the SC-FCL, the total impedance (source and FCL) ratio X/R decreases significantly, therefore, the d.c. component becomes negligible compared to sinusoidal component and the current waveform becomes symmetrical.
2. The time interval from the time fault is initiated to the time FCL is operated is approximately 4 m. seconds (1/4 cycle). During this short time the difference between fault current magnitude with source impedance ratio $X/R = 20$ and fault current magnitude with source impedance ratio $X/R = 50$, is approximately 4%.

Conclusions:

The predicted values of the required resistance, for each case discussed in the previous sections, are valid for a variety of source impedance ratio X/R ($X/R > 20 \rightarrow 50$) with a very good approximation.

2.4 REFERENCES

1. A. Greenwood, "Electrical Transients In Power Systems". 1971
2. Mr. T.H. Dodds reports of February 9, 1979

TABLE 1

Condition No.		Circuit Breakers Which Are Opened	Fault Location	Maximum Current at C.B
CONVENTIONAL MACHINE	1C	C1	L1	C12 = 74 kA
	2C	C1-C14-C17	L1	C12 = 94 kA
	3C	C1	BB5	C3 = 73 kA
	4C	C2-C7	L3	C8 = 108 kA
	5C	C2-C3	L2	C11 = 108 kA
	6C	C2-C3-C12	L1	C13 = 108 kA
	Any other cases, any combination of C,B's could stand short circuit current			
SUPERCONDUCTING MACHINE	2S	C1-C14-C17	L1	C12 = 126 kA
	4S	C2-C7	L3	C8 = 148 kA
	5S	C2-C3	L2	C11 = 148 kA
	6S	C2-C3	L1	C13 = 148 kA

APPENDIX I

SUPERCONDUCTING FAULT CURRENT LIMITER

Simple Switching Transients

Case 1

Special Case

Assume

$$E = E_m \sin(\omega t) \text{ ; phase angle is zero}$$

When the switch(1) is closed the equation expressing the current is

$$RI + L \frac{dI}{dt} = E_m \sin(\omega t) \quad (1)$$

Transforming both sides

$$R i(S) + LS i(S) - L i(o) = E_m \frac{\omega}{S^2 + \omega^2} \quad (2)$$

Note:

$$\text{at } t = 0 \quad i(o) = I_{load} \text{ at that time}$$

So the operational solution for current is:

$$i(S) = E_m \frac{\omega}{(S^2 + \omega^2)(R + LS)} + i(o) \frac{L}{(R + LS)} \quad (3)$$

i, e

$$I(t) \cong \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} [e^{-\alpha t} - \cos \omega t] + i(o) e^{-\alpha t} \quad (4)$$

$$\text{Where } \alpha = \frac{R}{L}$$

Equation (4) represents fault current at $0 < t < T$

When the switch (2) is opened (insert resistance) at time $t = T$, equation (4) is valid for different time and current constant.

i, e at $t > T$

$$I(t) \cong \frac{E_m}{\sqrt{(R+R)^2 + \omega^2 L^2}} [e^{-\alpha_1 t} - \cos \omega t] + i_1(o) e^{-\alpha_1 t} \quad (5)$$

$$\text{Where } \alpha_1 = \frac{R+r}{L}$$

$$i_1(o) = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} [e^{-\alpha T} - \cos \omega T] + i(o) e^{-\alpha T} \quad (6)$$

Case 2

General Case

Assume $E = E_m \sin(\omega t + \theta)$

Where

θ is phase angle, permits closing of the switch (1) at any instant in the voltage cycle.

When the switch (1) is closed, the equation expressing the current is^[1]

$$I(t) = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} [\sin(\omega t + \theta - \phi) - \sin(\theta - \phi) e^{-\alpha t}] + i(o) e^{-\alpha t} \quad (7)$$

Where

$$0 < t < T$$

$$\alpha = \frac{R}{L}$$

$$\phi = \text{ARC TAN } \left(\frac{\omega L}{R} \right)$$

θ = Voltage phase angle at $t = 0$

$i(0)$ = Load current at $t = 0$

Hence the current at $T < t$

$$I(t) = \frac{E_m}{\sqrt{(R+r)^2 + \omega^2 L^2}} [\sin(\omega t + \theta - \phi) - \sin(\theta - \phi) e^{-\alpha_1 t}] + i_1(0) e^{-\alpha_1 t} \quad (8)$$

Where

$t > T$

$$\alpha_1 = \frac{R+r}{L}$$

$$i_1(0) = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} [\sin(\omega T + \theta - \phi) - \sin(\theta - \phi) e^{-\alpha T}] + i(0) e^{-\alpha T} \quad (9)$$

Case 3

Inserting Inductance

$$E = E_m \sin \omega t$$

Similarly

$$I(t) = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} [e^{-\alpha t} - \cos \omega t] + i(0) e^{-\alpha t} \quad (10)$$

$0 < t < T$

Where

$$\alpha = \frac{R}{L}$$

$i(0)$ = load current at $t = 0$

Then

$$I(t) = \frac{E_m}{\sqrt{(R+r)^2 + \omega^2 (L+L_1)^2}} [e^{-\alpha_1 t} - \cos \omega t] + i_1(0) \left[\frac{L}{L+L_1} \right] e^{-\alpha_1 t} \quad (11)$$

$t > T$

Where

$$i_1(o) = \frac{E_m}{\sqrt{R^2 + \omega^2 L^2}} [e^{-\alpha T} - \cos \omega T] + i(o) e^{-\alpha T} \quad (12)$$

And

$$\alpha_1 = \frac{R+r}{L+L_1} \quad (13)$$

$$r = \frac{WL_1}{\phi} = \frac{WL_1}{100} \quad (14)$$

The voltage across the inductance is

$$V = L_1 \frac{dI(t)}{dt} \quad t > T \quad (15)$$

Where

$$\frac{dI(t)}{dt} = \frac{E_m}{\sqrt{(R+r)^2 + \omega^2 (L+L_1)^2}} [-\alpha_1 e^{-\alpha_1 t} + \omega \sin \omega] - \alpha_1 \left[\frac{L_1}{L+L_1} \right] i_1(o) e^{-\alpha_1 t} \quad (16)$$

$t > T$

Special Case

When $\theta - \phi = \pm 90^\circ$

the equation (7) reduce to equation (4), and similarly equation (8) reduce to equation (5).

A computer program is developed (basic language) to calculate the current (fault current) with and without the inserted resistance (r) for fully asymmetric case i.e $\theta - \phi = \pm 90^\circ$.

In this computer program several assumptions were made as follows:

1. Factor F = .5 (Initial Condition)
2. Load Current, (4kA rms Case 1), (2.5kA rms and 12.5kA rms, Case 2 and 3)
3. The value of resistance R_L is based on steady state
4. Using the current derivative in order to determine the time "T" at which switch (2) is open;

$$\begin{aligned} \left. \frac{dI}{dt} \right|_{\text{fault}} &\cong 6 \left. \frac{dI}{dt} \right|_{\text{no fault}} \\ &\cong 6 \times | [I_m \omega] | \\ &\cong 6 (\sqrt{2} \times 4 \times 377) \\ &\cong 12800 \end{aligned}$$

This value could reach 24000 if $I_{\text{Load}} = 8 \text{ kA}_{\text{rms}}$

APPENDIX II

EQUIVALENT SOURCE IMPEDANCE CASE I

In order to perform system study and determine the required resistance to be inserted, a circuit reduction should be performed first. (i.e., the right side of the substation could be reduced to a voltage source and series impedance as follows:

Per unit system

$$E = 242\text{kV rms} \quad 1 \text{ p.u.}$$

$$W = 10\text{GW}$$

$$I_{\text{base}} = 25\text{kA rms}$$

$$Z_{\text{base}} = \frac{(\text{kV}_{\text{LL}})^2}{\text{MW}} = \frac{(242)^2}{10 \times 10^3} = 5.86\Omega$$

Then,

$$I_{\text{fault p.u.}} = \frac{93}{\text{base current}} = \frac{93}{25} = 3.72 \text{ p.u.}$$

$$\text{Equivalent impedance } Z = \frac{1.0}{3.72} = .27 \text{ p.u.}$$

Assume $x \gg R$

$$\text{i.e., } x \cong Z$$

Then,

$$x = Z_{\text{p.u.}} \times Z_{\text{base}}$$

$$= .27 \times 5.86 = 1.58\Omega$$

$$L = \text{inductance} = \frac{x}{\omega} = \frac{1.58}{377}$$

$$= 4.2\text{mH} \quad (\text{equivalent source inductance})$$

Assume,

$$\frac{X}{R} = 20$$

Then,

$$R = \frac{1.58}{20} = .08\Omega \quad (\text{equivalent source resistance})$$

APPENDIX III
EQUIVALENT SOURCE IMPEDANCE CASE 2

$$\begin{aligned} Z &= 2.2 \text{ p.u. (Source Impedance based on 10 GW)} \\ &= 2.2 \times 5.86 \quad 12.9 \text{ ohms} \end{aligned}$$

Assume,

$$\frac{X}{R} \gg \gg \quad \text{then,} \quad \frac{X}{R} = 20$$

Then,

$$X \approx 12.9 \text{ ohms}$$

$$L = \frac{X}{\omega} = \frac{12.9}{377} = .0342 \text{ H}$$

$$R = \frac{X}{20} = \frac{12.9}{20} = .645 \text{ ohms}$$

then, the inserted resistance can be calculated as follows:

$$\begin{aligned} R_L &= \sqrt{X^2 \left(\frac{1}{F^2} - 1 \right)} \\ &= \sqrt{(2.2)^2 \left[\frac{1}{(.44)^2} - 1 \right]} \\ &\approx 4.5 \text{ p.u.} \\ &= 4.5 \times 5.86 = 26.4 \text{ ohms} \end{aligned}$$

It should be noted that this resistance value (26.4Ω) is for steady state limited current, since we are interested in the 1st loop (cycle), then this resistance value will be considered as an initial value (initial condition) in order to find a suitable value for the resistance to limit the first loop.

APPENDIX IV

EQUIVALENT IMPEDANCE FOR T.L. UNDER FAULT CONDITIONS CASE 2

$$I_{\text{fault}} = 57\text{kA rms symmetrical}$$

This current represents the total fault current from 3 T.L. (each line carries 19kA rms symmetrical).

Then,

$$I_{\text{p.u.}} = \frac{1.0}{Z_{\text{p.u.}}} = \frac{I_{\text{fault}}}{I_{\text{base}}} = \frac{57}{25} = 2.28 \text{ p.u.}$$

Then,

$$\begin{aligned} Z &= \frac{1.0}{2.28} = .439 \text{ p.u.} \\ &= .439 \times 5.86 = 2.57 \text{ ohms} \end{aligned}$$

Assume

$$\frac{X}{R} \gg \gg$$

$$\text{The asymmetric current} \cong \frac{E_{\text{max}}}{X} [\cos \omega t - 1]$$

APPENDIX V
EQUIVALENT IMPEDANCE FOR T.L. CASE 3

$$I_{p.u.} = \frac{19}{25} = .76 \text{ p.u.}$$

$$Z = \frac{1}{.76} = 1.32 \text{ p.u.}$$

$$= 1.32 \times 5.86 = 7.73 \text{ ohms}$$

Assume,

$$\frac{X}{R} = 15$$

Then,

$$X \cong 7.73\Omega$$

$$R \cong .52\Omega$$

$$L = \frac{7.73}{377} = .0205\text{H}$$

$$F = \frac{16}{19} = .84$$

$$I(0) \equiv \text{initial value} = 12.5 \sqrt{2} = 17.7\text{kA peak}$$

CONDITION 1C
CONVENTIONAL MACHINE

Figure 2-1

CONDITION 2C
CONVENTIONAL MACHINE
Figure 2-2

CONDITION 3C
CONVENTIONAL MACHINE

Figure 2-3

CONDITION 4C
CONVENTIONAL MACHINE

Figure 2-4

CONDITION 5C
CONVENTIONAL MACHINE

Figure 2-5

CONDITION 6C
CONVENTIONAL MACHINE

Figure 2-6

CONDITION 2S
SUPERCONDUCTING MACHINE

Figure 2-7

Figure 2-8

CONDITION 5S
SUPERCONDUCTING MACHINE

Figure 2-9

CONDITION 6S
SUPERCONDUCTING MACHINE

Figure 2-10

$$R_2 = 2.74 \, \Omega$$

$$E_{max} = 197.6 \, \text{KV}$$

CURRENT THROUGH RESISTIVE FCL (CASE 1)

FIGURE 2-11

$$R_2 = 2.74 \text{ } \Omega$$

$$E_{\text{max}} = 197.6 \text{ kV}$$

TRANSIENT VOLTAGE ACROSS RESISTIVE FCL (CASE 1)

FIGURE 2-12

-42-

CURRENT THROUGH INDUCTIVE FCL
FOR DIFFERENT INDUCTANCE (CASE 1)

FIGURE 2-14

TRANSIENT VOLTAGE ACROSS INDUCTIVE FCL (CASE 1)

TWO CURRENT WAVE SHAPES WHICH WILL GO
THROUGH A CIRCUIT BREAKER (CASE 1)

FIGURE 2-16

FIGURE 2-17

FIGURE 2-18

FIGURE 2-19

WITHOUT SCFCL (CASE 2 AND CASE 3)

FIGURE 2-20

CURRENT WAVEFORM FOR EACH SF-FCL (CASE 2)

FIGURE 2-21

VOLTAGE ACROSS SC-FCL (NOT TRANSIENT) (CASE 2)

FIGURE 2-22

TOTAL CURRENT THROUGH CIRCUIT BREAKER (CASE 2)

FIGURE 2-23

CURRENT WAVEFORM FOR EACH FCL AT EACH GENERATOR (CASE 3)

FIGURE 2-24

CURRENT WAVEFORM FOR EACH FCL AT EACH TRANSMISSION LINE (CASE 3)

FIGURE 2-25

SC-FCL FLOW CHART

FIGURE 2-26

3. INDUCTIVE TYPES OF SUPERCONDUCTING FAULT CURRENT LIMITERS

3. INDUCTIVE TYPES OF SUPERCONDUCTING FAULT CURRENT LIMITERS

3.1 Saturating Devices

As the core of an inductive device goes into or out of saturation, its impedance changes by a significant amount, and this phenomenon can be used to limit fault currents. One such type of device is shown in Figure 3.1. In this so called saturating superconducting fault current limiter, a DC bias field is superimposed upon the two cores by the high DC current in the superconducting winding. This winding is shown in the sketch as a single race track shaped coil but it could in fact be many turns. The DC flux in the two cores is high enough to drive those cores into the saturation region so that these two series connected coils have a very low inductive impedance. If, however, the AC current goes above a certain critical normal level, the AC flux in the two cores drives those cores alternatively on successive half cycles out of the saturation region, thereby imposing high impedance on the circuit. This device will now be analysed using the parameters shown in Illustration 3.2.

Refer now to Figure 3.3 which shows the idealized magnetization curves for the two cores. Sinusoidal currents are also plotted on Figure 3.3 in terms of their ampere-turn per meter value. The smaller current is the maximum allowable current without any limiting; the larger current shown is the level to which the fault current is to be limited under fault conditions. We now proceed to use the Figure 3.3 curves to construct flux and voltage waveforms, using the Ampere and Faraday relations shown in Illustration No. 3.4. These constructions are carried out on Figure 3.5. In Figure 3.5A the maximum limited AC current and the DC current are plotted again in terms of ampere turns per meter.

The Figure 3.5A plot is used with the magnetization curves of Figure 3.3 to construct the plots of flux in the two cores shown in Figure 3.5B. Faraday's law is then applied to derive the voltage curve shown in 3.5C from the Figure 3.5B flux curves.

The derivation in Illustration 3.6 shows that the voltage times the change in current from normal to limiting condition is governed only by the energy stored in the inductor. This means that setting the values for voltage and current determines both the type and volume of iron which must be selected.

Illustration 3.7 outlines the calculation procedure which is used to evaluate any particular fault current limiter design. One first selects the voltage and currents for the design, an iron is then chosen in terms of its critical B and H fields as defined in Illustration 3.2. The required iron volume is then calculated. An area must next be chosen from which the length of the winding and the number of turns on each winding can be calculated. Finally, the required superconducting DC saturating current is evaluated. Some numerical results using this procedure are shown in Illustration 3.8. The volume shown in Illustration 3.8 is for one of the two identical cores required in each phase of a saturating type fault current limiter. An evaluation of the saturating type superconducting fault current limiter is outlined in Illustration 3.9. This device does meet required performance objectives in terms of the rated and limiting currents, the required impedance and the speed of response. It operates in an instantaneous and self-controlling fashion. It does not appear to have any recovery time problem and the superconducting

winding is not required to go between normal and superconducting states. There are some considerations to be made in this device, however. It does involve a large volume of iron, the cores appear to require specialty steels which could add to the cost of the device. Two cryo-bushings are required in order to attach the DC winding to an external DC supply. Losses in the iron have not yet been evaluated. The approximate analysis carried out in this section neglected the nonlinear character of the iron, which undoubtedly would generate transients in the DC and AC lines as the device is passing from normal to limiting conditions. Finally, one must evaluate the induced voltage in the DC line.

A fault current limiter based on the saturating core concept is now being developed by the International Research and Development Co. Ltd., in England. (See References 3.24 and 3.25 of the First Quarterly Report.) A 5MVA prototype is about to be tested. Further description and comments on this development are found in Sections 3.23 - 3.25 of the First Quarterly Report.

Figure 3.1. Elemental Sketch of Saturating Superconducting Fault Current Limiter

.2. Parameters

H_C "critical" value of intensity;
A-t/m.

Figure 3.3. Iron Magnetization Curves (Idealized) for Construction of Flux and Voltage Plots

gui .4. Basic Equations

Ampere Law $\sum H \ell = \sum N I$
at instant of maximum limiting:

$$- H_C \ell = I_{dc} - N I_{LM}$$

at instant of entry into unsaturated region:

$$+ H_C \ell = I_{dc} - N I_{CM}$$

Faraday Law $v = N \frac{d\phi}{dt}$

at instant of maximum limiting:

$$v_L(t) = N \frac{d}{dt} \phi$$

$$= N \frac{d}{dt} \phi_m \sin \omega t$$

$$= N \omega \phi_m \cos \omega t$$

$$V_L = N \omega B_C A$$

Figure 3.5a Plot of maximum limited a-c current

Figure 3.5b Plot of flux in each core during maximum limited current Condition.

Figure 3.5c Plot of total voltage induced in the two series coils during maximum limited current condition.

Figure

3.6. Design Decision: choice of iron and dimensions to meet I_{LM} , I_{CM} , V_{LM} requirements

$$\begin{aligned}
 \Delta I_m &= I_{LM} - I_{CM} \\
 &= \frac{2\ell H_C}{N} \quad \text{from E5, E6} \\
 &= \frac{2\ell H_C}{V_{LM} / \omega B_C A} \\
 &= \frac{2 \omega \ell A B_C H_C}{V_{LM}}
 \end{aligned}$$

Now, ℓA = volume

$1/2 B_C H_C$ = energy density in iron at
critical condition (J/m³)

So $\Delta I_m V_{LM} = 4 \omega \times$ energy stored

Thus, setting I_{LM} , I_{CM} , V_{LM} requires selection of correct iron type and volume.

Figure

3.7. Calculations Procedures

1. Given V_{LM}, I_{LM}, I_{CM}
2. Choose: iron (B_C, H_C)
3. Calculate Volume $\ell A = \frac{V_{LM} \Delta I_m}{\omega B_C H_C}$
4. Choose A
5. Calculate $\ell = \text{volume} / A$
6. Calculate $N = V_{LM} / \omega B_C A$
7. Calculate $I_{DC} = NI_{LM} - H_C \ell$

Figure
3.8. Numerical Results

V_{LM}	I_{LM}	I_{CM}	ΔI_M	B_C	$\frac{H_C}{A-t}$	Volume	A	ℓ	N	I_{DC}
V	A	A	A	T	m	m ³	m ²	m	"turns"	A
1×10^5	2.83×10^4	1.83×10^4	1×10^4	1.5	33333	26.5	1	26.5	177	4.12×10^6
							2	13.3	88	2.06×10^6
							4	6.6	44	1.03×10^6
1×10^5	2.83×10^4	1.83×10^4	1×10^4	1.0	20000	66.3	2	33.2	133	3.09×10^6
							4	16.6	66	1.54×10^6
							6	11.1	44	1.03×10^6

Figure 3.9. Evaluation

1. Meets required performance:

rated and limited currents
impedance - voltage during limiting
speed - instantaneous and self-
controlling
- no recovery time problem
- no normal/superconducting transition

2. Considerations

- a. Large volume of iron
- b. Possibly must use special steels
- c. Need two cryostat bushings, into and out of d-c winding - d-c supply.
- d. Problem of losses in iron?
- e. Generation of harmonics in d-c and a-c lines during transition and limiting operation.
- f. Induced voltages in d-c line.

3.2 Shielded SCFCL

A schematic of the device is shown in Figure 3.10. An iron toroid of cross section area A and length ℓ is surrounded by a Type I superconducting shield. A coil having N_1 turns is uniformly wound around the SC shield. This coil is connected in series with the line to be protected.

During continuous operation, the SC shield excludes flux from the interior of the coil, resulting in a low device impedance. A fault current I_c will produce a critical magnetic field B_c which will be sufficient of drive the shield into the resistive state (Figure 3.11). Magnetic flux will then flow in the iron coil. The impedance of the device can then be calculated by reference to the transformer equivalent circuit shown in Figure 3.12 with very good coupling ($k \approx 1$), the resistance of the secondary circuit dominates and so this is really a transformer-coupled resistive limiter.

Coil Turns/Length

During continuous operation, the magnetic field produced by the coil must be less than B_c .

$$B_c = n_1 \mu_0 I_f$$

$$n_1 = \frac{B_c}{\mu_0 I_f}$$

where I_f is the critical (fault) current.

Coil Turns

During current limiting, the full generator voltage must be dropped across the coil. Therefore, by Faraday's Law,

$$V_1 = N_1 \frac{d\phi}{dt}$$

Taking $V_1 = \sqrt{2}E \cos \omega t$, we find .

$$\begin{aligned} \phi_{\max} &= \frac{\sqrt{2}E}{N_1 \omega} \\ N_1 &= \frac{\sqrt{2}E}{\omega A B_S} \end{aligned} \quad (2)$$

where B_S is the saturation magnetization of the iron.

Length of Toroid

$$\ell = \frac{N_1}{n_1} = \frac{\sqrt{2}E}{\omega A B_S} \frac{\mu_0 I_f}{B_C} \quad (3)$$

Volume of Toroid

$$\begin{aligned} V &= \ell A = \frac{\sqrt{2} \mu_0}{\omega} \frac{E I_f}{B_S B_C} \\ V &= (4.7 \times 10^{-9}) \frac{E I_f}{B_S B_C} \end{aligned} \quad (4)$$

Resistance of Normal Shield

The shield may be wound as N_2 turns.

circuit length, $\ell_2 = (\text{circumference}) \times N_2 = 2\sqrt{\pi} \sqrt{A} N_2$

circuit width, $W_2 = \frac{\ell}{N_2}$

resistance $R_2 = \rho \frac{\ell_2}{W_2 T}$

where T is the shield thickness.

$$R_2 = (7.5 \times 10^8) \frac{\rho A^{3/2} B_S B_C N_2^2}{T E I_f} \quad (5)$$

Primary Impedance

The effective resistance reflected into the primary circuit is given by,

$$\begin{aligned} R_1 &= \frac{N_1^2}{N_2^2} R_2 \\ R_1 &= \frac{(1.05 \times 10^4) \rho B_C E}{T I_f A^{1/2} B_S} \end{aligned} \quad (6)$$

Power Dissipated in Shield

$$P = E^2/R_1$$

$$P = (9.5 \times 10^{-5}) \frac{TI_f A^{1/2} B_S E}{\rho B_C} \quad (7)$$

Helium Evaporated

In a 3 cycle fault, the amount of helium evaporated due to shield heating will be given by

$$\text{Helium Loss} = \frac{P \times \Delta T}{3600 \text{ Joules/liter}}$$

$$\text{Helium Loss} = 1.3 \times 10^{-9} \frac{TI_f A^{1/2} B_S E}{\rho B_C} \quad (8)$$

Assuming a lead shield and a high saturation iron core, we set

$$T = 10^{-7} M$$

$$B_S = 1.5 \text{ Tesla}$$

$$B_C = 0.1 \text{ Tesla}$$

$$\rho = 1 \times 10^{-8} \Omega\text{-M}$$

In Equa. 8, the helium loss is seen to be insensitive to the core cross sectional area A. We, therefore, set $A = 1M^2$.

CALCULATION SUMMARY

I_f (kA)	E (kV)	V (M ³)	R_1 (Ω)	Helium Loss (liters)
5	100	15.5	1400	98
10	100	31	700	195
20	100	62	350	390

The above values for V, R_1 and Helium Loss are the most optimistic that can be anticipated. A very large volume is required, and the helium loss per fault is excessively high.

SHIELDED SCFCL

Figure 3.10

Figure 3.11

Figure 3.12

4. ANALYSIS OF RESISTIVE SUPERCONDUCTING FAULT CURRENT LIMITERS

4. ANALYSIS OF RESISTIVE SUPERCONDUCTING FAULT CURRENT LIMITERS

The resistive superconducting fault current limiter (SCFCL) described in the following, meets the requirements for system protection outlined above. There are, however, key factors in the operation which have not been completely verified experimentally. These factors will be specifically pointed out and a program of experiments and further analysis will be given to address them.

The operating principle is very similar to the SCFCL described previously^{1,2}. Therefore only the essential features and important differences will be discussed in detail.

In this device, (see fig. 4-1) a superconducting element, in series with the circuit to be protected, is switched into its normal, resistive state when the current exceeds some predetermined level. The current is commutated into a shunt resistor at ambient temperature which limits the fault current to a level which protects equipment and allows a circuit breaker to operate (see fig. 4-2). An isolation switch disconnects the superconducting element (which is now normal and dissipating heat into the liquid helium) to limit the helium boiloff and allow quick reclosure of the device.

For true fault currents a conventional circuit breaker opens the circuit until the fault clears, but for momentary impulses, one can just reclose the isolation switch after the overload and superconductor have recovered their usual operating conditions. The losses into liquid helium occur during the time interval between commutation and opening the isolation switch and are proportional to V_o^2/R_N where V_o is the r.m.s. line to ground voltage and R_N the normal resistance of the superconducting element. To limit these losses, R_N must be large, which implies a high value of normal state resistivity ρ_N .

This denies the use of metallic stabilizers which protect the superconductor against hot spots by giving a current bypass, but greatly reduce the effective resistivity.

For thermal stability, in the absence of metallic stabilizers, and for a fast recovery time, intimate contact with the liquid helium coolant is essential. This implies a thin film superconductor rather than bulk. For example, bulk devices³ recover only after 2-10 minutes, whereas thin films⁴ can recover as fast as 10 μ sec.

The various methods of switching the superconductor into its normal, resistive state will be thoroughly discussed after the next section which deals with more general considerations. The conclusions of this analysis are necessary to rate the various methods of switching. This is followed by the suggested program for experiments and further analysis.

4.1 ANALYSIS OF GENERAL CONSIDERATIONS

Our study is for a 242 KV system for which the line to ground voltage V_0 is 140 KV (r.m.s.). The usual operating currents through the limiter located in one of the buss tie positions will be 4 KA (r.m.s.). Ideally the limiter will pass all currents less than 56 KA (peak), however we shall consider a smaller value ($I(o) = 20$ KA (peak)) since this will decrease the size of the limiter. The isolation switch will allow reinsertion without opening the breaker for momentary overloads between 20 KA and 56 KA.

The important features of the SCFCL from the point of view of system operation are the shunt resistance R_s , the switching time τ_s , the recovery time τ_R and the volume of the device Ω . Typical required values of R_s (1 to 20 Ω) do not affect the switch design since the normal resistance of

the superconducting element R_N is always much greater. As long as the switching time τ_s is much faster than the 60 Hertz period, it will not affect the system operation. The problem of overvoltages, which can occur for very fast switching will be discussed in the section on switching. In the following, Ω is shown to depend on τ_R as well as other parameters, and we indicate the additional experimental information needed for a more precise evaluation.

In order to calculate the volume Ω , we start by calculating the normal resistance of the superconducting element R_N . This is given by $\rho_N \ell / A$ where ℓ is its length and A its cross sectional area. This area A is given by $I(0)/J_c$, where J_c is the critical current density of the superconductor. After switching, the power dissipation P_N is V_o^2/R_N and the energy absorbed by the helium, ΔE , depends on the time (τ_{IS}) until the isolation switch operates. Hence $\Delta E = \tau_{IS} P_N$ and the specific absorption (per unit surface area a) is $\Delta E/a$ where $a = \ell w$ and w is the width of the superconducting element. Combining these relationships, we find

$$\epsilon \equiv \frac{\Delta E}{a} = V_o^2 \tau_{IS} d / \rho_N \ell^2,$$

where d is the superconductor film thickness. The minimum volume occupied by such a device is simply given by $w \ell c$, where c is the helium cooling channel dimension perpendicular to the film plus the substrate thickness, each of which are greater than d . Therefore,

$$\Omega = (c V_o I(0)/J_c) (\tau_{IS} / \rho_N \epsilon d)^{1/2}$$

although there is some additional volume for the switching magnet and for

thermal and electrical insulation.

Now V_o and $I(o)$ are fixed by the system to be protected, although a smaller value of $I(o)$ may be used to reduce Ω at the expense of operation for some smaller overload currents. Although limited by available switches, τ_{IS} should be as small as possible. The superconductor material properties ρ_N and J_c should be as large as possible, and $c/(\epsilon d)^{1/2}$ should be as small as possible consistent with sufficiently rapid recovery time ($\tau_R \lesssim 10$ m sec).

Several of these limitations have not been sufficiently well determined for a final evaluation of Ω . Is there a relatively cheap isolation switch which can open at the first zero crossing (or sooner)? The requirements on this switch are not severe: the current is almost exactly in phase with the voltage, and the voltage at a current zero is less than one volt. Some sparse preliminary data^{4,5,6} is available on c and ϵ , however an experimental program directed at this specific design is urgently required (see section on proposed experiments). Little is known on how thick these films can be made before J_c decreases⁷ or the recovery time becomes too long.

On the other hand ρ_N and J_c are better known. Thin superconducting films⁸ of NbN have been made with $\rho_N \sim 300 \mu\Omega \text{ cm}$ and $J_c \sim 3 \times 10^6 \text{ A/cm}^2$. These provide good working numbers for calculations. The system indicates $V_o = 140 \text{ KV}$ and $I(o) = 20 \text{ KA (peak)}$ and assuming $\tau_{IS} \sim 3 \text{ m sec}$, $c \sim 2 \text{ mm}$, $\epsilon \sim 0.01 \text{ joules cm}^2$ and $d = 5 \text{ microns}$, the volume is found to be

$$\Omega \sim 0.28 \text{ m}^3.$$

Other determined parameters are $\ell \sim 1 \text{ km}$, $w \sim 13 \text{ cm}$, $R_N = 4,500\Omega$, and helium loss = 4.1 liter. Additional volume is required for high voltage and thermal insulation.

Clearly certain parameters are less crucial (those entering as the square root) and hopefully reasonable values have been used. The conclusion is that the size is reasonable and the preliminary design warrants further analysis and an experimental program.

Another extremely important consideration is that of voltage breakdown in the switch. During normal operation the superconducting element swings between ± 200 KV with respect to ground potential, whereas during a fault it can have up to 200 KV across its terminals. The problem of insulation is compounded by the thin films which have relatively sharp edges. It was proposed in ref. 1, that the long bifilar strip of superconductor be broken into several smaller modules to decrease the dielectric requirements (i.e. thickness) of the substrate. Such a configuration was necessary to lower the inductance of the superconducting element to facilitate rapid commutation. Fortunately, this also greatly reduces the electric fields at the film edges and hence deters voltage breakdown. However, it may also be necessary to use metallic shields at intermediate voltages around each of the modules to prevent large field gradients to ground and from module to module. Each shield might be electrically common to the connection between modules for example, and could be massive with smooth surfaces to eliminate breakdown to each other and to ground. Further analysis and experiments are essential for this extremely important problem.

4.2 SWITCHING CONSIDERATIONS

This section presents the analysis and conclusions on the merits of all reasonable methods of switching thin film superconducting elements known to us. In many cases the conclusions depend crucially on the particular application and information is drawn liberally from the previous sections.

Critical Current. This is the most obvious choice since it is self sensing and requires no complications. When the current exceeds $I(o)$, superconductivity breaks down and the ensuing dissipation heats the element rapidly above its transition temperature T_c , so that the full normal resistance R_N is quickly achieved. This method is not promising however, because of the practical difficulty of achieving sufficiently uniform breakdown. Instead, hot spots will develop in the first part of the switch to become normal.

This is a particularly serious problem in a superconductor without a metallic stabilizer since there is no alternative current path through a low resistivity stabilizer. To compound this, it was also shown that ρ_N and J_c must be large so that the dissipation per unit volume in the hot spot $\sim \rho_N J_c^2$ is $\sim 3 \times 10^9$ watts/cm³ and leads to melting (fusing) of the superconductor in about 2 μ seconds (see fig. 4-3). Therefore such a switching method requires a substantial fraction of the superconductor to switch in a short time. Unfortunately thermal propagation of the normal-superconducting boundary is much too slow; it only covers 1 cm in 2 μ sec.

(using a sound velocity of 5×10^5 cm/sec). Therefore, non-uniformities of J_c coupled with the relatively slow rate of rise of the fault current preclude sufficiently uniform switching to avoid fusing at hot spots. However, even a faster rate of rise of fault current cannot save this device unless the breakdown of superconductivity is uniformly triggered along its entire length l (see next paragraph).

Pulsed Current. Although the rate of rise of the fault current cannot be increased, an external current pulse can be applied to the superconductor (fig. 4-4). The device is no longer self sensing and must be triggered below I_c to avoid premature switching of one part of the device. Unfortunately, examination of fig. 4-4 shows the flaw in this scheme - once the superconducting element has a resistance greater than R_s , the external pulse will flow into R_s and be ineffective at further switching the superconducting element. N.B. This technique works for bulk devices, where hot spots are not a problem, and relies on heating by thermal conductivity.³

Magnetic Field. The phase diagrams for both types of superconductors are shown in fig. 4-5. All superconductors with large ρ_N are type II and the Gorkov-Goodman relation⁹ shows that H_{c2} is proportional to ρ_N ; $300 \mu\Omega \text{ cm}$ implies $H_{c2} > 100 \text{ KOe}$. In addition, for type II superconductors, the zero resistance state only occurs for a field less than H_{c1} which is very small. Hence switching the superconductor by a field requires extremely large fields $\sim H_{c2}$ over large volumes Ω - a unpalatable prospect.

Pulsed Heating. Referring to fig. 4-5, another way to switch the superconductor into its normal, resistive state is to raise its temperature above T_c by external heating. Direct heating by conduction is unrealistic due to the conflicting requirements of high voltage insulation and good

thermal conductivity. However indirect heating by radiation looks very promising. Of the various possibilities (x-rays, neutrons, charged particles, etc) optical radiation seems best because there is no adsorption in liquid helium and pulsed laser sources are readily available commercially.

Pulsed Laser.¹⁰ A Q-switched laser delivers extremely high light intensity (up to 5000 MW) for very short periods of time (typically 15-25 n sec). This can be exploited to switch the superconductor: such a fast pulse will adiabatically heat the element above T_c , i.e., the heat loss to the helium and substrate can be neglected because of the much longer thermal response time, $\tau_H \sim 10 \mu\text{sec}$. The total energy needed is just the superconductors' enthalpy difference between T_c and T_0 (the helium bath temperature). For niobium this is 0.06 joules/cm^3 times the superconductor volume $\ell w d$, or 10 joules for the parameters of the previous section. The cost of lasers for outputs of 15 joules to 100 joules is between \$40 K and \$100 K.

The light must be distributed sufficiently uniformly along the length ℓ to switch the entire element with a minimum total laser energy. This can be accomplished by a light pipe running alongside the length of the element. Such a configuration is particularly well suited to simultaneously solving the overvoltage problem and minimizing hot spots. Overvoltage occurs when the resistance of the superconducting element changes too fast relative to the time to commutate the current into the shunt R_s . On the other hand, hot spots occur in the superconducting element if the current is not commutated quickly enough. The short laser pulse (about 5 meters long) travels down the length ℓ at the speed of light in the light pipe c' so the entire switching is accomplished in a time $\tau_s = \ell/c' \approx 3 \mu\text{seconds}$. This is fast enough to avoid hot spots, if the inductance of the superconducting element and shunt resistor is small; but in addition dR_{sc}/dt

and hence the overvoltage can be controlled by varying the resistance per unit length.

The overvoltage is calculated by solving the differential equation for the loop containing the superconducting element and shunt resistor (fig. 4-6):

$$(L_s + L_{sc}) \dot{I}_{sc} / R_s + (1 + R_{sc}(t)/R_s) I_{sc} = I(o). \quad (4-1)$$

This equation assumes that the total current $I(o)$ does not change significantly during switching. This assumption is shown to be an excellent approximation when similar calculations are made including the source voltage and its impedance of 0.1Ω and 5 mHy . Recall also that the switching is much faster than the rate of rise of fault current.

The overvoltage V across the terminals of the loop is given by $V = L_{sc} \dot{I}_{sc} + R_{sc}(t) I_{sc}$. Setting V equal to the peak line to ground voltage in the system ($\sqrt{2} V_o$) the resistance $R_{sc}(t)$ can be calculated for the period of time of maximum overvoltage. For the other times eq. 4-1 is solved by iteration using a constant dR_{sc}/dt . Such a solution is shown in fig. 4-7.

Knowing $I_{sc}(t)$ it is straightforward to calculate the energy dissipated in the first region to go normal. The temperature rise for this hot spot is found to be over 500K . This is too high for thermal stress and precludes fast recovery time τ_R . In order to avoid this, the first part of the element to be switched is made of lower resistivity material and the resistivity is gradually increased up to $300 \mu\Omega \text{ cm}$ while keeping the temperature rise at some lower value ($50\text{--}75\text{K}$). N.B. the thickness could also be varied changing J/J_c . More precise details of such a device require further analysis.

The advantages of optical switching are that it definitely switches and it does so in a controllable way. In addition the device could be stretched out along its length ℓ to provide the first part of a cryogenic

transmission line (see fig. 4-8).

Pulsed Magnetic Field. There is another example^{1,2} of internal heating which has promise for a SCFCL. A relatively small magnetic field pulse can lower the I_c of the superconductor below $I(o)$ and cause a dissipative state which heats the element above T_c . If the field pulse is large enough the switching is uniform because $I_c < I(o)$ everywhere along the length l . As in the case of the pulsed laser, hot spots and overvoltage must be considered; however in addition the long element must be compacted into a small volume to minimize the pulsed field energy $\mu_0 H^2 \Omega / 2$.

The requirement that the overvoltage be less than $\sqrt{2}V_o$ places certain limits on the switching time. In order to reduce the overvoltage the current must be commutated quickly into the shunt resistor - i.e., the inductance of the switch element, shunt resistor and connections must be as small as possible. This implies bifilar winding of the superconducting element and shunt; i.e., two films evaporated on each side of a long, thin insulating substrate (e.g., 20 mil mylar). In this way, inductances of order 10 μ Hy are feasible for L_s and L_{sc} . Using these values, eq. (4-1) is solved iteratively for various rates of change of R_{sc} . The solutions give acceptably small overvoltage only if $(dR_{sc}/dt)/R_N \gtrsim 100 \mu\text{sec}$ for the first few microseconds (i.e. 1% of the resistance recovered in 1 μsec).

This rather slow switching is unfortunate, because of a very important difference between magnetic field and laser switching. For the pulsed field, all regions must initiate switching before a significant fraction of the current is commutated into the shunt. Otherwise I_{sc} will fall below I_c (in spite of I_c being somewhat lowered by the pulsed field), and some regions will not switch. Hence, the switching time is determined by the rate of increase of resistivity with time after the pulsed field uniformly initiates

breakdown. This is only a function of the microscopic details of the flux flow and runaway heating; unfortunately, on the time scale required, these details are not known.

There are several methods to estimate the rate of rise of resistivity in a superconductor, but none of them are on firm theoretical grounds and they all lack any experimental verification. (a) Because of eddy current damping the pulsed field requires a time $\sim a^2 \mu_o / 2\rho_{eff}$ to penetrate a distance a into the superconductor where μ_o is permeability of free space and ρ_{eff} is the effective resistivity ($\rho_{eff} \leq \rho_N$). Therefore the time to penetrate 1% of the width ($w = 13.3$ cm) is found to be at least 0.2 microseconds depending on ρ_{eff} . (b) Heat can be carried across the film by phonons and electrons. Phonons travel at the sound velocity while electrons are ineffective because the large ρ_N implies too short a mean free path. For a phonon to travel 1% of the width requires a similar time of 0.2 μ sec.

What is unknown is how the time dependence of the resistivity depends on these details. Therefore no firm conclusion can be made until experiments are forthcoming.

For interruption at lower fault currents, the problems are not so severe. A workable solution is shown in ref. 1. for $I(o) = 4KA$ and 1% of the normal resistivity in 0.04 μ sec.

Pulsed Magnetic Field with Capacitor. Fortunately there is another way to overcome the overvoltage problem. A capacitor placed across the terminals (see fig. 4-10) will greatly reduce the overvoltage and at the same time decrease the commutation time to reduce the heating.

The results of an iterated solution to the differential equations similar to eq. (4-1) are shown in fig. 4-11. A 0.1 μF capacitor and a rate of increase in R_{sc} of 450 Ω/μ sec were used. The overvoltage peaks at 4.6% above

$\sqrt{2} V_0$ and the current drops quickly to about 1.5% so that the total dissipation in the superconductor is about 2000 joules (i.e. about one half liter of helium boiloff and a uniform temperature rise of about 30 K). Thus the solution is particularly promising and should be given first priority in further work.

Pulsed Magnetic Field (Self Sensing). The combination of a magnetic shield and a pulsed magnetic field resistive switch offer the potential for a self sensing device. Fig. 4-12 shows a schematic drawing of the resistive switch surrounded by a type I superconducting shield. The total system current also flows through the windings around the outside of the shield. When the total system current exceeds some preset value $I(o)$ the critical field H_c of the shield is exceeded; this destroys its superconductivity and allows the field to penetrate into the volume occupied by the switch, producing a field pulse of magnitude H_c .

It was shown above that pulsed field switching must be initiated over the entire length l before a significant fraction of the current is commutated (i.e., within $\sim 1 \mu\text{sec}$). Hence the field must rise uniformly over the entire volume Ω in this time Δt . This can only be accomplished if the field applied to the shield by the windings and the critical field H_c of the shield are highly uniform over the surface of the shield. Unfortunately the required uniformity will depend on the rate of increase of fault current dI/dt ; this can be up 10^8 A/sec for a "worst case" fault, but more than two orders of magnitude smaller for a "grazing" fault.

It is easily shown that the field uniformity $\delta H/H_c$ (or $\delta H_c/H_c$) is given by

$$\frac{\delta H}{H_c} = (dI/dt) (\Delta t/I(o)) .$$

The evaluation for $I(o) = 20,000A$, $\Delta t = 1 \mu\text{sec}$ and $dI/dt = 10^6 A/\text{sec}$, yields $\delta H/H_c = 1/20,000$. This requires large magnets which are wound to better than 0.01% - a formidable task even for small research magnets. Even if this field uniformity could be achieved, the uniformity of critical field will be doubtful. In all probability a pure, bulk type I material like lead or tin would exhibit a small $\delta H_c/H_c$. However in order to reduce eddy current heating in this shield (after switching and before the circuit breaker opens) it would have to be high resistance implying very thin films with impurities to increase the resistivity. Control of H_c to 0.01% under these circumstances seems out of the question.

Finally, irrespective of an isolation switch it would be essential to open the circuit breaker each time the device operated in order for the shield to recover its superconductivity. The firm conclusion is that in spite of the attractiveness of self sensing this idea is not a practical alternative and should not be considered further.

Pulsed Magnetic Field with Shield. A shield of a type I superconductor may be useful for the pulsed field SCFCL. Placed between the pulse magnet and superconducting switch element it will decrease the switching time by decreasing the rise time of the pulsed field. In this case, the rise time of the pulsed field is fixed, independent of the size of the fault current. To see this effect, assume that the current in the pulse magnet increases linearly in time, so that H_c of the shield is reached in a time τ_M ; then the field inside the shield will increase from 0 to H_c in a time $\tau_M \delta H/H_c$. Hence even 10% non-uniformity of H and H_c will greatly improve the rise time of the magnetic field. This can enhance the uniformity of switching or allow a slower pulsed field rise time or both.

Conclusions. The conclusions of this analysis are firm and straightforward. There are two very promising devices which have withstood detailed scrutiny and which warrant further analysis or experimentation. It is recommended that a magnetically switched resistive SCFCL with a capacitor be given top priority and that a series of experiments to determine the key outstanding questions be conducted. The nature of these experiments, and a preliminary design is given in the next section.

As a viable backup, a more complete analysis of pulsed laser switching should be concurrently conducted. Some experimental questions to be answered for the magnetically switched SCFCL would be equally important to the pulsed laser SCFCL.

REFERENCES

1. K. E. Gray and D. E. Fowler, EPRI EL-329 (1976).
2. K. E. Gray and D. E. Fowler, JAP 49, 2546-50 (1978).
3. A. Ulbricht, IEEE MAG-15 172-4 (1979).
4. K. E. Gray, T. Lenihan and J. Tarczon, IEEE MAG-15 175-7 (1979).
5. W. G. Steward, N.B.S. Boulder, Preprint.
6. J. R. Miller, J. W. Lue, S. S. Shen and J. C. Lottin, IEEE MAG-15 351-4 (1979).
7. R. P. Huebener, R. T. Kampwirth, R. L. Martin, T. W. Barker, Jr. and R. B. Zubeck, J. Low Temp. Phys. 19, 247-58 (1975).
8. J. R. Gavaler, M. A. Janocko, A. Patterson and C. K. Jones, J. Appl. Phys. 42, 54 (1971).
9. K. E. Gray, Phys. Rev. B13 3774-8 (1976).
10. K. E. Gray, Patent application pending.

Fig. 4-1

Fig. 4-2

Fig. 4-3

Fig. 4-4

Fig. 4-5

$$(L_s + L_{sc}) \dot{I}_{sc} + (R_s + R_{sc}(t)) I_{sc} = I(t)$$

$$V = L_{sc} \dot{I}_{sc} + R_{sc}(t) I_{sc}$$

$$V_0 = 140 \text{ kV}$$

$$R_s = 2.75 \Omega$$

$$I(t) = 20 \text{ kA}$$

$$R_{sc}(\infty) = R_N = 4500 \Omega$$

$$L_0 = 5 \text{ mHy}$$

$$L_{sc} = L_s = 10 \mu\text{Hy}$$

$$r = 0.1 \Omega$$

Fig. 4-6

OPTIMIZED SOLUTION

Fig. 4-7

Conventional
Circuit Breaker

Pulsed Laser Superconducting

Fault Current Limiter

Fig. 4-8

SLOW SOLUTION

$$\dot{R}_{sc} = 45 \Omega / \mu\text{sec}$$

Fig. 4-9

$$L_{sc} \dot{I}_{sc} + R_{sc}(t) I_{sc} + V(t) = 0$$

$$L_s \dot{I}_s + R_s I_s + V(t) = 0$$

$$V(t) = Q(t)/C \quad Q(t) = \int_0^t [I_{sc} + I_s - I(0)] dt$$

$$I(0) = 20 \text{ kA}$$

$$R_s = 2.75 \Omega$$

$$C = 0.1 \mu\text{F}$$

$$R_{sc}(\infty) = R_N = 4500 \Omega$$

$$L_{sc} = L_s = 10 \mu\text{H}$$

Fig. 4-10

CAPACITOR SOLUTION

$$\dot{R}_{sc} = 450 \Omega / \mu \text{sec}$$

Fig. 4-11

Type I
Superconducting
Shield

$$\delta H = \frac{dH}{dt} \Delta t$$

$$\frac{\delta H}{H_c} = \frac{dI}{dt} \frac{\Delta t}{I(0)}$$

$$\Delta t = 1 \mu\text{sec}, I(0) = 20 \text{ kA}$$

$$\frac{dI}{dt} = 10^6 - 10^8 \text{ A/sec}$$

$$\boxed{\frac{\delta H}{H_c} = 0.005\%}$$

Fig. 4-12

5. PROPOSED EXPERIMENTAL PROGRAM AND FURTHER ANALYSIS

5. PROPOSED EXPERIMENTAL PROGRAM AND FURTHER ANALYSIS

5.1 EXPERIMENTAL PROGRAM

In evaluating the technical feasibility of the pulsed magnetic field SCFCL, there were several points which were unverified experimentally. In this section we describe an experimental program to answer these questions, which include high voltage breakdown, uniform switching and a more accurate evaluation of the volume.

The most crucial of these questions for the pulsed magnetic field is whether the element switches uniformly along its length or by slow thermal propagation of a normal-superconducting boundary from initial breakdown at hot spots. Although this question was addressed in ref. 4 of chapter 4, no conclusion could be reached due to the short distance between voltage probes (~ 1.5 mm).

We propose similar experiments, using longer, wider samples which are essential to completely understand the switching: thermal propagation from a hot spot in a longer film (75 mm) would give a much longer switching time; on the other hand wider films (~ 1 cm) may improve the uniformity; finally, if the switching is uniform, the increase of resistivity with time can be measured to evaluate if a capacitor is needed to reduce overvoltages. A fairly complete study, varying the width and thickness is anticipated, to adequately understand the mechanisms and limitations of pulsed magnetic field switching. For example, intentional hot spots can be created by a small pulsed laser.

These studies will also yield further information on the thickness and width dependence of J_c , which is important for any resistive SCFCL regardless of the switching method. Another crucial question which is

independent of the switching method is that of recovery time. In an earlier section the volume Ω was calculated, and the minimum was achieved for large film thickness d , large heat dissipation per unit area $\Delta E/a$ and for small cooling channels c . Unfortunately, as these parameters minimize the volume, they also increase the recovery time τ_R . Therefore τ_R must be measured as a function of these parameters to find acceptable compromises. These will in turn dictate the volume Ω and verify the estimate given earlier. The same experiments as outlined above could also measure τ_R , using the techniques of ref. 4 of Chapter 4.

Thus the above tests provide the crucial information about the operation of a SCFCL. The measurement of τ_s in long films can unambiguously show whether switching in a pulsed magnetic field is uniform - an essential requirement for that method of switching. The measurement of τ_R and J_c as a function of c , ϵ , d and w will provide the necessary data for an accurate evaluation of the volume Ω which is independent of the method of switching.

The above tests would use d.c. currents of order 500A and d.c. voltages of order 10 volts. They would be conducted in liquid helium at 4.2K. Samples of Nb and NbN would be 7.5 cm long and from 1 to 2.5 cm wide with thicknesses up to 5 microns.

Most of the equipment and facilities for these tests are available at Argonne. These include: high rate sputtering system; cryostat with 500A feedthroughs; 100A, 5 μ sec pulsed magnet supply; pulse generators for field and control of sample current; sampling oscilloscope; fast oscilloscope; x-y recorder; transient recorder; 10V, 500A a.c. source with powerstat; and other assorted instrumentation and facilities (machine shops, etc.). The new purchases under this contract include: (a) film thickness measuring device with strip chart recorder \$10K; (b) ultrasonic bonder for high

current connections to the superconducting films \$6K; (c) 6V, 500A d.c. power supply for sample current \$3K; and (d) 15V, 20A fast programmable power supply for recovery time studies \$1.5K. Items (c) and (d) were not listed in the original proposal since they were available at Argonne. Since the proposal was submitted, item (c) was recalled by EPRI. Because thicker films are necessary for the larger values of $I(0)$ found in this system study, our 5A fast programmable power supply is insufficient so item (d) must be purchased.

Finally, a shunt resistor and capacitor (unless the capacitor is not needed) will be used in d.c. tests and with a simulated fault on an a.c. source, to further verify the principle of commutation. Overvoltages will be measured with and without the capacitor.

Some effort should eventually go into sample preparation with the goal of increasing ρ_N to 300 $\mu\Omega\text{cm}$ and of investigating the use of thin, flexible dielectric substrates.

Experiments on high voltage breakdown are essential. Details of these experiments require further analysis, but two major questions must be answered: (a) how much does the insulator dielectric strength have to be de-rated due to the film edges; and (b) are metallic shields between modules necessary and sufficient to prevent breakdown between modules and to ground.

It is not clear whether this entire program can be satisfactorily or completely finished during the present contract period, but the essential questions about thermal propagation and recovery time will be answered.

5.2 PROPOSED FURTHER ANALYSIS

Further analysis into the problems of high voltage breakdown is necessary. These will hopefully determine the limitations on the thin films but also will dictate the specific experimental program to verify the conclusions.

As a backup to magnetic field switching, the pulsed laser SCFCL should be studied further. In particular, more detailed information on fabrication of leaky light pipes is necessary. A more complete analysis of hot spots and overvoltages must be made to see if a capacitor is also needed here. Finally, tests of the switching principle could be contemplated, if the pulsed magnetic field device proves unworkable.