Development and Testing of a Prototype Current Limiting Protector

EL-1250
Research Project 1142-1

Final Report, December 1979

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ABSTRACT

A prototype pyrotechnically operated "Current Limiting Protector" (CLP) and a compatible high speed level sensing and trigger circuit were developed and tested. On operation in response to a short circuit a series of gaps are formed by chemical charges. The gap voltages permit commutation of the current to a parallel fusible element, which interrupts the current in a current limiting mode.

The theory of the CLP was developed and confirmed with simulated d.c. tests and on a.c. tests in a high power short circuit laboratory. Prospective short circuits of 40,000 ampere (RMS sym) were limited to let-through currents of 9 to 22 kA (instantaneous), depending on the setting of the level sensing device. Some improvement of the packaging of the device and of the control circuits is required.

The CLP offers economic single shot current limiting protection of systems and devices, because of the low let-through current and i^2t. In addition the CLP may prove valuable as a means to extend the service life of equipment and of systems where the available short circuit has outgrown the equipment ratings.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

By their principle of operation, current limiting fuses cannot carry high continuous currents (above 200 amps) and still be capable of limiting fault currents to acceptable levels. This is the final report on the first phase of a research project to develop a new type of protective device designed to overcome the limitations of conventional current limiting fuses and to provide other benefits for utility distribution systems. The device being developed, being separately triggerable, can also function as a one-shot current limiting circuit breaker. The use of the current limiting protector (CLP) should extend the service life of electrical equipment where the growth of the available short-circuit current has surpassed the rating of existing installations. It can also permit lower-rated equipment to be used in many new installations. Results of the ongoing second phase of this project will be reported upon completion in 1981.

PROJECT OBJECTIVES

This is a 42-month project to develop and demonstrate on a utility system a cost-effective, single-shot current limiting device. The device should be self-contained and applicable to distribution systems up to 15 kV, 1000 amperes continuous current, and with available short-circuit currents up to 40,000 amps rms symmetrical. It should respond to the onset of the short-circuit current to limit the peak current to less than 20,000 amperes, and then isolate the protected circuit. The goals of this 18-month phase (Phase 1) were to develop the principle of the CLP and to demonstrate its feasibility in a high-power laboratory.

PROJECT RESULTS

A current limiting protector concept was developed that uses a copper conductor shunting a current limiting fuse of conventional design but with specially tailored characteristics. On command from an in-line sensor, multiple gaps are cut in the conductor by action of chemical charges, thus commutating the current into the fuse. The fuse then melts and develops high arc voltage to limit the growth of the fault current and force it to zero. The CLP can carry continuous currents of 1000 amps or greater. Prototypes were tested in a high-power laboratory at voltages from 7-15 kV and available currents from 15-40 kA rms symmetrical. In most cases the current was limited to 15 kA peak or less. While the feasibility was demonstrated, there were several failures due to design deficiencies believed to be readily correctable. The ongoing Phase 2 part of the program aims to correct these deficiencies and to demonstrate the CLP in one or more utility systems. The CLP promises to be economical and versatile for use in utility distribution or industrial applications. Its use in industrial applications should broaden the manufacturing base with resultant cost savings to the utility industry.

Joseph W. Porter, Project Manager
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ACKNOWLEDGMENTS

The research described in this report has greatly benefited from the enthusiastic and active participation of the Distribution Task Force of the Electric Systems Division, from the EPRI Program Manager Mr. W. E. Shula, from the EPRI Project Managers Messrs. E. Ballard, T. Kendrew and J. Porter and the Industry Advisor Mr. J. Murphy of the Boston Edison Company.

The project owes its success in a large measure to Dr. B. Montgomery, Dr. D. Overskei and Mr. Charles Park, all of the M. I. T. Francis Bitter National Magnet Laboratory for permitting and carrying out d.c. interruption tests in the "Alcator A" circuit.

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SUMMARY

A short circuit current limiting device could extend the service life of electrical equipment where the continued growth of the available short circuit has surpassed the ratings of existing installations. Enormous savings could result which would benefit utilities and industrial users. Further, a current limiting device which can limit both the magnitude and the duration of short circuit currents would have appeal for the protection of liquid filled apparatus. Such a device could prevent or minimize the consequences of tank explosions of transformers and capacitors due to internal faults. Considering the safety of personnel, product and service liabilities such a device would be highly desirable.

Present current limiting fuses, in part, can fulfill the above needs. However, the principle of current limiting fuses mutually excludes high continuous currents and low let-through currents. Recognition of this short coming led to the concept of separating the continuous current and the current limiting functions in the "Current Limiting Protector". (CLP).

In the course of research project RP 1142-1, Phoenix Electric Corp. has developed and tested prototype CLP's with the following ratings:

Application	Indoor
Voltage class	Up to 15 kV
Continuous current	1000 ampere (RMS)
Prospective short circuit	40 kA (RMS Sym)
Peak let-through current	9 - 22 kA (adjustable)

A current limiting device to be effective in a.c. circuits must become operational before the current rises significantly. The CLP derives its speed from the application of chemical charges. Thus, upon activation by a suitable sensing and trip circuit, several chemical charges cut gaps into a copper conductor. The arc voltages appearing at these gaps commutate the short circuit current to a fusible element which then interrupts the current in a current limiting mode.

The development effort of the CLP required the exploration and perfection of pyro-cutting of suitably prepared main conductors. Containment of the chemical charges was explored and achieved. Precisely melting fuse elements with controlled peak and sustained arc voltages were also developed. Suitable electronic sensing and trip circuits for high speed operation were also developed which would allow activation of the CLP in microsecond response times. Dielectric and thermal tests were conducted to verify the voltage and continuous current ratings.

The entire performance of the CLP was computed in the course of this research program and confirmed later with short circuit tests in a d.c. circuit and for a.c. in a high power test laboratory. Prospective currents of 40,000 ampere (RMS sym) were successfully limited to as low as 9 kA (instantaneous) in a 15 kV circuit.

While the short circuit tests were successful in large measure, (4) failures were experienced because of insufficient mechanical rigidity at the end flanges. This deficiency was corrected in the design but requires experimental verification.

After correcting the short coming which was experienced during some of the short circuit tests, it is expected that a fully developed CLP will be available for trial installation in about one year.

Section One

INTRODUCTION AND SUMMARY

The operating economics and the reliability of electric power systems have been improved by interconnections and parallelling of generation. This has resulted in increased short circuit requirements of the associated electrical equipment and often its replacement long before its useful life expectancy. A short circuit current limiting device could prolong the life of such installations and result in economic advantages to the user. Since short circuits are a major cause of equipment damage a current limiting device could also serve to extend the life of electrical apparatus.

Current limiting fuses now serve to protect electrical apparatus, although their application is limited because of inherently low continuous current ratings. The Current Limiting Protector (CLP), which is the subject of this report, overcomes the limited continuous ratings of fuses by separating the current carrying and interrupting functions and providing for independent trip means. As presently developed the CLP is capable of carrying currents of 1000 ampere and to limit prospective short circuit currents of 40 kA (RMS sym) to less than 15 kA. The research and prototype development effort of the CLP is described in this report.

1.1 PROJECT OBJECTIVES:

In this research program the feasibility of the application of pyrocutting as a means to initiate short circuit current limitation was to be explored. A prototype current limiting protector was to be developed utilizing this principle.

The basic tasks in the performance of this project were the following:

- Demonstrate pyrocutting with suitable conductors and containment of charges.
- Develop a current sensing and firing circuit.
- Develop the theory of the operation of the CLP and its interaction with electric power circuits.
- Develop suitable fusible elements, which meet the exacting time requirements of the CLP.
- Build first prototype models and test in a high current, low voltage circuit.
- Build a second group of prototype devices and test to the proposed rating in a suitable high power lab.

1.2 DEFINITION OF THE CLP:

In principle, the Current Limiting Protector (CLP) consists of a large cross section main conductor and a parallel fusible element. A multiplicity of gaps can be cut upon command into the main conductor at very high speed. The sum of the arc voltages appearing across these gaps permit commutation of the current - even high currents - to the parallel fusible element. This fusible element is laid out to melt in a time sufficiently long to allow deionization of the main gaps. Upon melting of the fusible element a high arc voltage is produced. This high arc voltage produces a backward moving current which limits the prospective short circuit current to a low (let-through) level and quickly forces a current zero in a manner well known from conventional current limiting fuses (see Section 2.1).

Some of the differences between the CLP and a conventional fuse are:

- The CLP can be triggered on command.
- The CLP can be built to carry very high continuous current without affecting the let-through current.
- The CLP can be triggered such as to substantially reduce the let-through current over conventional fuses, where comparable ratings are available.
- The CLP provides current limiting protection for apparatus with high continuous currents. Such protection is not available at this time.
- The ability of the CLP to commutate relatively high currents in microseconds permits simple current level sensing. This is in contrast to di/dt sensing, which could lead to false trigger on high frequency inrush currents.

1.3 SUMMARY OF RESULTS:

The project specification called for the requirements of Table 1-1. This table lists also the achievements to date, which will be discussed in detail in this report.

The work plan for this project calls for the following tasks:

Task 1: Demonstrate feasibility of cutting the main conductor and containing the chemical charge. A multiplicity of cutting blocks were prepared and the following variables tested:

Conductor Material:	Aluminum, Copper
Conductor Size:	1.5 to 5 mm (1/16 to 3/16) thickness
Cutting Charge:	5 to 35 grains per linear foot
Type of Charge:	Line, cord - and shaped charges
Conductor Support:	Fiberglass, gray fiber
Conductor Configurations:	Plain bar, grooved bar, with and without support

Straight conductors, but also sandwich types, were found suitable. Aluminum and copper were cut equally well, however, the aluminum bridges have a tendency to rip at the bridge edge.

Containment of charges was explored. A fiberglass cylinder of 11.5 cm (4½") OD and only 1.5 mm (1/16") wall thickness was sufficient to withstand the detonation.

Table 1-1

CLP SPECIFICATION AND ACHIEVEMENT

	Project Specification	Achievement
Application	Indoor	Indoor
Voltage Class	15 kV	4, 7, 15 kV
Continuous Current	600 ampere	1000 ampere (RMS)
Short Circuit Rating	40 kA (RMS sym)	40 kA (RMS Sym)
Peak Let-Thru Current	5 - 15 kA	9 - 22 kA
	(Adjustable)	(Adjustable, still lower values are possible with different fuse element)
Sensing & Trigger	Separate from fuse	Separate from fuse body (CT sensing, power supply from isolation transformer)
Size	12.7 cm (5") OD, 50 cm (20") length	17 cm (6.75") OD, 50 cm (20") length (27" with spade termination)
Packaging	Explosion proof	Sealed housing, which does not require a Federal license to transport, to use or to store

Task 2: Develop Elements of the CLP

CLP - Configuration

A CLP configuration was developed. It was successfully subjected to cutting and containment experiments. A heat run was conducted next and a maximum continuous rating of 1000 ampere was established.

Sensing and Firing Circuit

An electronic sensing and firing scheme was conceived, built and tested. In this circuit a current transformer, a burden and a bridge provide the sensing signal to a comparator. If the signal exceeds the pre-set threshold the comparator switches low and causes an SCR to trigger via a transistor and to discharge the energy of a capacitor into the Hot Wire. The Hot Wire in turn ignites the primary and the cutting charges of the CLP.

This circuit was checked out under 60 Hz and under pulse (approximately 1 kHz) conditions. It was hardened against pick-up signals.

Theoretical Analysis of CLP

Critical times in the operation of a CLP were defined. The time intervals were analyzed and the interruption process formulated mathematically.

Fuse elements were developed and tailored to meet the exacting time requirements of the CLP.

Task 3: Model Testing

A number of CLP configurations were built and synthetically tested in the "ALCATOR A" circuit of the M. I. T. National Magnet Laboratory. We have successfully and repeatedly interrupted currents up to 20,000 ampere d.c. against recovery voltages from 1100 to 10,000 Volts. Interrupting times were typically 400 microseconds. In these experiments we observed the following:

- Identical devices performed almost identically within a few microseconds.
- Hardware related information was gained.
- Taking an approximate fuse voltage characteristic the entire interruption process could be calculated fairly accurately.
- The final version of the CLP was successfully tested and is also suitable for d.c. circuits, such as protection of batteries or fuel cells.

Tasks 4 and 5: Prototype CLP and High Power Testing

The interruption process in a 15 kV a.c. circuit, with a prospective short circuit current of 40 kA (RMS) sym. was calculated. Current limiting interruption tests were carried out at the General Electric High Power Laboratory in Philadelphia with the following results:

Test Voltage	4	7	15 kV
Prospective Current	15, 25, 30, 40 kA (RMS) Sym.		
Sensing Level	5 and 7.5 kA (instantaneous)		

- (23) CLP's and (17) fuses were tested.
- None of the fuses experienced any failures.
- (4) out of the (23) CLP's failed, none at 4 kV, one at 7 kV and (3) at 15 kV.

Aside from the (4) failures, due to insufficient mechanical rigidity of the CLP and fuse end caps, we believe the program was a success and the CLP's capability has been demonstrated as is summarized below:

- The CLP as demonstrated is suitable for service from ¬ to 15 kV and can very likely be extended to much higher voltages.
- Interrupting 40 kA (RMS) sym. prospective current, the CLP cleared faults in a current limiting mode in 3.6 milliseconds, of which 3 milliseconds were arcing time.
- The CLP became current limiting within 655 microseconds after start of the short circuit current.
- The tests demonstrated that the CLP had adjustable let-through currents from 10 to 15 kA and thus reduced the peak of the sym. prospective current of 56 kA by 82 and 73% respectively. Even higher reductions, as high as 90%, appear practical with faster fuse elements.
- The CLP, as tested, has a rating of 1000 ampere.
- Phoenix Electric Corp. and one special commercial fuse were tested with CLP's and met the timing requirements.

Section Two

CURRENT LIMITING DEVICES (CLD)

A brief survey of the better known current limiting principles is presented in this section. Such a discussion serves also to emphasize the features of the Current Limiting Protector, which is the subject of this report, over other devices.

The basic functions of a fault current limiter are:

- Carry continuous current with low power loss.
- Upon occurrance of a short circuit sense the fault current and initiate the current limiting device.
- Rapidly increase the device impedance or produce a backward moving current so as to limit the short circuit current before it reaches the crest value.
- Interrupt the limited short circuit current at the earliest current zero.
- Reset the device for the next current limiting operation.

Because of the high rate of rise of the fault current in a.c. systems a CLD must operate very fast. This imposes severe time restrictions on the fault current sensing and trip means and requires, moreover, low mass and short stroke of any mechanically operated device. An equally severe electrical requirement, which a CLD must meet is the dissipation of the electromagnetic energy of the system. If this energy were merely converted into electrostatic energy excessive overvoltages could arise not only when the current limiting action is started, but also when the current is finally interrupted. The latter is a well known problem of d.c. circuit breakers using the injection current principle, which require separate devices to dissipate the fault energy.

2.1 THE CURRENT LIMITING FUSE:

The simplest current limiting device is the current limiting fuse. In today's near technical perfection, and within applicable constraints,*it meets all the above requirements of continuous current carrying, fault sensing, current limitation, energy dissipation and interruption. A fusible link melts and evaporates upon passage of

* See e.g. American National Standards Institute ANSI C37.40, 41, 46, 47, 48

excessive currents. Efficient heat transfer from the highly ionized metal vapor plasma to the tight silica sand packing produces a high arc voltage. The time integral over this voltage divided by the circuit inductance produces the so-called backward moving current.* It forces the prospective current to zero and makes interruption possible. This backward moving current is the more effective the larger the area under the arc voltage trace, i.e. the higher the arc voltage and the more rectangular its time dependence.

It should be noted, however, that the arc voltage is superimposed on the system voltage and must, therefore, be limited to avoid excessive overvoltages.** On the other hand, energy considerations and fuse size limitations require that the fuse arc voltage is typically not less than twice peak line to neutral voltage. A typical interruption of a current limiting fuse is shown in Figure 2-1.

A current limiting fuse is not without short comings: High continuous current and low melting, i.e. let-through current are mutually exclusive by the inherent principle of a fuse. Thus, a fuse may have a continuous rating of 50 ampere and a let-through current of 10,000 ampere, while another rating may be able to carry 200 ampere but will not melt until 40,000 amperes are reached assuming of course the same short circuit conditions. Expressed differently the system short circuit protection is decreasing with increasing continuous current.

2.2 TRIGGERED CURRENT LIMITING DEVICES:

The above short comings are overcome by separation of the current carrying and interrupting functions in triggerable current limiting devices. The fusible element is shunted by a current carrying link, which can be removed upon command. The interrupting function is reserved for the fuse once the current has been commutated from the shunting means. Various such devices are known and are shown schematically in Figure 2-2. These devices are:

*-E.W. Boehne, "The Geometry of Arc Interruption I," AIEE Transactions, Vol. 60, 1941, pages 524-32.

**-E. W. Boehne, et al, Coordination of Lightning Arresters and Current Limiting Fuses, IEEE T-PAS, May/June 1972, pp. 1075-1078.

- The Phoenix Electric "Current Limiting Protector" (CLP), Figure 2-2a, utilizes a pyrocutting technique to open the shunt path in several places and to commutate the current onto the fusible element.*
- The Brown Boveri (Calor Emag) "I_s-Limiter", Figure 2-2b, employs generally a single exploding bridge as a shunt element, which ruptures upon command along pre-cut stress grooves.**
- The U. S. Navy explosively actuated switch*** is being developed by the Plasma Physics Division, Naval Research Laboratory, Washington, D.C. Figure 2-2c shows the switch before and after operation. A cord-like explosive is embedded in paraffin along the axis of the device. Upon firing, the explosive force is transmitted via the paraffin filling to the concentric aluminum cylinder. This cylinder is then alternately cut and formed at the periphery by suitably spaced anvils as the paraffin expands.

  As in the previous devices current normally flowing through the aluminum cylinder is commutated to a parallel fusible element by the multiple arc-lets across the gaps just formed.

2.3 SWITCHED CURRENT LIMITING DEVICES:

Inherently slower devices are those which provide, unlike the preceding single shot shunting bars, a set of repetitively operable parallel contacts, or multiple sets of expendable chemically actuated contacts. Also, "Lenz Coil" operating schemes (essentailly an electromagnetic driving mechanism)# have been employed to achieve the short response times required.

Some of these devices commutate the current to resistors using other than fuses to effect commutation and current limitation.

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*-H. M. Pflanz, et al, "A New Approach to High Speed Current Limitation", Symposium Proceedings - New Concepts in Fault Current Limiters and Power Circuit Breakers. EPRI EL-276-SR, April 1977, Sec. 18, pp. 18-53.

**-E. Marx and L. Schmitz, "High Speed Switching Apparatus Using Explosive Caps", ETZ-A, Vol. 75 (1955) pp. 765-768, (in German).

***-R. D. Ford, Ihor M. Vitkowitsky, "Explosively Actuated 100 kA Opening Switch for High Voltage Applications", presented at IEEE International Conference on Plasma Science, Troy, N. Y., May 25-27, 1977.

#-R. J. Rajotte, M. G. Drouet, "Experimental Analysis of a Fast Acting Circuit Breaker Mechanism - Electrical Aspects", IEEE PAS 75, Ja./Feb. 1975, pp. 89-96.

- Hughes* has developed and field tested a 145 kV, 5 kA current limiter (Fig. 2-2d). Current is first commutated to the so-called cross-field interrupter tubes by opening the "in-line" switch. As the magnetic field of the cross field tubes is excited current is shifted to the current limiting resistor. The circuit is then opened by the regular circuit breaker.
- BBC-Gould** has under development a multishot 69 kV current limiting device. (Fig. 2-2e). Current is shunted in steps from a by-pass to a fuse and finally to a current limiting resistor. The circuit is ultimately interrupted by a circuit breaker.

A third type of current limiting means are devices, which use the injection current technique:

- General Electric *** employes a counteracting capacitor discharge current to force a current zero in a vacuum circuit breaker. High speed contact operation, proper polarity, and precise timing of the injection current are required. Even though this is a d.c. breaker, the principle is valid for a.c. current limiting operation.

A fourth type of current limiter makes use of magnetically induced arc instability in a vacuum device and/or the generation of a high arc voltage. The instability and high arc voltage are used to commutate the current into a capacitor and then into a resistor. These current limiters are under development at Westinghouse# and State University of New York at Buffalo.##

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* - Gallagher, H. E., et al, "145 kV Current Limiting Device - Field Test", Presented at IEEE PES Summer Meeting, Vancouver, Canada, July, 1979.

** - Kroon, P. S., Rothenbuhler, W. N., "The Development and Application of a 69 kV Fault Current Limiter". 7th IEEE/PES Transmission and Distribution Conference, April 1979, IEEE Publication 79CH1399-5 PWR, pp. 237-244.

*** - Greenwood, A. N., Lee, T. H., "Theory and Applications of the Commutation Principle for HVDC Circuit Breakers, IEEE PAS Vol. 91, July/Aug. 1972, pp. 1570-1574.

- Kimblin, C.W., "Developmental Studies of a Current Limiter Using Vacuum Arc Current Commutation", Symposium Proceedings - New Concept in Fault Current Limiters and Power Circuit Breakers. EPRI E1-276-SP, April, 1977, Section 18/ pp. 18-53.

- Gilmour, A. S., "Feasibility of a Vacuum Arc Fault Current Limiter", IBID. Sect. 17, pp. 1-19.

2.4 OTHER CURRENT LIMITERS:

The enumeration of current limiting devices would not be complete without at least mentioning the Series Resonance current limiter* and the Current Limiting Conductor (CLC).** The first of these devices becomes current limiting by automatic de-tuning of a series L C circuit with a saturable reactor when a certain current is exceeded. The second device acts like a linearly extended solenoid, the armature of which is pulled in, in response to excess current. Thereby the circuit inductance and resistance are increased to effectively limit the current. Both devices are self-resetting and can be operated repetitively. But they are bulky and expensive to purchase and because of high losses also expensive to operate.

2.5 SOME GENERAL OBSERVATIONS:

A very cursory examination of the various devices, excepting the last two, suggests that the complexity increases in sequence with our listing. Considering further cost, the series resonance device and the CLC probably top the list. The simplicity of their principles, their ability for repetitive almost unlimited operation and well known manufacturing techniques, however, suggest that they are also the most desirable and reliable devices.

If the requirement for repetitive operation is dropped the triggered current limiting devices, in our opinion, rank first in reliability and certainly low cost. They will maintain this position if a fairly slow recharging mechanism is added. This opinion is based on the observation that these devices have no moving parts, and use highly reliable chemical charges which are not subject to degradation under the prevailing environmental conditions. Also the manufacturing techniques of the fuses that are employed in these devices are well known and subject to good quality control checks. The reliability, however, could be decreased because of the electronic sensing and firing circuits operating under hostile conditions of high electrostatic and magnetic interference.

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* - Kalkner, B., "Short Circuit Limiter for Coupled High Power Systems", Cigre - Report P. 301 (1966).

** - Pflanz, H. M. et al, "Development of Current Limiting Conductor, EPRI Report, EPRI EL-286, 1977.

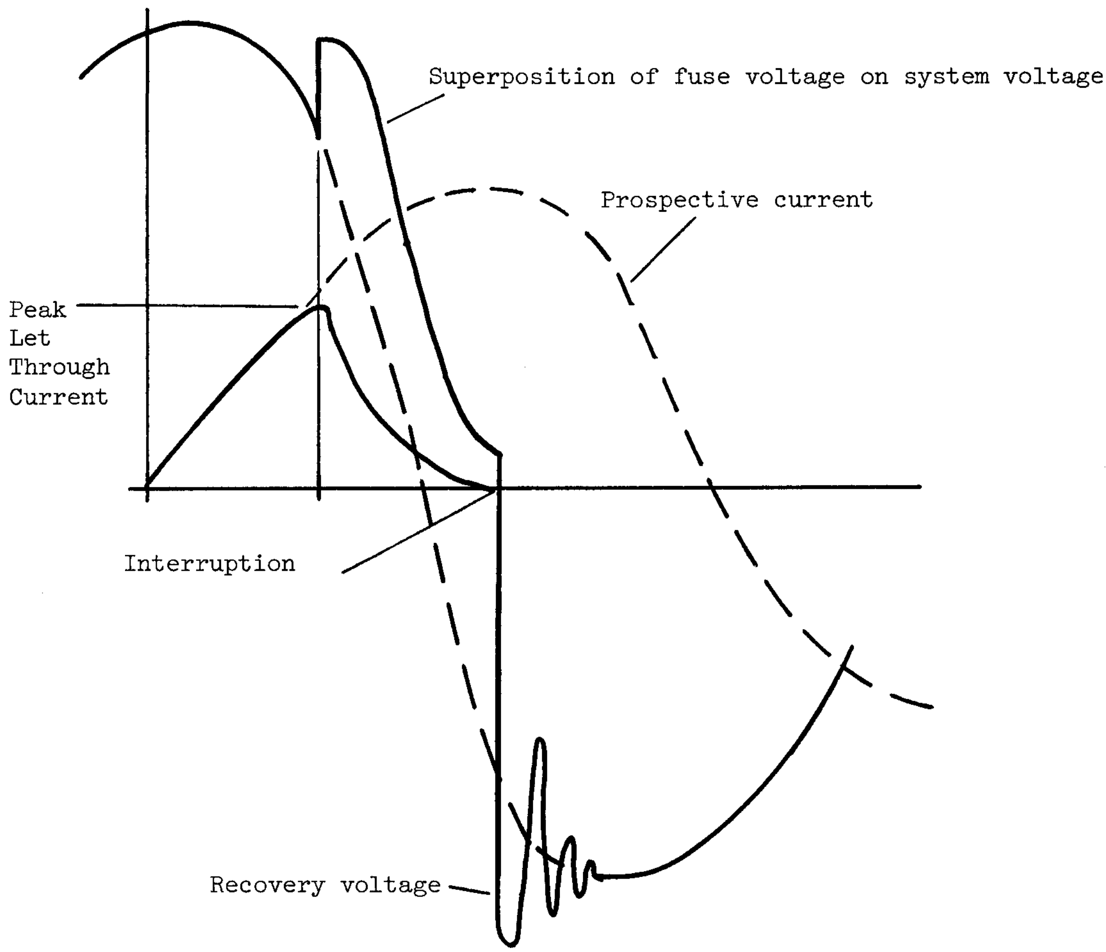


FIGURE 2-1

TYPICAL INTERRUPTION OF A CURRENT LIMITING FUSE

FIGURE 2-2: Schematics of Triggered Current Limiters

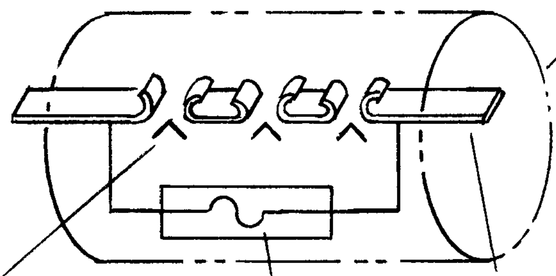


FIGURE 2-2a
PHOENIX ELECTRIC CORP.
CLP

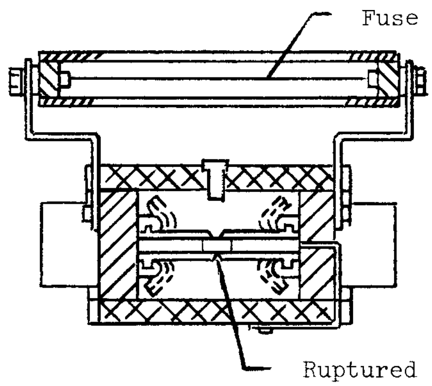


FIGURE 2-2b
BBC (CALOR EMAG)
I_S Limiter

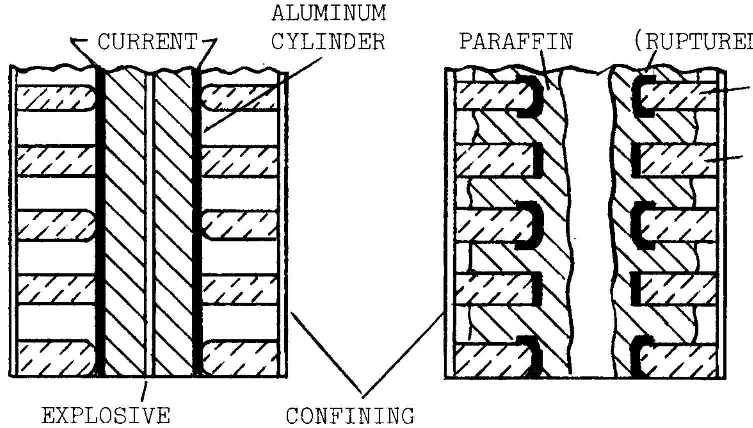


FIGURE 2-2c

U. S. NAVY SWITCH
OPERATED WITH
CHEMICAL CHARGE

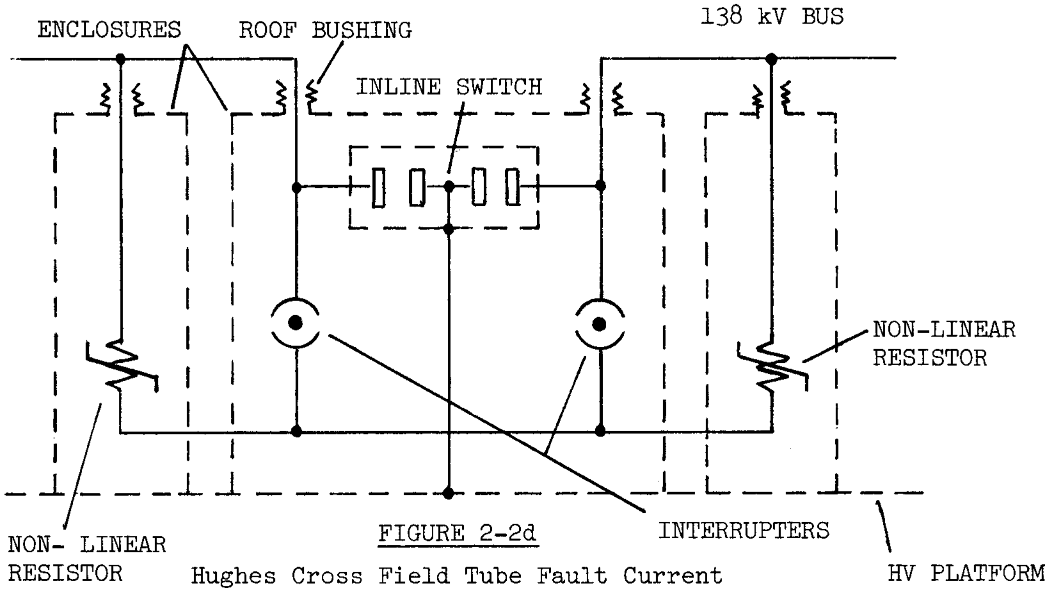


FIGURE 2-2d

Hughes Cross Field Tube Fault Current Limiter Schematic

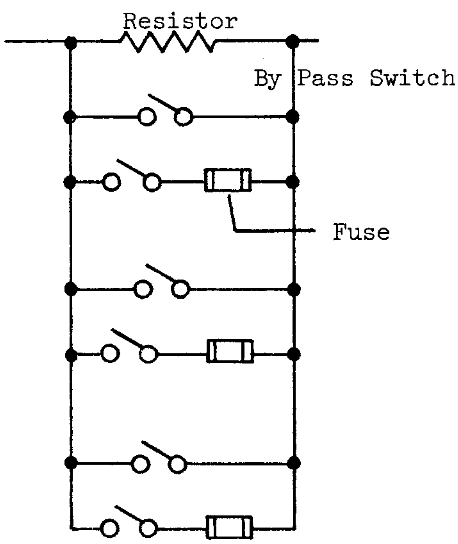


FIGURE 2-2e

BBC-Gould 69 kV Current Limiter

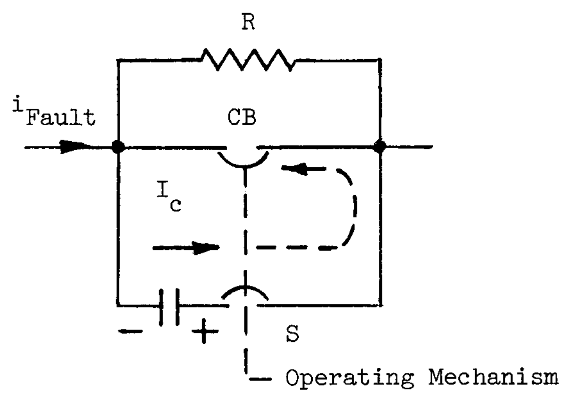


FIGURE 2-2f

G. E. d.c. Breaker (Injection Principle)

Section Three

THE CURRENT LIMITING PROTECTOR (CLP)

The Current Limiting Protector was cataloged as a triggered current limiting device in Section 2. As such it overcomes the counteracting short comings of continuous current and let-through current of conventional current limiting fuses.

In the CLP the current carrying and interrupting functions are separated and independent sensing and actuating means are additional elements over conventional fuses. The first two functions are accomplished by shunting a silver-sand current limiting fuse by a large cross section copper conductor, which carries the continuous current. Upon command, several series related gaps are cut into the copper conductor by a chemical charge. Current is thereby commutated to the fusible element, which is melted and in a known current limiting manner reduces the current to zero. The gaps of the conductor and the fuse are designed such that they can withstand the recovery voltage and thus separate the fault from the circuit.

It is apparent that the independence of sensing and actuating means lends great flexibility to the application of the CLP. For example, the CLP could be triggered in response to a short circuit current level or the rate of change of current, or quite unconventionally in response to a change in the magnetic field or a light signal or any other desirable function, which requires the opening of an electric circuit.

The operation of the CLP can be described in terms of very specific time intervals. These time intervals are defined in Figure 3-1 together with their associated performances, which lead to current limitation. Equally important is the fortuitous coincidence that associated with each time interval is a sub-function of the CLP, which requires a specific development effort. This is likewise indicated in Figure 3-1, and serves as a guide for this report. Figure 3-1a shows the initial essentially linear rise of the short circuit current. The main conductor of the CLP carries nearly the total current with only a very small portion flowing through the higher impedance fuse path. Assume that the instantaneous current

i_o is sensed and a signal to initiate the CLP is given at that instant. This sets off the primary and the secondary charges, which cut the conductor at high speed during the time interval $t_1 - t_o$. Arc-lets develop at the gaps thus formed. This is shown in Figure 3-1b. The arc-lets introduce impedance into the main circuit. Thereby the current is commutated into the fuse and eventually the arc-lets are extinguished. The commutation process begins at time t_1 and ends at time t_2. (Figure 3-1c). Now, the fuse current heats up the fuse element and melts it at time t_3. The resulting high arc voltage of the fuse causes the reversal of the short circuit current, i.e. current limitation and the reduction of the current to zero as shown in Figure 3-1d.

Column 3 of Figure 3-1 indicates the development effort that was required in resolving the problems associated with the different time intervals. In the following sections these efforts will be described in detail.

3.1 PYROTECHNIC CUTTING:

The use of chemical charges under controlled conditions is not new. For example, slow burning chemical charges are used to weld copper conductors to ground rods or to structures.* Chemical charges are also used in plasma physics experiments as a means to crowbar high intensity discharge circuits.

The first commercial us of chemical charges in current limiting devices was made by Calor Emag in the so-called I_S-Limiter (see Section 2). A conductor which is filled with a chemical charge is ruptured upon command along pre-machined stress grooves, Figure 3-2a. We shall term this technique"pyrotechnic rupturing".

A second technique employs a chemically driven piston which shears off the conductor at an appropriate cutting edge. This principle is sketched in Figure 3-2b and is employed by the U. S. Navy. It is likewise outlined in Section 2.

A third possible technique uses a linear charge directly as the driving piston and a portion of the material to be cut as an anvil (Figure 3-2c), along which the material is to be sheared off. This is one of the techniques, which was explored by Phoenix Electric Corp.

* - See e.g. trade brochures on "Cadweld" of Erico Products, Inc., Cleveland, Ohio.

Still another technique also originated by Phoenix Electric Corp. focusses the chemical charge along a line across the conductor which is to be cut. (See Figure 3-2d).

In the course of this project methods c and d of Figure 3-2 were explored and the following parameters were considered:

- Type of charge and grain size considering environmental conditions, such as temperature, humidity and life.
- Encasement of the linear charges: plastic, lead, aluminum.
- Directional or focussing effects.
- Effects of back-up material.
- Metal to be cut, (copper and aluminum), metal thickness, retention of material.
- Effects of delayed charge assists, or conductor mass for metal forming were also considered.
- Finally, cutting configurations giving straight, spiral or circular cuts were explored.

For our further evaluation linear charges using PETN material of various grain sizes from 3 to 35 grains per foot were selected. Because of the large number of variables, the cutting block of Figure 3-3, which can accommodate (8) different cutting experiments in one shot was designed. Figure 3-4 shows typical conductor configurations which were explored.

Figures 3-5 through 3-10 are photographs of the more significant cutting experiments. A basic description of the experimental parameters is given with each figure, while the results follow from Table 3-1. The sample number should be used for cross reference between the Figures and the Table.

A total of 45 cutting experiments were conducted, from which the following conclusions were drawn:

- Copper and aluminum can be cut with charges of up to 35 grains of PETN up to 3 mm (1/8") thickness.
- Shaped charges require fewer grains of PETN than straight charges.
- Shaped charges permit cutting without elaborate retention means.
- Linear and shaped charges permit cutting and subsequent folding of the conductor. This is important to avoid severed material, which may deteriorate the dielectric strength of the arrangement.
- The cutting speed was measured to be approximately 5 mm/μsec (the time to fold the contact bridge was not determined).
- The conductor configuration, Version 2 of Figure 3-4, was chosen for further prototype tests.

Table 3-1

TEST RESULTS

Test #	Sample #	Version #	Cutting Thickness In.	GAP In.	PETN Cord or LSC	Coreload/results gr/ft See Key 1st Slot	2nd Slot	DESCRIPTION AND REMARKS
1	101	1	1/16	1	Cord	25/F.O.	19/F.O.	
		2	1/16	1	Cord	25/F.O.	19/P.O.	
2	102	3	1/16	1	Cord	25/P.O.	19/P.O.	
		4	1/16	1	Cord	25/F.O.	19/P.O.	
3	103	5	1/16	1	Cord	25/C.B.	19/C.B.	
		6	1/16	1	Cord	25/P.O.	19/C.B.	
4	104	2	1/16	1	Cord	25/F.O.	19/F.O.	
		6	1/16	1	Cord	25/P.O.	19/P.O.	
5	105	7	1/16	1.25	Cord	2x8/C.B.	2x12/F.O.	
		7	1/16	1.25	Cord	2x8/C.B.	2x12/F.O.	
6	106	7	1/16	1.5	Cord	2x8/C.B.	2x12/P.O.	3/8" Cu Strip Backing Not Used
		7	1/16	1.5	Cord	2x8/C.B.	2x12/C.B.	3/8" Cu Strip Backing Not Used
7	107	9	1/16	1.63	Cord	25/C.B.	25/C.B.	Stress Riser-Up-1st Slot/Down-2nd **
		9	1/8	1.5	Cord	25/C.B.	25/C.B.	Stress Riser-Up-1st Slot/Down-2nd
8	108	9	3/32	1.5	Cord	25/C.B.	25/P.O.	Stress Riser-Up-1st Slot/Down-2nd
		9	1/16	1.5	Cord	25/P.O.	25/P.O.	Stress Riser-Up-1st Slot/Down-2nd
9	109	-	1/16	1.75	LSC	7/F.O.	15/F.O.	3/8" Cu Strip Backing Not Used
		-	1/16	1.75	LSC	10/F.O.	20/F.O.	3/8" Cu Strip Backing Not Used
10	110	-	1/8	1.75	LSC	20/P.O.	20/P.O.	
		-	1/8	1.75	LSC	30/F.O.	30/F.O.	Fiber Block Broke During Firing
11	111	-	1/16	1	LSC	5/C.B.	7/F.O.	
		-	1/16	1	LSC	10/F.O.	15/F.O.	
12	112	-	1/8	1	LSC	10/C.B.	15/C.B.	
		-	1/8	1	LSC	20/C.B.	30/F.O.	

KEY:

F.O. - Cu Strip Fully Opened

P.O. - Cu Strip Partially Opened (Bend Less than 90 Degrees

C.B. - Cu Strip Closed but Bent Slightly

LSC - Linear Shape Charge

** - Flat Side Away from Backing (Cu Strip Upside-Down)

3.2 CONTAINMENT:

Safe handling, transportation, installation and operation of the CLP all require the reliable containment of the primary and secondary chemical charges. A test device as shown in Figure 3-3 was placed in the 11.5 cm (4.5") diameter fiberglass housing of Figure 3-11 and ignited using a total of 25 grains of charge plus a primary cap. The fiberglass tube had a wall thickness of 1.5 mm (1/16") and has a catalog burst pressure of 1300 psi.

On the first such experiment the end plates were made of plywood. The (4) retaining bolts were pulled through the wood. On a second experiment the end plates were reinforced fiberglass plates. They withstood the pressure, however, the primary charge was resting on the inside wall and caused local cutting of the tube wall. This is depicted in the photograph of Figure 3-12. Shown are also the cutting experiments that were conducted simultaneously.

Correcting the above short comings, the gases and forces generated by the primary and secondary charges were readily contained in a third experiment. Thus it was shown that the CLP can be packaged such that there is no danger to any personnel. In fact, this experiment has shown the path to an epoxy sealed device which prevents access to the interior and as well ensures that none of the explosive gases can escape from the device on actuation of the charges. If both of these requirements are met the device does not constitute a safety or security hazard. Consequently such a CLP will not be a regulated device. We wish to point out, however, that this determination will have to be made for each type of device by the Department of the Treasury, Bureau of Alcohol, Tobacco and Firearms. The CLP, which was developed in the course of this project has met this requirement.

3.3 ACTUATION OF PRIMARY CHARGES:

Secondary charges, such as are used in the cutting of the conductor of the CLP cannot be set off by heat or mechanical shock. They require a shock wave as produced for example by the firing of a so-called primary charge. Two types of such firing caps were selected for evaluation. The first, known as an "Exploding Bridge Wire" (EBW), requires a high current pulse rising to the firing level in approximately 1½ microseconds. The current required to set it off is typically 750 to 1000 ampere. Perhaps more informative is a value for a firing i^2t which must be met in 1½ microseconds, viz: 0.3 A^2 sec. The EBW has a typical resistance of 0.5 Ohms. As a consequence a high voltage discharge in excess of 2000 Volt is required considering also the surge impedance of the firing circuit. The advantage of the EBW is that it cannot be set off by heat or mechanical shock, rather it requires a very specific electrical firing pulse. However, this is outweighed by uncertainties in the high voltage firing circuit. Such a circuit is shown in Figure 3-13. Two firing stages are required. An SCR is triggered in response to any desired function. It discharges a 200 Volt capacitor through a pulse transformer, which provides a high voltage trigger pulse to the high voltage trigger gap. The high voltage capacitor C_2 upon discharge fires the EBW.

The uncertainty in this circuit is the trigger gap's ability to withstand 2500 Volts for an indefinite period of time or to withstand it and be ready to fire without jitter. No such data could be obtained from the literature or the supplier of such a gap.

The so-called "Hot Wire" is a lower energy firing device. Normally it is set off with a battery, which heats a wire element. This element is in contact with a temperature sensitive charge, which is actuated by temperatures in excess of 400°C. As used conventionally this cap is a slow device. However, we determined experimentally that it too can be fired with a pulse of microsecond rise time and moreover of much lower current magnitude. The Hot Wire used in our experiments has a 1.5 Ohm maximum resistance. The firing i^2t was found to be 0.05 A^2 sec. and is, therefore, a little over 1/10 of that for the EBW. This is very advantageous because the Hot Wire requires a pulse which can be obtained from a relatively low voltage supply as is indicated in Figure 3-14. Because of the lower voltage the Hot Wire is triggered in a single stage from a relatively low voltage SCR. The voltage of the trigger circuit could be further reduced to 400 Volts when the Hot Wire was fired via a low surge impedance strip line instead of a 50 Ohm co-axial cable. Figure 3-15 shows typical firing current pulses for the EBW and the Hot Wire systems. Clearly the Hot Wire is favored.

In order to check out the firing circuits, (6) EBW's and more than (40) Hot Wires were fired. In addition hundreds of test firings were done with Hot Wires from which the chemical charges had been removed. Glowing of the Hot Wire was always taken as a successful test. In none of these tests was any failure of the firing circuit observed. However, in parallel experiments at 600 to 700 Volts two SCR failures were reported. As a consequence we feel that the reliability of the firing circuit must be further evaluated.

It is desirable in certain applications to isolate the primary charges from ground. An isolation pulse transformer meeting the specifications below was built and likewise tested. Thus simultaneous firing of two isolated Hot Wires from one source was demonstrated.

Core:	Magnetic Metals Part #58-M-3302-P with (2) .001 gaps.
Primary:	3 turns of #20 AWG wire with 20 kV insulation.
Secondary:	3 turns of #20 AWG wire with 20 kV insulation.
Tertiary:	3 turns of #20 AWG wire with 20 kV insulation.

The core was wrapped with several layers of insulating tape. Next the windings were applied, taped and the entire transformer was then encapsulated in silicone rubber. 30 kV (RMS) 1 minute 60 Hz test voltages were applied between the windings and successfully withstood.

In summary the firing experiments of the primary charges yielded the following results:

- EBW and Hot Wires are suitable for triggering CLP's and have microsecond response times.
- Hot Wire firing requires a much lower voltage power supply and only a single stage firing circuit.
- The Hot Wire technique of firing the CLP is lower in cost and more reliable than the EBW technique.
- Firing the Hot Wire via a strip line permits a still lower voltage circuit than is possible with the co-axial cable.
- Hot Wires, but also EBW's can be fired via an isolation pulse transformer.
- Simultaneous firing of two isolated Hot Wires via an isolation pulse transformer was demonstrated.

3.4 THE COMMUTATION INTERVAL:

Commutation of current from the main current path to the fusible element is the third time interval in the operational sequence of the CLP. (See Figure 3-1). For analysis we refer to Figure 3-16, which shows the overall circuit and the loop of the CLP in which commutation is to take place. Generator voltage v_g drives the short circuit current i_{sc}. Prior to operation of the CLP only the line inductance, L_{sc}, limits the short circuit current. In a typical grounded 15 kV circuit we find with i_{sc} = 40 kA (RMS) the short circuit inductance, viz:

$$L_{sc} = 15{,}000 \;/\; (1.73 \times 40{,}000 \times 377) = 574 \times 10^{-6} \text{ H}$$

By comparison the inductance L_M of the main path of the CLP is estimated to be approximately 0.3×10^{-6} H. The associated resistance R_M is in the order of micro-Ohms and therefore likewise negligible. Therefore, i_{sc} is not affected by the CLP during the commutation process, but is dominated by the circuit. Since R_F and L_F, the resistance and inductance of the fuse path respectively, are both greater than R_M and L_M, almost the entire short circuit current will flow in the main branch of the CLP. Further R_F is of the order of the circuit resistance, L_F is much lower than L_{sc}, but the latter dominates the circuit. Therefore, shifting of the current from the main path to the fuse will not affect the short circuit current either, certainly not until the fuse melts as we shall see later. Thus commutation requires consideration of the CLP loop only.

The analytical object of current commutation is to produce a counteracting current, $i_b = i_{sc}$, which reduces the current to zero in the main conductor and commutates it into the fuse branch of the CLP. This so-called backward moving current* is driven by the arc voltage, e_{arc}, of the arc-lets, which were formed by the pyro-cutting technique in the preceding time interval. With reference to Figure 3-17, the backward moving current, I_b, is derived by the operational equation (a constant arc voltage is assumed):

$$e_{arc} / s = ((R_M + R_F) + (L_M + L_F)\ s)\ I_b \qquad (3\text{-}1)$$

Solving for I_b and performing the inverse transformation gives

$$i_b(t) = e_{arc}(1 - \exp(-t\ R / L)) / R \qquad (3\text{-}2)$$

or solving for time we find

$$t = -T \ln(1 - i_b(t)\ R / e_{arc}) \qquad (3\text{-}3)$$

where $R = R_M + R_F$ and $L = L_M + L_F$

and $T = L / R$ is the time constant

We conclude that the backward moving current rises exponentially with a time constant L/R and depends on the arc voltage divided by the resistance of the commutating loop.

Generally speaking the backward moving current has reached its end value after 5 times the time constant. This gives with equations 3-2 and 3-3 the backward moving current and the total commutation time, respectively

* - Boehne, E. W., "The Geometry of Arc Interruption I", AIEE Transactions, Vol. 60, 1941, Pages 524-532

$$i_b(5T) \approx e_{arc} / R \tag{3-4}$$

$$\text{and } t_{5T} \approx -5R \ln(1- i_b(t)\, R / e_{arc}) \tag{3-5}$$

Considering typical values we obtain the data of Table 3-2

$1 < L < 5$ μH
$5 < R < 25$ mOhm
$.05 < iR / e_{arc} < .8$

Table 3-2

TABULATION OF EQUATIONS 3-4 and 3-5

$e_{arc}/(i_b R)$	100	50	20	10	5
t_{5T} μsec ($L/R=10^{-3}/5$)	10	20	51.3	105	223

As a frame of reference from our experiments:

e_{arc} = 2000 to 3200 Volts, L = 2 μH R = 10 mOhms i = 10,000 ampere

Then $e_{arc}/(iR) = 20$; T = 200 μsec and t_{5T} = 51 μsec

Hence a commutation time of 70 μsec as observed was not unexpected.

A short commutation time is desirable because arc contamination could otherwise adversely affect the deionization of the arc gaps during the melting process. Fast commutation, in accordance with the above is achieved by decreasing the inductance and increasing the arc voltage. Increasing the resistance, R, for a given set of conditions on the other hand hardly affects the commutation time. This follows from Figure 3-18, in which commutation time is plotted vs. fuse resistance in accordance with equation (3-5). Other conditions for this plot are: e_{arc} = 2000 Volts and 3200 Volts, commutation current i = 12,000 ampere and the loop inductance is taken as parameter.

In the preceding a constant arc voltage was assumed. If the arc voltage is decreasing with time as one would expect, different conditions prevail. However, it is readily seen from the following that the backward moving current is proportional to the area under the time dependence of the arc voltage reduced by the iR-drop. Thus considering again Figure 3-17 and writing the circuit equation in the time dependent form we find

$$e_{arc} = L\, di_b/dt + i_b R \qquad (3\text{-}6)$$

$$\text{or } i_b = \int \frac{e_{arc} - v_R}{L}\, dt \qquad \text{where } v_R = i\, R \qquad (3\text{-}7)$$

Commutation is accomplished when i_b becomes equal to the short circuit current. The commutation time is the shorter the faster the current rises, i.e. the lower the commutating inductance. Again we remind the reader that fast commutation is essential to the dielectric recovery of the main gaps following the melting of the fuses.

3.5 MELTING OF FUSE ELEMENTS - ELEMENT DESIGN:

The fourth step in the sequence of events leading to current limitation (see Figure 3-1) is the melting of the fusible element and the subsequent current limitation. The proper operation of a CLP imposes a number of constraints on the fusible element.

- Even though the fuse will carry but a fraction of the total current, the continuous current must not melt it.
- The fraction of the short circuit current which the fuse carries as the CLP is readied for firing must not significantly affect the melting time.
- The fuse must not be melted by inrush currents.
- The melting time of the fuse must be sufficiently long at maximum current to assure deionization of the main gaps.
- The peak over-voltage upon melting of the fuse must not exceed the values specified by ANSI Standards C37.46 Table 5. (e.g. the maximum peak over-voltage is 45 kV for 15.5 kV fuses).
- The sustained arc voltage (i.e. the arc voltage after the peak has passed must exceed the driving system voltage).
- The fuse and CLP gap combination must successfully withstand the recovery voltage. (We note the CLP gaps must withstand also the peak arc voltage of the fuse).

The first of these constraints is readily met by the typical values of Table 3-3. If now the nominal current is 1000 ampere the fuse must have a continuous rating of not less than 12 ampere. In the devices that were developed this condition was always met.

Table 3-3

DATA OF MAIN CONDUCTOR AND FUSE

	Main Conductor	Fuse
R Ohms	33×10^{-6}	10×10^{-3}
L Micro-Henry	.3	1
X Ohms	113×10^{-6}	377×10^{-6}
Z Ohms	118×10^{-6}	10×10^{-3}
% of i_{total}	98.8%	1.2%

In addition the fuse must have a melting i^2t which is substantially above the i^2t of the fractional short circuit current through the fuse prior to firing of the CLP. Thus inappropriate melting would not occur. In order to substantiate this, assume the peak of the short circuit current should be just below the firing level of 10,000 ampere (peak). Further we assume that a 5 cycle circuit breaker will clear this fault. The i^2t to which the fuse is subjected to is then determined by 1.2% of the current. Thus

$$\int_0^{10\pi} i^2 dt = \int_0^{10\pi} (.012 \times 10,000)^2 \sin^2 \omega t \, dt = 120^2 \times \frac{5\pi}{377} = 599 \text{ A}^2 \text{ sec}$$

This value is typically only 1/50 to 1/30 of the melting i^2t of the fusible element used in a CLP. The second constraint is, therefore, met. In fact a 2.5 to 4 sec. short time rating would be met as well. $(599 \times \frac{60}{5} \times 2.5 = 17{,}970 \text{ A}^2\text{sec})$

The third constraint causes us some concern since the impedance ratio of the fuse and the main conductor change as a function of frequency. At high frequencies the current distribution is determined by the inductances of the branches of the CLP giving the percent currents of the total high frequency inrush current:

$i_{fuse} = 23.8\%$ $\qquad$ $i_{conductor} = 76.2\%$

Because of the inherently high damping of high frequency inrush currents and their consequential short duration, this may not be a problem. However, we suggest that this point be explored further.

The melting i^2t of the fusible element is determined next. For a linear rise of the short circuit current as is the case over the first few degrees the current and the i^2t are given respectively by the forms

$$i(t) \approx I_m \omega t \tag{3-8}$$

$$i^2t\big|_{t=t_n} \approx \frac{(I_m \omega t_n)^2 t_n}{3} \tag{3-9}$$

The melting interval lasts from t_2 to t_3 as follows from Figure 3-1. The maximum let-through current, which is equal to the melting current is specified in Section 1 as 15,000 ampere. If we assume a melting time of 100 microseconds and take the rate of rise of the specified 40 kA short circuit current as 21 A/μs then in accordance with Figure 3-1d we find

$$i_3 = 15{,}000 \qquad t_3 = \frac{15{,}000}{21} = 714\ \mu\text{sec}$$

$$i_2 = 614 \times 21 = 12{,}900 \text{ where } t_2 = 714-100 = 614\ \mu\text{sec}$$

and the melting i^2t becomes

$$i^2t_{melt} = \frac{i_3^2 t_3}{3} - \frac{i_2^2 t_2}{3} = 53550 - 34058 = \underline{\underline{19{,}491}}\ A^2\text{sec}$$

The melting time integral of fusible elements is a constant peculiar to each material*

Material	$\frac{\int i^2dt}{A^2}$	
Silver	11.72×10^8	$(A/cm^2)^2$ sec
Copper	8.00×10^8	

Where A = cross section in cm^2.

The melting time integral permits layout of fusible elements for short time melting or evaluation of existing commercial current limiting fuses for any required i^2t.

* - Rudenberg, Reinhold, "Transient Performance of Electric Power Systems M.I.T. Press, Cambridge 1969", page 447.

In such an evaluation it was determined that commercial current limiting fuses were either too fast or too slow for use with a CLP. Too fast a fuse does not provide a sufficient deionization time for the CLP gaps. Too slow a fuse causes the let-through current to increase. A program was, therefore, initiated to develop a suitable fusible element for the CLP. The objective was to determine precise melting times and to measure peak arc voltages per unit length and obtain an idea of the sustained arc voltage of the element.

These tests were performed in our capacitor discharge system. Results of a melting test together with the overall circuit schematic are shown in Figure 3-19. In these experiments silver fuse links typically 12.5 cm (5") long and having a cross section of 0.7 mm^2 (1.1×10^{-3} in^2) were placed in a sand filled tube for test. The reproducibility of the tests was remarkable and melting times on repeat tests could be held within less than 5%. The ribbons were provided with different size holes. Plotting the melting i^2t vs. the hole pattern resulted in the plot of Figure 3-20. The peak arc voltage generated per hole is approximately 500 Volts. For the sustained fuse arc voltage a gradient of 200 V/cm was taken as typical. With this preceding information single and multiple parallel element fuses were laid out for 4.16, 7.2 and 15 kV CLP devices.

We also attempted to shape the arc voltage of the fuse by combinations of different hole sizes so as to keep the peak arc voltage low by comparison to a single hole pattern. In fact the information of Figure 3-20 was used to generate the melting pattern of Figure 3-21, where 3 different notch sizes melted with 6 and 10 microsecond delays relative to the first. Using this information the arc voltage of the CLP fuses, once the first peak had passed, could be increased by superimposing an additional melting stage of a series of smaller sized holes.

The fuses were packaged using the conventional manufacturing practice of straight elements or wrapping the ribbon elements on a ceramic mandrel, placing them inside a fiberglass tube and tightly sand filling the assembly on a shaker table. The fuse dimensions adopted for the 4, 7 and 15 kV CLP devices are as given in Table 3-4. Reference to Figure 3-18 shows that the fuse resistances are well within the essentially constant range of the commutation time.

Table 3-4

FUSE SIZES AND RESISTANCES

kV	Length	Diameter	Fuse Resistances Milli Ohms
4	12"	2 or 2-7/8	4, 6 and 12
7	18"	2-7/8	9, 18
15	18"	2-7/8	30

3.6 CONTINUOUS CURRENT RATING OF THE CLP:

The copper main current path of the CLP was laid out and enclosed in a 20 cm (8") diameter fiberglass housing. Heat runs were performed, for which a number of thermocouples were placed along the current path giving the results of Figure 3-22. $15^{\circ}C$ and $45^{\circ}C$ temperature rises were measured for 600 and 1000 ampere continuous currents, respectively. Considering also that the ambient temperature could be as high as $40^{\circ}C$ the hot spot temperature would be $85^{\circ}C$. This is considered the limit for linear charges without degrading aging effects.* The CLP in the present form can, therefore, be rated for a maximum service of 1000 ampere.

3.7 THE SENSING AND FIRING CIRCUIT:

The CLP requires only 200 microseconds (1/80 of one cycle) from sensing a short circuit to onset of current limitation. The CLP specifications call for a maximum symmetrical short circuit current of 40 kA (RMS sym.). This translates into a rate of rise of the short circuit current of 21 ampere/microsecond. Hence the current rises 4200 ampere in the above operational time. Deducting this rise from the specified maximum let-through current of 15,000 ampere requires that the short circuit current must be level sensed not in excess of approximately 11,000 ampere.

Alternatively, the short circuit current could be sensed by di/dt. However, the CLP would then be responsive to transient currents such as are experienced on switching of capacitor banks.

Still another alternative is to sense current level and di/dt. However, since transient currents could exceed both, the trigger signal must be delayed until the transient has died out, or has at least been reduced to a value below the level sensor. But then the di/dt sensing is superfluous. We believe this is the case with the CLP because of its speed and because of the permissible high setting of

*-Ordnance Engineering Design Handbook Explosives Series, Properties of Explosives of Military Interest, Section 1, 31 May 1960, page 192.

the level sensor.

A brief analysis of inrush currents appears in order to better judge the magnitude of these.

a) Energization of a Single Large Capacitor Bank

System 15 kV	Typical Large Capacitor Bank 7500 kVAR
$i_{sc} = 40$ kA	$i_N = 288$ ampere
$X_{sc} = .216$ Ohms	$X_c = 30$ Ohms
$L_{sc} = 574$ μH	$C = 88.4$ μF
$f_o = 706$ Hz	

Inrush current peak $i = v\sqrt{C/L} = \underline{9.9 \text{ kA}}$

In this case it was assumed that the bank has been re-energized under phase opposition. If the bank is discharged prior to energization as is usually the case this current is only 5 kA. Clearly the CLP will not be triggered if it is level sensed at 10 kA.

b) Energization of Back to Back Capacitor Banks

It is assumed that two 15 kV, 7500 kVAR each capacitor banks are switched back to back. Such banks are typically switched with vacuum switches. Generally, it is required that the inrush current is reduced to 10,000 ampere peak. This is achieved with transient limiting reactors, the value of which is computed with the formula (see ANSI C37.0731-1973).

$$i_{peak} = 940\sqrt{\frac{kVAR}{L_T}}$$

The total phase inductance between the capacitor banks becomes with this

$$L_T = \left(\frac{940}{10,000}\right)^2 7500 = \underline{66.27} \ \mu H$$

while the rate of change of the inrush current is with di/dt = e/L = $15000\sqrt{2/3} / 66.27 = 360$ A/μsec.

In many instances this inductance is at least in part provided by the lines between the banks. The inrush is now less than 10,000 Ampere and short circuits could be level sensed above this value. However a di/dt sensor would not prevent false triggering because the rate of change of the inrush current by far exceeds the rate of the short circuit current. Thus in the absence of a scheme that prevents false triggering due to inrush currents a small transient limiting reactor is required.

Proposals have been made to prevent false tripping of current limiting devices by additional time delays* or other more elaborate means approaching micro-computer capabilities.** This appears necessary with inherently slower operating devices, which must sense at substantially lower current levels than the CLP.

The CLP with its extremely short operating time and high current sensing level does not need to anticipate the short circuit current and, therefore, overcomes these problems. However, we do suggest that combination level and di/dt sensing including time delays would allow substantial coordination for the clearing of short circuits in different circuit branches.

The basic circuit schematic is shown in Figure 3-23, which should be referred to in the following description of the circuit: The current is sensed by current transformer T1. A voltage signal is obtained from burden R1 and is rectified by bridge B1. Potentiometer R3 allows for matching the signal level to the comparator A1a which is biased by R6 and R7. In the normal state the positive terminal of the comparator A1a is biased to exceed the signal at the negative terminal. When overload occurs the signal on the negative terminal exceeds the positive bias and the comparator terminal 13 swings negative, thereby turning on transistor Q1. The 10 Ohm resistor R20 limits the emitter current, while the 100 Ohm collector resistor R5 draws current and provides the drive for SCR-D2.

The firing circuit is initiated by triggering the SCR-D2, which allows the stored energy of C_1 to discharge into the "Hot Wire". The Hot Wire ignites the primary charge and therby activates the CLP.

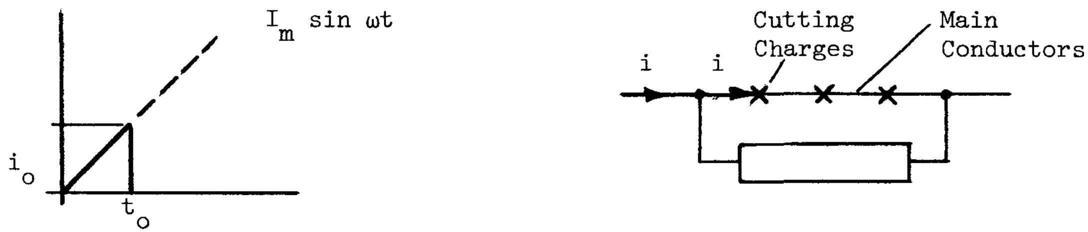
In the version shown on Figure 3-23 the sensing and firing circuit is at line potential, power is supplied from ground potential by the isolation transformer T3, which feeds the power supply transformer T2, bridges B2 and B3. Their outputs provide + 9.5 Volts and + 480 Volts to the electronic components and to the energy discharge capacitor C, respectively.

*-Development of Fault Current Limiters for Electric Power Systems, Final Report, EPRI,TD-130 Project 281-1, March 1976, Section 4.

**-I. Lee, et al, "An Ultrafast Fault Sensor for a Fault Current Limiting Device", IEEE, PAS-98, #3, May/June 1979, Pages 1069-1080.

Figure 3-23 shows as an alternate a version which uses an isolation current transformer T1, and an isolation pulse transformer, while the entire sensing and firing unit operates at ground potential. Transformer T3 is not required in this case since the 110 Volt supply may be connected directly to transformer T2. Both versions were successfully used in the short circuit tests at the General Electric High Power Laboratory which are described in Section 6.

The above circuit was checked out under 60 Hz conditions up to several thousand amperes and under pulse conditions (approximately 1 kHz) in excess of 20,000 amperes. The circuit was hardened against pick-up by strategically located shunting capacitors. The firing time from sensing of the current level to ignition of the primary charge was found to be less than 3 microseconds. The sensing level is adjustable from 2000 to 12,000 ampere.



DEVELOPMENT EFFORT

FIGURE 3-1a

TRIGGER: Overall packaging, continuous current capability, sensing of current, triggering of primary charge

FIGURE 3-1b

CUT: Development of pyro-cutting, development of enclosure to contain charges and associated shock wave.

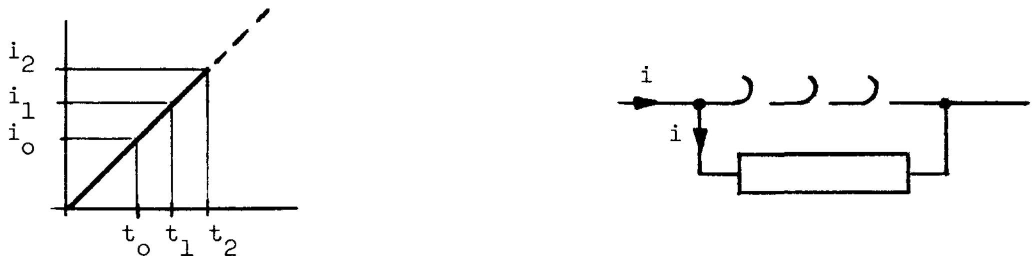


FIGURE 3-1c

COMMUTATE: Analysis of commutation problem, layout of fuse

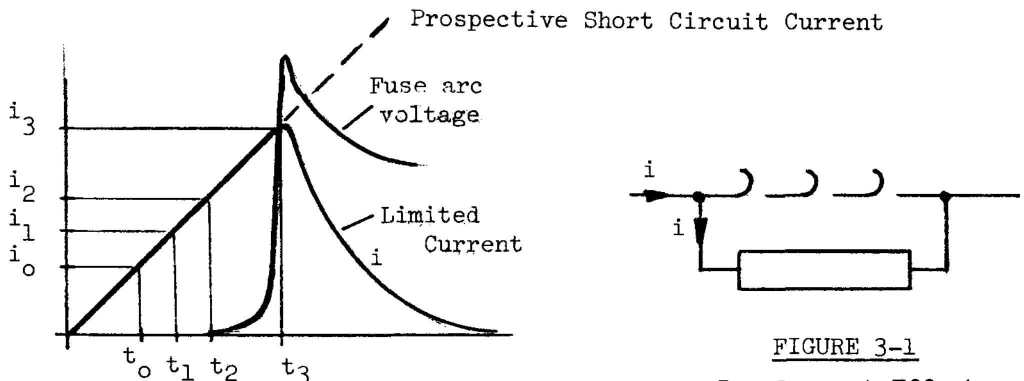


FIGURE 3-1d

MELT, LIMIT CURRENT: Deionization of gaps, melting time and arc voltage of fuse

FIGURE 3-1

Development Effort

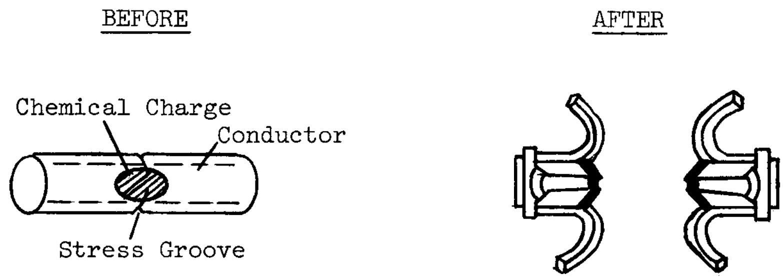


FIGURE 3-2a

Pyrotechnic Rupturing

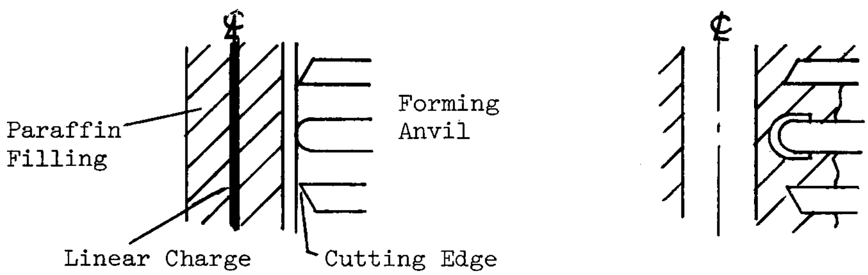


FIGURE 3-2b

Pyrotechnic Punching

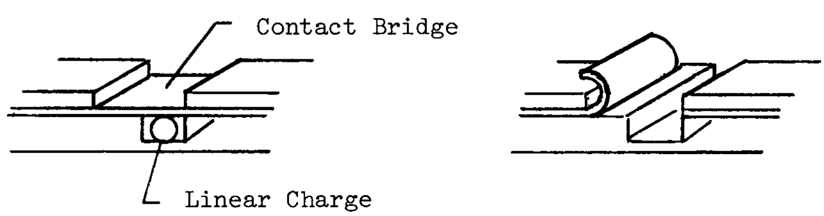


FIGURE 3-2c

Pyrotechnic Cutting

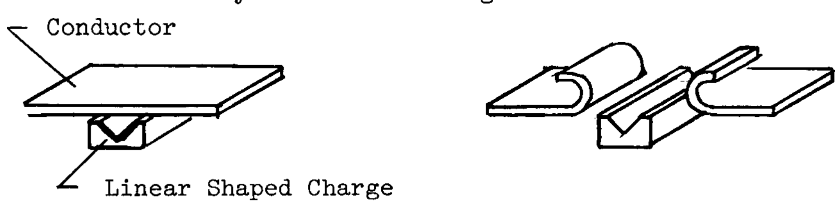


FIGURE 3-2d

Pyrotechnic Freecutting

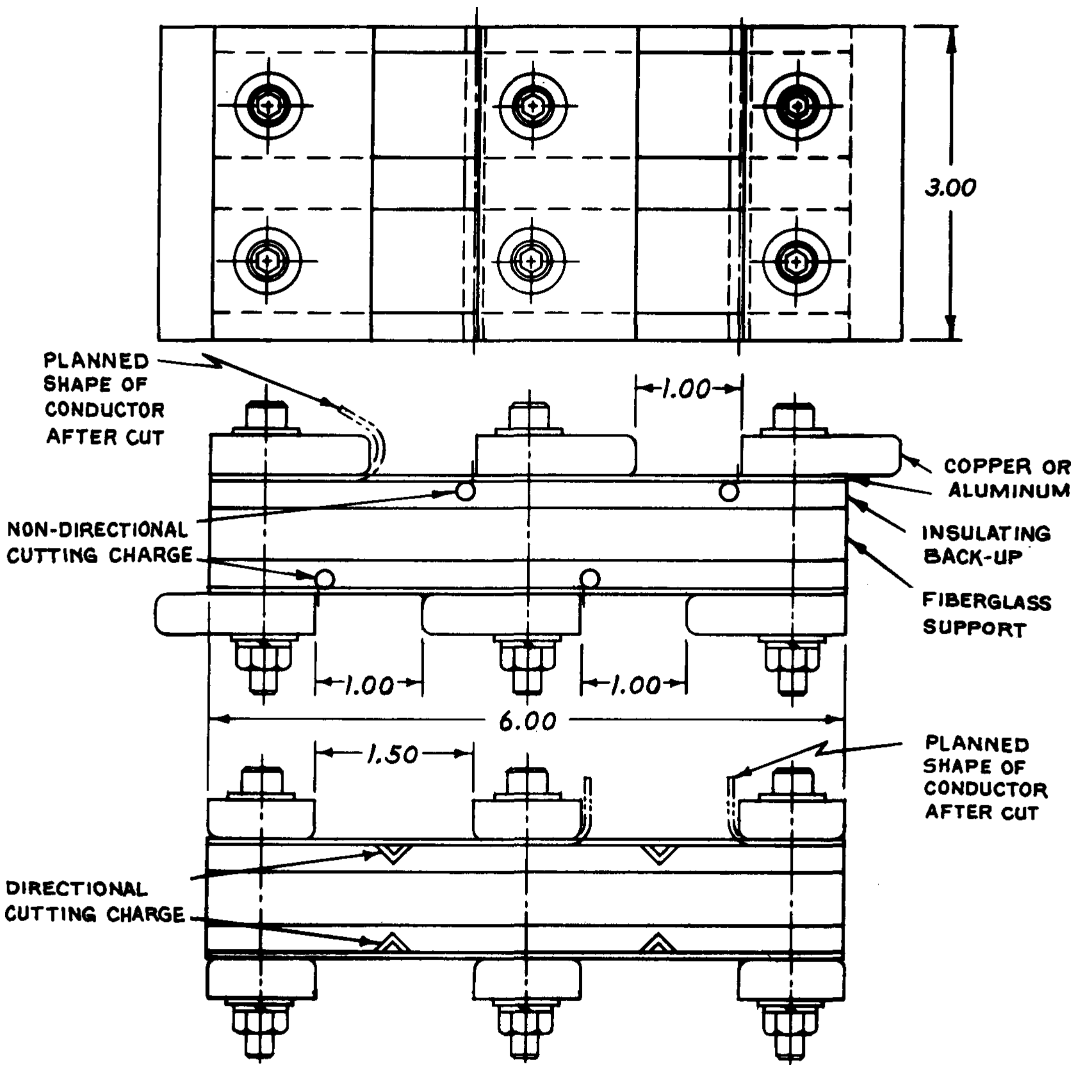


FIGURE 3-3

Cutting Block

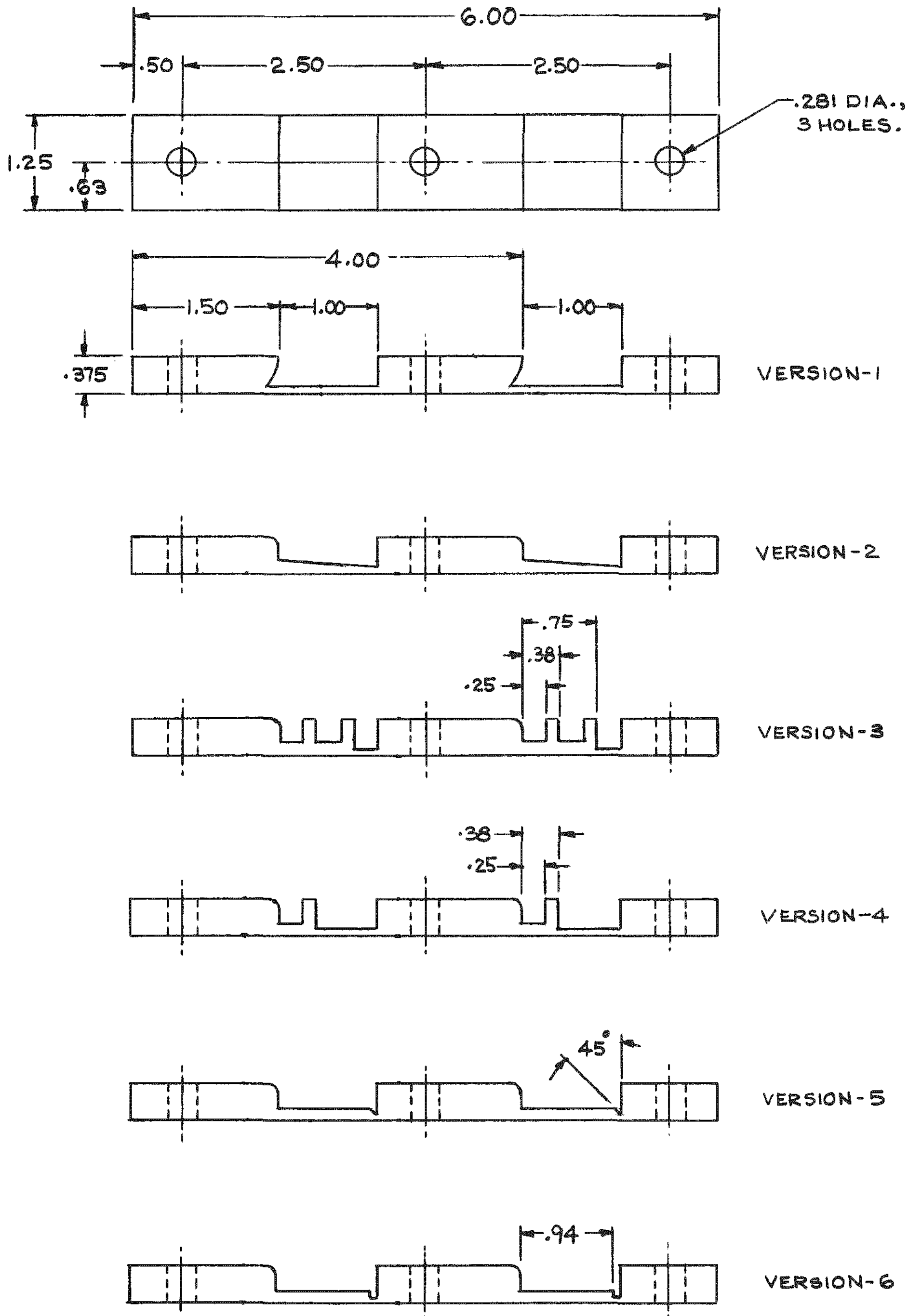
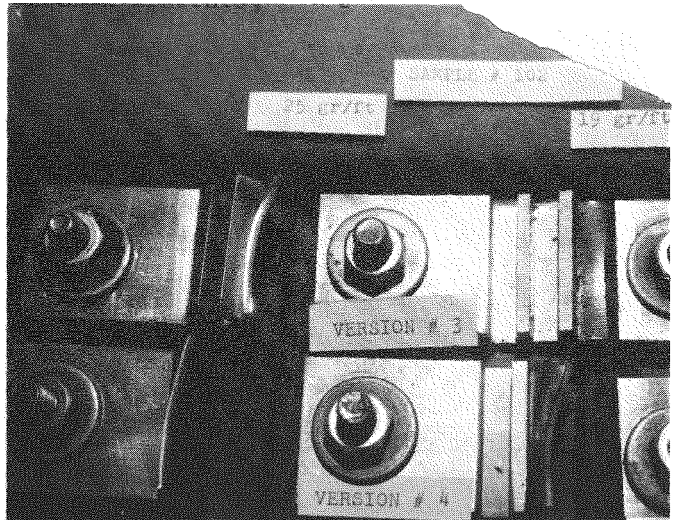


FIGURE 3-4

Conductor Configurations

PHOENIX ELECTRIC; No. 2; P.O. # 11850



PHOENIX ELECTRIC; No. 2; P.O. # 11850

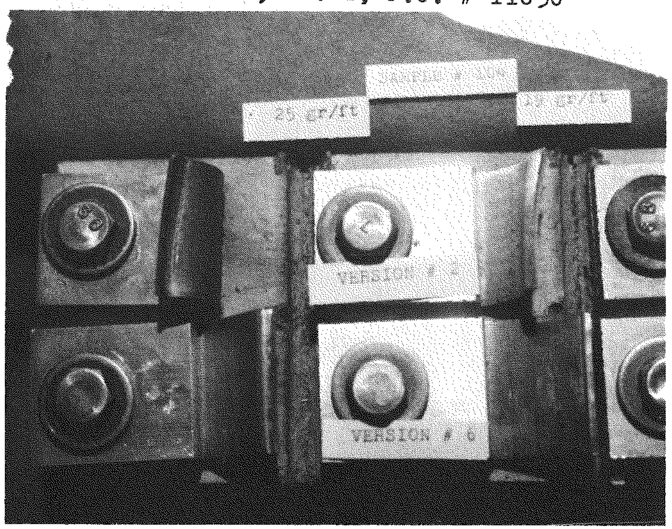
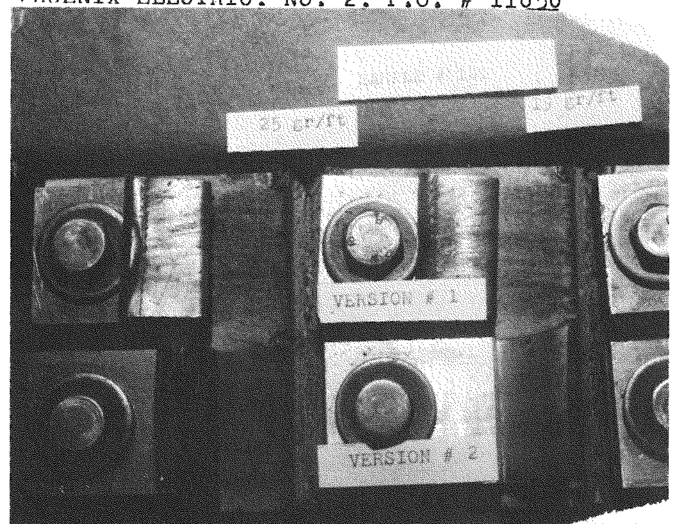


FIGURE 3-5

PHOENIX ELECTRIC; No. 2; P.O. # 11850



PHOENIX ELECTRIC ; No. 2; P.O. # 11850

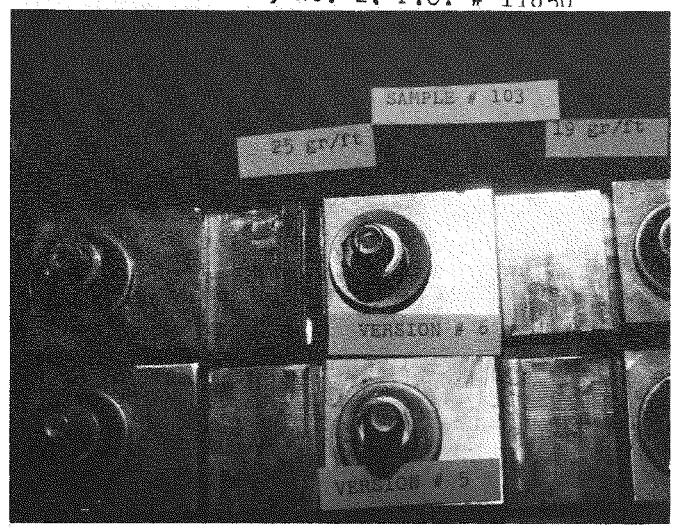
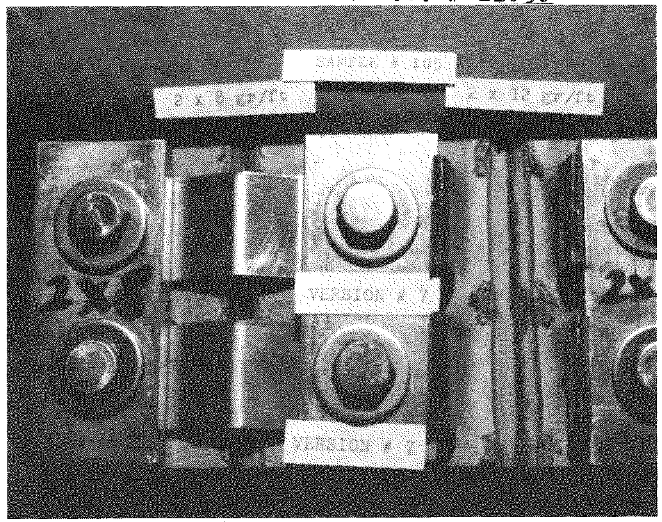


FIGURE 3-6

PHOENIX ELECTRIC: No. 2 : P.O. # 11850

PHOENIX ELECTRIC: No. 2: P.O. # 11850



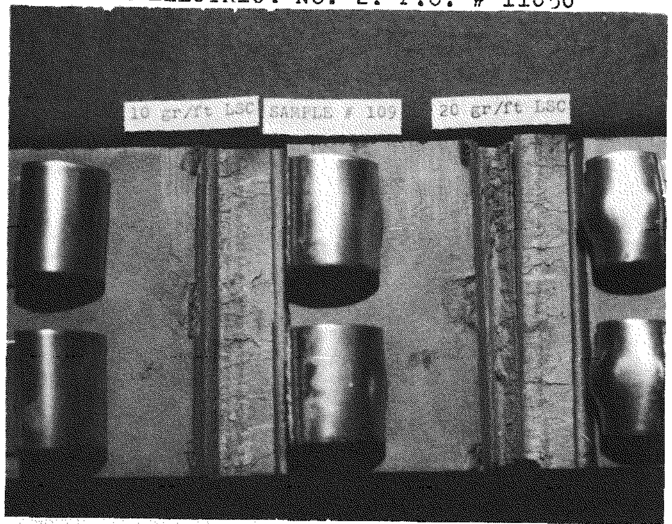
PHOENIX ELECTRIC: No. 2; P.O. # 11850

FIGURE 3-7

PHOENIX ELECTRIC; No. 2; P.O. # 11850

FIGURE 3-8

PHOENIX ELECTRIC: No. 2: P.O. # 11850



PHOENIX ELECTRIC; No. 2; P.O. # 11850

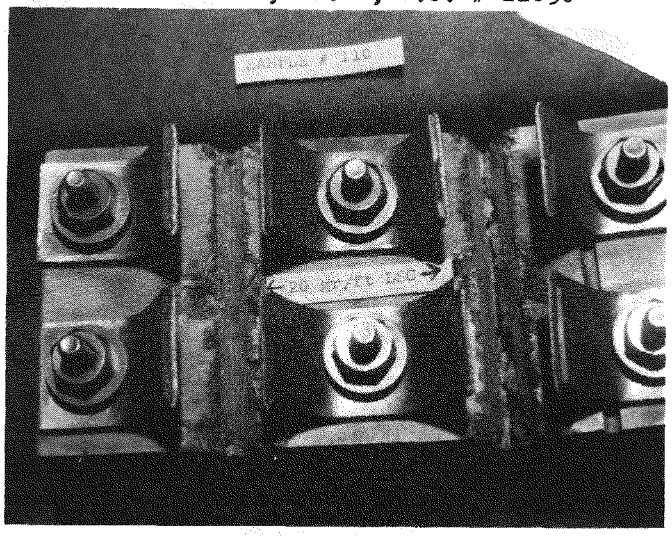
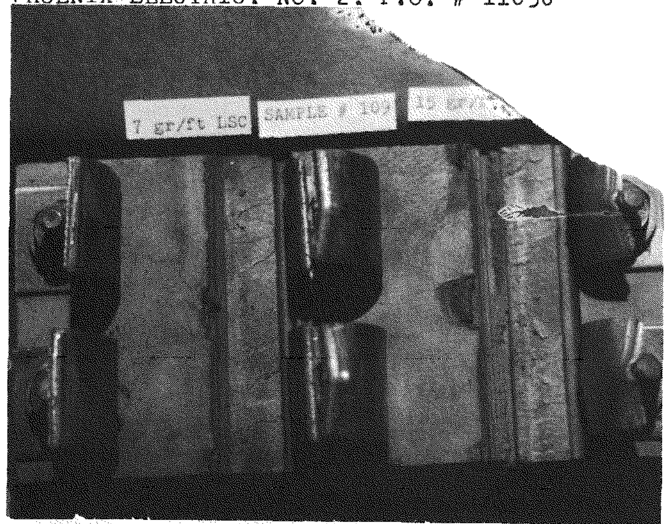


FIGURE 3-9

PHOENIX ELECTRIC: No. 2: P.O. # 11850



PHOENIX ELECTRIC; No. 2;P.O. # 11850

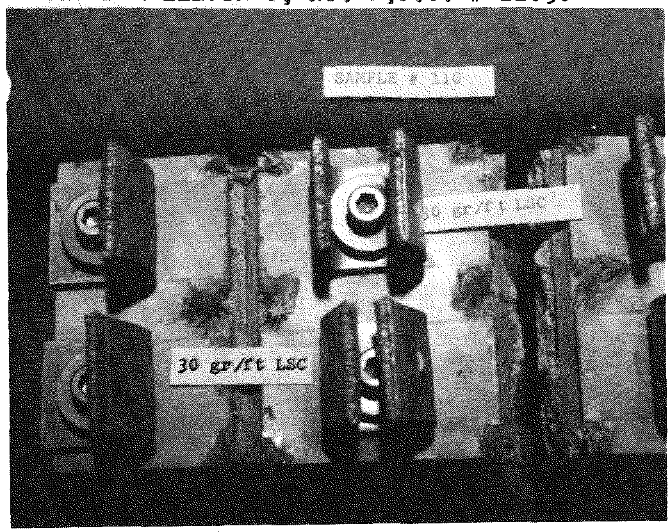


FIGURE 3-10

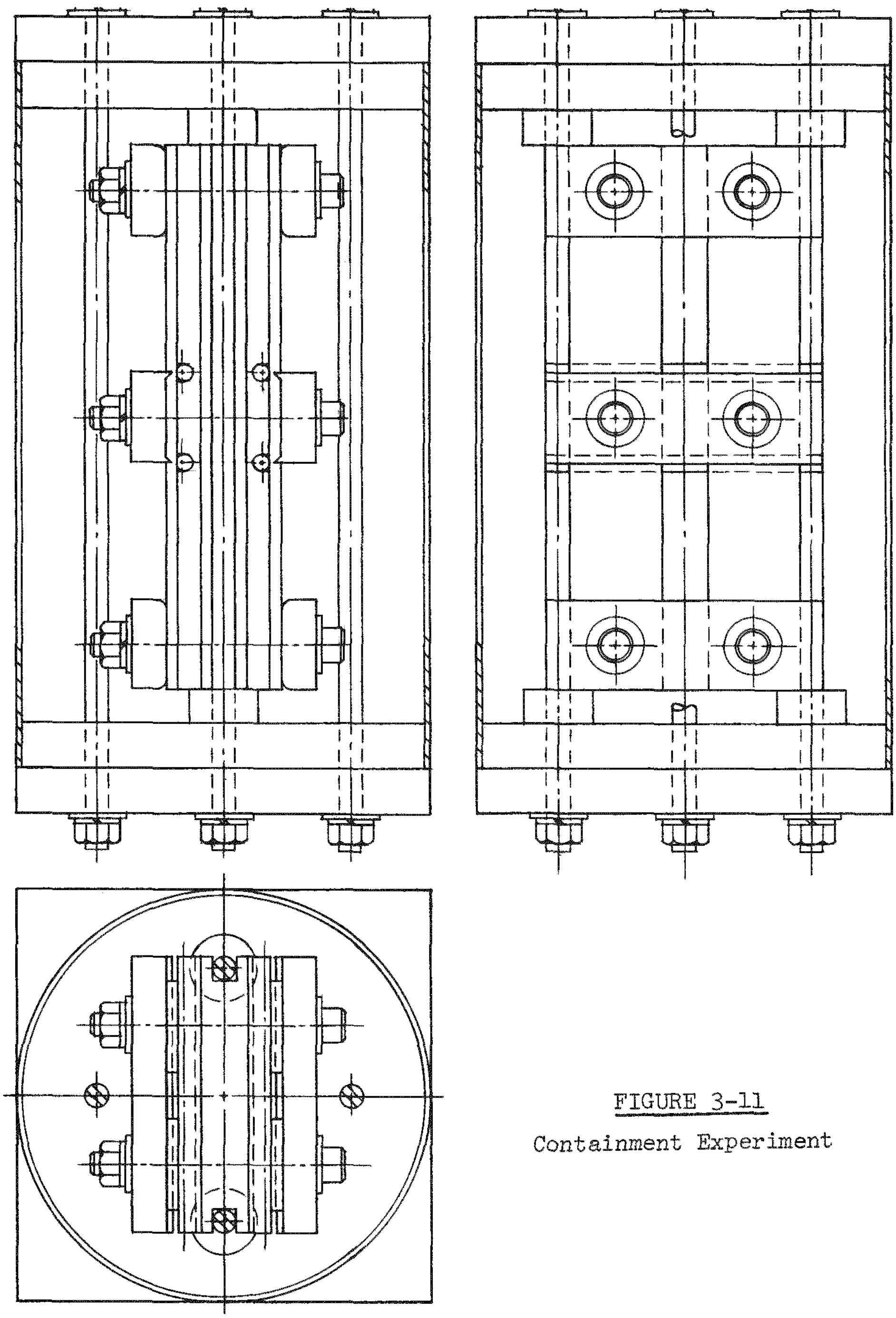
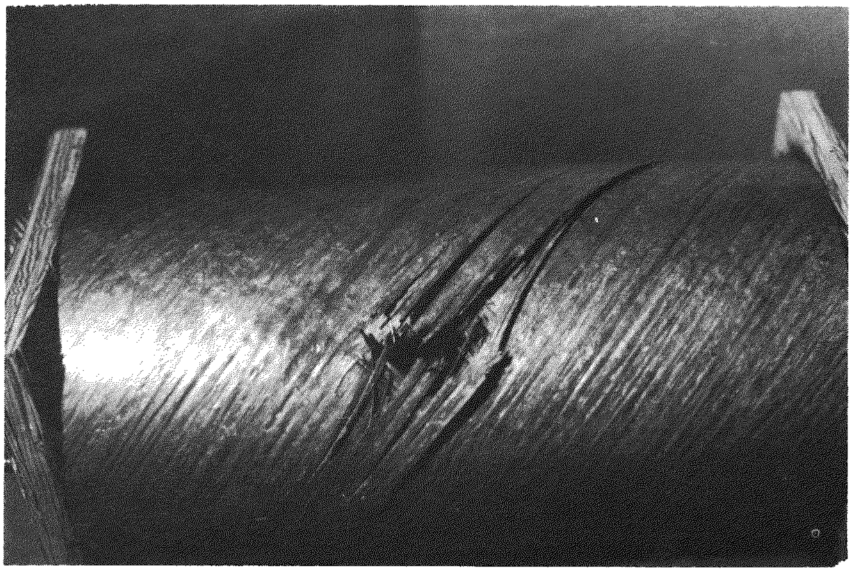
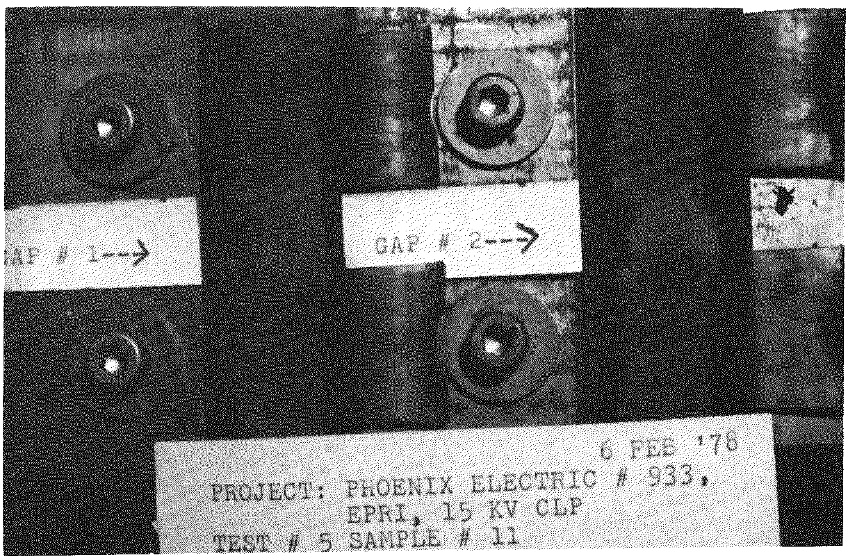


FIGURE 3-11

Containment Experiment





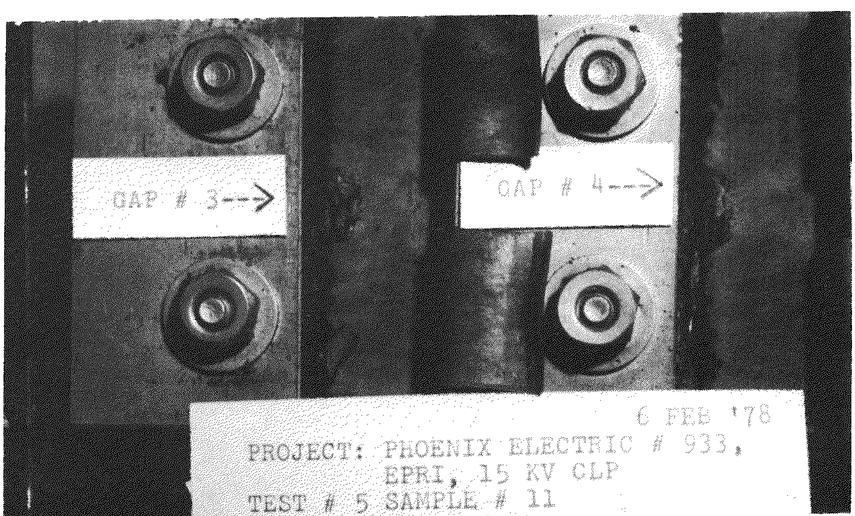


FIGURE 3-12

Photograh of Containment test. Cut in housing was caused by primary charge resting on wall. Lower (2) pictures show cutting experiment with 1/16" Cu and 25 grains of PETN.

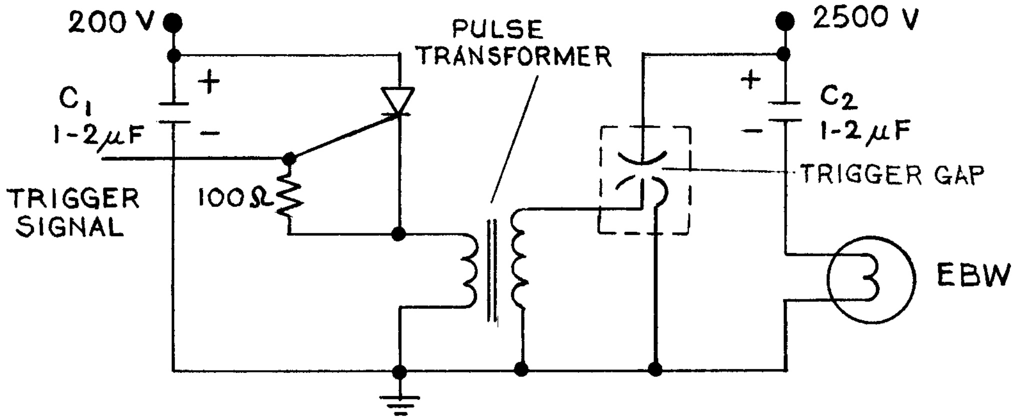


FIGURE 3-13: Firing Circuit for EBW

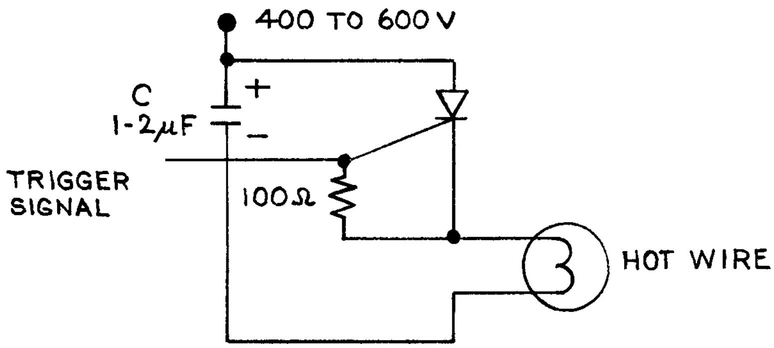


FIGURE 3-14: Firing Circuit for Hot Wire

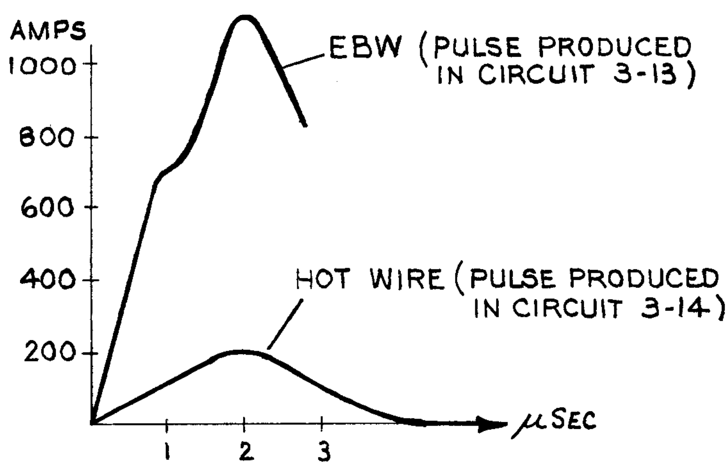


FIGURE 3-15: Typical Firing Pulses

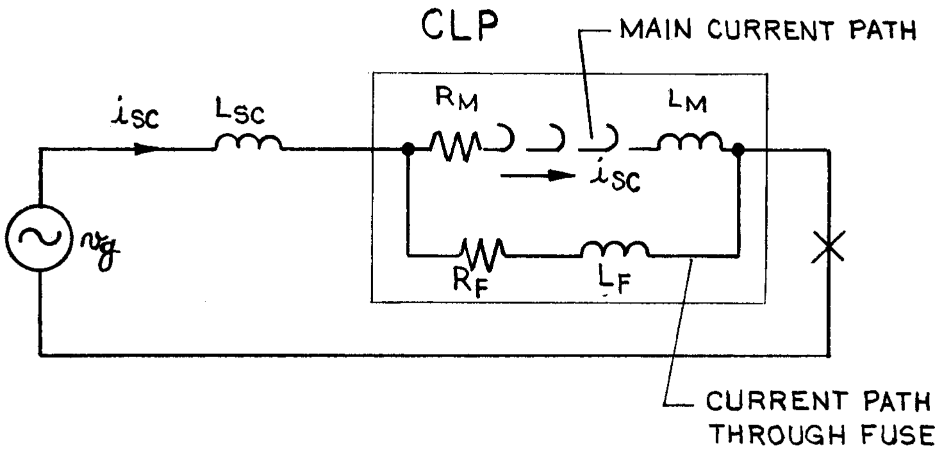


FIGURE 3-16: Single Phase Circuit with CLP

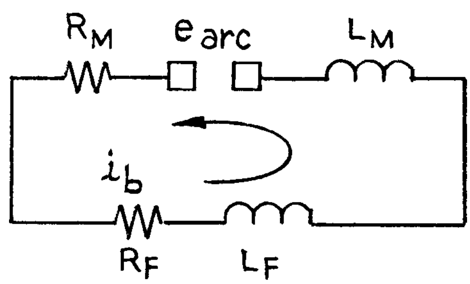


FIGURE 3-17: Commutation Loop of CLP

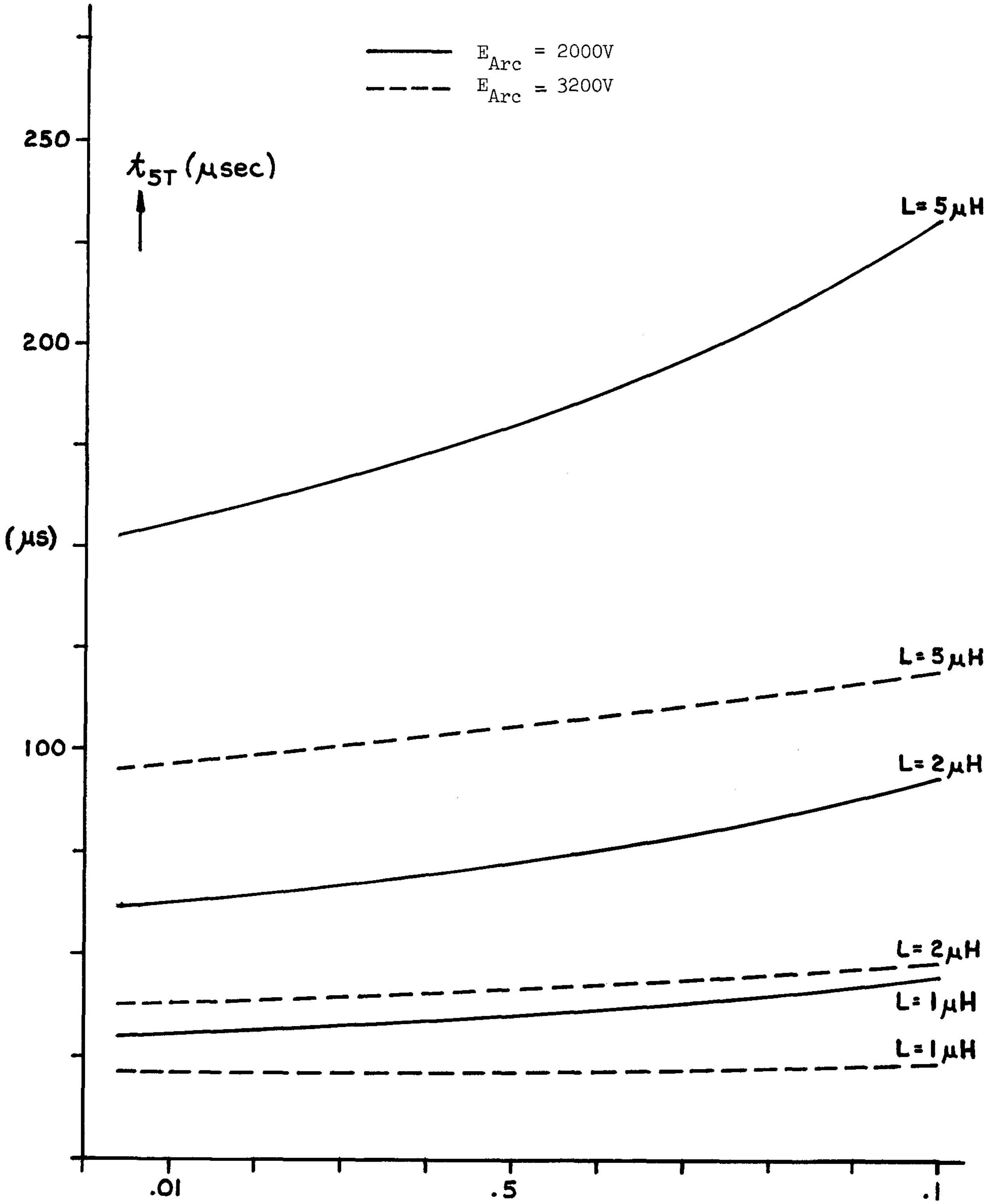


FIGURE 3-18

Commutation Time vs. Fuse Resistance

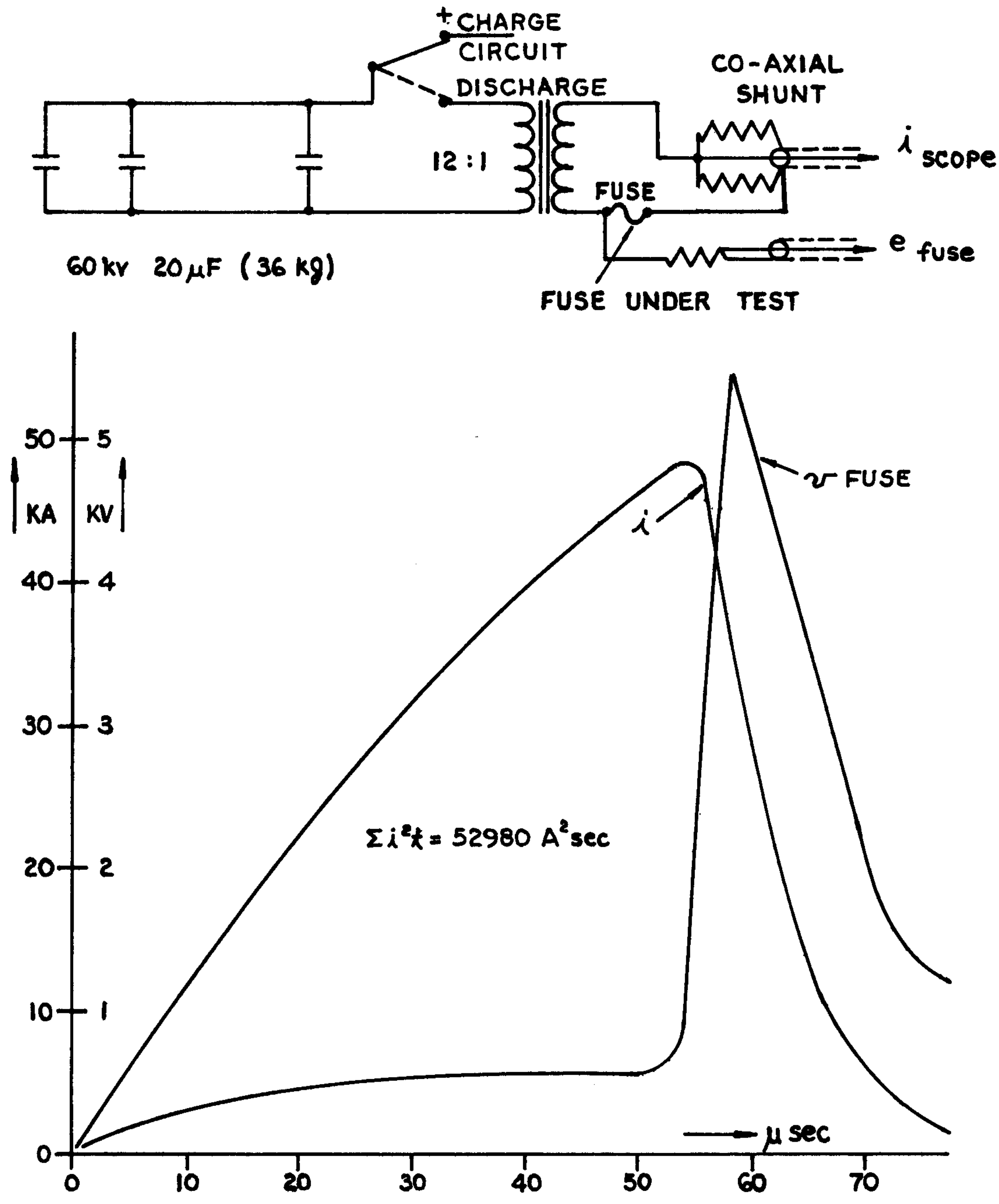


FIGURE 3-19

FUSE MELTING TEST AND TEST CIRCUIT

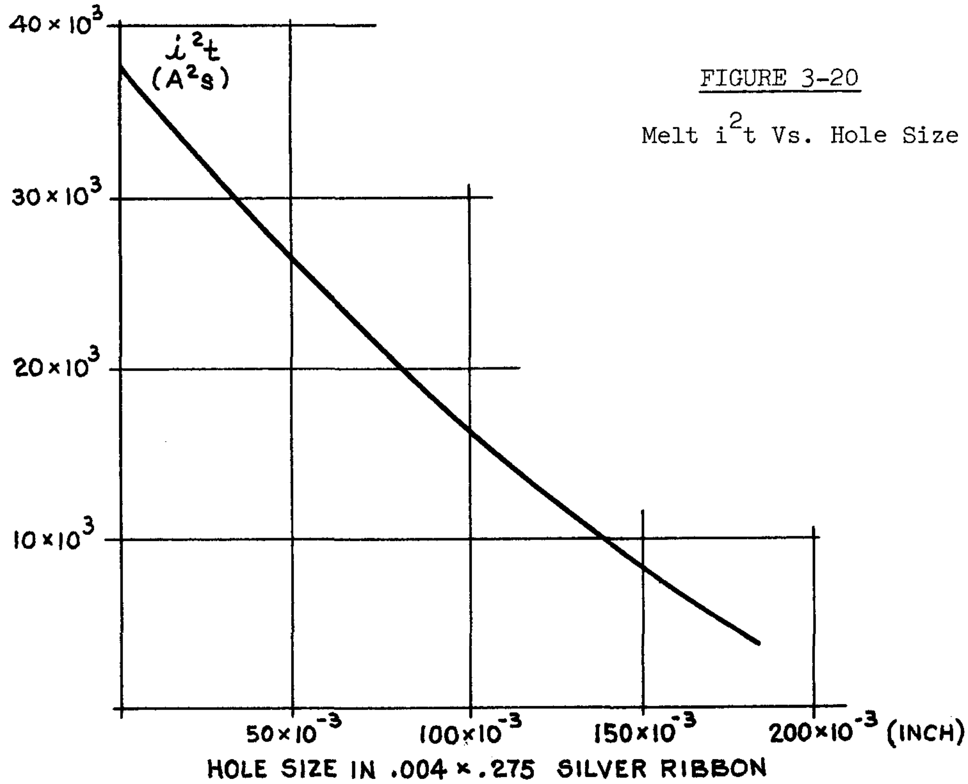


FIGURE 3-20

Melt i^2t Vs. Hole Size

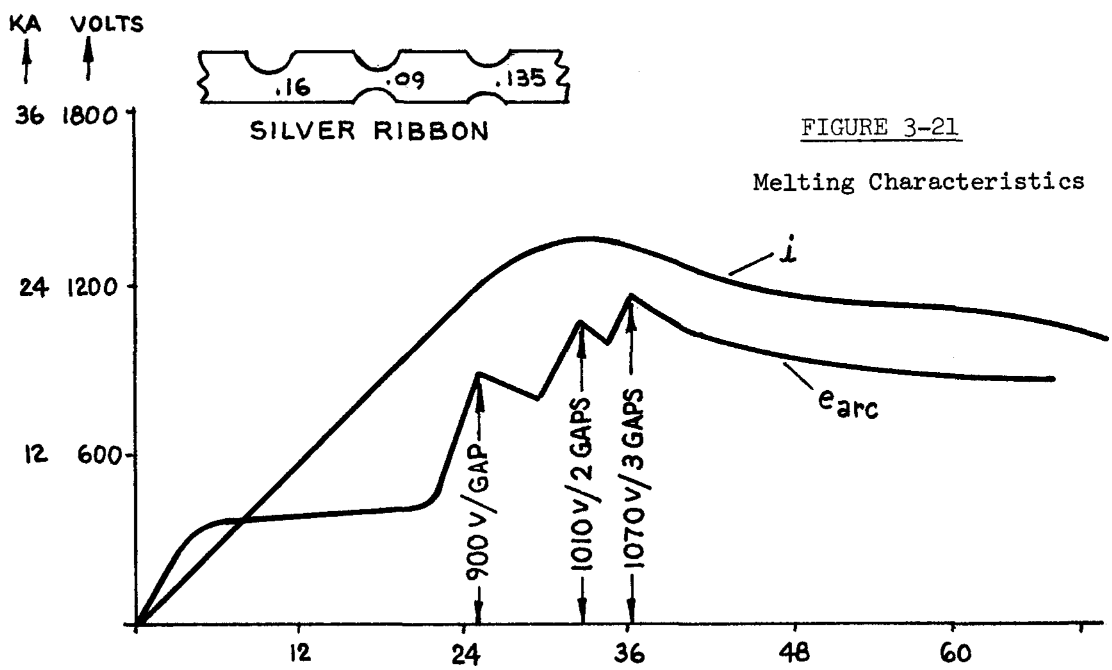
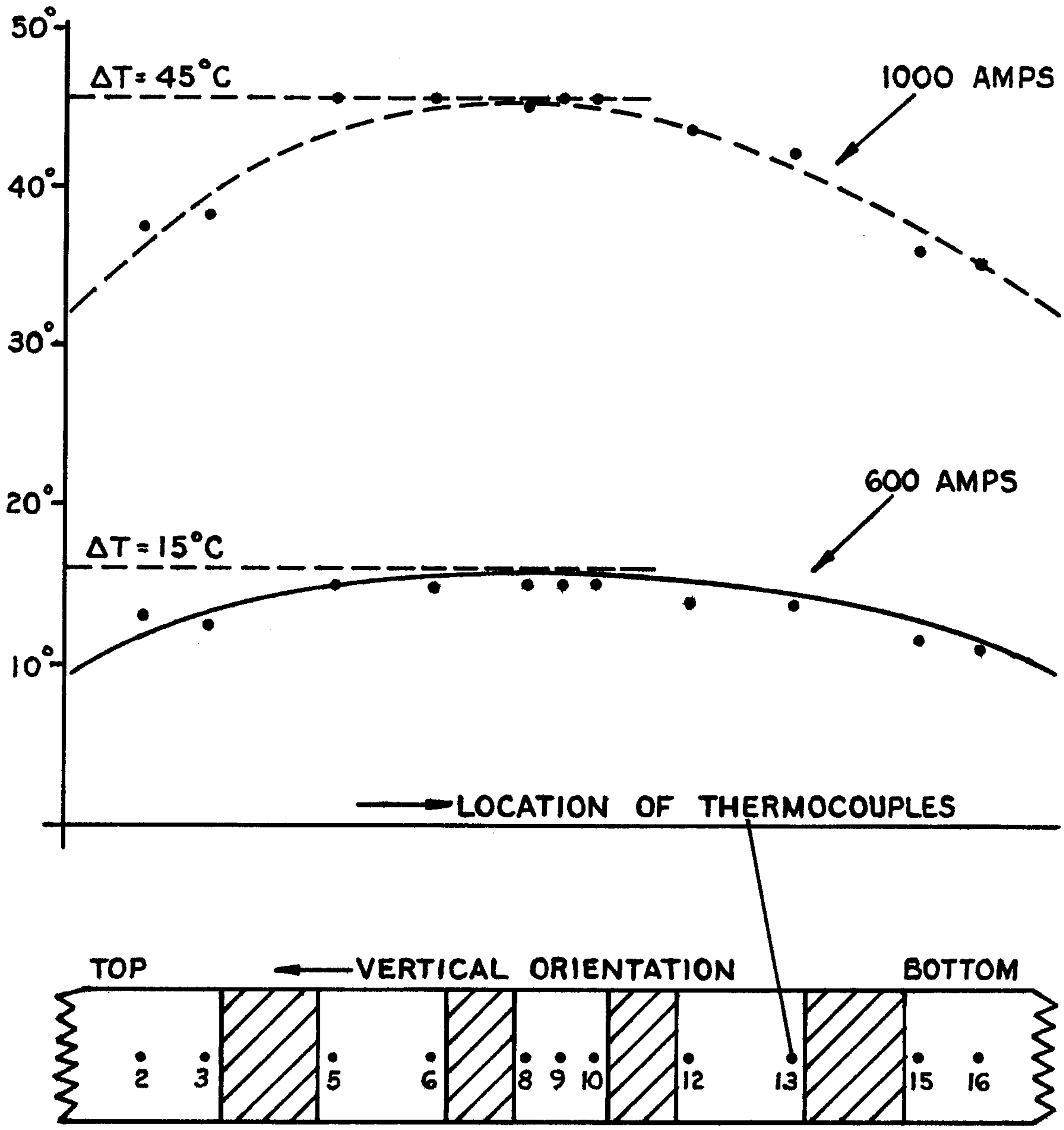


FIGURE 3-21

Melting Characteristics



Main Conductor 1 in^2 Copper Cross Section Enclosed in 8" Diameter Fiberglass Tube

FIGURE 3-22

CLP Heat Run

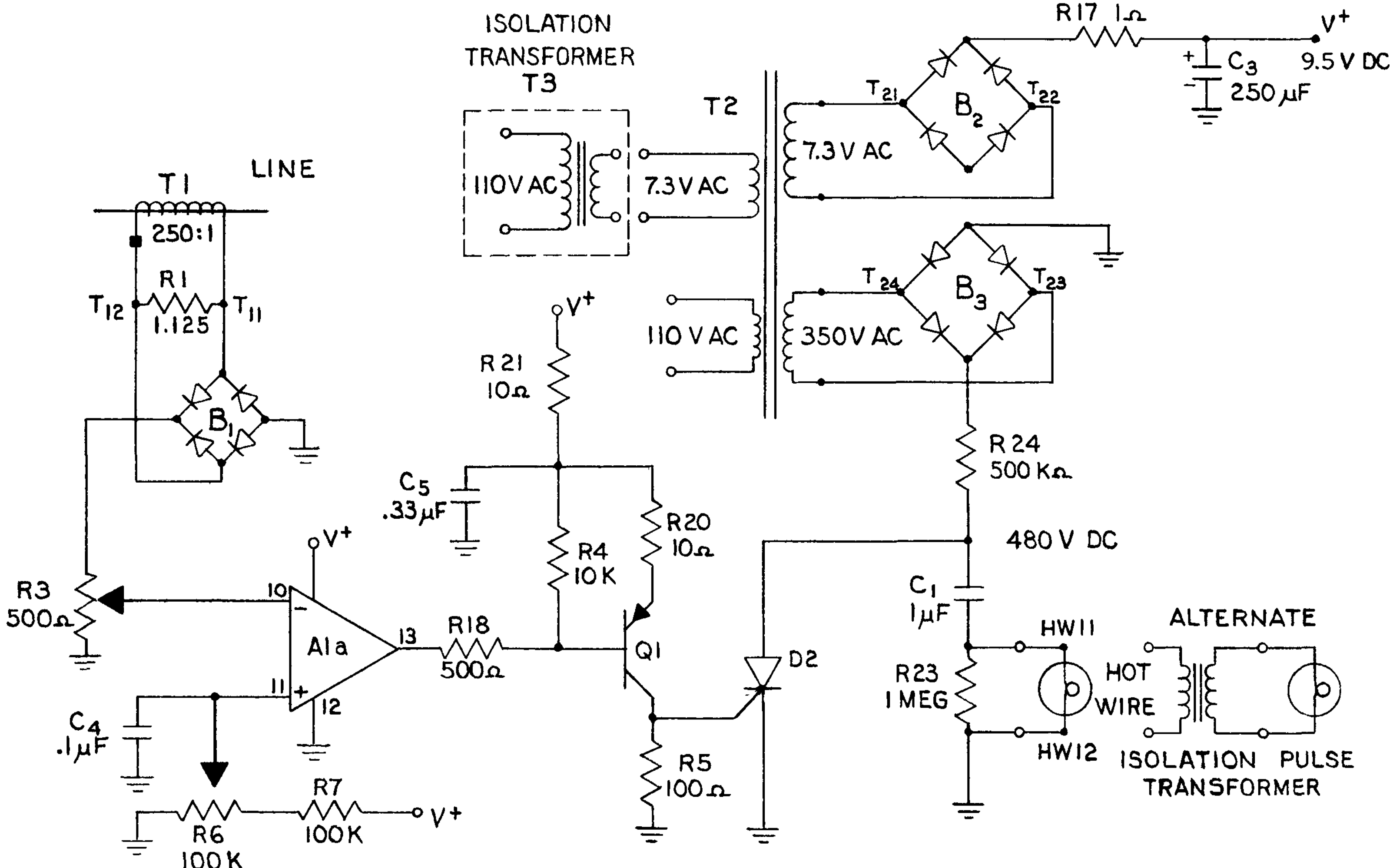


FIGURE 3-23

Sensing and Firing Circuit

Section Four

PERFORMANCE OF THE CLP IN THE M.I.T. CIRCUIT

4.1 THEORETICAL PERFORMANCE:

The current limiting process of a CLP is fast by comparison to the change of current in an a.c. circuit. Therefore, interruption can be simulated in a synthetic d.c. circuit. Such a circuit is the "ALCATOR A" at the M.I.T. National Magnet Laboratory. The circuit and its functioning in combination with the CLP are shown in Figure 4-1. A relatively low voltage d.c. source charges the cryogenic main inductance, L = 5 or 9 mH. Neglecting the leakage inductance and the parallel protective resistor R it is seen that the CLP completes the circuit. The series resistance of this circuit is small and dictates together with the main inductance L the rise of the current. Thus typically 20,000 ampere are reached in approximately 2 seconds. At that time the CLP is initiated. In sequence the conductor is cut, the current commutated to the fuse, the fuse is melted and creates an arc voltage, which drives the current through the CLP to zero. These events are also sketched in Figure 4-1. At the same time the current in the resistor R, builds up and produces a voltage drop, which simulates the recovery voltage across the CLP. The sketch of Figure 4-1 illustrates this. The oscillation in the recovery period is due to the stray inductance and capacitances. Figures 4-2a, b show typical oscillograms of an interruption of 18,300 Amps. The interpretation of the various time intervals is provided by Figure 4-1.

<u>Interruption - Theory</u>

Interruption of the d.c. current is accomplished in the CLP concept by driving the current to zero with the so-called backward moving current (see Sections 2 and 3). This current is a consequence of the time integral over the arc voltage of the fuse.

The loop equation of a circuit containing an arc voltage and some inductance may be written

$$v = L\, di/dt + e_a \qquad (4\text{-}1)$$

integration gives

$$i(t) = \int \frac{v\, dt}{L} - \int \frac{e_a\, dt}{L} \qquad (4\text{-}2)$$

It follows that the current is zero if

$$\int \frac{v\ dt}{L} = \int \frac{e_a\ dt}{L} \qquad (4\text{-}3)$$

or in other words: prospective current = backward moving current, where v is the source voltage driving the prospective short circuit current and e_a is the arc voltage which causes the backward moving current to flow. Equation (4-3) teaches that the interruption interval $t_4 - t_3$ of Figure 4-1 is short, if the arc voltage is high, and has a sustained square top pulse appearance. The arc voltages, e_a, developed by fuses, however, have more the appearance of a sharply rising pulse and a fairly rapidly decaying tail as idealized for a wire fuse in Figure 4-3. Using this fuse characteristic we shall now calculate the interruption process beginning at the instant of melting i.e. appearance of e_a of the fuse. In simulating interruption, equation (4-1) will be solved in increments. Rewriting this equation gives the basic scheme

$$\Delta i = \frac{v - e_a}{L} \Delta t \quad (i_R \text{ drop is neglected}) \qquad (4\text{-}3)$$

Knowing the system voltage v and arc voltage e_a at any given instant results with the inductance, L, in the change of the current over the time interval Δt. The first few intervals following fuse melting reduce already the current of 20,000 amperes. The length of the interval was chosen as 5 μsec, the inductance L = 60 micro Henry. The circuit voltage in this example is 4.6 kV and the average fuse voltage over the first time interval is 2 kV. The following computational scheme illustrates the procedure which leads to current interruption. Steps 1 and 2 are given below:

Δi_1 = (4600 - 2000) x 5/60 = +216 ampere

i_1 = 20,000 + 216 = 20216 ampere

Step 2 fuse voltage from Figure 4-3 e_a = 6000 Volts

Δi_2 = (4600 - 6000) x 5/60 = -116 ampere

i_2 = 20216 - 116 = 20,100 ampere

.

. Etc.

.

.

We have achieved simulated interruption at 650 microseconds in 19 time steps of varying length. The results are plotted in Figure 4-4. It is evident that the interruption would be delayed if L were larger or if the arc voltage were lower. Interruption in such a d.c. circuit would be prevented altogether if the sustained arc voltage were less than the system voltage.

Interruption in the M.I.T. circuit though similar is somewhat different. The equivalent circuit of Figure 4-5 illustrates how the driving voltage is really derived from the voltage across the resistor R. The total current is given by the equation

$$i_{total} = 20{,}000 = v/R + \int \frac{v-e_a}{L}\,dt \qquad (4\text{-}4)$$

differentiation gives

$$0 = \frac{1}{R}\frac{dv}{dt} + \frac{v-e_a}{L} \qquad (4\text{-}5)$$

since e_a is non-linear this equation will again be solved in increments by re-writing Equation (4-5) in the form

$$\frac{\Delta v}{R} = \Delta i_R = \frac{e_a - v}{L}\,\Delta t \qquad (4\text{-}6)$$

The current through the CLP is obtained by subtracting the sum of the incremental currents from the total current, viz:

$$i_{CLP}(t) = 20{,}000 - \Sigma\Delta i_R = 20{,}000 - \Sigma\,\frac{e_a - v}{L}\,\Delta t \qquad (4\text{-}7)$$

The initial conditions are $i_R = 0$ at $t = 0$.

The arc voltage used in solving this equation was assumed similar to Figure 4-3, except the peak was taken as 16kV and the sustained voltage was 3 kV. The parallel resistance R of Figure 4-5 was .11 Ohms, giving a recovery voltage of 2000 Volts in this particular case.

Several interruptions with different circuit inductances were simulated and are shown in Figure 4-6. An actual interruption was superimposed on this figure.

It is between the 25 and 50 μH curves. In checking out the circuit the inductance was determined at 20 μH, however, lead inductances could have contributed 10 to 15 μH in addition. Considering also uncertainties in the arc voltage the match of the theoretical and actual performance appears gratifying.

4.2 EXPERIMENTAL RESULTS:

4.2.1 Test Circuit and Instrumentation:

The performance of the CLP was first tested in a test program at the M.I.T. Magnet Laboratory late in 1977. The synthetic circuit and circuit data together with the basic instrumentation and the firing circuit are shown in Figure 4-7. This circuit is normally used for arc plasma studies and was made available for CLP tests. The instrumentation circuits were not free of interference, nor was the ground connection ideal for our testing and record keeping. These short comings were accepted as a trade-off against test cost and a long waiting time in a suitable outside laboratory.

The circuit was instrumented to measure the main circuit current with a shunt and the current through the CLP with a Rogowski coil and an integrating circuit. The voltages across the resistor R and the CLP were measured differentially with 1000:1 Tektronix probes.

The primary charge was initiated with the firing circuit of Figure 4-7. It was triggered by a master control which started the sequence of events after the d.c. supply had reached a preselected current value. It also provided trigger signals to the oscilloscopes.

A total of 10 CLP devices were tested. The results are listed in Table 4-1. Since this was the first test series a detailed description appears in order to set the stage for future work by evaluation of experimental problems and peculiarities of the test device.

The CLP devices of this series were equipped with (3) charges each cutting through 1.5 mm (1/16") copper or aluminum. Fuses with multiple silver wire elements as given in Table 4-1 were used. (The fuse numbers refer to American Wire Gauge).

Tests 0 through 4 were preliminary. The timing of the devices was determined and instrumentation was improved. For the timing tests a foil type ionization switch was placed in front of the charge. On actuation the switch would make contact

Table 4-1

CLP TEST AT M.I.T. MAGNET LAB

Test Number	Fuse Wire	Initial Current Amps	Time from Trigger Pulse to Open Conductor μsec	Time to Cut Conductor μsec	Time from Trigger Pulse to Start of Fuse Current μsec	Transfer Time from Conductor to Fuse μsec	Fuse Melting Time μsec	Fuse Melting Plus Interrupting Time μsec	Fuse Arcing Time μsec	Total Interrupting Time Less 200 μsec Initiation Time μsec	Peak Fuse Voltage Volts	Sustained Fuse Voltage at Extinction Volts	Average Recovery Voltage Volts	Peak Recovery Voltage Volts	F_1 of Recovery Voltage Hertz	F_2 of Recovery Voltage Hertz
0	timing test: Time interval from trig pulse to detonation of primary charge ≈ 200 μsec															
1	2x#24	3660 CLP not fired														
2	2x#24	Insufficient oscillographic records														
3	24/ /25	3430	CLP not fired, dry run to check out traces													
4	24/ /25	3460	Interruption O.K., but time expanded voltage and current traces must be improved													
5	24/ /25	8800					180	254	74		> 2000	790	700	730		947
6	24/ /25	10420					133	217	84		> 4000	1000	870	960		1200
7	24/ /25	16020	225	25	325	100	65	142	77	267	≥ 11000	2150	1660	2000	40000	947
8	2x#24	17660	225	25	300	75	75	150	75	250	≥ 11400	2300	2000	2270	40000	946
9	2x#25	17600	Left gap not fired				50	CLP Failed, arc voltage of 2 gaps varied from 1670/800								
10	2x#25	18060	Middle gap not fired - CLP failed - no recovery voltage record													
11	2x#24	18310	250	≈50	325	75	67	142	75	267	≥ 11000	2300	2000	2320	40000	940
12	3x#25	14000	222	22	365	143	132	217	85	382	8000	2000	1600	1830		947
	Outer 2 gaps were fired only															

and thus permit measurement of the time interval between the trigger pulse and the initiation of the linear charge. With the circuit of Figure 4-7 this time was 200 microseconds. In later experiments it was reduced to 3 microseconds by a higher energy pulse firing circuit.

Beginning with Test #5 pertinent data were obtained by analysis of oscillograms. These are listed in Table 4-1. Column 1 gives the test number, column 2 the number and the size of the silver wire elements of the fuses. The current, commutation, melting and arcing times as well as fuse voltage and recovery data are given in subsequent columns.

Of particular interest is the total interrupting time. Not included is the actuation time of the primary charge. At currents above 16 kA and identical fuse elements the interrupting time is in the order of 250 microseconds. The fuse arcing time is approximately constant at 75 to 85 microseconds. A longer arcing time was expected in view of the theoretical analysis of the interrupting process in Section 4.1.

The observed fuse melting times compare favorably on an i^2t basis. This confirms that the melting time integral permits scaling of fuses in the time intervals, which are of interest here.

The oscillographic records of this test series are insufficient to make any claims of accuracy, however, they do give an indication of the peak and of the sustained arc voltages.

The current transfer times from the instant at which the conductor was cut till the fuse carried the entire current ranged from 75 to 100 microseconds. 140 microseconds, or doubling of the transfer time was observed, when the number of arc gaps and thus the arc voltage was reduced to 2/3. This increase in commutation time is expected in view of Section 3.4 and is readily verified by the values of Table 3-2.

The recovery voltage in the M.I.T. circuit is due to the voltage difference of the fuse voltage and of the voltage drop across the resistor R (Figure 4-1) at interruption of the current. No unusually high recovery voltages were observed, which indicates that the current is not forced to zero at an excessive rate. Peak recovery voltages up to 2300 Volts were observed in this series of experiments. The frequencies of the transient recovery oscillations were 9000 and 40,000 Hertz.

Failure was induced in two test devices, viz: on Tests #9 and #10 when only 2 out of 3 gaps were fired and fuses with short melting times were used. This becomes clear when Tests #9, #10 and #12 are compared. The fuse melting time on Test #9 was 50 microseconds. For Test #10 we compute on an i^2t basis 47 microseconds, while on Test #12 we measured 132 microseconds. (The reason for the longer melting time is the use of 3 elements instead of 2). Since on Tests #9 and #10 two main gaps broke down independent of the position of the gaps but the two gaps of Test #12 did not fail, we conclude that the failure cause is insufficient thermal recovery in the first 50 microseconds after current commutation. Therefore, it appears immaterial during the thermal recovery period whether 2 or 3 or more gaps are fired.

The thermal recovery period can be gauged even closer from the above experiments comparing the failures for example with the successes of Tests #8 and #11. In both these cases the interrupting currents were about the same, but the fuse melting times which are equal to the recovery times of the gaps were 67 and 75 microseconds respectively, i.e. slightly longer than on the failures.

In conclusion the gaps of the CLP recover dielectric strength between 50 and 67 microseconds after completion of commutation. The recovery is dramatic if one considers that the gaps withstand the peak fuse arc voltage of 11 kV.

(7) additional experiments were performed at higher voltages and using wire fuses with higher peak arc voltages. These devices recovered against recovery voltages of 5800 to 9000 Volts. On these experiments peak fuse voltages up to 64 kV were measured and successfully withstood by 3 gaps. We could not verify the accuracy of these voltages due to loss of instrumentation, however, we wish to state, that the voltage is consistent with the length of the fuse wire in this case and, therefore, not unexpected.

In the last test series at M.I.T. (13) CLP devices were tested using ribbon fuse elements. The ribbon elements were developed at Phoenix Electric Corp. This fuse program was described in Section 3.5. The purpose was to provide fuses with a low controlled peak arc voltage and a fairly high sustained arc voltage. The second object was to provide fuses with a precise melting time.

This last test series at M.I.T. using ribbon elements resulted as a practical spin-off in a d.c. device suitable for protection of batteries or fuel cells. Application was verified to voltages of 5kV continuous currents to 2000 amperes and interrupting currents to 20,000 ampere d.c. in circuits with possible rates of rise of the short circuit current of up to 80 A/μsec.

4.3 SUMMARY AND CONCLUSIONS:

- The theory of the interaction of the CLP with d.c. circuits and in particular the M.I.T. ALCATOR A circuit was developed and verified.
- Experimental CLP prototypes were built and tested.
- A multiplicity of interrupting tests were performed at currents up to 20,000 ampere d.c. and recovery voltages up to 10,000 Volts.
- The CLP performed the interrupting function within less than 1 m second depending on the selected melting time of the fuse, the fuse arc voltage and the circuit inductance.
- The CLP becomes current limiting in less than 200 microseconds. (this is the time from initiation to melting of the fuse).
- The CLP operational times are highly repetitive.
- The test results have encouraged the further development of an a.c. current limiter.
- The test results have verified a CLP design for application in the protection of batteries or a fuel cell circuit with ratings of 5 kV, 2000 ampere continuous current and 20,000 ampere interrupting duty with rates of rise of current up to 80 ampere/microsecond.

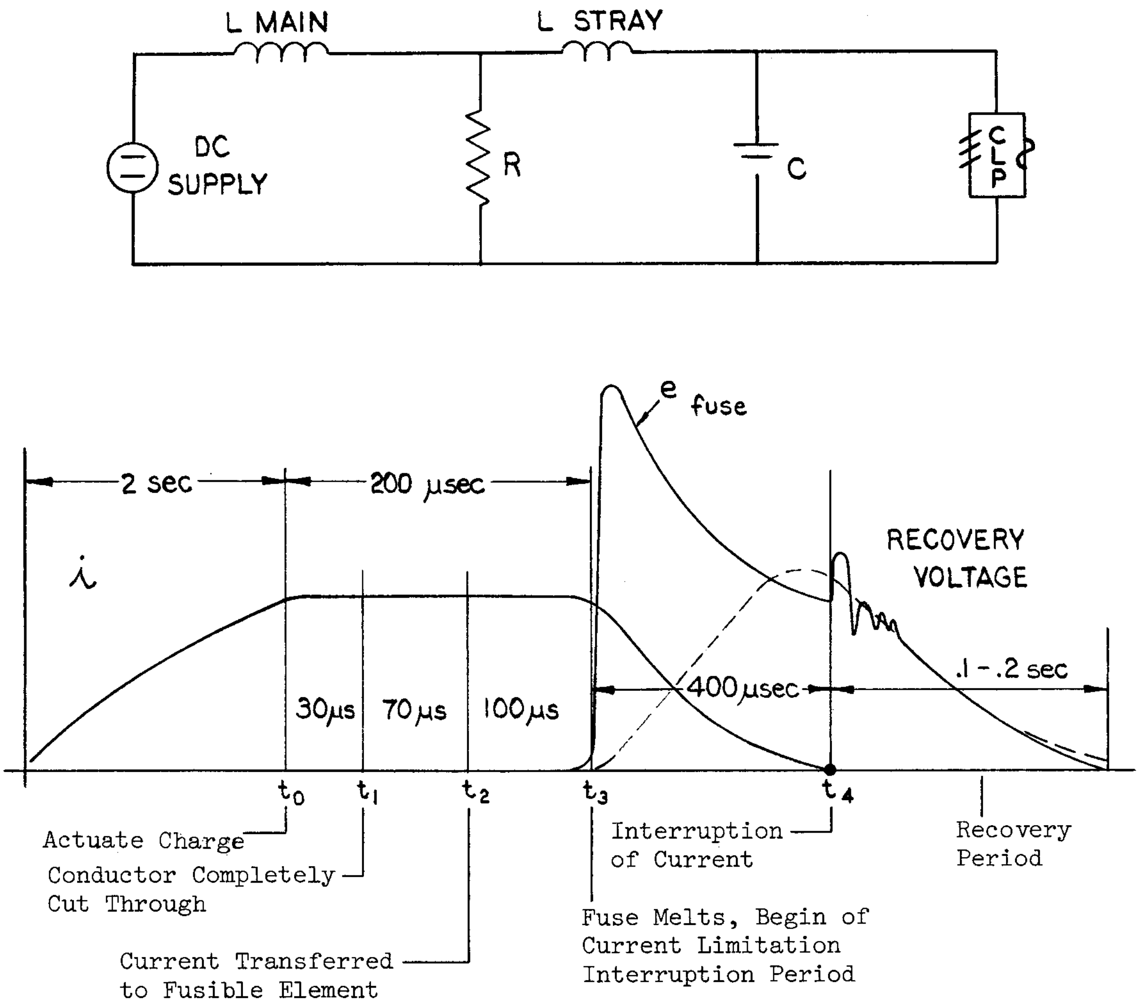


FIGURE 4-1

Interruption Process of CLP
in M. I. T. ALCATOR circuit.

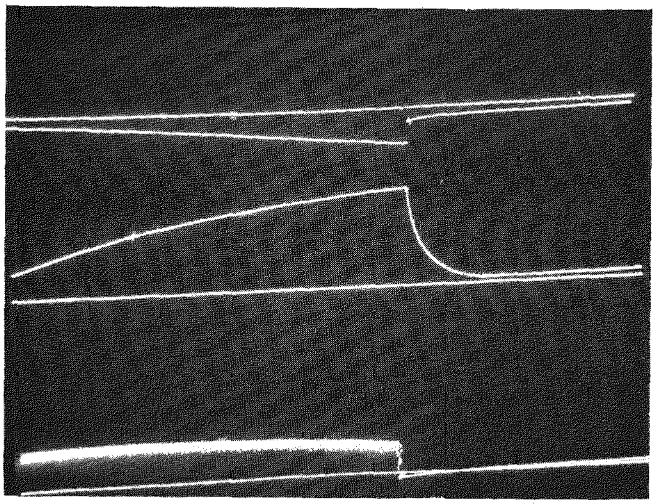


FIGURE 4-2a: Oscillogram of interruption process. Trace 2 is current reaching a crest of 18,300 ampere. Sweep = 100 ms/division current rise time is greater than 1.5 seconds. The current is interrupted in the CLP in approximately 200 μ sec

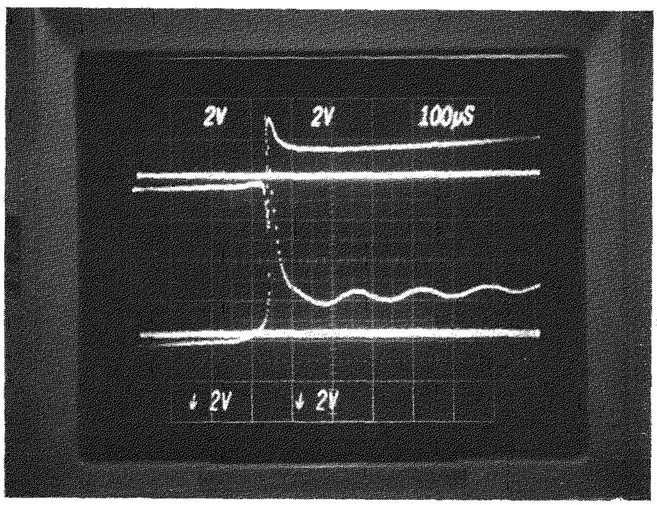


FIGURE 4-2b: Oscillogram of voltages across resistor R and the CLP. The melting peak of the fuse (lower trace) reaches 11 kV. The subsequent recovery voltage oscillates about 2 kV.

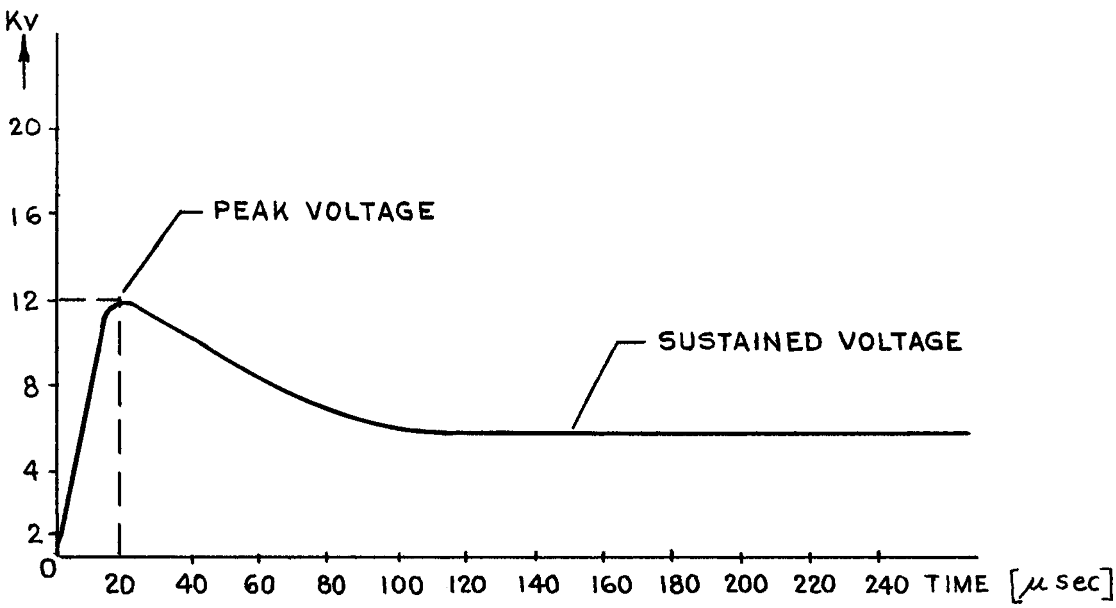
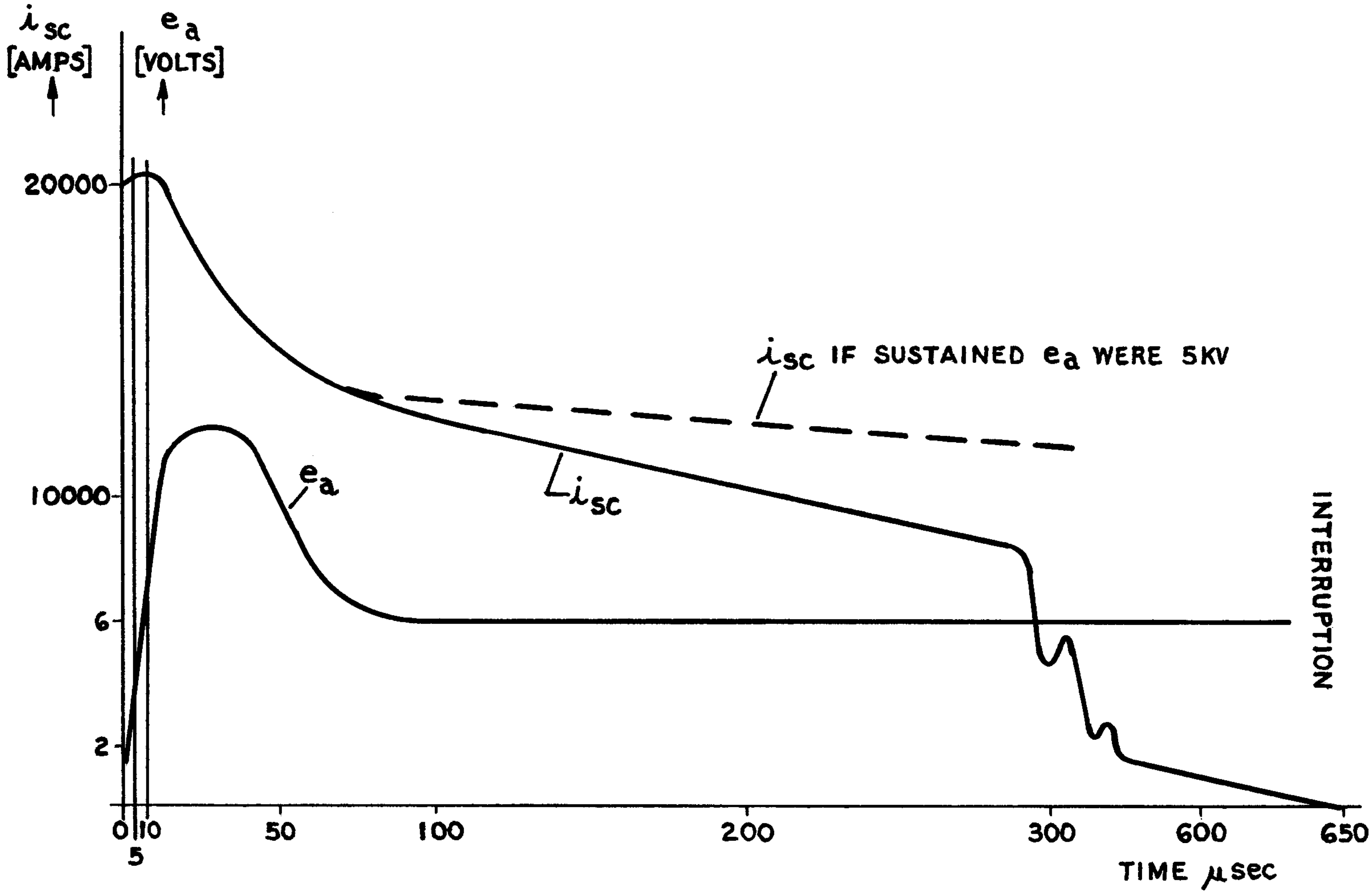


FIGURE 4-3: Idealized Arc Voltage of 25cm Long Wire Fuse Element. Current to be Interrupted Approximately 20 kA d.c.

FIGURE 4-4: Interruption of Short Circuit Current by CLP
(System Voltage 4.6 kV, L = 60 μH
Fuse Voltage per Figure 4-3)



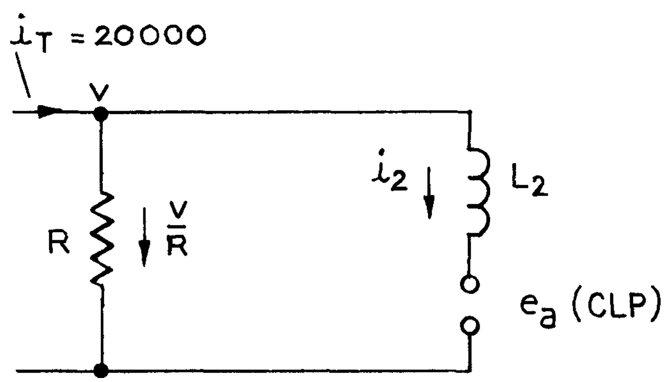
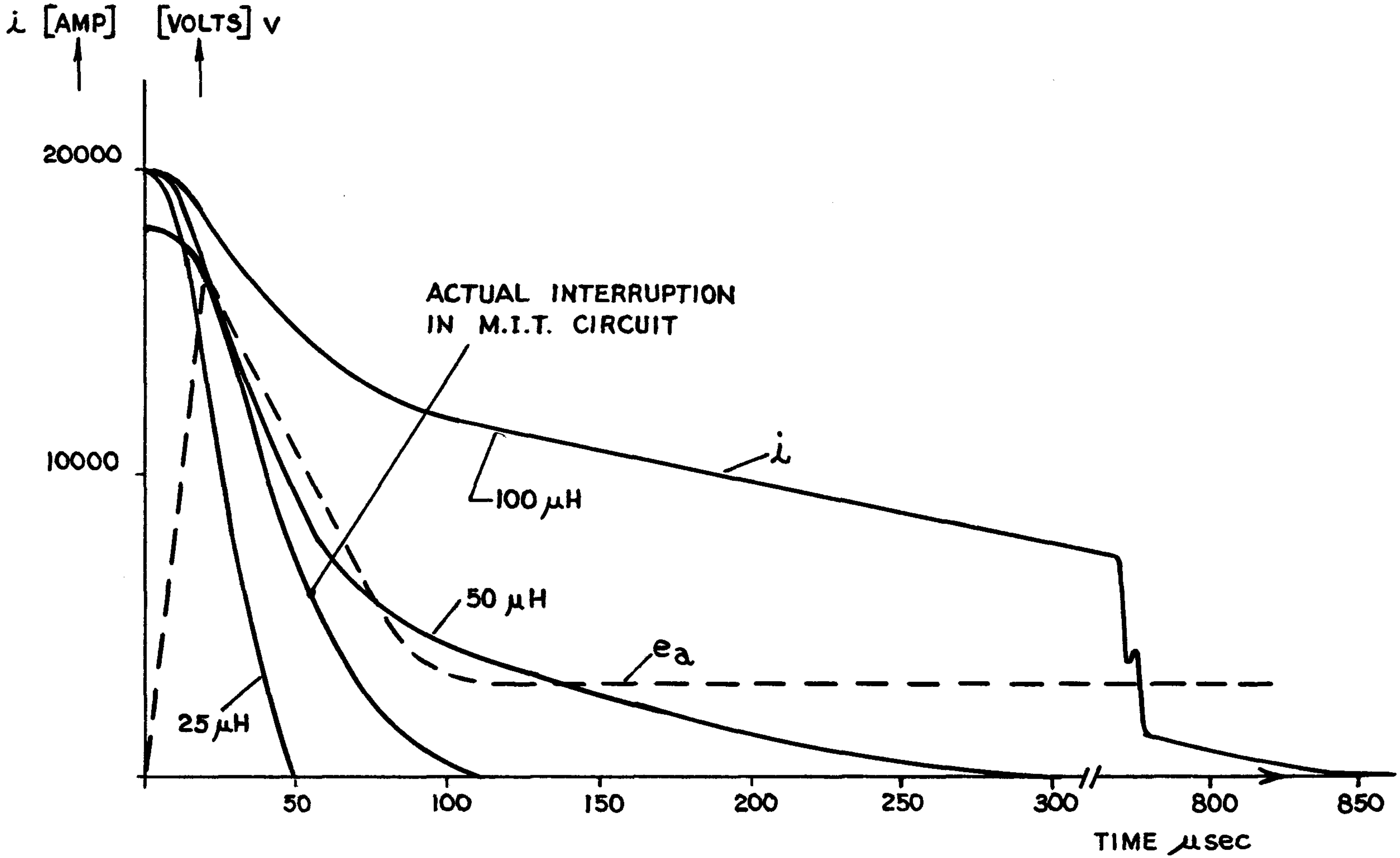
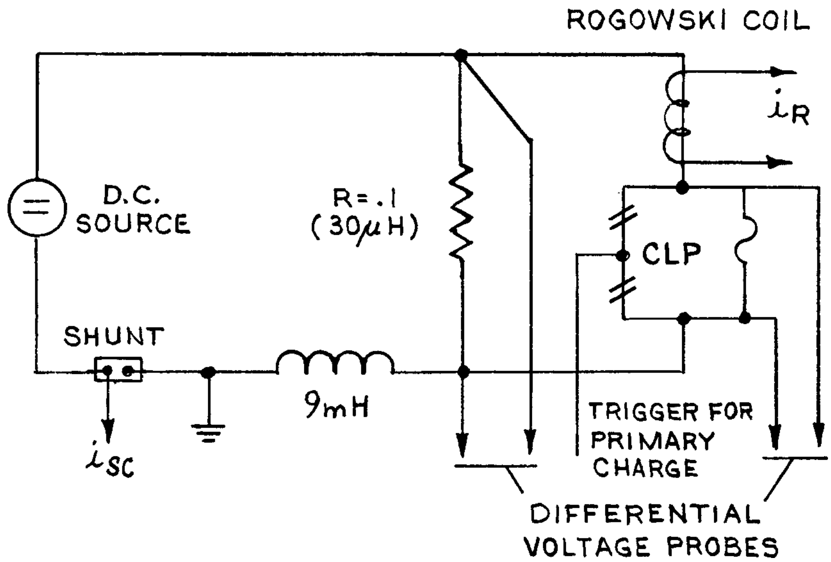


FIGURE 4-5

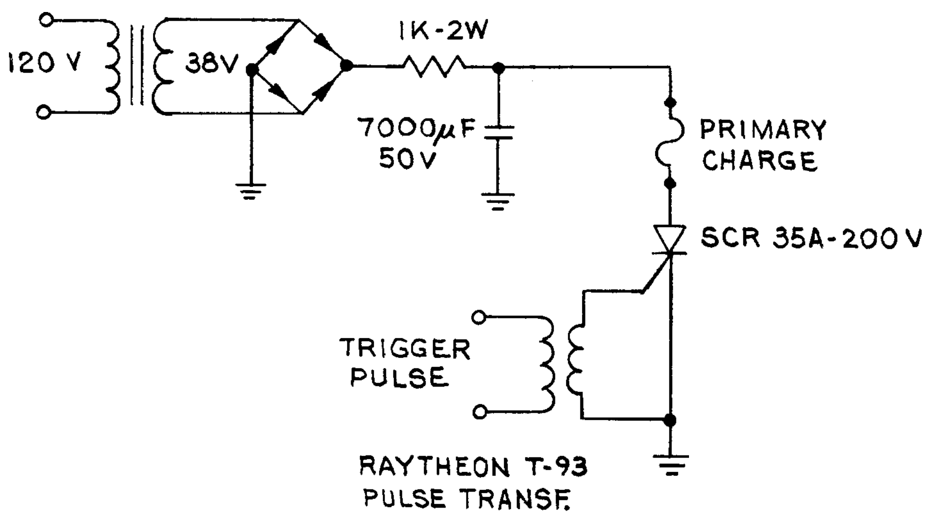
Equivalent Interrupting Circuit

FIGURE 4-6: Interruption of 20,000 Ampere d.c. in Test Circuit of M. I. T. National Magnet Laboratory





M. I. T. Test Circuit



Firing Circuit for CLP

FIGURE 4-7

Section Five

DESIGN OF THE CLP

Considering all elements of the partial developmental efforts and preliminary testing of Sections 3 and 4 the CLP of Figure 5-1 evolved in the final design stages. The basic elements are identified in the following and will be briefly described:

ITEM	DESCRIPTION
1	Main conductor
2	Current limiting fuse
3	Charge holder with Charge
4	Support block
5	End plate
6	Housing
7	Hardware

The main conductor may be copper or aluminum, its function is to carry continuous current and to form into suitable gaps upon operation of the CLP.

The current limiting fuse is typically a sand filled device with a silver wire or ribbon element wound on a mandrel. The particular fuse used here has a very precise melting time, a controlled peak arc voltage and a fairly high sustained arc voltage. Its function is to limit the current and to interrupt the circuit. As such we feel the fuse must meet appropriate ANSI Standards.

The charge holder is made of a special insulating material. Its function is to hold the charges in the proper location relative to the gaps to be cut. It must withstand the cutting action, direct the charge and aid in the deionization of the gaps.

The function of the support block is to provide stiffness to the structure once the cutting has been performed. It is made of insulating material.

The end plates provide seals at the conductor and at the periphery to prevent access to the charge and ingress of moisture, thus forming with the housing an explosion proof unit which can be handled safely.

The weight of the overall unit is approximately 30 pounds. The overall dimensions are shown in Figure 5-1. Not shown in this figure is the separate package of the sensing and firing circuit. While this unit including a special current transformer has been packaged it is considered not final and, therefore, has been omitted from the picture. The following dimensions, however, may serve as a reference:

CT: Window type to fit over a 7.6 x 1.3 cm (3" x 1/2") bus bar
Overall size 12.7 x 12.7 x 12.7 cm (5" x 5" x 5")
Sensing and firing Package: 15.2 x 12.7 x 7.6 cm (6" x 5" x 3")

In addition the pulse transformer was fully encapsulated to provide high voltage insulation. Its size is approximately 10 x 12.7 x 7.6 cm (4" x 5" x 3"). Reduction of the packaging is desirable and will be accomplished in a future project. One of the packages as described above has successfully withstood the short circuit tests. The second unit was destroyed by a failure. With hindsight a fiberglass package would probably have withstood also the failure.

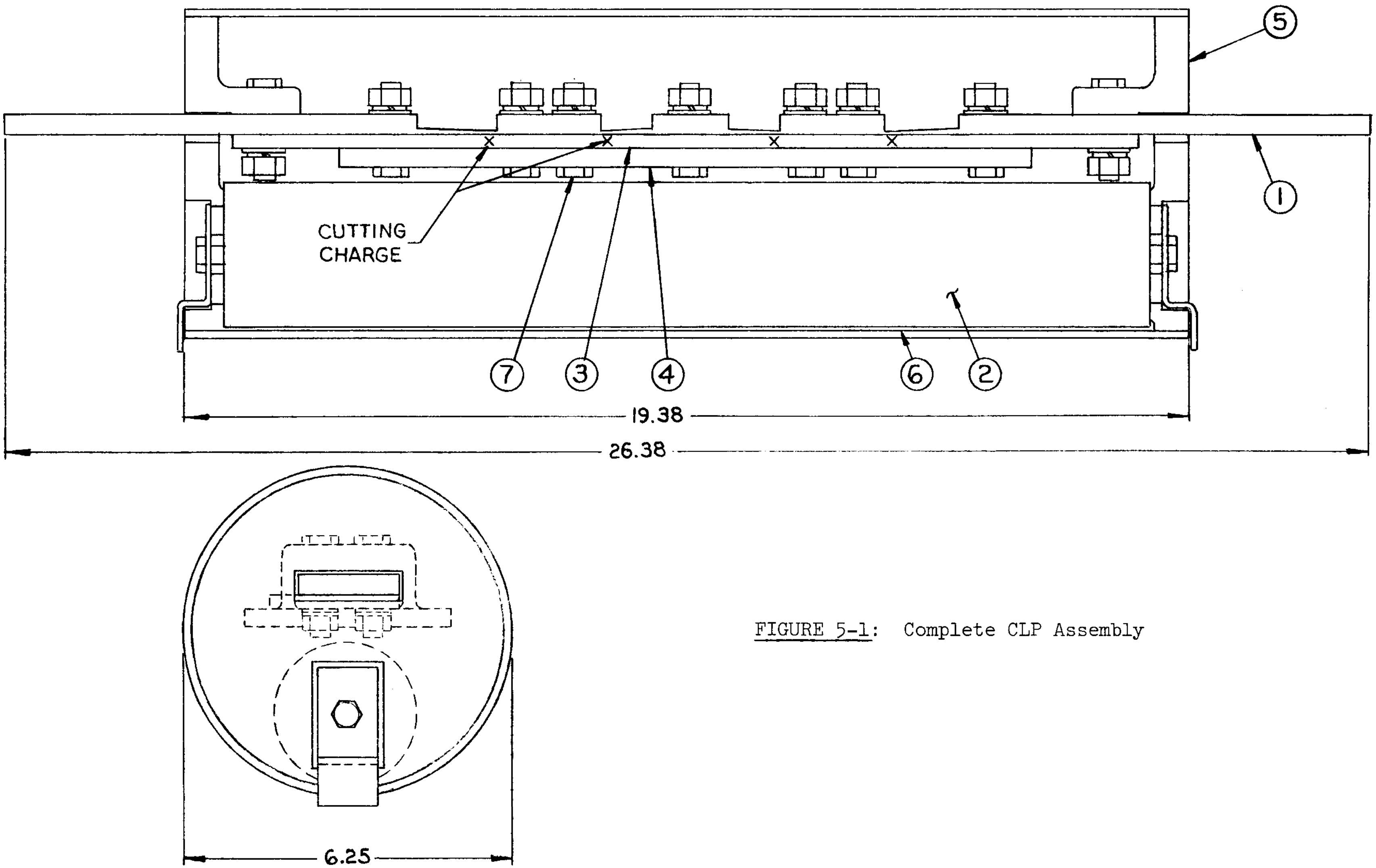


FIGURE 5-1: Complete CLP Assembly

Section Six

PERFORMANCE OF THE CLP IN THE A.C. CIRCUIT

6.1 THEORETICAL PERFORMANCE:

The events leading to current limitation have already been defined in Figure 3-1 of Section 3. This figure is repeated here as Figure 6-1 with very specific time intervals, pertaining to the CLP design of Section 5.

The initial rise of the symmetrical short circuit current is nearly linear certainly over the time interval, which is considered here and which is approximately 20 el. degrees or 1/4 of the peak of the symmetrical short circuit current. This assumption significantly simplifies the problem of determining onset of current limitation.

The short circuit current is then given by

$$i_{sc} = I_m \omega t \tag{6-1}$$

Where I_m = peak of sym. short circuit current, which is with the specification of Section 1, $I_m = \sqrt{2} \times 40 = 56$ kA.

The sensing and trip current is $i_o = I_m \omega t_o$. The time required from sensing to cutting of the main conductor is

$$t_1 - t_o = 25 \ \mu\text{sec} = \text{const.}$$

The actual cutting is approximately 5 mm/μsec. Similarly we assume that the commutation time is constant. This is nearly correct considering the current range. Thus, as also confirmed experimentally

$$t_2 - t_1 = 75 \ \mu\text{sec} = \text{const.}$$

The melting time is a variable and depends on the square of the current, viz:

$$\int_{t_2}^{t_3} i^2 dt = \frac{i_3^2 t_3}{3} - \frac{i_2^2 t_2}{3} \tag{6-2}$$

This equation is readily verified for a linearly rising current. i^2 is a parabola with an area of $i^2t/3$ beginning from the origin.

The melting i^2t is a constant (see Section 3.5) for a given fuse. Therefore, it is possible to associate the terms in equation (6-2).

Since $i = I\omega t$ equation (6-2) becomes

$$\int i^2 dt = \frac{I\omega^2}{3} \quad (t_3^3 - t_2^3)$$

Solving for the melting time gives

$$t_3^3 = \frac{3\int i^2 dt}{(I\omega)^2} + t_2^3$$

From Figure 6-1 it follows that

$$t_2 = t_o + \Delta t_{cut} + \Delta t_{commutate} = t_o + 100 \times 10^{-6}$$

Hence

$$t_3^3 = \frac{3\int i^2 dt}{(I\omega)^2} + (t_o + \Delta t_{cut} + \Delta t_{com.})^3 \qquad (6\text{-}3)$$

If the sensing current level is given then the associated time $t_o = i_o/(I\omega)$ and we have

$$t_3^3 = 3\int i^2 dt/(I\omega)^2 + (i_o/I\omega + \Delta t_{cut} + \Delta t_{com})^3 \qquad (6\text{-}4)$$

Using the preceding cutting and commutation times and the rate of change of the specified short circuit current, viz. $I\omega = \sqrt{2} \times 40{,}000 \times 377 = 21$ A/μs, we find for equation (6-3)

$$t_3^3 = 3\int i^2 dt/21^2 + (i_o/21 + 100)^3$$

Assuming further a typical value for the melting time integral of 20,000 A^2sec and a sensing level of 10,000 ampere we find

$$t_3 = 689 \text{ μsec.}$$

The melting time interval in this case is easily obtained by subtracting out the time at which commutation has been accomplished. This time is simply the second term of equation (6-4). Thus with

$$t_o = i_o/I\omega \text{ and } t_2 - t_o = 100 \text{ μsec we find} \qquad (6\text{-}5)$$

$$t_2 = i_o/I\omega + 100 = 576 \text{ μsec} \qquad (6\text{-}6)$$

Hence the melting time becomes

$$\Delta t_{melt} = t_3 - t_2 = \underline{\underline{113\ \mu sec}}$$

Because of the linear rate of change of current also the associated current levels are quite readily obtained.

In summary Table 6-1 shows the association of current levels and time

Table 6-1

ASSOCIATION OF CURRENT LEVEL AND TIME

	Time	Current
Initiation	t_o	$i_o = I\omega\ t_o$
Completion of cutting	t_1	$i_1 = I\omega\ t_o + 25 \times 10^{-6}$
Completion of Commutation	t_2	$i_2 = I\omega\ t_o + 100 \times 10^{-6}$
Onset of current Limitation (i.e. Melting of Fuse)	t_3	$i_3 = I\omega\ t_3$ with t_3 from equ. (6-4)

We have computed let-through currents versus available symmetrical short circuit currents for different sensing levels and for (3) different fuse elements. Figure 6-2 is a plot of these data. It demonstrates dramatically the wide range over which the CLP can control the let-through current of a given prospective short circuit level.

The theoretical performance of the CLP in the M.I.T. test circuit was discussed in Section 4.1 and the performance was confirmed experimentally in Section 4.2 This was a d.c. circuit, however, it is not difficult to apply this analysis to an a.c. circuit as shown in Figure 6-3.

We assume a sinusoidal short circuit current is initiated at t = 0 at the voltage peak. Thus the circuit loop equation can be written.

$$v = L\frac{di}{dt} + iR \qquad (6\text{-}7)$$

At t_o the CLP is initiated and the processes of Figure 6-1 take place. Up to t_3 the CLP has essentially no influence on the short circuit current. However, as the fuse melts an arc voltage is introduced with the current limiting effects as described already in Section 4. This arc voltage modifies the circuit and we have by comparison to equation 6-7.

$$v - e_{arc} = L\frac{di}{dt} + iR \tag{6-8}$$

Because of the non-linear character of the arc voltage this equation will be solved in increments. Thus rewriting equation (6-8) we find

$$\Delta i = (v - iR - e_{arc})\,\Delta t/L \tag{6-9}$$

The initial current is given by $i_3 = I\omega t_3$.

Assuming an arc voltage characteristic similar to Figure 4-3, except that the peak of the voltage is 36 kV and the sustained arc voltage is 20 kV, equation (6-9) was solved for a 15 kV circuit with a prospective symmetrical short circuit current of 40 kA. Also sensing levels of 4,6 and 10 kA were assumed. The incremental solutions yielded Curves 1,2 and 3 respectively of Figure 6-4. However, it should be pointed out, that a faster fuse was used for Curve #1 than for Curves 2 and 3. The table insert of this figure shows the possible current limitation to be as high as 9:1 in the case of the symmetrical short circuit current and 18:1 in the case of the asymmetrical short circuit current (Curve 1). We note that the peak let-through current of the asymmetrical case is somewhat less than that of the symmetrical current. The reason is the slower rise of the short circuit current and the consequential lower melting current of the fuse.

The theoretical performance was also compared to a 200 E current limiting fuse (Curve #5). Clearly the CLP is capable of substantially reducing the let-through currents over such a fuse. The table insert shows also the continuous current of the CLP and the computed let-through i^2t after the fuse melting. Again the superior performance of the CLP is evident. Figure 6-5 shows the total let-through i^2t for Cases 1 through 5 of Figure 6-4. Accordingly the CLP promises to reduce the total let-through i^2t of a 200 E fuse from 1.65×10^6 to $.02 \times 10^6$ i.e. by a factor of 80. This , of course, is an extreme case. A factor of 8 is more normal. Certainly such a reduction of the i^2t could save transformers or capacitor tanks from catastrophic failures in case of internal faults.

The conclusions for this section are:

- The CLP can provide a lower let-through current than fuses while being capable of much higher continuous currents.

- The CLP can provide lower let-through i^2t.
- The let-through current is adjustable.
- The symmetrical short circuit current is the most stringent case as far as timing of the CLP is concerned.
- Current limitations as high as 18:1 appear feasible for asymmetrical currents and 9:1 for symmetrical currents.
- The CLP can provide better protection against tank rupture than fuses.

6.2 EXPERIMENTAL PERFORMANCE:

A total of (23) prototype CLP's were built and equipped with 4, 7 and 15 kV fuse elements. Extra fuses were also built for control experiments to demonstrate in case of a failure whether the CLP or the fuse failed. This, though difficult to discern because of the lower melting current of the fuse alone, nevertheless, was considered the best approach. With hindsight perhaps the melting time integral of these fuses should have been increased such that their melting time would have corresponded to that of the CLP. (Considering Figure 3-20 such a selection is readily made by changing e.g. the hole size of the fuse elements).

The test variations of the Summary Table 6-2 were carried out at the G.E. High Power Laboratory in Philadelphis, Pa.

Table 6-2

SUMMARY TABLE

Test Voltage	4, 7 and 15 kV (RMS)
Prospective Sym Currents	15, 25, 30, and 40 kA (RMS Sym.)
Sensing Level	5, 7.5, and 10 kA (instantaneous)

(23) CLP's and 17 fuses were tested. None of the fuses experienced any failures. (4) CLP's failed, none at 4 kV, one at 7 kV and three at 15 kV.

The failures appear to be related to design deficiencies of the end plugs of the fuse and of the end plates of the CLP. While the end plates withstood the gas pressure of the chemical charge on containment tests, apparently the pressure developed in the fuse plus the short circuit forces on the fuse holder were sufficient to loosen the end plates of the CLP and the plugs of the fuses. This permitted in the case of the failures plasma discharge from the fuses, which in our opinion resulted in a reignition of the gaps in the main conductor. The clue to this opinion comes from the sharp decay of the fuse arc voltage to approximately one half of the peak value. This indicates loss of pressure and arc containment in the fuse. Later the arc voltage drops even lower to a value consistent with the breakdown across the gaps. Design modifications made after these tests should alleviate this failure mode.

Figures 6-6 through 6-10 give an impression of the current limiting tests that were performed. Figure 6-6 shows an oscillogram of the prospective current. Trace 1 is timing, Trace 2 is voltage, Trace 3 is current, Trace 4 is arc voltage.

Figure 6-7 is a time expanded oscillogram. It shows a 7kV current limiting test in a 40 kA circuit. The current rises at a rate of 20 ampere per microsecond. It is limited to 10 kA. For the particular fuse involved in this test we compute backwards that the sensing current was approximately 5 kA, which is in agreement with the setting.

Figure 6-8 is a failure oscillogram in the same circuit as Figure 6-7, except the trigger level was set at approximately 10 kA. The let-through current would have been 15 kA. We note that the failure mode is essentially as described above, with the fuse voltage dropping to half value shortly after the peak and the subsequent further reduction by commutating the current back to the gaps.

Figure 6-9 shows a test in a 15 kV circuit with a 40 kA prospective symmetrical current. The current was limited to 12 kA from a sensing level of approximately 7.5 kA. In order to appreciate the reduction of the current due to current limitation we have superimposed the prospective short circuit current on this oscillogram.

Figure 6-10 shows a current limiting test under the same conditions as Figure 6-9 except the current and time scales have been changed for better interpretation of the results. We note, however, a slightly different transition of the current to zero. This is due to the different sustained arc voltages of the fuses. The sustained arc voltage of Figure 6-10 was higher.

The preceding selection of oscillograms gives an impression of the interrupting and current limiting capability of the CLP. In the preceding cases the performance of the CLP was verified theoretically within reasonable accuracy as comparison of Figure 6-4 with Figures 6-6 through 6-10 shows. In fact the shaded area of Figure 6-4 corresponds roughly to the above oscillograms, except the actual current decay shows a concave trace, whereas the computed values suggest a slower convex trace apparently due to the faster decay of the theoretical fuse voltage.

In summary the tests have demonstrated:

- The CLP as developed at this time is suitable for service in 4 to 15 kV circuits with modifications to the fuse mounting as discussed earlier.
- The CLP can interrupt and limit prospective currents up to 40 kA.
- The experimental performance of the CLP confirms the theory developed earlier.
- The sensing and firing level is adjustable and triggers the CLP apparently correctly.
- The Phoenix Electric Corp. fuses and a special fuse by another manufacturer met the precise melting requirements.
- The CLP requires improvement of the seals of the end caps and fuses by proper mechanical restraints to prevent the failures uncovered during the last test series.

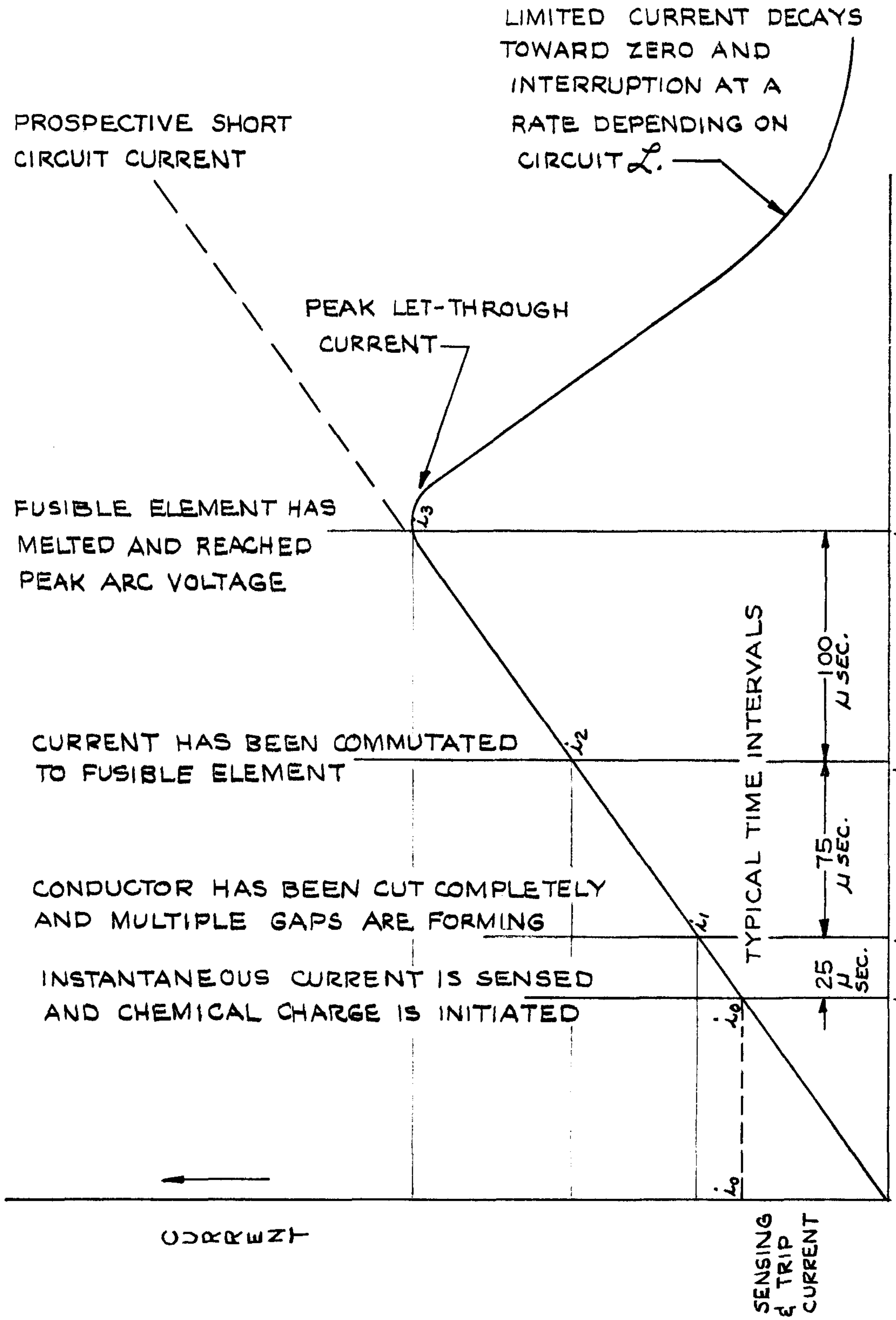
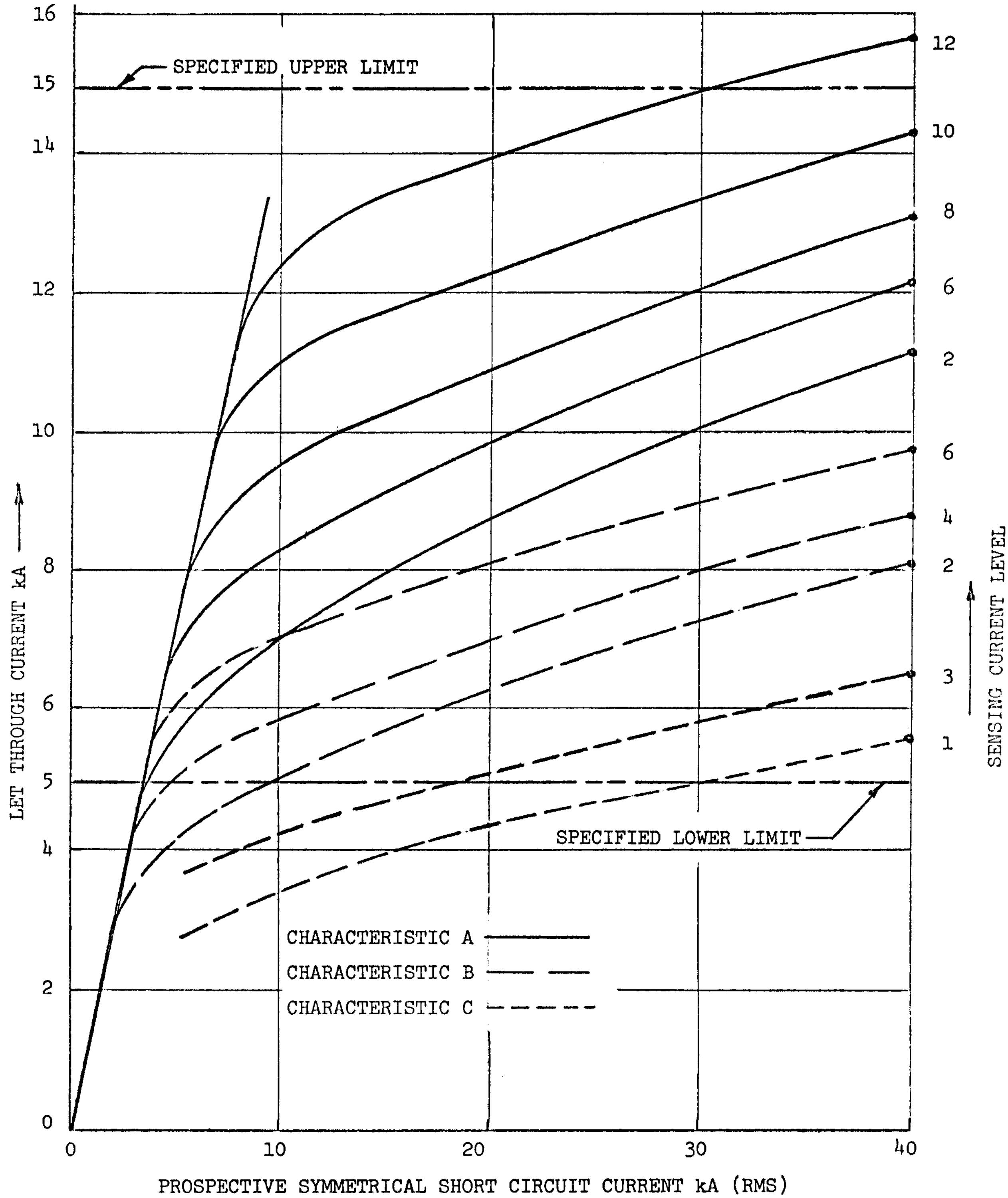


FIGURE 6-1

Typical Events and Time Intervals Leading to Current Limitations



SPECIFIED UPPER LIMIT
SPECIFIED LOWER LIMIT
CHARACTERISTIC A
CHARACTERISTIC B
CHARACTERISTIC C
LET THROUGH CURRENT kA
SENSING CURRENT LEVEL
PROSPECTIVE SYMMETRICAL SHORT CIRCUIT CURRENT kA (RMS)
0
2
4
5
6
8
10
12
14
15
16
0
10
20
30
40
12
10
8
6
2
6
4
2
3
1

FIGURE 6-2

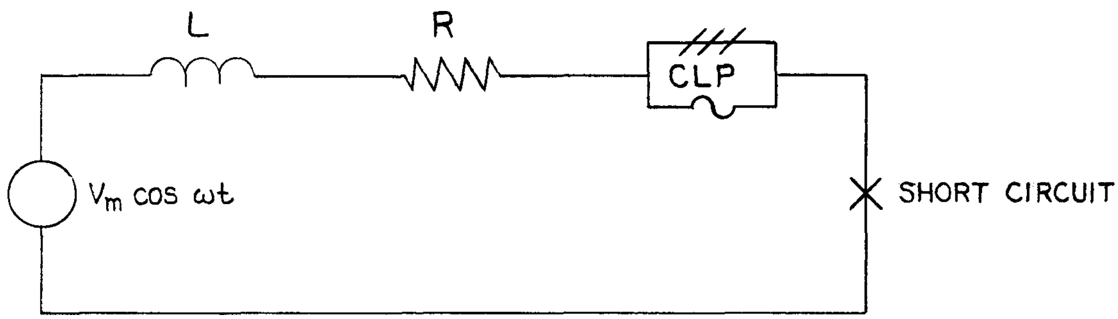
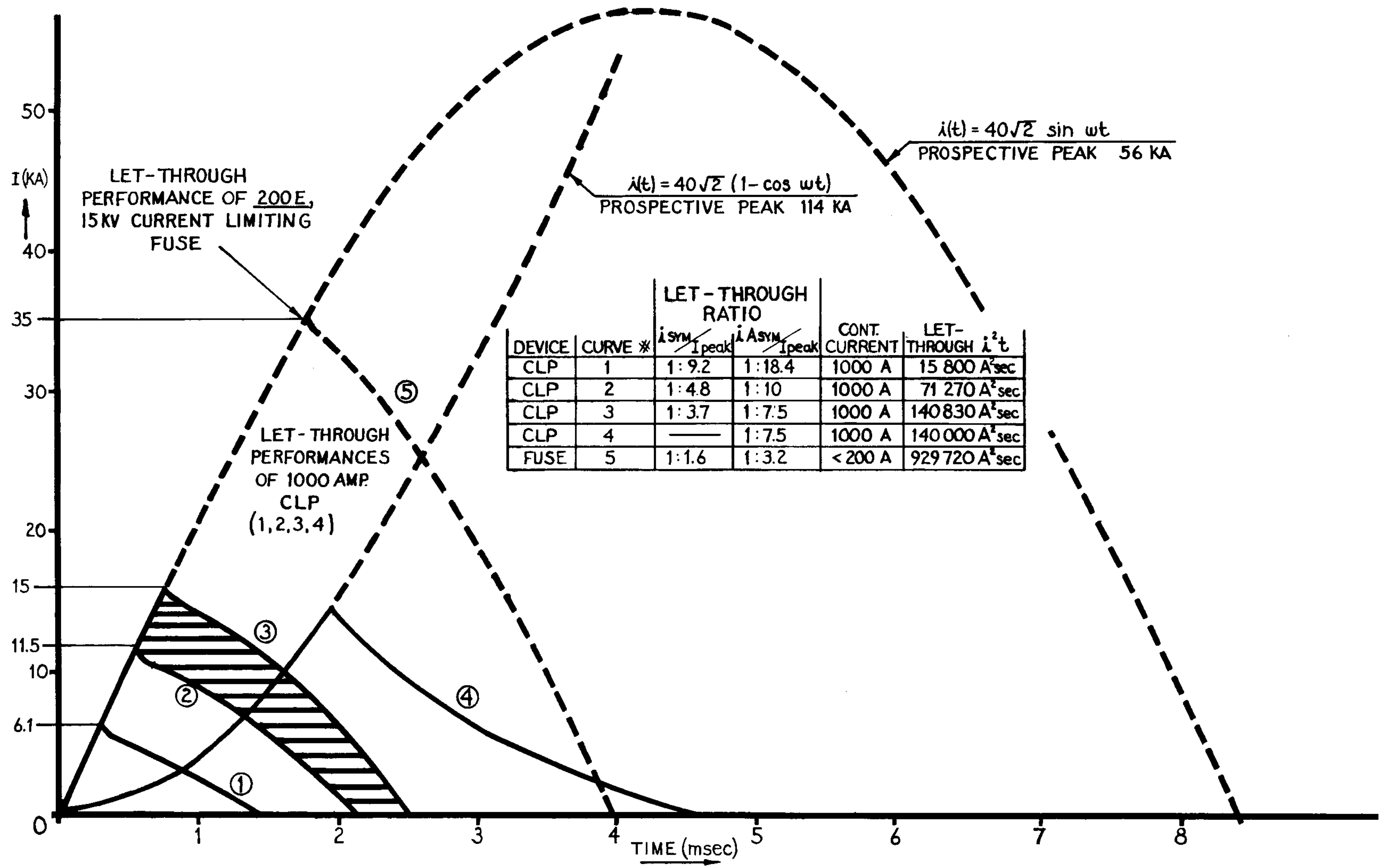


FIGURE 6-3

Equivalent a.c. circuit



DEVICE	CURVE ※	LET-THROUGH RATIO i_{SYM}/I_{peak}	i_{ASYM}/I_{peak}	CONT. CURRENT	LET-THROUGH i^2t
CLP	1	1 : 9.2	1 : 18.4	1000 A	15 800 A^2sec
CLP	2	1 : 4.8	1 : 10	1000 A	71 270 A^2sec
CLP	3	1 : 3.7	1 : 7.5	1000 A	140 830 A^2sec
CLP	4	———	1 : 7.5	1000 A	140 000 A^2sec
FUSE	5	1 : 1.6	1 : 3.2	< 200 A	929 720 A^2sec

FIGURE 6-4

Let-through Performance of CLP

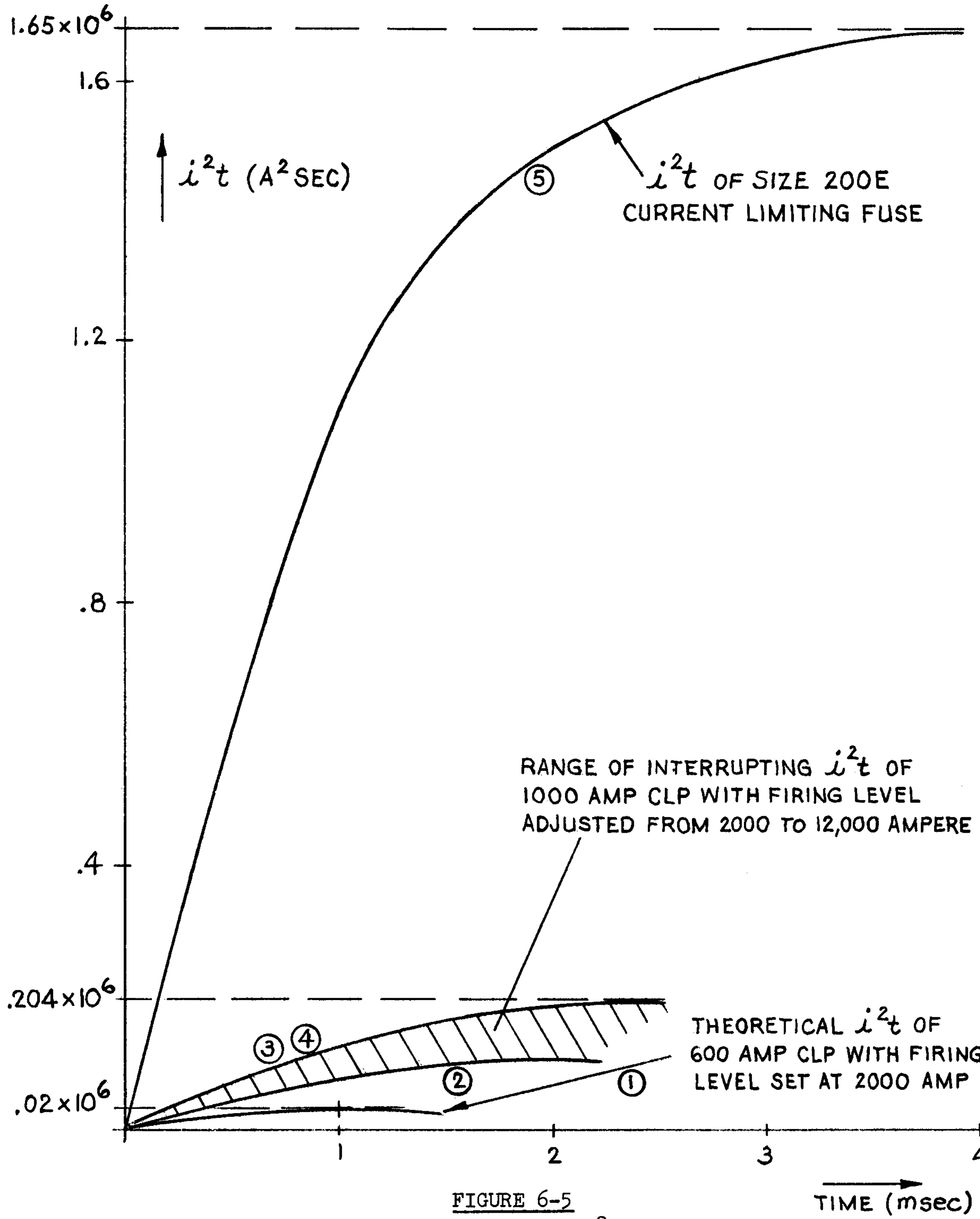


FIGURE 6-5

Total Interrupting i^2t of 200E Current Limiting Fuse as Compared to CLP Devices

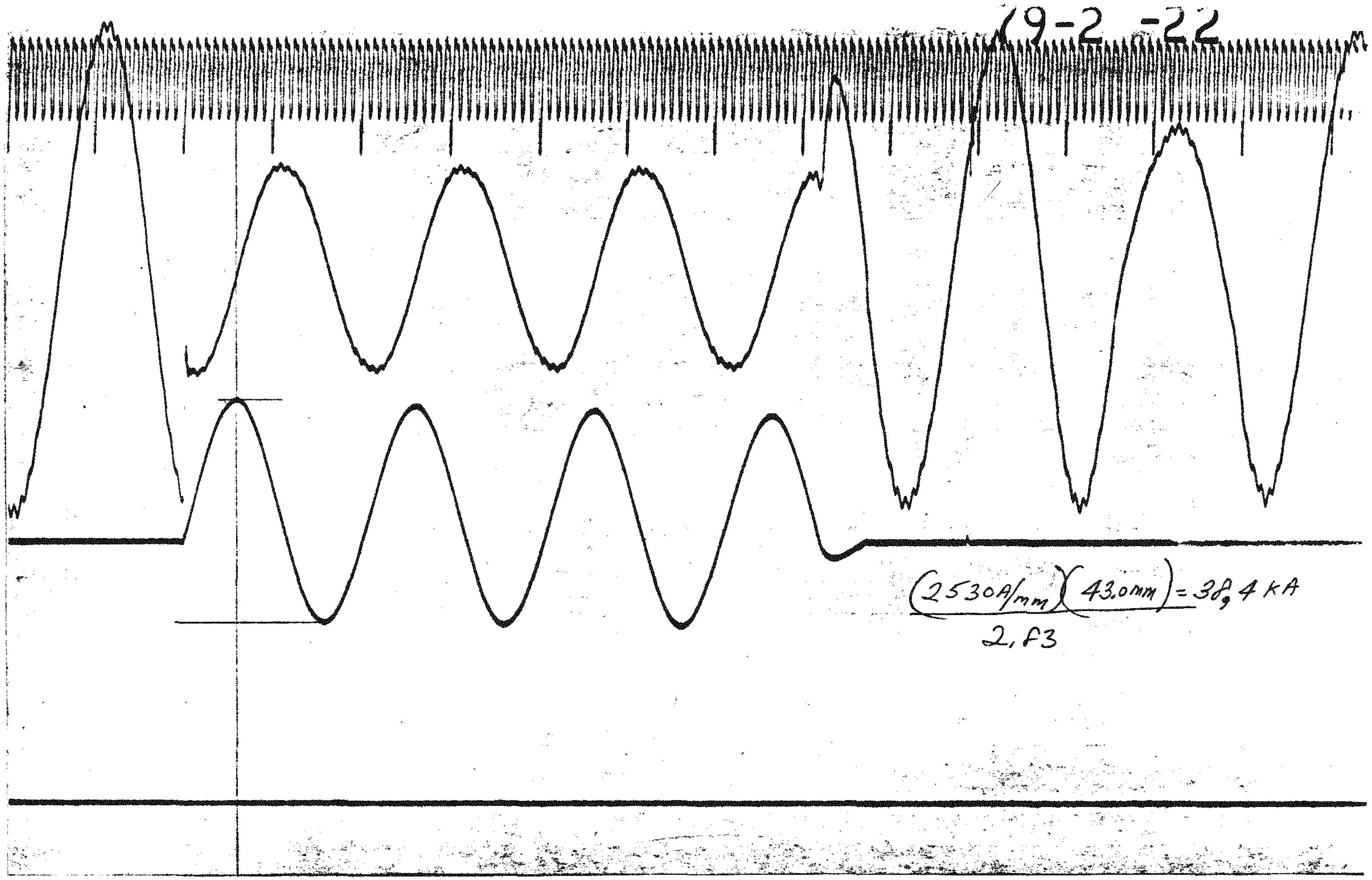


FIGURE 6-6

Prospective Short Circuit Current

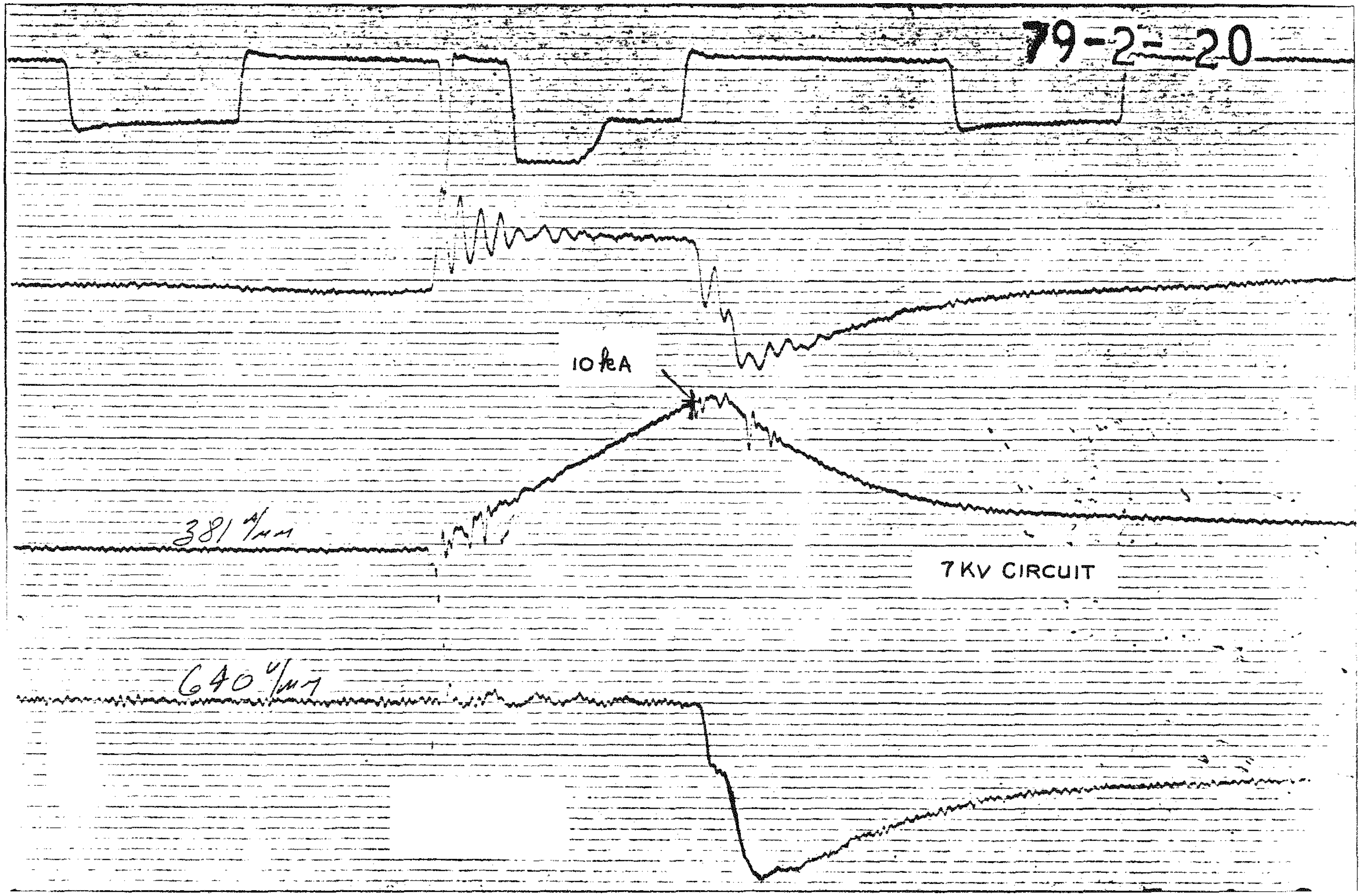


FIGURE 6-7

A Current-Limited Interruption of CLP

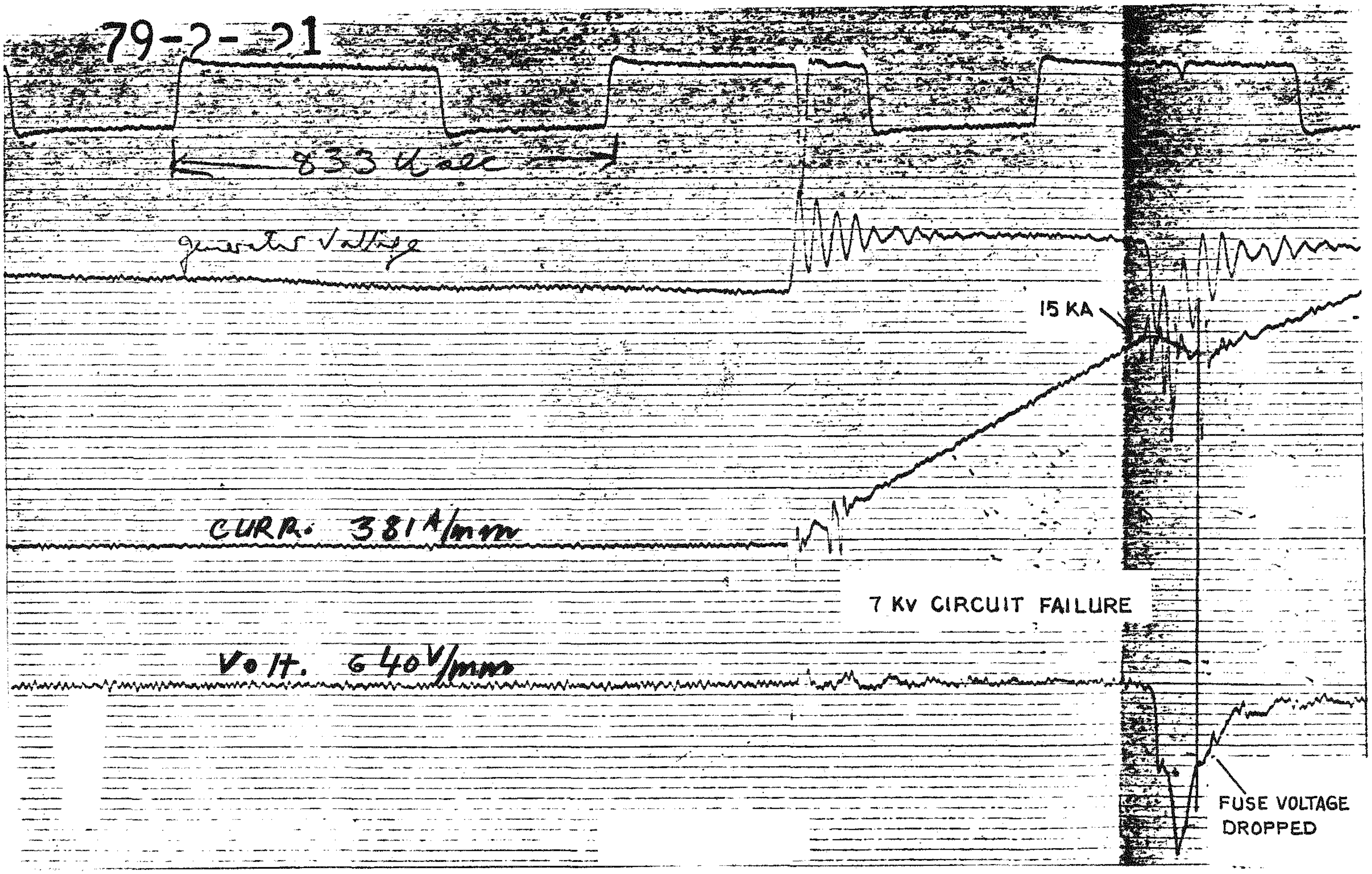


FIGURE 6-8

Failure to Interrupt

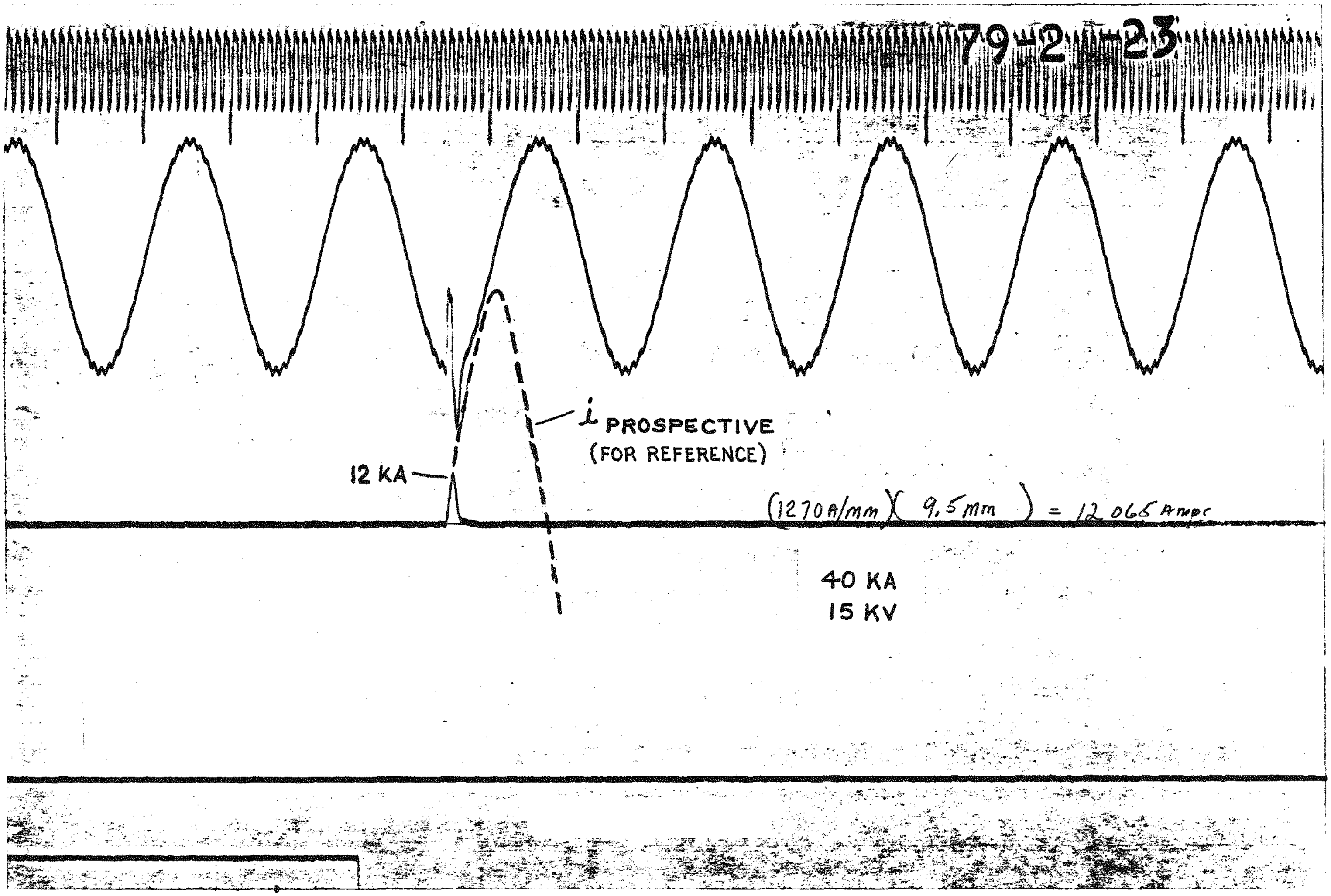


FIGURE 6-9

Current-Limited Interruption

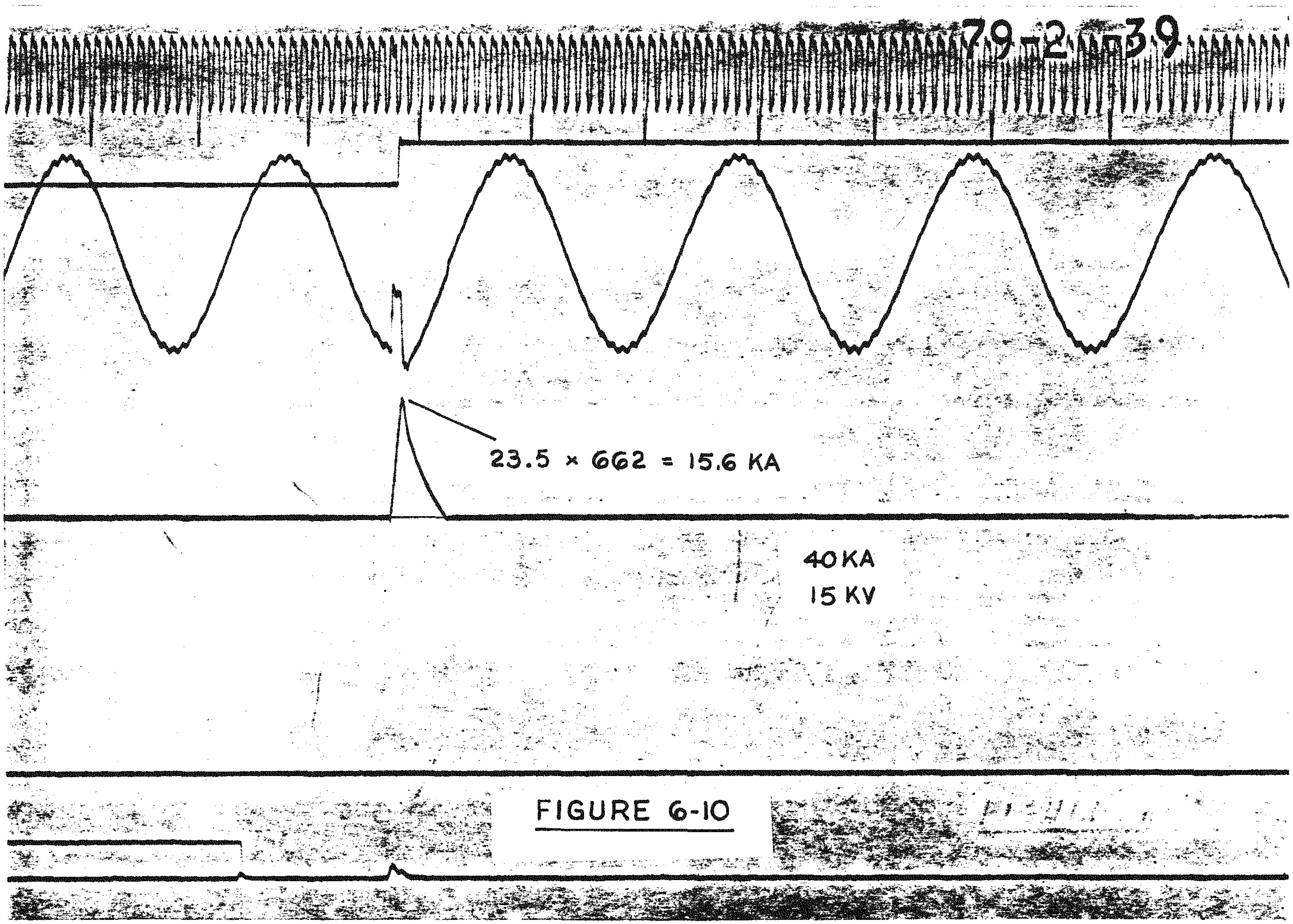


FIGURE 6-10

Current-Limited Interruption

Section Seven

APPLICATIONS

The current limiting performance of the CLP suggests numerous possible applications. Through-fault protection of transformers or internal fault limitation to prevent catastrophic failures of tanks are a first example. In general the CLP may find application where the continuous current is too high for the lower cost current limiting fuses.

The CLP may also be used as a series single shot protective device in place of much higher cost circuit breakers or as means to prolong the life of existing under-rated breakers.

The firing scheme of the CLP which allows expansion to 3-phase triggering may suggest unique applications for example in the protection of low voltage high current circuits with low fault current levels where unique sensing schemes may be employed.

Major applications are foreseen in feeder circuits the branches of which are protected by reclosers or current limiting fuses. These applications frequently require coordination to avoid the triggering of multiple protective devices. For example low current fuses frequently can protect branch circuits. If the CLP is set above the let-through current of these fuses it would be triggered only on faults in the main feeder.

In branch circuits where the steady state current exceeds the ratings of fuses multiple CLP's could be coordinated to different let-through current levels by proper choice of sensing current and fuse element. The wide range of let-through currents of Figure 6-2 suggests that at least 3 such separate and independent protective levels are available by level sensing alone. We believe that even better selective coordination would be possible if multiple combined level and di/dt sensing devices were employed, which would allow rather narrow operational windows. This, however, has not yet been fully researched by Phoenix Electric Corp. nor are we aware of such a study by others.

The preceding listing of possible applications is not all encompassing, rather it is intended to stimulate. We are certain that the users: utilities and industrial companies will be the pioneers in the application of the CLP.

Perhaps applications may even be found in the power electronic field for the protection of semi-conductor devices because of the high speed of the CLP.

Section Eight

ECONOMICS OF THE CLP

Besides the service related factors of the preceding section also economic factors must be considered when applying a CLP. In the following an attempt is made to discuss some of these and to relate them to presently available technology.

The layout and the cost of electrical equipment and systems depends mainly on the transient voltage and current requirements, better known as the BIL and short circuit levels. In fact the relative decrease of the BIL levels, which was made possible by modern surge arresters allowed the reduction of insulating structures of all major equipment and resulted in significant savings to the utilities and users of electric power. The dual to the overvoltage limiting arrester is the short circuit current limiting device.

The effects of short circuit currents are electromagnetic forces, thermal stress and destruction by arcing. The electromagnetic forces and thermal overloads are both proportional to the square of the short circuit currents. Hence, current limitation will permit a significant reduction of the mechanical bracing of bus structures, windings and apparatus and therefore cost.

The economic advantages follow more clearly from an example. The CLP, as described in this report can reduce an asymmetrical current peak from approximately 120,000 ampere to less than 15 kA. This reduction from 8 to 1 corresponds to a reduction of the short circuit forces from 64 to 1.

Simultaneously the CLP reduces the duration of the short circuit and hence the duration of the mechanical stress, but also the short time thermal duty on electrical apparatus. Clearly cost effective design advantages can be derived from the CLP.

A more specific evaluation may be made by considering the cost reduction made possible by the use of lower rated equipment in combination with current limiting devices.

Compare the cost of a 15 kV, 1000 MVA circuit breaker line up, having ratings which would meet the CLP specifications of Section 1.3, with an installation using a CLP in series with compatible 250 or 500 MVA circuit breakers and associated bus system.

For purposes of comparison, the cost of a CLP system, including current limiters (CLP's) sensing equipment, controls and enclosures are taken to be in the order of one bay of the 500 MVA circuit breaker. (The actual replacement cost of the expendable CLP unit is estimated to be in the order of less than three times the cost of a 200 E fuse).

Taking now a cost factor of 100 for the 1000 MVA circuit breaker and a cost factor of 60 for a 500 MVA equipment, we can, to some degree, quantify the cost savings, viz:

Cost of four (4) bays of 1000 MVA each vs. (4) bays of 500 MVA & CLP

Cost = Units x Cost Factor

1000 MVA: Cost = 4 x 100 = 400

500 MVA: Cost = 4 x 60 = 240

CLP System: Cost = 1 x 60 = 60

Total Cost of 500 MVA + CLP = 300

Total Cost of 1000 MVA = 400

Thus, there appears to be a 25% reduction in equipment cost with the use of lower rated equipment upon initial installation. As more circuit breakers are added, the savings increase.

Similarly, if the CLP is to be used to avoid the expense of upgrading the short circuit capability of existing apparatus, consider the following:

Replace four 500 MVA circuit breakers with four 1000 MVA circuit breakers

Cost = 4 x 100 = 400

Use CLP to "upgrade" the 500 MVA breakers to handle "1000 MVA" service.

Cost = 1 x 60 = 60

The cost advantage of more than six to one favors the CLP application in this case.

These preceding considerations are simplistic indeed. No allowance for the change out of the equipment nor the planning or the site preparation has been made. Thus, considerable additional savings can be materialized by upgrading underrated switchgear with a CLP.

Arcing on internal faults for example in liquid filled equipment is the third destructive mode of short circuits. In this case the damaging action resulting often in tank explosions is proportional to the arc energy. In certain cases such tank failures have been related to the i^2t.* It follows clearly from Figures 6.4 and 6.5 that the let-through i^2t of the CLP is substantially less than that of a comparable current limiting fuse and certainly far less than that of a circuit breaker. Again economic advantages could be derived by reducing the mechanical rigidity of transformers and tanks. However, is this advisable? We prefer to consider the reduced risk to the safety of personnel and other apparatus as the over-riding issue in this case.

Continuity of service is a consideration when deciding on the application of the CLP. At this time multishot devices, while feasible, have not yet been developed. Therefore, this application remains, at least for the time being, the domain for circuit breakers and current limiting reactors, the latter where current reduction is required.

The continuous losses of conventional current limiting reactors result in considerable operating cost. A CLP, if used as a low cost by-pass to such a reactor, reduces the operating cost essentially to zero, while continuity of service is maintained.

The CLP represents a new technology, which is judged in competition with the mature application of protective switchgear. All the preceding examples recognize substantial economic advantages for the application of the CLP.

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* - E. A. Goodman, et al, "Dual Fusing Improves Transformer Fault Energy Control", Presented to Pennsylvania Electric Association, Transmission & Distribution Committee.

In addition we believe the CLP characteristics are such that it will gain quickly user confidence. Production quantities will, therefore, increase, which requires improved production techniques and results in lower per unit cost, thus further improving the cost benefits previously discussed.

Finally, we consider low cost circuits and maintenance. The CLP is maintenance free. Further, it is known that current limiting fuses, which are likewise maintenance free, are an economic alternate to circuit breakers in circuits with low incidence of short circuits and low continuous currents. The CLP is expected to provide an economical extension of such circuits where continuous currents exceed fuse ratings.

In conclusion, the CLP has been introduced as a device with a low let-through current which reduces the electromagnetic and the thermal effects of short circuits. The application of this device can result in economic advantages in new installations, in installations where the system short circuit has outgrown the equipment ratings and in low cost, high continuous current circuits. The elimination of the continuous losses of current limiting reactors shunted by a CLP was also discussed.

Finally, the CLP was said to provide a novel protection by reducing the risk of tank failures and consequential damages due to internal arcing faults of transformers.

Section Nine

SUMMARY - CONCLUSIONS - FUTURE WORK

- In this report the Current Limiting Protector was defined.
- Experimental prototypes were developed to meet a 15 kA let-through current for a 40 kA RMS sym. prospective short circuit current requirement.
- Known other current limiting devices were reviewed and related to the CLP.
- The developmental efforts leading to the present status of the CLP were described. In particular problems with cutting, containment and firing were discussed. Also the basic steps in the development of precisely melting fuses were presented.
- The current sensing and pulse circuits for the firing of the primary charge for operation at line potential or at ground potential which were developed in this project were described.
- The theoretical performance of the CLP in d.c. and a.c. circuits was proven by short circuit experiments to the specified limits.
- A number of possible applications were discussed.

In the course of this project some design deficiencies were uncovered in two areas, viz:

- Electrostatic and/or electromagnetic interference in the fault sensing circuit.
- Failure of mechanical restraint of the fuse and CLP end caps.

Correction requires some design effort, model building, electrical interference tests of a hardened sensing and trip circuit, and mechanical containment tests. Finally additional short circuit tests must verify the ability of the CLP to withstand the combined mechanical and electrical short circuit duty.

The successful application of the CLP depends to a large measure on the understanding of the interaction of the CLP and of the circuit. However, service experience can be gained in the field only. It is recommended to carefully study possible application and their steady state and transient characteristics. Next, operating procedures for CLP's should be established in cooperation with experienced utility personnel. Finally a few trial installations and possible staged tests should be conducted to establish user confidence in the CLP.

GENERAL ELECTRIC COMPANY HIGH POWER LABORATORY

APPARATUS *PHOENIX ELECTRIC CORP.*

KEY NO. *LETTER*

CALCULATIONS

INVESTIGATION NUMBER 79 ESP 2
1 Ø TEST AT 60 HZ IN CELL # 2

CALCULATIONS FROM TAPE RECORDER

CONN. GEN. / TRANS.	CONN. REACT. / OHM	DUTY CYC.	TEST KV. / V.	CUR. CAL. AMP. PER MM.	INRUSH ORDINATE MAJ	INRUSH ORDINATE MIN.	INRUSH ORDINATE AC	INRUSH ORDINATE RMS	INRUSH AMPERES PEAK	INRUSH AMPERES AC	INRUSH AMPERES RMS TOTAL	"K" ORDINATE MAJ	"K" ORDINATE MIN.	"K" ORDINATE AC	"K" ORDINATE RMS	"K" AMPERES AC	"K" AMPERES RMS TOTAL	RATIO RMS AC	SHORT DUR. ½~	TRIP IMP TO INT ½~	ARC DUR ½~	NFRV CAL	NFRV mm	NFRV KV	PEAK RECOVERY TAPE CAL	PEAK RECOVERY TAPE mm	PEAK RECOVERY TAPE KV		RECOVERY VOLT CAL / CAL RATE	RECOVERY PEAK MM / KV	RECOVERY MULT-FACT RATE V/U	REMARKS	TEST NO.
MΔ	52M / 52M	5~ CC	4.2	1132	22.5	17.0	14.0	14.2	25500	15800	16100							1.01	6.5														1.
↓	22M / 22M	↓		2650	19.5	14.0	11.8	12.2	51700	31300	32300							1.03	7.7														2
U	45M / 45M		13.8	↓					13800 x 2.83 / 31.5	=		1240		V/mm		(ATTN 2)		TAPE														VOLTAGE CALIBRATION	3
SΔ	34M / 34M		6.8						6790 x 2.83 / 30.0	=		640		V/mm		(ATTN 1)		TAPE														↓	4
MΔ	32M / 32M		3.4						3400 x 2.83 / 29.5	=		326		V/mm		(ATTN .5)		TAPE															5
↓	22M / 22M	↓	2.16	↓					2160 x 2.83 / 47	=		130		V/mm		(ATTN .2)		TAPE														↓	6
	52M / 52M	INT + 1.0 MIN.	4.2	1042	7.5				7815										.40			326	36.5	4.20	326	45.0	14.7						7
	↓	↓		381	20.0				7620										.35			↓	36.0	4.14	↓	50.0	16.3						8
↓	↓	↓			35				13300										4.0			640	18.5	4.18	640	17.0	10.8						9

FILMS READ AND CALCULATED BY A. RICCHIUTI TEST CONDUCTED BY A. SCHUSTER DATE JAN. 23, 1979

9-2

A-1

GENERAL ELECTRIC COMPANY HIGH POWER LABORATORY

APPARATUS PHOENIX ELECTRIC CORP.

KEY NO. LETTER

CALCULATIONS

CALCULATIONS FROM TAPE RECORDER

INVESTIGATION NUMBER 79 ESP 2
1 Ø TEST AT 60 HZ IN CELL #2

CONN. GEN. / TRANS.	CONN. REACT. / OHM	DUTY CYC.	TEST KV. / V.	CUR. CAL. AMP. PER MM.	INRUSH ORDINATE MAJ	INRUSH ORDINATE MIN.	INRUSH ORDINATE AC	INRUSH ORDINATE RMS	INRUSH AMPERES PEAK	INRUSH AMPERES AC	INRUSH AMPERES RMS TOTAL	"K" ORDINATE MAJ	"K" ORDINATE MIN.	"K" ORDINATE AC	"K" ORDINATE RMS	"K" AMPERES AC	"K" AMPERES RMS TOTAL	RATIO RMS / AC	SHORT DUR. ½~	TRIP IMP TO INT ½~	ARC DUR ½~	NFRV CAL	NFRV mm	NFRV KV	PEAK RECOVERY CAL	PEAK RECOVERY mm	PEAK RECOVERY KV		RECOVERY VOLT CAL / CAL RATE	RECOVERY PEAK MM / KV	RECOVERY MULT- FACT / RATE V/U	REMARKS	TEST NO.
MΔ	52M / 52M	INT + 1 MIN.	4.2	381	59.0				22500										20.2			640			640								10
↓	↓	↓	↓	↓	59.5				22500										16.0			↓			↓								11
	↓				33				12600										.50				18.5	4.18		21.0	13.4						12
	22M				26.5				10096										.40				18.5	4.18		25.0	16.0						13
	↓				50.0				19050										.35				18.5	4.18		19.0	12.1						14
	21M / 31M				28.0				10668										.15				18.5	4.18		23.5	15.0						15
	↓				54.5				20764										.35				18.5	4.18		20.0	12.8					CURRENT CLIPPED	16
					40.0				15240										.55				18.5	4.18		25.0	16.0						17
↓	↓	↓	↓	↓	40.0				15240										.50			↓	18.5	4.18	↓	17.0	10.8						18

FILMS READ AND CALCULATED BY A. RICCHIUTI

TEST CONDUCTED BY A. SCHUSTER

DATE JAN. 24, 1979

9-4

GENERAL ELECTRIC COMPANY HIGH POWER LABORATORY

APPARATUS PHOENIX ELECTRIC CORP.

KEY NO. LETTER

CALCULATIONS

CALCULATIONS FROM TAPE RECORDER

INVESTIGATION NUMBER 79 ESP 2

1 Ø TEST AT 60 HZ IN CELL # 2

CONN.		DUTY CYC.	TEST KV. / V.	CUR. CAL. AMP. PER MM.	CURRENT DATA													RATIO RMS / AC	SHORT DUR.	TRIP IMP TO INT	ARC DUR	NFRV			PEAK RECOVERY				RECOVERY			REMARKS	TEST NO.
					CURRENT AT "INRUSH"							CURRENT AT "K"																	VOLT CAL / CAL RATE	PEAK MM / KV	MULT. FACT / RATE V/U		
					ORDINATE				AMPERES			ORDINATE				AMPERES																	
GEN. / TRANS.	REACT. / OHM				MAJ	MIN.	AC	RMS	PEAK	AC	RMS TOTAL	MAJ	MIN.	AC	RMS	AC	RMS TOTAL		½~	½~	½~	CAL	mm	KV	CAL	mm	KV						
SΔ	10 M	2∼ CC	7.2	4000	15.0	15.0	10.6	10.6	60000	42400	42400							1.00	5.8			640			640							BUS SHOT	19
↓	↓	INT + 1 MIN	↓	381	27.0				10287										.45			↓	32.0	7.23		33.5	21.4						20
↓	↓		↓	↓	*				*										*			↓	*	*		34.0	21.7					* FUSE FAILED	21
U	32M/32M	8∼ CC	15.0	4000	17.0	10.0	9.5	10.2	68000	38000	40800							1.07	7.2			↓										BUS SHOT	22
SΔ	10M/10M	INT + 1 MIN	7.2	381	29.0				11049										.40			↓	32.0	7.23		27.5	17.6						23
U	32M/32M	↓	15.0	↓	38				14478										.55			1240	34.0	14.8	1240	24.0	29.7						24
↓	21S	↓	↓	↓	38				14478										.50			488	87.0	15.0	488	57.5	28.1					1-25-79	25
↓	↓	↓	↓	↓	38.5				14668													↓	85.0	14.6		58.0	28.3						26
↓	↓	↓	↓	↓	38.5				14668										.60			↓	87.0	15.0		48.0	23.4						27

FILMS READ AND CALCULATED BY A. RICCHIUTI

TEST CONDUCTED BY A. SCHUSTER

DATE JAN. 24, 1979

A-3

GENERAL ELECTRIC COMPANY HIGH POWER LABORATORY

APPARATUS PHOENIX ELECTRIC CORP

KEY NO. LETTER

CALCULATIONS

CALCULATIONS FROM TAPE RECORDER

INVESTIGATION NUMBER 79 ESP 2

1Ø TEST AT 60 HZ IN CELL #2

CONN. GEN. / TRANS.	CONN. REACT. / OHM	DUTY CYC.	TEST KV. / V.	CUR. CAL. AMP. PER MM.	CURRENT AT "INRUSH" ORDINATE MAJ	MIN.	AC	RMS	CURRENT AT "INRUSH" AMPERES PEAK	AC	RMS TOTAL	CURRENT AT "K" ORDINATE MAJ	MIN.	AC	RMS	CURRENT AT "K" AMPERES AC	RMS TOTAL	RATIO RMS / AC	SHORT DUR. ½~	TRIP IMP TO INT ½~	ARC DUR ½~	NFRV CAL	mm	KV	PEAK RECOVERY CAL	mm	KV		RECOVERY VOLT CAL / CAL RATE	PEAK MM / KV	MULT. FACT / RATE V/U	REMARKS	TEST NO.
U	21S	0+1 MIN	15.0	381	*				*													488	*	*	488	*	*					* MIS-FIRE	28
↓	30M	↓	↓	↓	23.0				8763										.50			1230	34.5	14.99	1230	33.5	41.2						29
↓	↓	↓	↓	↓	25.0				9525										.50			↓	35.0	15.2	↓	32.0	39.3						30
↓	↓	↓	↓	↓	25.0				9525										.50			↓	34.5	14.99	↓	32.5	39.9						31
↓	↓	↓	↓	↓	26.5				10100										.50			↓	33.0	14.3	↓	32.5	39.9					1-26-79	32
↓	21S	↓	↓	↓	28.0				10668										.45			↓	34.5	14.99	↓	36.0	44.2						33
↓	↓	↓	↓	↓	39.0				14859										.50			↓	35.0	15.2	↓	28.0	34.4						34
↓	↓	↓	↓	↓	*				*										*			↓	*	*	↓	*	*					* FUSE FAILED	35
↓	↓	↓	↓	↓	26.5				10100										.50			↓	34.0	14.8	↓	30.5	37.5						36

FILMS READ AND CALCULATED BY A. RICCHIUTI TEST CONDUCTED BY W. KRACHT DATE JAN. 25, 1979

9-5

A-4

GENERAL ELECTRIC COMPANY HIGH POWER LABORATORY

CALCULATIONS

CALCULATIONS FROM TAPE RECORDER

APPARATUS PHOENIX ELECTRIC CORP.

KEY NO. LETTER

INVESTIGATION NUMBER 79 ESP 2

1 Ø TEST AT 60 HZ IN CELL # 2

CONN. GEN. / TRANS.	CONN. REACT. / OHM	DUTY CYC.	TEST KV. / V.	CUR. CAL. AMP. PER MM.	INRUSH ORDINATE MAJ	INRUSH ORDINATE MIN.	INRUSH ORDINATE AC	INRUSH ORDINATE RMS	INRUSH AMPERES PEAK	INRUSH AMPERES AC	INRUSH AMPERES RMS TOTAL	"K" ORDINATE MAJ	"K" ORDINATE MIN.	"K" ORDINATE AC	"K" ORDINATE RMS	"K" AMPERES AC	"K" AMPERES RMS TOTAL	RATIO RMS / AC	SHORT DUR. ½~	TRIP IMP TO INT ½~	ARC DUR ½~	NFRV CAL	NFRV MM	NFRV KV	PEAK RECOVERY CAL	PEAK RECOVERY mm	PEAK RECOVERY KV		RECOVERY VOLT CAL / CAL RATE	RECOVERY PEAK MM / KV	RECOVERY MULT-FACT / RATE V/U	REMARKS	TEST NO.
U	21 S	INT + 1 MIN	15.0	381	35.0				13300										.50			1230	34.5	15.0	1230	36.5	44.9						37
↓	↓	↓	↓	↓	41.0				15600										9.6			↓	*	*	↓	24.0	29.5					* FUSE FAILED	38
↓	↓	↓	↓	↓	38.5				14700										.50			↓	34.5	15.0	↓	22.5	27.7						39
↓	↓	↓	↓	↓	33.5				12800										.40			↓	34.0	14.8	↓	25.5	31.4						40

FILMS READ AND CALCULATED BY A. RICCHIUTI

TEST CONDUCTED BY W. KRACHT

DATE JAN. 26, 1979

Appendix

TEST LOG AND RESULTS

HIGH POWER TEST

HIGH POWER TESTS - CURRENT LIMITING PROTECTOR - CLP

PLACE: GENERAL ELECTRIC WILFRED SKEATS HIGH POWER LAB, PHILADELPHIA

DATE: 1/23 TO 1/25/1979 - G. E. TEST NO. M-79ES P2

PURPOSE: TO DETERMINE SHORT CIRCUIT CURRENT LIMITING ABILITY OF CURRENT LIMITING PROTECTOR AND CONTROL FUSES

G.E. TEST #	PEC TEST #	DEVICE DESCRIPTION	CIRCUIT kV	AVAIL. kA(RMS)	i_{Sense} kA	LET-THRU kA	PEAK RECOVERY kV	REMARKS	
1-6	1	Shorting Bar	4.2	15	-	-	-	Timing Test	OK
7	2	Fuse (1) 73-110-456-001	4.2	15	-	12	14.7	Fuse Test to Check)	OK
8	3	Fuse (1) 73-110-456-001	4.2	15	-	12	16.3	Circuit & Instrumentation)	
9	4	CLP + NXC 100A	4.2	15	7.5	13.3	10.8	Sym. Current	OK
10-12	5	CLP + (1) 73-110-456-001	4.2	15	7.5	12.4	13.4	" "	OK
13	6	Fuse (1) 73-110-456-001	4.2	30	-	10.8	16	Circuit Check-Out	OK
14	7	CLP + NXC 100A	4.2	30	12	20.3	12.1	Sym. Current	OK
15	9	Fuse (1) 73-110-456-001	4.2	40	-	12.7	15	Circuit Check-Out	OK
16	10	CLP + NXC 100A	4.2	40	12	22.2	12.8	Sym. Current	OK
17	11	CLP + (1) 73-110-456-001	4.2	40	12	16.5	16	" "	OK
18	12	CLP + (2) 73-110-433-008	4.2	40	12	16.8	10.8	" "	OK
19	28	Shorting Bar	7.2	40	-	-	-	Prosp. Current Test	OK
20	31	CLP + (1) 73-110-456-002	7.2	40	7.5	12.1	21.4	Sym. Current	OK
21	32	CLP + (1) 73-110-456-002	7.2	40	12	-	21.7	Sym. Current Failed	
23	33	CLP + (2) 73-110-433-009	7.2	40	12	16	17.6	Sym. Current Test	OK

HIGH POWER TESTS - CURRENT LIMITING PROTECTOR - CLP (Continued)

G.E. TEST #	PEC TEST #	DEVICE DESCRIPTION	CIRCUIT kV	AVAIL. kA(RMS)	i_{Sense} kA	LET-THRU kA	PEAK RECOVERY kV	REMARKS
24	40	CLP + CF-Fuse	15	40	5	16	29.7	Sym. Current Test OK
25	41	CLP + CF-Fuse	15	40	7.5	15.2	28.1	" " " OK
26	42	CLP + CF-Fuse	15	40	10	16.3	28.3	" " " OK
27	43	CLP + CF-Fuse	15	40	12	15.9	23.4	Sym. Current Test-Failed
28	Misfired							
29	35	Fuse (1) 73-110-456-003	15	25	-	9.9	41.2	Fuse Test to Check Cir.
30	51	CLP + (2) 73-110-433-010	15	25	*	10.1	39.3	Sym. Current Test OK
31	45	CLP + (1) 73-110-456-003	15	25	*	9.9	39.3	" " " OK
32	46	CLP + (1) 73-110-456-003	15	25	*	11.2	39.3	" " " OK
33	39	Fuse (1) 73-110-456-003	15	40	-	11.2	44.2	Fuse Test to Check Cir.
34	44	CLP + CF-Fuse	15	40	7.5*	16.2	34.4	Sym. Current Test OK
35	47	CLP + (1) 73-110-456-003	15	40	10*	17	-	Sym. Current-Failed
36	48	CLP + (1) 73-110-456-003	15	40	*	11.2	37.5	" " OK
37	49	CLP + (1) 73-110-456-003	15	40	*	13.2	44.9	" " OK
38	50	CLP + (1) 73-110-456-003	15	40	*	16.6	29.5	Sym. Current - Failed
39	52	CLP + CF-Fuse	15	40	*	15.6	27.7	" " OK
40	53	CLP + CF-Fuse	15	40	*	13.9	31.4	" " OK

* - FIRED FROM STATION CONTROL TIMER