CURRENT LIMITING FUSE STUDY

EPRI EL-453
(Research Project 428)

Final Report

June 1977

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ABSTRACT

A study of current limiting fuses aimed to improve performance with corresponding higher current ratings in a single barrel is presented. The overall program was directed towards new element design, gas impregnation, and composite polymer sand fillers. The new element design is based on a freestanding cylinder approach with a large surface area-to-volume ratio. The new element design provides better heat transfer and higher arcing gradients. New filler mixtures also increase arcing gradients and improve interruption capability. Better heat transfer, higher arcing gradients and improved interruption capability will improve overall performance of the fuse and increase the current rating.

The full-size experiments (15 kV, 200 A) demonstrated significant improvements in the average arc voltage and rating capability when compared to existing state of the art technology. The information, ideas, and technical data disclosed in this report do not necessarily represent practicable or thoroughly tested devices and should not be used as the basis for manufacture or construction without further investigation as to safety and suitability. The experiments also revealed some critical problem areas which must be addressed before significant fuse progress can be made available to the utility market.

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Section 1

INTRODUCTION AND SUMMARY

Current limiting fuses have many features which make them ideally suitable as protective devices. They primarily limit the fault current to a fraction of its potential within the first major loop. They do not expel any gases and are completely silent during operation. These characteristics are particularly useful for protective devices in constricted areas such as indoor and underground applications. By limiting the fault current, they greatly reduce the mechanical and thermal stress imposed on the system components.

The modern silver sand medium-voltage power fuse contains either helical-wound or straight silver ribbon elements embodied in a sand matrix.(1-1, 2) The fuse elements contain a combination of geometrical (perforations or parallel elements with small spark gaps) or metallurgical (metal eutectics) combinations which control the melting characteristics, arc voltage spike and, to some extent, the average arc voltage. The arc is stabilized by a thin sand channel with dynamics which are determined by ablation from silicon dioxide. Although the modern fuse represents considerable evolution characterized by the transition from cylindrical elements to ribbon elements, from solid elements to perforated elements, from homogeneous elements to metal eutectic elements, and from pure sand to sand with gas-emitting spiders, they still offer a great scope for further development and refinement with corresponding larger current ratings in a single barrel.

Under the sponsorship of EPRI, Allis-Chalmers conducted a current limiting fuse study aimed toward improving the performance and advancing the technology in this field. The purpose of the "Current Limiting Fuse Study" was to study and evaluate three suggested concepts to improve the performance of the state of the art fuses. These improvements were directed towards higher continuous current ratings in a single barrel with corresponding lower let-through characteristics.

The first concept deals with element geometry and is based on achieving improved heat transfer and larger arcing gradients. Element geometry has a great impact on the performance of the fuse. Also, its design has to meet conflicting requirements. The steady-state current rating of the fuse is determined by heat generation and dissipation under normal load conditions. Whereas a higher element cross section would permit higher current rating by decrease in resistance, it also tends to increase the melting and the cutoff current and thus increase the let-through energy under high fault current interruption. An ideal fuse would be one which, although permitting higher currents under steady-state conditions, does not increase the let-through substantially. Such a compromise can only be achieved by improving the heat transfer.

The current limiting fuse derives its capability of limiting the fault current by the development of an arc voltage equal to or greater than the system crest voltage which quickly drives the current to zero. When a high fault current flows, the silver element is quickly heated and vaporizes. The vapor is driven and condensed in the sand filler. Arcing is then initiated in this section which gradually extends to the full length. The magnitude and shape of the arc voltage, which depends on perforations and multiple arcing, can be controlled by element design.(1-3) The arc voltage affects the current limiting action of the fuse and thus the let-through. A large arc voltage is important for forcing the current to zero but must be compromised to coordinate with system protection devices.(1-4) Also, once the arc is developed to the full length, the arc voltage soon collapses to a low value. From the point of view of minimum let-through, it is more desirable to obtain a gradual increase in arc voltage, sustained constant thereafter for the duration of arcing, rather than a sudden peak.

With these requirements in view, a cylindrical geometry for the element was proposed. The study uncovered some problems associated with the cylindrical element, particularly the low arc voltage, and finally converged on a diamond cylinder design which provides both improved heat transfer and higher arcing gradients. The concept is based on an increase in the surface area-to-volume ratio which increases the heat transfer from the element to the barrel and therefore increases the current rating. The expanded diamond mesh lengthens the arc to achieve a high arc voltage. The final element design is a compromise over the proposed concept but still provides a considerable improvement in the surface area-to-volume ratio which leads to improved performance. The developed design is still far from optimum and offers great scope for further improvements.

The second concept is an extension of organic binders and gas-emitting spiders used by various manufacturers in today's market. Organic fillers mixed with sand have the advantage of more direct contact with the arc which decreases the response time over a gas-emitting spider and is therefore not limited to the low end of the time-current characteristics. A second advantage is the ease over which its concentration can be varied which allows an easy compromise between response time and excessive pressure buildup. The polymer mixture study resulted in selection of large polymer resin particles (typically 2.5 mm). A controlled concentration of polymer particles will increase the arc voltage up to 20% without generating an excessive gas pressure which cannot be contained within the fuse barrel. The low melting and vaporization temperature of the polymer, however, presents some problems for which a suitable solution has yet to be found.

The third concept was based on better arc quenching performance due to a gas like SF_6. Gas impregnation has a noticeable effect on the time-current characteristics (TCC) and the arc voltage, but to date the effects have all been negative. The arc voltage has decreased using either two atmospheres of nitrogen or one atmosphere of SF_6. The results have been confirmed using an impulse dielectric recovery test method. During the first 40-50 μs, this shows a poor recovery voltage compared to one atmosphere of air. The long delay time recovery characteristics are better than air but do not help the interruption capability.

All three concepts were based on their ability to either increase the heat transfer or increase arcing gradient, both of which are required to increase the load rating of a fuse in a single barrel.

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1-3 H. W. Mikulecky, "Current Limiting Fuse Arc-Voltage Characteristics," IEEE PAS Trans. 87, pp. 438-448, 1968.

1-4 "Coordination of Lightning Arrestors and Current Limiting Fuses," IEEE Switchgear Committee and Surge Protective Devices Committee Working Group, IEEE Trans. PAS Vol. PAS 91, pp. 1075-1078, May/June, 1972.

Section 2

ELEMENT DESIGN

CONCEPT INVESTIGATION

The earliest type of fuses consisted of thin wires embedded in granular silica filler. Because of their cylindrical geometry, they have a low surface area-to-volume ratio and therefore little surface in contact with the filler. This results in poor heat transfer and a lower current-carrying capability under steady load conditions. Moreover, they are generally placed in the center of a fuse vehicle and thus have a higher thermal resistance to the fuse ambient. Both of these factors reduce heat transfer and the fuses have a large cross-sectional area to reduce heat generation which can be dissipated under steady load conditions.

Under fault current interruption, because of greater cross-sectional area, the wire elements have a higher cutoff current as well as the critical current-to-melting current ratio. This permits higher let-through. Because of higher let-through, they permit greater amounts of energy to be passed on to the system which not only causes damage to the system components but also makes interruption difficult for the fuse. On account of this, the fuses with wire elements are restricted to low rated currents only.

The current limiting fuse derives its current limiting capability by production of an arc voltage of the order of the system crest voltage or higher, sustained over a period of several milliseconds. The sustained arc voltage drives the current quickly to zero. The arc voltage generation depends to a great deal on the element design. On early wire elements, because of dominance of radial over longitudinal heat transfer, the major part of the element melts at once, giving rise to a large arc voltage spike. The remaining part of the silver then quickly vaporizes to form a continuous cylindrical arc which causes a quick collapse in arc voltage.

Both of these factors (i.e., production of a voltage spike and the quick collapse of arc voltage) are undesirable. A large voltage could trigger a protective device such as a surge arrestor.(2-1) The quick collapse of arc voltage would result in poor current limiting capability.

Introduction of ribbon elements in the 50's provided improved performance and they were readily accepted.(2-2) They have a larger surface area-to-volume ratio as compared to the wire elements. Because of greater surface in contact with the filler, they have better heat transfer, which results in higher current rating even for the same cross-sectional area. This provides better performance in critical current or fault current interruption range because of earlier cutoff currents and therefore lower let-through.

Ribbon elements also offer an easy means of providing areas of reduced cross section. Areas of reduced cross section under fault current interruption will melt first, providing multiple arcing. The remaining section then burns gradually till the complete silver is burned to exhaustion. This gradual and controlled burning of silver provides a means for control of arc voltage, both in its magnitude and the wave shape. Moreover, multiple arcing also has a distinct advantage of distributing the arc energy longitudinally within the barrel instead of being concentrated to one or few points. The multiple arcing in the ribbon-type elements can be easily controlled by spacing between the holes or notches provided to create areas of reduced cross sections. Because of distribution of this arc energy uniformly, the silica filler is able to absorb the energy and still maintain the dielectric strength.

In view of the above facts, a cylindrical geometry should provide a better heat transfer and therefore improved performance, and, as such, was proposed. Heat transfer was expected to improve because of larger surface area-to-volume ratio of the cylinder and because of lower thermal resistance to the fuse ambient temperature. Further, by going to a larger surface area, the thickness of the element decreases for a given load rating. This was expected to provide a thin arc channel, producing higher arc voltage.

Low current melting tests conducted on the cylindrical elements showed better heat transfer. An element with a diameter of 2.0 cm and a thickness of 0.0013 cm would provide a rating of 100 amps when C-rated. Resistance for this fuse with 40 cm length was 8.2 mΩ, and the silver mass 3.27 grams. Melting I^2t for this fuse would be 4.4×10^4 amperes^2 second as against 10^5 amperes^2 second for a commercially available fuse. Melting time current characteristics are shown in Figure 2-1.

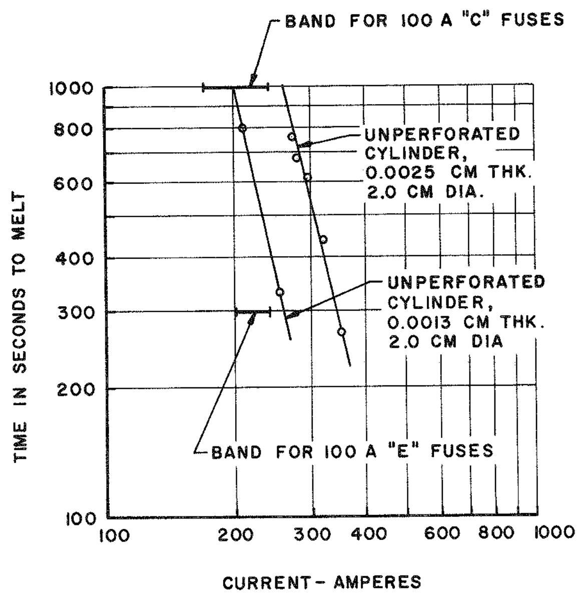


Figure 2-1. Low Current Melt Characteristics of Cylindrical Element Fuses

In the critical current tests, the fuse, when tested at 15 kV, 7.5 kA, failed to interrupt. It was observed that the sustained arc voltage was too low (6-8 kV) so that the current limiting action was not adequate. Also, the brief voltage spikes appeared at the arc initiation. The pertinent details are listed in Table 2-1. Further tests showed that this fuse will not interrupt beyond 6 kV and would be accompanied with voltage spikes.

The expected behavior of the arc restricting to a thin arc channel did not occur (Figure 2-2). Because of this, they failed to develop a sustained arc voltage and rather developed into a continuous arcing channel to the full length. This was concluded to be on account of uncontrolled burning of silver which is provided by the perforations or notches in the ribbon elements. Also, intolerable voltage spikes appeared. However, the exceptional load current to melting current ratio inherent in this geometry encouraged a search for modifications of the initial concept which would improve the arc voltage characteristics.

ARC VOLTAGE STUDY

A means to increase the arc voltage of the elements was investigated, first to provide multiple arcing by creating areas of reduced cross section, thus controlling both the arc voltage magnitude and the wave shapes, and, second, to increase the arc path length, without increase of the axial length, by increasing the tortuosity of the arc path.

Table 2-1

POWER TESTS AND RESULTS, UNPERFORATED CYLINDER FUSES

SPEC NO.	TEST VOLTAGE (kV)	PROSPECTIVE kA	CLOSING ANGLE DEGREES	TIMES (ms) MELT	TIMES (ms) ARC	CURRENT MELT** (kA)	ARC VOLTAGE (kV) CREST	ARC VOLTAGE (kV) 1 ms AFTER MELT	ARC VOLTAGE (kV) 4 ms AFTER MELT	REMARKS
S7	15.0	7.5	+7°	2.9	--	8.3	18.7	7.8	5.7	Failed
S10*	15.0	7.5	+28°	3.2	--	11.9	17.0	8.5	5.7	Failed
S8	4.6	7.9	+26°	2.5	5.2	8.5	15.4	6.8	4.2	Cleared
F11	5.4	7.8	+10°	3.2	6.1	8.5	16.4	7.0	4.9	Cleared
F12	8.7	7.8	-44°	5.5	--	8.3	16.4	7.5	5.1	Failed

*S10 had a 0.0025 cm element; the other had 0.0013 cm element.

**The current at melt is substantially the peak current for successful fuses.

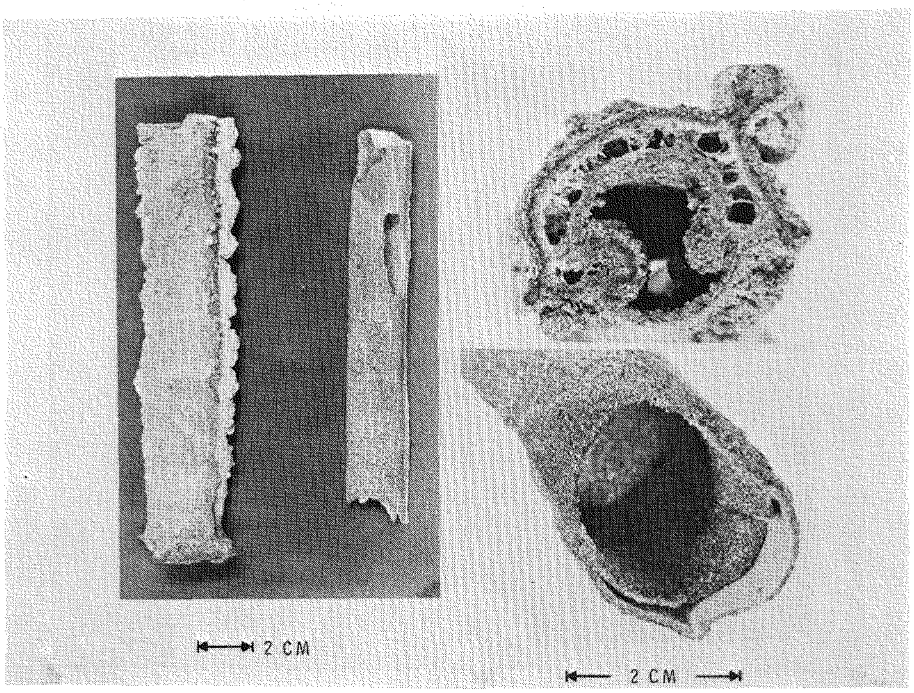


Figure 2-2. Fulgurites of Unperforated Cylindrical Elements

To expedite the study and obtain a quick turnaround, this study was conducted on a capacitor bank.(2-3) The Advanced Technology Center capacitor bank laboratory was used (Appendix A). As explained in the appendix, this type of equipment is restricted to production of symmetric-prospective waveforms, differing in this respect from conventional machine laboratories. However, for quick evaluation of the prototype elements, this laboratory is cost-effective.

The current limiting fuse derives its current limiting action by production of an arc voltage of the order of system crest voltage or higher, sustained over a period of several milliseconds. A well sustained arc voltage would quickly limit the current and thus the let-through.(2-4) Thus in comparing the relative performance, the integral of the arc voltage over the arcing period was compared and will be used for discussion in this report.

At first a study was conducted to examine the effect of various parameters like thickness and width of the strip elements on the arc voltage. Figure 2-3 shows the effect of thickness in reducing the voltage spikes when the cross-sectional area is maintained constant. There was, however, no significant gain in the average arc voltage either by increase of thickness or the width (Figure 2-4).

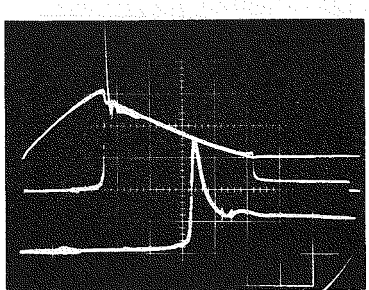
As a next step, the effect of perforation pattern was examined on element performance. This was expected to provide gradual burning of silver, suppressing the peak arc voltage and providing sustained arc voltages by multiple arcing initiated between perforations. This would also prevent rapid coalescence of the arc into a long, cylindrical arc channel and thus promote sustained arc voltages (Figure 2-5).

With perforated patterns, the strip thickness or the width has little consequence (Figure 2-6) as long as the punching pattern is constant. Decrease in lateral spacing also does not improve or change performance. Decrease in axial spacing, however, improves the arc voltage considerably. This is on account of increase of series arclets (Figure 2-7).

The gain in average arc voltage is considerable over the unperforated strip, confirming clearly the benefit of perforation. Perforations also inhibit undesired overvoltages and spikes (Figure 2-8). However, the gain is not sufficient to provide a fuse for 15 kV in acceptable length and, as such, means to increase the ratio of arc length to axial length were investigated.

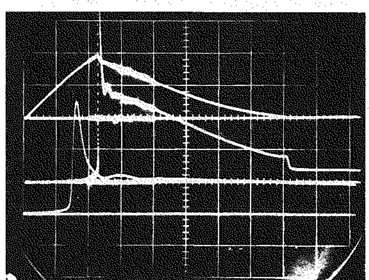
DESIGN DEVELOPMENT

During the course of these tests, a novel concept for increasing the arc path length was generated. Briefly, the idea consisted of a judicious use of large diamond perforations to constrain the current to elongated paths. The concept was quickly



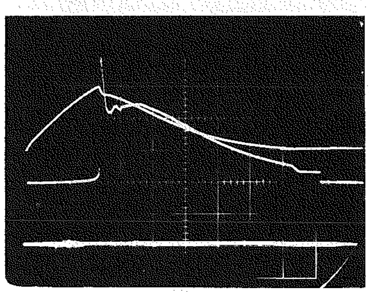
FUSE No. 22

0.0013 CM TH. x 3.14 CM W.
PLAIN STRIP
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
MIDDLE TRACE: ARC VOLTAGE,
2.2 KV/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE,
5.5 KV/CM, 0.2 MS/CM



FUSE No. 43

0.0025 CM TH. x 1.57 CM W.
PLAIN STRIP
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
MIDDLE TRACE: ARC VOLTAGE,
2.2 KV/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE,
5.5 KV/CM



FUSE No. 21

0.0051 CM TH. x 0.78 CM W.
PLAIN STRIP
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
MIDDLE TRACE: ARC VOLTAGE,
2.2 KV/CM, 1 MS/CM

Figure 2-3. Oscillograms, Tests of Plain Strips

tested and developed by making prototype patterns representing half of the element (Figure 2-9). When fully developed, this would have a depicted half and its mirror image along either side. The fully developed element would have diamond openings and would also be wrapped and joined to form a diamond cylinder. In this way a ratio of arc path length to axial length of greater than 2.5 could be obtained.

Various steps of developments are shown in Figure 2-9. Each of the tests aided the stepwise element evolution. For example, the fulgurite of element 41 (Figure 2-10) encroached too heavily on the narrow notch, suggesting the wider notch incorporated in the successors. Also, the burn-down in the notch region was grossly incomplete, suggesting the perforation or necking down of the notch region of elements 44 and 45 respectively. Only one constriction (hole) was used in the web of element 44 to avoid excessive fulgurite buildup in the notch at the expense of slower arc voltage development. However, the feared buildup of fulgurite did not occur in the artifact of element 45 which had two constrictions in each web and a quicker arc voltage development.

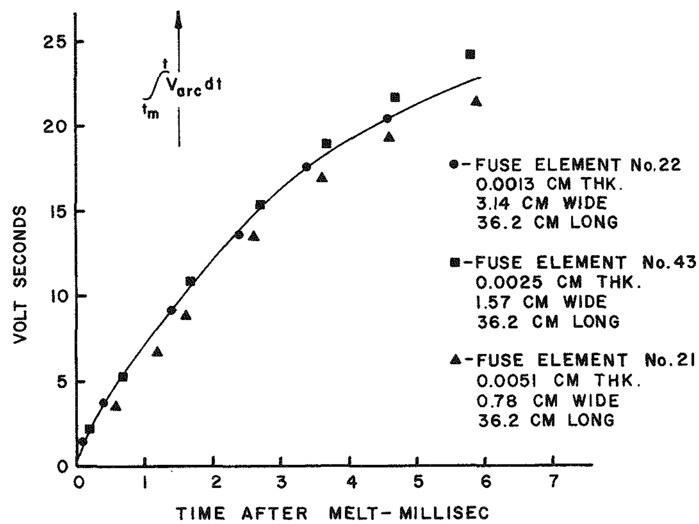


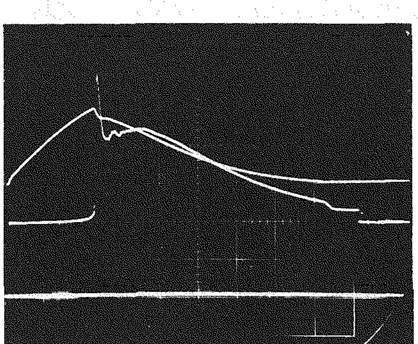
Figure 2-4. Arc Voltage Integral, Plain Strips

Tests conducted on the capacitor bank revealed improvements. The extent of improvement over perforated ribbons is shown in Figure 2-11. The arc voltage integral $\left(\int_{tm}^{ta} \text{Varc dt}\right)$ is far superior. This would provide better current limiting action.

The elements were designed to have simultaneous arcing in the neck as well as the web sections. This was desired to dissipate energy over the entire volume so as to avoid overheating in one region and provide sustained arc voltage. Figure 2-12 shows the improvement in the arc voltage magnitude and the wave shape and its effect on the current limiting action of the fuse.

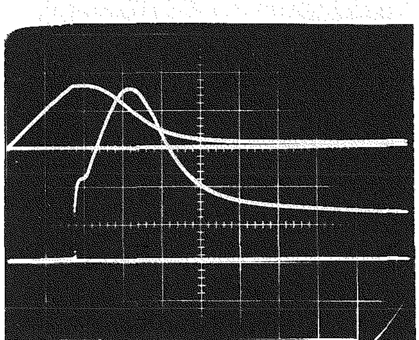
The results obtained in the prototype elements encouraged the construction of cylindrical elements with large diamond perforations. Silver element fuses were made having a thickness of 0.05 mm and a cylinder diameter of 2.67 cm. The arc path length was kept at 90 cm, considered enough to provide sufficient arc voltage for a

15 kV fuse. The expanded pattern for the element is shown in Figure 2-13.



FUSE No. 21

0.0051 CM TH. x 0.78 CM W.
PLAIN STRIP
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
MIDDLE TRACE: ARC VOLTAGE,
2.2 KV/CM, 1 MS/CM



FUSE No. 46

STATE-OF-ART
PERFORATED ELEMENT E
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE
2 KV/CM, 1 MS/CM

Figure 2-5. Effect of Perforation on Arc Voltage

The pattern, when rolled in the form of a cylinder, is a compromise between the helical-wound perforated ribbon and the proposed cylindrical element. It has a greater surface area-to-volume ratio and lower thermal resistance and therefore should have better heat transfer. A comparison of the two elements is shown in Figure 2-14.

A few fuses with these diamond pattern cylinder elements were constructed. The fuse vehicle used was a melamine bonded fiberglass barrel with an internal diameter of 66.7 mm and a wall thickness of 3.2 mm. The fuse construction is shown in Figure 2-15. The filler composed of granular silica sand, Ottawa #17, the characteristics of which are listed in Table 2-2. The insertion of diamond cylinder element required careful handling techniques. To keep the convolutions apart, they were glued with a glass cord. The barrel was back-filled with sand filler after insertion of the element, and the end caps fitted. The fuse assembly is shown in Figure 2-15.

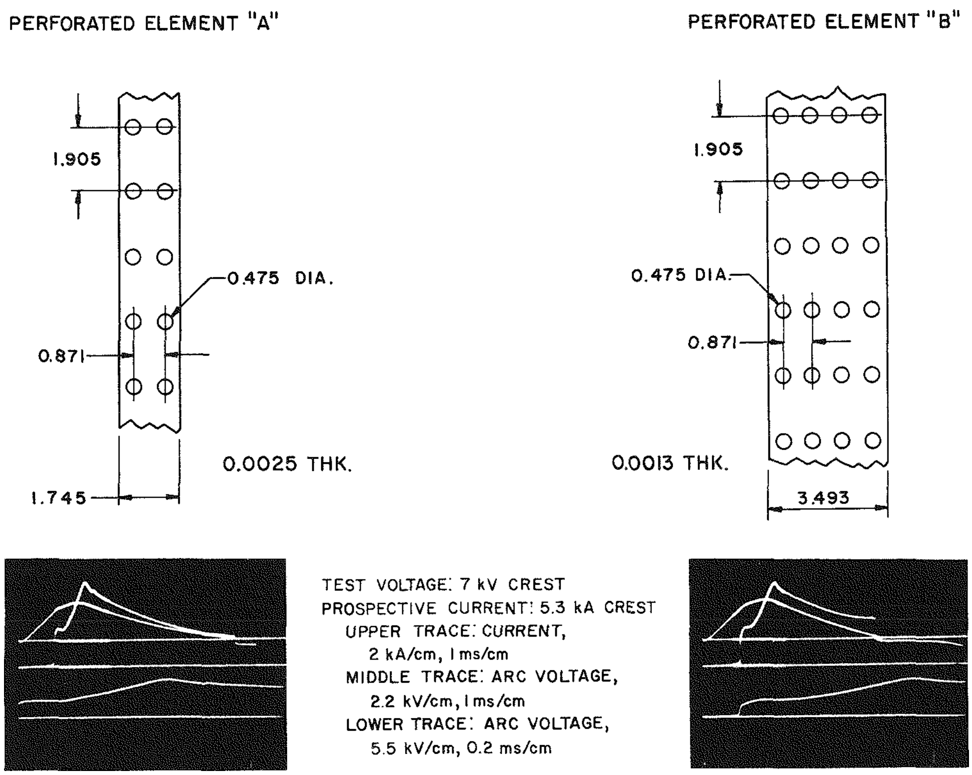


Figure 2-6. Effect of Lateral Spacing of Perforations on Arc Voltage

Oscillograms of the tests conducted on the capacitor bank are shown in Figure 2-16. A helical-wound ribbon tested under identical conditions is also shown. Helically-wound ribbon has an estimated current rating of 44 amps as against 55 amps for a diamond cylinder element. In spite of the higher current rating, the let-through is less for a diamond cylinder element.

Figure 2-17 compares the let-through, arc voltage and the current limiting action of the two fuses. Though the performance of the diamond cylinder element is superior, it is far from optimized. They still offer a great scope for further improvement by element design.

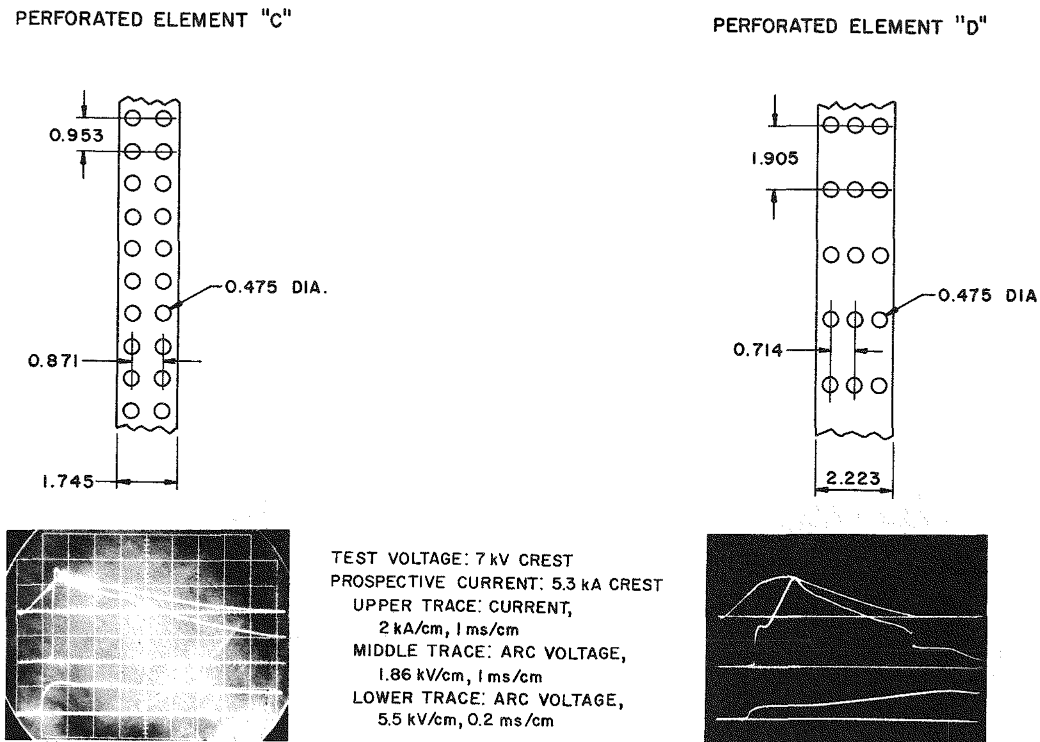


Figure 2-7. Effect of Axial Spacing of Perforations

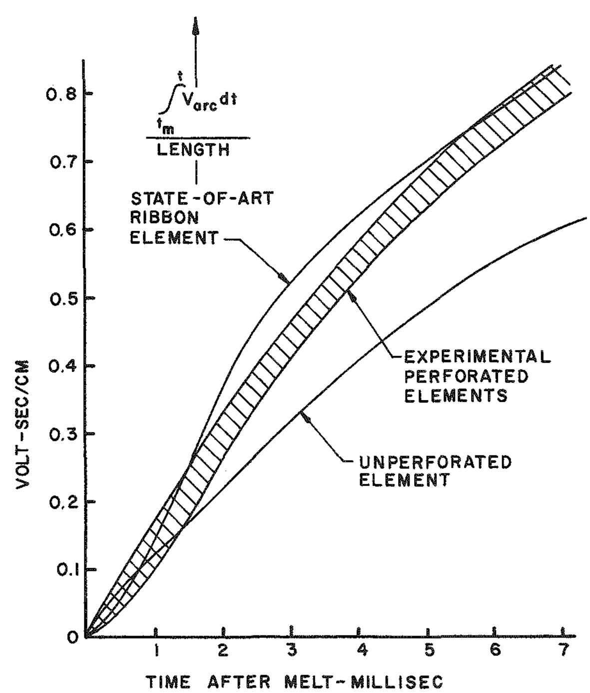


Figure 2-8. Normalized Arc Voltage Integrals. Perforated Strips Compared to Unperforated Strip

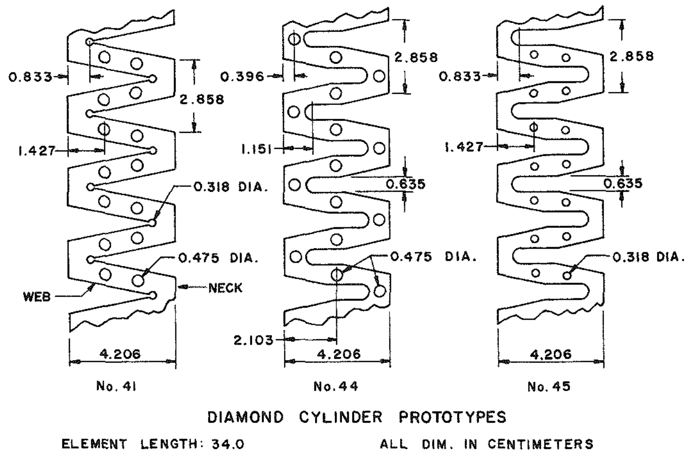


Figure 2-9. Diamond Cylinder Prototype Patterns

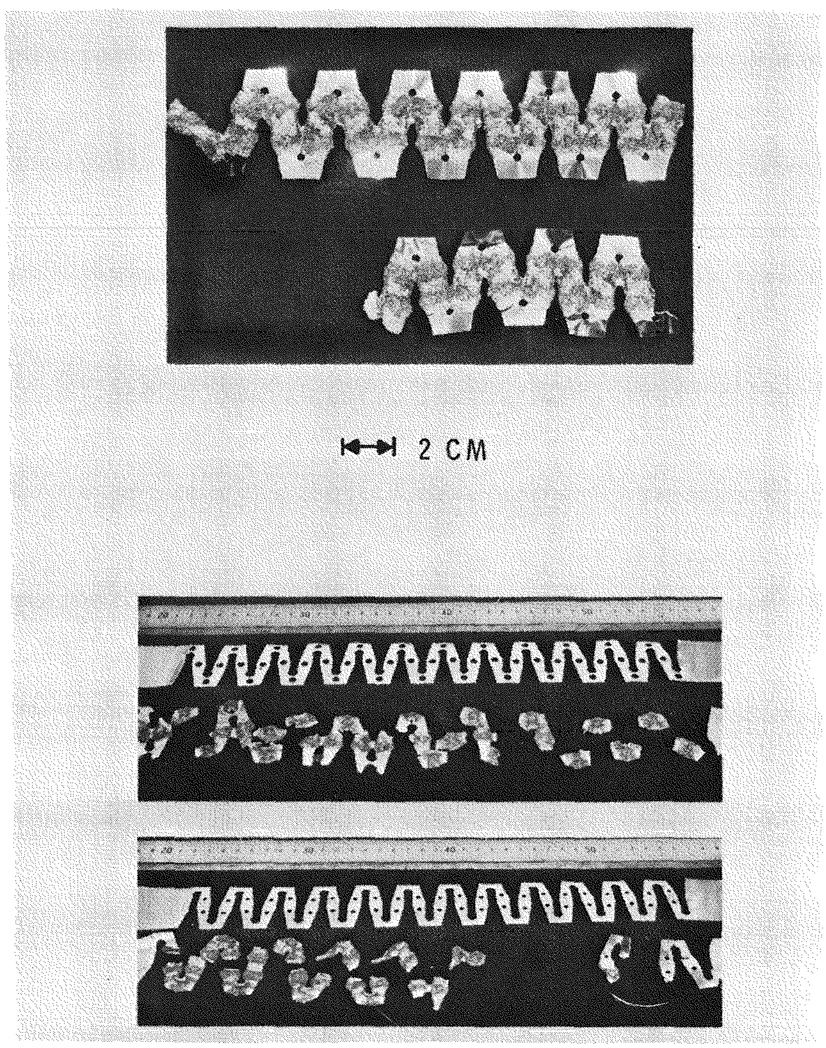


Figure 2-10. Fulgurites, Diamond Cylinder Prototype Elements

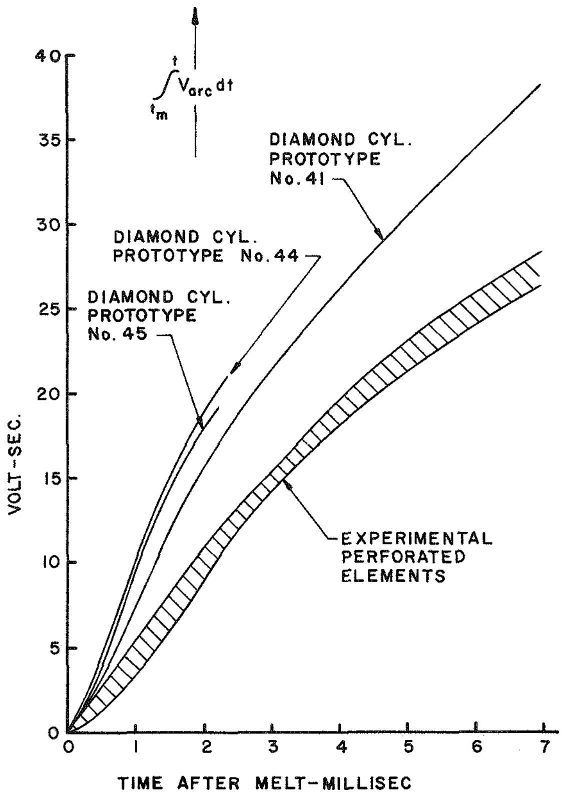
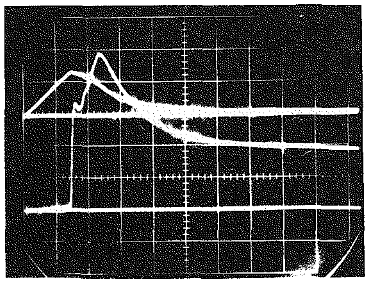


Figure 2-11. Arc Voltage Integrals, Diamond Cylinder Prototypes Compared to Perforated Strips

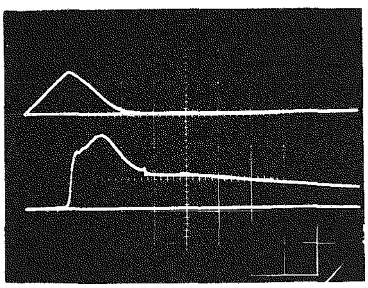
Tests conducted in a standard short-circuit laboratory are listed in Table 2-3. Tests were conducted at critical current (3.1 kA) with a sufficiently offset current wave at voltages between 12.5 kV to 15.0 kV.(2-5) Results indicate that the fuse with these parameters will develop sufficient arc voltage to interrupt circuits up to 12.5 kV. With further improvement in the design, their performance can be improved further and they offer great potential for application for higher rated current fuses.

Expansion of silver sheet into a diamond mesh offers a means for production of fuse elements with elongated arc paths. Some samples produced by the state of the art production process were also tested. A wide range of strand width and diamond size are available, and a product suitable for fuse application can be selected.



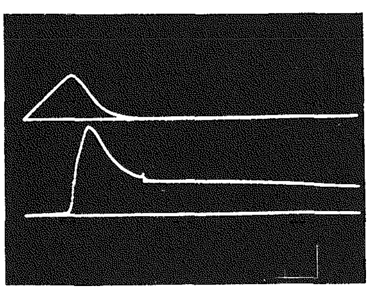
DIAMOND CYLINDER PROTOTYPE No.41

TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, I MS/CM
LOWER TRACE: ARC VOLTAGE,
2 KV/CM, I MS/CM



DIAMOND CYLINDER PROTOTYPE No.44

TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.4 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, I MS/CM
LOWER TRACE: ARC VOLTAGE
5 KV/CM, I MS/CM



DIAMOND CYLINDER PROTOTYPE No. 45

TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.4 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, I MS/CM
LOWER TRACE: ARC VOLTAGE,
5 KV/CM, I MS/CM

Figure 2-12. Oscillograms, Diamond Cylinder Prototype Tests

The oscillograms of tests conducted on expanded mesh (Figure 2-18) indicate promising increase in arc voltage above those obtained from perforations (Figure 2-19). The fulgurites of one of the meshes tested are shown in Figure 2-20. The arcing is fairly well distributed with no tendency to collapse into a short large arc channel. With proper design, an optimized geometry may be achieved in which the voltage spikes may also be reduced and a well sustained arc voltage obtained.

LOAD RATING FLEXIBILITY

The low current melt test (test setup shown in Figure 2-21) conducted on the diamond cylinder element fuses (2.67 cm diameter, 0.05 mm thick) showed they would have a current rating of 55 amps with C rating. Further increase in the rating could be obtained by increasing the thickness as well as the diameter of the diamond cylinder. Effect of variation of both the parameters was examined. Since the increase in heat transfer would offer higher current rating without increase in the let-through energy, effort was directed in achieving better heat transfer by extrapolation of these parameters.

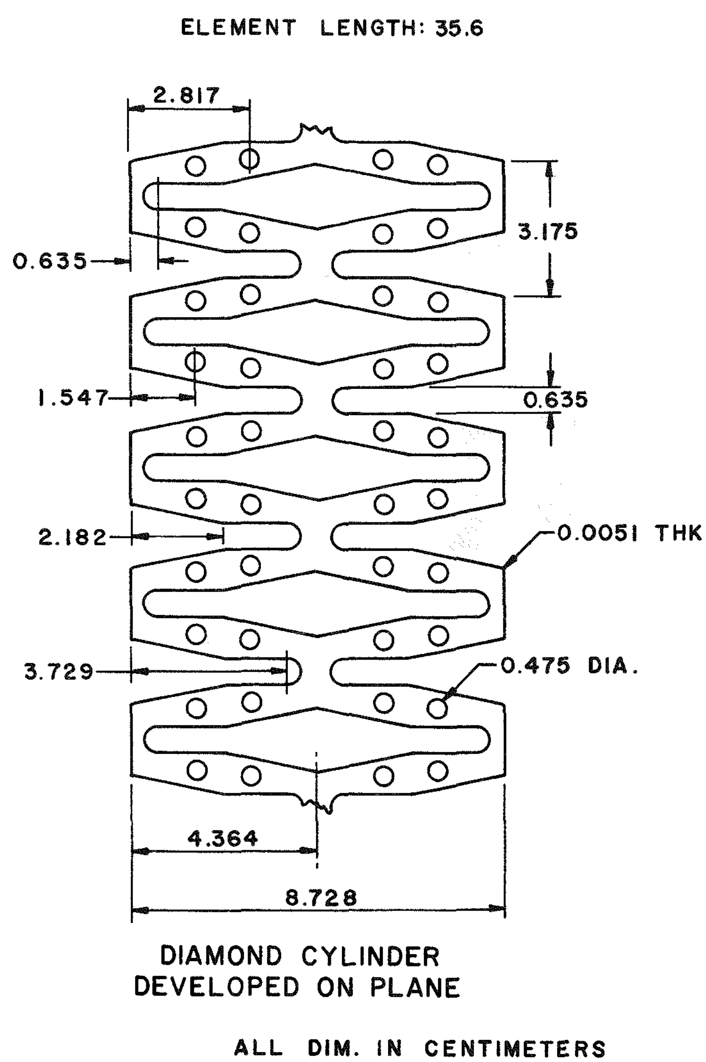


Figure 2-13. Diamond Cylinder Element Developed on a Plane

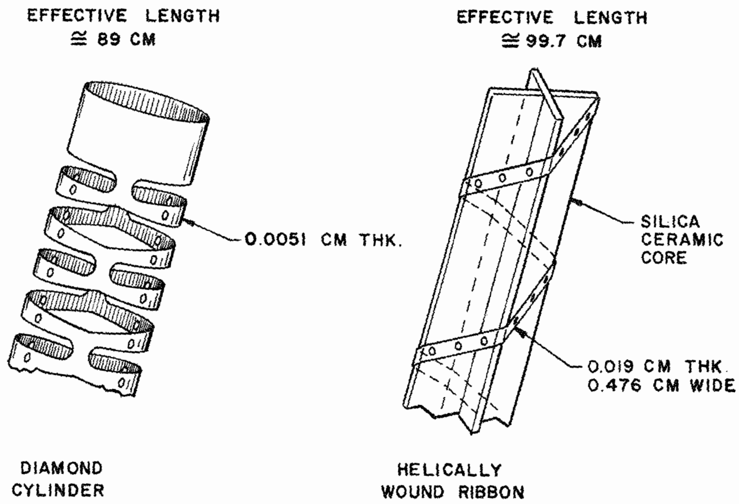


Figure 2-14. Comparison of Diamond Cylinder and Helical Ribbon Elements

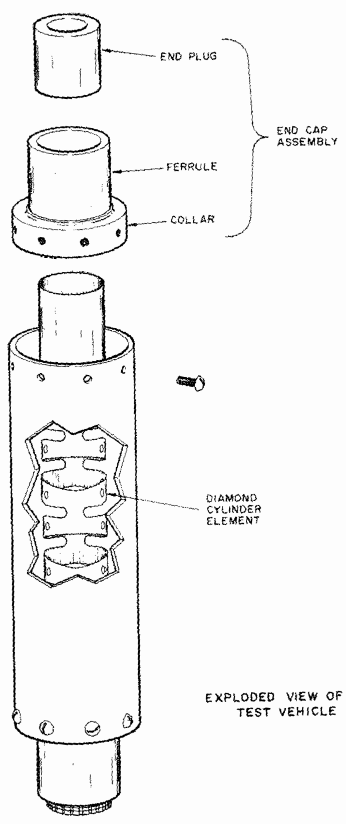


Figure 2-15. Exploded View of Test Vehicle

Table 2-2

CHARACTERISTICS OF SILICA FILLER

SCREEN ANALYSIS		
TYLER MESH	OPENING (MICRONS)	% DISTRIBUTION
28	590	0
35	420	7
48	297	44
65	210	34
100	149	12
150	105	3
200	74	0

Bulk Density: 1.68 $\frac{g}{cm^3}$

Specific Gravity: 2.65

Approx. Surface Area: 100 cm^2/g

Base Permeability*: 230

Impurities:

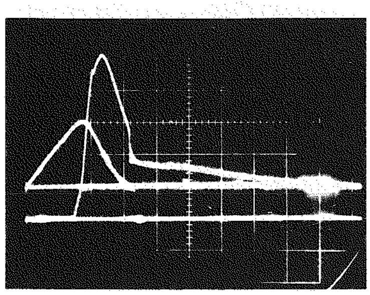
Fe_2O_3 less than 0.02%

Al_2O_3 less than 0.05%

*Specific air conductance as defined by Am. Foundry Soc.

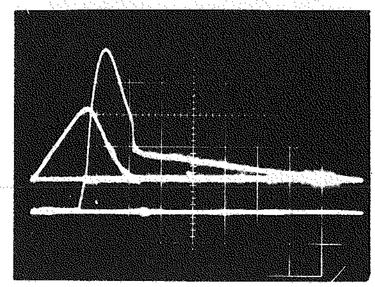
The increase in thickness of the diamond cylinder element had no effect on the heat transfer. Whatever increase in the current rating was achieved was on account of reduction of the element resistance. Tests were conducted on fuses made with element thicknesses of 0.05, 0.1, 0.15, 0.229 and 0.4 mm. Elements with a smaller thickness were easy to punch and roll. However, the thicker elements presented problems in rolling into a cylinder due to work hardening and other stresses. They were therefore annealed after cutting by heating under a controlled temperature for one-half hour at 600°F. and then cooling them with a normal cooling rate. They could be rolled into a cylinder easily thereafter.

Figure 2-22 shows a plot of melting time-current characteristics for fuses with different thicknesses. The resistance of these fuses was also measured prior to the tests. A graph of current rating plotted against thickness and 1/R is shown in Figure 2-23. This indicates that the current rating would increase in proportion to the square root of the thickness or inversely as the square root of the resistance, thus keeping the I^2R losses constant. The current rating for a 0.4 mm fuse would be 170 amps, according to C rating, and the resistance 4.25 mΩ.



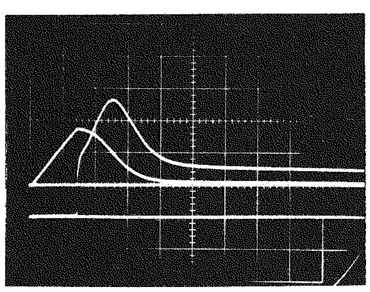
FUSE No. 47

DIAMOND CYLINDER
TEST VOLTAGE: 12 KV CREST
PROSPECTIVE CURRENT: 7.0 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE,
5 KV/CM, 1 MS/CM



FUSE No. 48

DIAMOND CYLINDER
TEST VOLTAGE: 12 KV CREST
PROSPECTIVE CURRENT: 7.9 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE,
5 KV/CM, 1 MS/CM



FUSE No. 56

99.7 CM LONG PERFORATED
RIBBON, HELICALLY WOUND
TEST VOLTAGE: 12 KV CREST
PROSPECTIVE CURRENT: 7.0 KA CREST
UPPER TRACE: CURRENT,
2 KA/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE,
5 KV/CM, 1 MS/CM

Figure 2-16. Oscillograms, Diamond Cylinder and Helical Ribbon Tests

In examining the effect of increasing the diameter of the diamond cylinder, the design proportions were maintained constant. Simply, the dimensions were increased 150% increasing the diameter of the diamond cylinder to 4.0 cm. Further, to keep the arc path length constant, the number of convolutions was reduced from 11 to 7. Expanded pattern developed on a plane is shown in Figure 2-24. An element having a thickness of 0.229 mm with 4.0 cm diameter has a resistance of 4.5 mΩ.

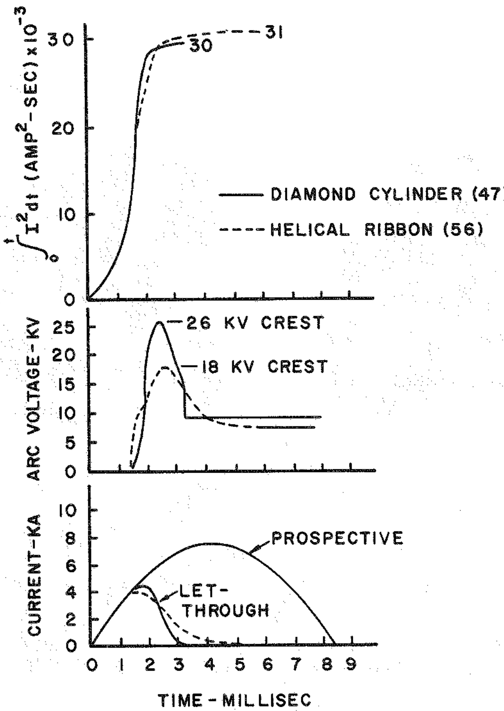


Figure 2-17. Performance Characteristics, Diamond Cylinder and Helical Ribbon

Melting time-current characteristics for this fuse are shown in Figure 2-25 and compared to a fuse with 2.67 diameter and 0.4 mm thickness. The load rating for the fuse with wider diameter is 188 amps, C rating. The two elements shown have resistances closely matched. The resistance of the diamond cylinder element having a thickness of 0.4 mm and a diameter of 2.67 cm is a little lower than that of a fuse with a thickness of 0.229 mm and a diameter of 4.0 cm; however, in spite of this, the fuse rating for the 4.0 cm diameter is higher. This is due to better heat transfer achieved on account of lower thermal resistance to the fuse ambient and higher contact surface of element with the filler.

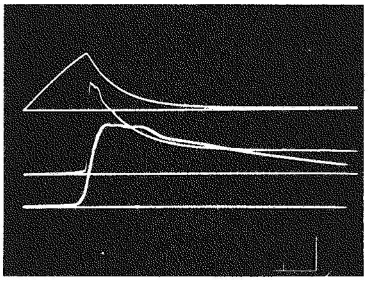
A 10% increase in current rating has been obtained with the fuse having 4.0 cm diameter over the fuse with 2.67 cm diameter. This is a significant increase since this increase should be obtained with almost no increase in the let-through energy as the silver mass is about constant.

Table 2-3

HIGH-POWER LABORATORY TESTS OF DIAMOND CYLINDER FUSES*

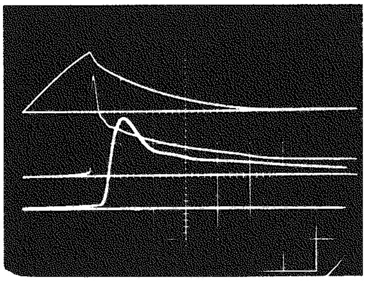
TEST LEVEL kV rms	PEAK ARC VOLTAGE (kV)	ARC VOLTAGE AFTER 3 ms (kV)	REMARKS
12.5	33.3	11.3	Circuit was cleared.
13.2	31.8	9.2	Arcing continued after current zero.
13.2	35.1	11.3	Circuit was cleared.
15.0	31.0	10.6	Circuit cleared momentarily. Reignition occurred at 19.8 kV, 3 ms after current zero.
15.0	26.2	10.2	Abnormally low, erratic arc voltage. After momentarily clearing arc reignition occurred at 19.8 kV, 2.7 ms after current zero.
15.0	29.0	8.6	Abnormally low, erratic arc voltage development. Arcing continued after current zero.

*The nominal prospective current was 3100 A rms, roughly the critical current. The circuit was closed near 10° after voltage zero to produce "fully" offset current waves.



FUSE No. 52

COARSE DIAMOND SCREEN
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT, 2 KA/CM, 1 MS/CM
MIDDLE TRACE: ARC VOLTAGE, 5 KV/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE, 5 KV/CM, 0.2 MS/CM



FUSE No. 54

FINE DIAMOND SCREEN
TEST VOLTAGE: 7 KV CREST
PROSPECTIVE CURRENT: 5.3 KA CREST
UPPER TRACE: CURRENT, 2 KA/CM, 1 MS/CM
MIDDLE TRACE: ARC VOLTAGE, 5 KV/CM, 1 MS/CM
LOWER TRACE: ARC VOLTAGE, 5 KV/CM, 0.2 MS/CM

Figure 2-18. Oscillograms, Tests of Expanded Silver Diamond Mesh

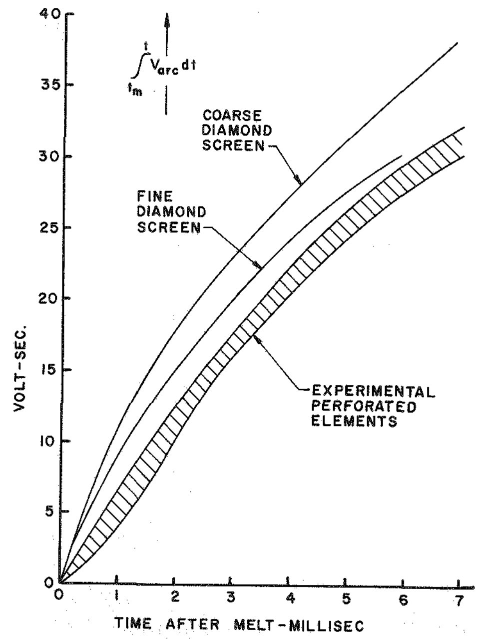


Figure 2-19. Arc Voltage Integrals, Diamond Mesh Compared to Perforated Strips

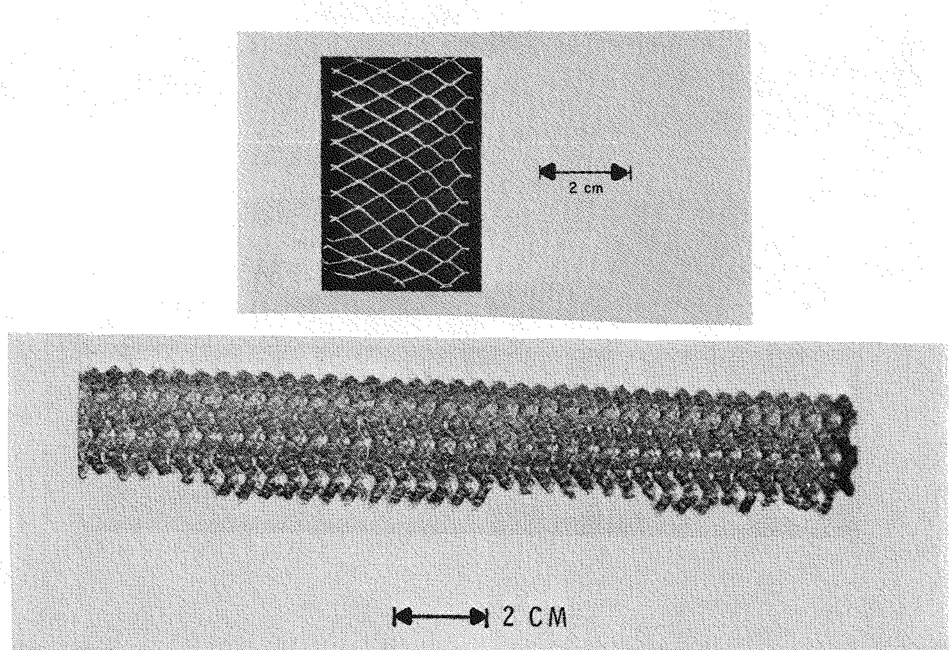


Figure 2-20. Fulgurite, Coarse Mesh

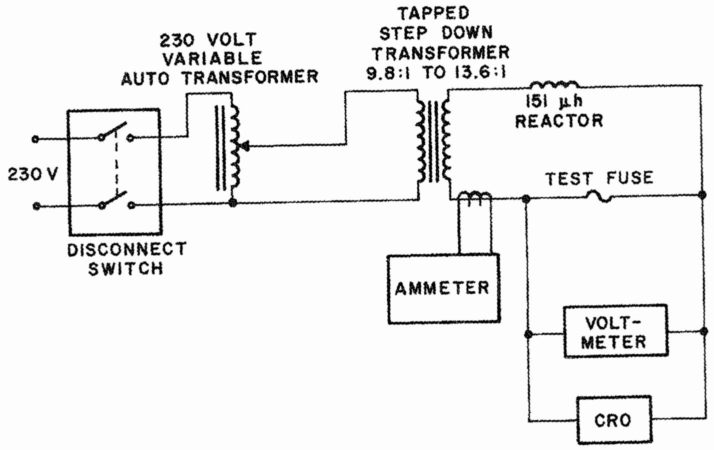


Figure 2-21. System for Low Current Melt Tests

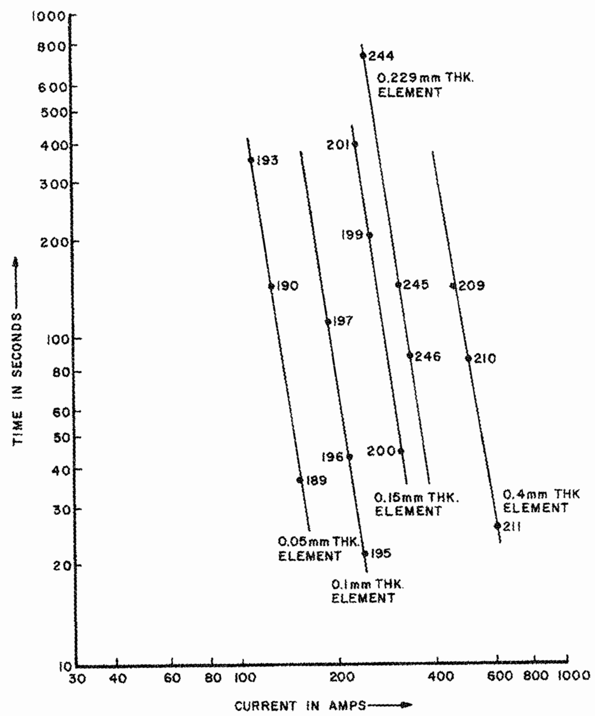


Figure 2-22. Melting Time Characteristics for 2.67 cm Diameter Silver Element Diamond Pattern Fuses With Different Thicknesses

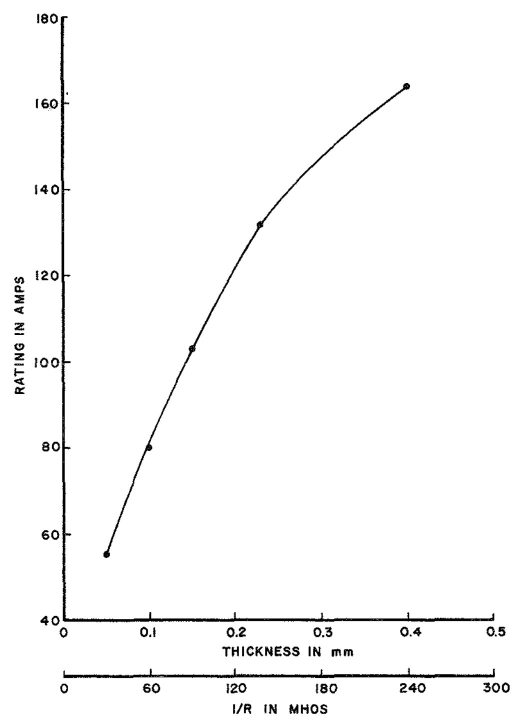


Figure 2-23. Load Rating Vs. Thickness of Diamond Pattern 2.67 cm Diameter Fuses

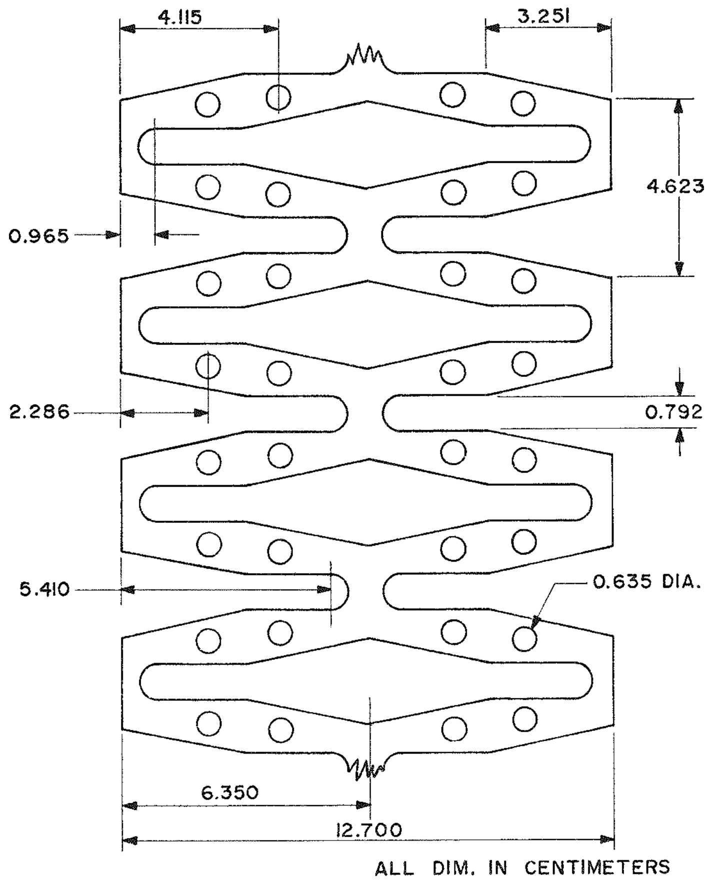


Figure 2-24. Diamond Cylinder Element for 4.0 cm Developed on a Plane

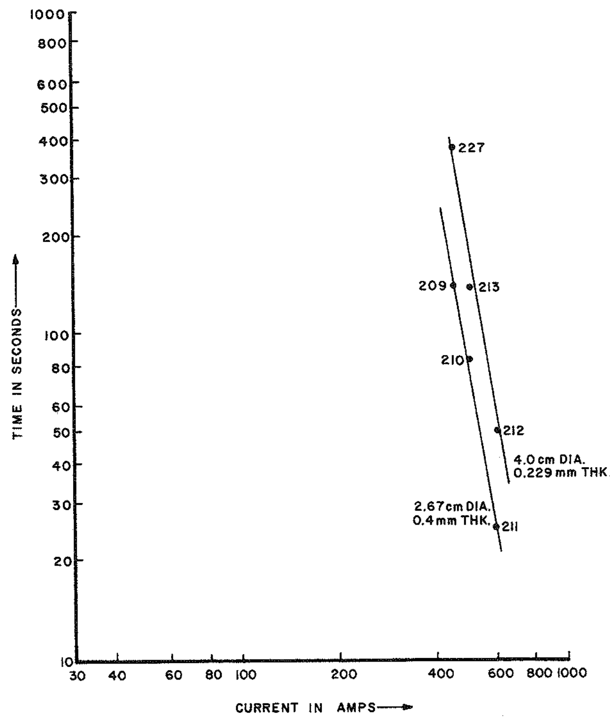


Figure 2-25. Comparison of Fuse Melt Characteristics for 0.229 mm Thick With 4.0 cm Diameter and 0.4 mm Thick With 2.67 cm Diameter Element Fuses Having Identical Resistance

REFERENCES

2-1 "Coordination of Lightning Arrestors and Current Limiting Fuses," IEEE Switchgear Committee and Surge Protective Devices Committee Working Group, IEEE Trans. PAS Vol. PAS 91, pp. 1075-1078, May/June, 1972.

2-2 A. H. Powell and C. L. Schuck, "Ribbon Elements for High-Voltage Current Limiting Fuses," IEEE PAS Trans. 74, pp. 635-643, 1955.

2-3 M. Hudis, "New Test Facility Examines Arc Interruption Technology," Allis-Chalmers Engineering Review 41, pp. 8-11, 1976.

2-4 E. W. Boehne, "The Geometry of Arc Interruption," AIEE Trans. 60, pp. 524-532, 1941.

2-5 H. W. Mikulecky, "Pre-Test Determination of Current for Maximum Thermal Arc Energy Release in Current Limiting Fuses," IEEE PES Summer Meeting Paper, F75-556-1, July 1975.

Section 3

FILLER COMPOSITION

GAS IMPREGNATION

The replacement of air by an electrically superior gas in a sand-filled fuse was proposed as a hypothetically promising means to improve dielectric recovery and arc voltage characteristics. The published literature demonstrates that the arc channel in the fuse has a nonuniform area and therefore nonuniform recovery voltage. The nonuniform recovery voltage, coupled with a low corona onset gas like air, was thought to be a failure mode. Replacement of air by a superior dielectric strength gas like SF_6 should provide better recovery voltage and was therefore proposed. SF_6 offered the greatest promise for the following two reasons:

- Exceptionally high dielectric strength and recovery associated with its electronegative character.
- An exceptional heat transfer peak associated with dissociation-recombination phenomena near 1800°C, a temperature in the vicinity of the vitrification range of silica.

Increase in dielectric strength of a gas as its pressure is increased provides an easy check on the improvement of the recovery voltage. Further, to prevent any possibility of SF_6 chemically reacting with silver and sand under arcing conditions, producing toxic gases (SiF_4 and SOF_2) and solid residue (silver sulfide), two atmospheres of an inert gas (nitrogen) was used to separate possible chemistry and check the above concept. Tests showed no such chemical reaction with SF_6 and no increase in pressure within the fuse vehicle due to production of gases as product of chemical action.

The test vehicle shown in Figure 3-1 was used with end seals to provide a leakproof vehicle. To prevent loss of sand during evacuation, a fine mesh screen was also mounted at the filling end. The sand-filled fuse was at first evacuated to a level of 200 microns and then back-filled with the gas under test. Fuse elements used were identical, having flat element strips.

Tests were conducted in the Advanced Technology Center Capacitor Bank Laboratory

(Appendix A) using the compound circuit. A peak current of 3.1 kA was applied, and the bypass contactor was closed after 4 ms when dielectric recovery voltage was applied.(3-1) Measurements were recorded for the terminal arc currents (current through the bypass contactor), breakdown recovery voltage, and the time from current zero to breakdown. Dielectric recovery curves (Figure 3-2) were generated by varying the time delay from current zero. The curve for SF_6 is inferior to that air, although there is dependance of arc voltage on the gas impregnation.

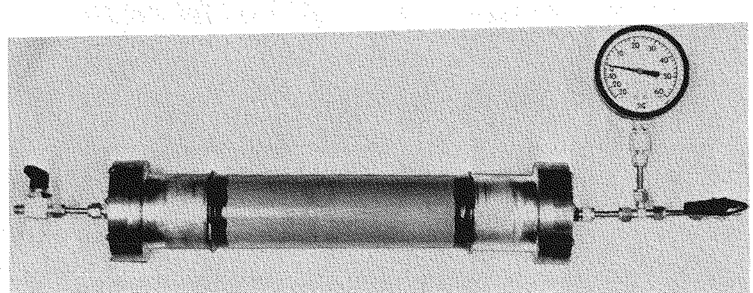


Figure 3-1. Test Vehicle for Gas Impregnation Study

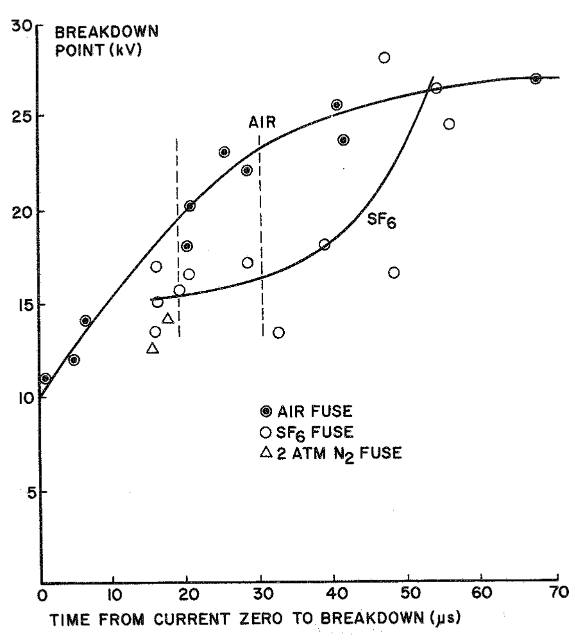


Figure 3-2. Free Recovery Dielectric Curve for Air and SF_6

Figure 3-3 shows the oscillograms for air, SF_6 (1 atmosphere) and nitrogen (2 atmospheres). The arc voltage reduced from 5.5 kV to 5.0 kV with SF_6, and further to 4.9 kV with 2 atmospheres of nitrogen. Dielectric recovery curves for SF_6, shown in Figure 3-2 also show poor dielectric recovery, at least within the first 50 μs.

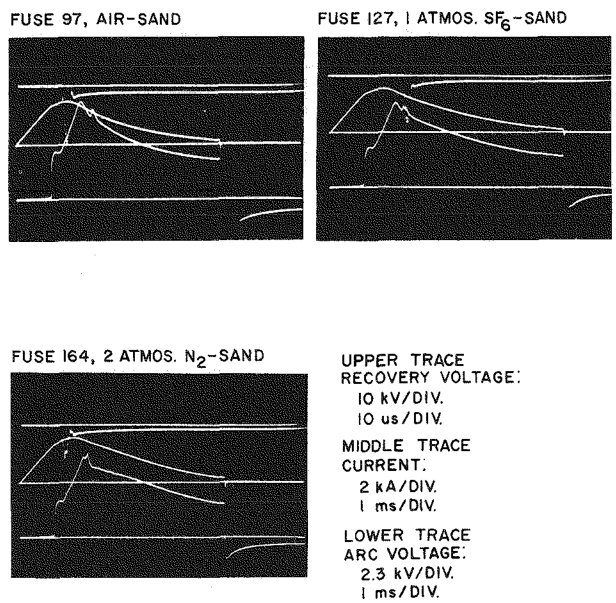


Figure 3-3. Oscillographs for Air, SF_6 and N_2 Impregnated Fuses

The dielectric recovery for SF_6 is better after 50 μs, but may not help interruption. Two atmospheres of nitrogen also decreased the dielectric recovery voltage, indicating a negative correlation between gas pressure and dielectric strength recovery.

POLYMER/SAND FILLER MIXTURES

Polymer Selection

Use of gas-evolving spiders and organic binders has developed over the past few years as they improve the interruption capability of the fuse.(3-2) As an extension of this concept, ablation from polymer particles, directed at short time-constant gas generation, was suggested and investigated as part of this work.

Polymers were selected on account of two distinct advantages which they have over the gas-evolving spiders. Firstly, when mixed with the sand filler they have a closer contact with the arc, and, secondly, their particle size, concentration and composition can be varied easily over a broad range and optimized strictly according to requirements.

Several chemically different polymers with a wide range of particle size were selected. Particle size varied from small powders (30 μm) to large pellets (2.5 mm). This was done to examine the effect of grain size on the arc voltage and expected performance of the fuse. Sand particle size is already known to have such effects. The sand particle size distribution determines the compressibility and gas porosity, both of which have influence on the arc voltage.

Table 3-1

EFFECT OF FILLER VOID CONTENT ON ARC VOLTAGE

FILLER MIXTURE RESIN	PERCENT	FUSE NO.	BULK DENSITY g/cm^3	RESIN DENSITY g/cm^3	VOID CONTENT (PERCENT)	AVERAGE ARC VOLTAGE (kV)
None		97	1.69	2.65*	36.2	5.5
Acetal(Delrin**) (2.5 mm pellets)	5	129	1.68	1.4	32.8	5.54
	10	153	1.65		30.2	5.74
	20	149	1.63		23.6	6.0
Polyethylene (420 micron)	1.25	138	1.62	0.93	37.4	5.2
	2.5	119	1.60		36.7	5.2
	5	116	1.43		40.8	4.4
	10	115	1.32		40.5	3.7
Polypropylene (2 mm pellets)	7.5	139	1.52	0.91	34.3	5.3
Polytetrafluorethylene (30 micron)	5	135	1.5	2.2	42.5	2.6
	10	134	1.3		49.3	2.1
Polytetrafluorethylene (450 micron)	5	133	1.5	2.2	42.5	3.0
	10	132	1.24		51.7	2.1

*Density of solid sand particles
**Manufacturer's trademark

A list of polymers studied is shown in Table 3-1. Mixtures with varying concentration of these polymers were also tested. Fine particles (30 μm) mixed in sand produced somewhat spongy, compressible mixtures. They lowered the bulk density significantly and also increased free volume. Coarse particles, on the other hand, produced incompressible mixtures, although they lowered the bulk density and increased void content, but to a lesser degree. The addition of large acetal pellets reduced the free volume over and above that with pure sand.

Tests were conducted in the capacitor bank laboratory (Appendix A). Average arc voltage for different filler mixtures was calculated and is listed in the table. The addition of polymers in sand fillers has a strong effect, both in increasing or decreasing the arc voltage. The particle size of the polymer also affects the arc voltage generation. Resins which decrease free volume tend to increase arc voltage, whereas those which increase free volume, reduce it.

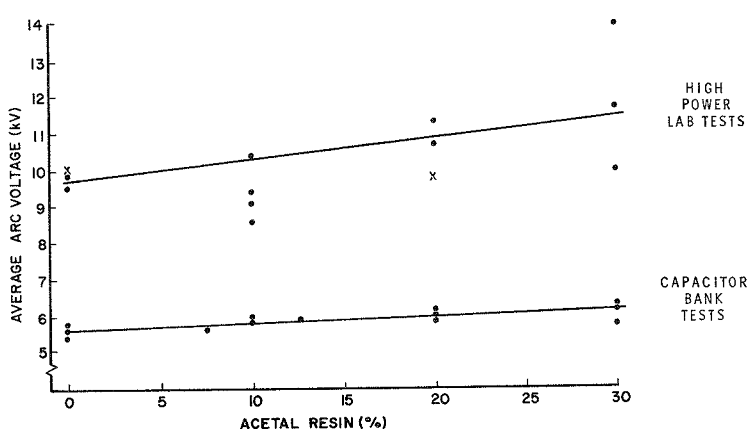


Figure 3-4. Average Arc Voltage as a Function of Resin Composition with Capacitor Bank and High-Power Lab Tests

Acetal resin pellets which reduce the free volume increase arc voltage. The arc voltage increases steadily as the concentration is increased (Figure 3-4). Increase of concentration results in lowering the free volume and thus the compressibility. Fulgurites recovered from a fuse with 10% acetal resin fillers (shown in Figure 3-5) had a thin arc channel, typically 0.2 to 0.3 mm. The arc channel was thus confined to a narrow width which reflected in higher arcing gradient.

Fulgurites recovered from other mixtures are shown in Figure 3-6. A 5% polytetrafluorethylene/sand filler had an arc channel thickness of 4.0 mm (arc voltage also lowered). The free volume in this case was 42.5%. The fulgurites from a 10% mixture of this polymer were so spongy that they could not be recovered intact; they had an arc channel thickness of 10-15 mm. Other polymers having smaller particles likewise created lower arc voltages.

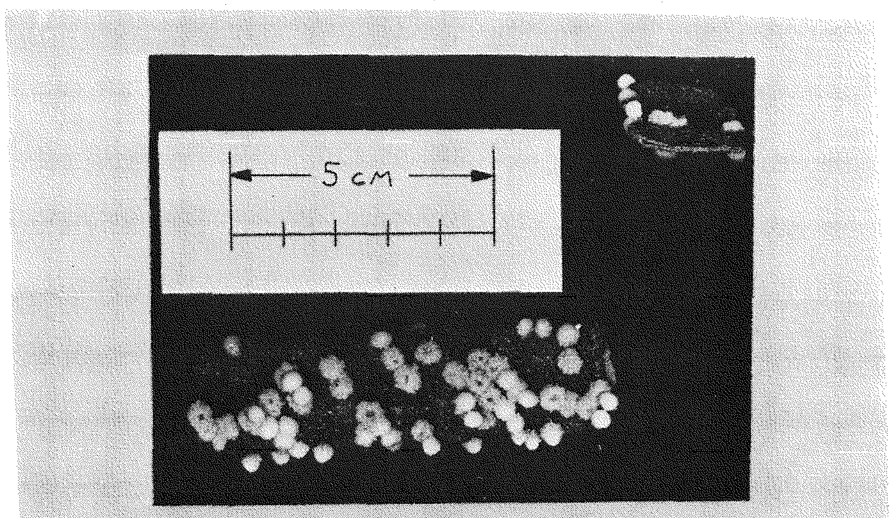
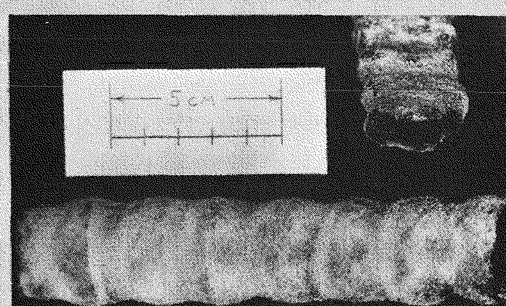
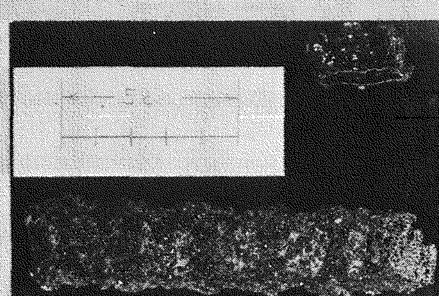


Figure 3-5. Fulgurite of a 10% Acetal Resin/Sand Mixture



FULGURITE OF A 10% POLYETHYLENE / SAND MIXTURE



FULGURITE OF A 5% POLYTETRAFLUORETHYLENE / SAND MIXTURE

Figure 3-6

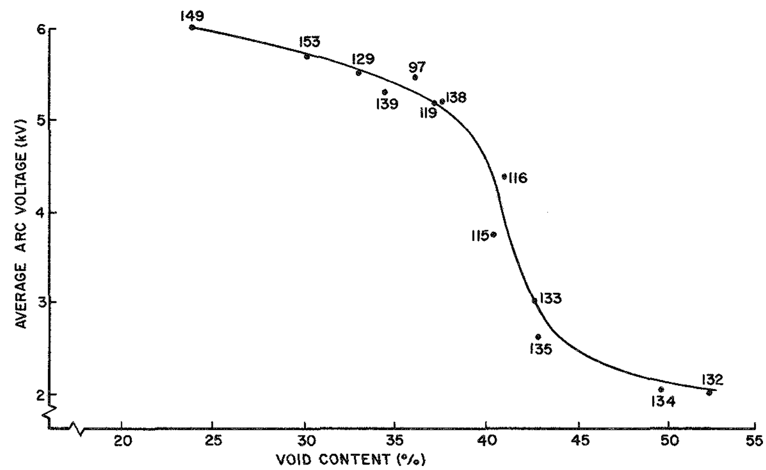


Figure 3-7. Effect of Filler Void Content on Arc Voltage

Figure 3-7 shows a curve between arc voltage and void percent. It is seen that arc voltage has a strong dependance on void content.

From these observations it was concluded that the failure of powders was due to failure in maintaining rigidity. Pellets, on the other hand, provided gas generation and also reduced free volume, thus maintaining a thin arc channel. This conclusion is further reinforced from the inspection of fulgurites recovered from a stratified filled mixture shown in Figure 3-8. The arc channel in the polymer mixture strata bulged to 1-2 mm. In sand strata it maintained a thin section. Average arc voltage also improved slightly, indicating that gas generation was obtained at modest expense of arc confinement. With the same filler, but this time homogeneously filled, the arc voltage dropped. Figure 3-9 shows the effect of filling mixture in an arc voltage in two different ways.

Fuse arc energy appears to have a strong effect on the fuse recovery strength. Table 3-2 contains a collection of dielectric recovery data for a broad spectrum of fuses. Due to various fillers, each fuse has a different arc voltage and therefore arc energy. All the fuses listed in the table were tested with similar plain, perforated ribbons. Corresponding dielectric recovery data for these fuses is also listed in the table. The data has been split into three time zones; i.e., 20 μs, 25 μs and 30 μs. Within each time grouping there is a direct correlation between arc voltage (gradient) and recovery voltage. Independent of the fuse construction, there is a corresponding improvement in the dielectric recovery capability of the fuse if there is an increase in the arc voltage. This agrees with the data in Figure 3-2 which represents cooling of the sand channel with increased delay time.

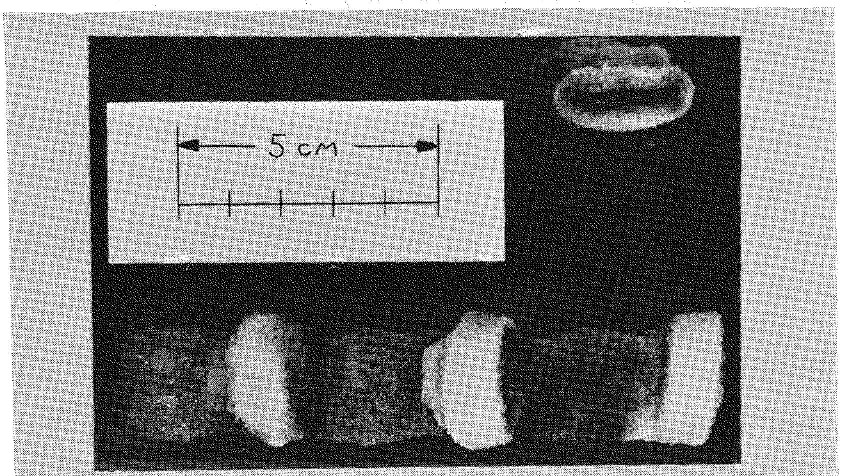


Figure 3-8. Fulgurite Recovered From a Stratified Filled Polymer Sand Fuse

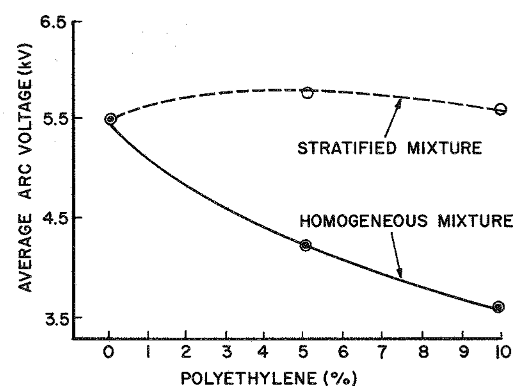


Figure 3-9. Effect of Homogeneous and Stratified Filled Mixtures on Arc Voltage

PRESSURE CONFINEMENT PROBLEMS DUE TO GAS GENERATION BY THE ORGANIC RESIN

Since the addition of acetal pellets with sand filler showed maximum improvement in arc voltage, acetal pellets were selected for further tests. The previous model test results revealed a linear correlation between arc voltage and percent addition of the organic filler. The model test was restricted to the capacitor bank where the available energy is limited to 170 kJ. At this level pressure, confinement was not anticipated and did not turn out to be a problem. In a full-size fuse which must handle 0.5 to 1.5 MJ, pressure confinement was identified as a potential problem. A series of experiments was conducted to evaluate the problem and possible solutions.

Table 3-2

EFFECT OF ARC VOLTAGE ON DIELECTRIC RECOVERY VOLTAGE

FILLER MIXTURE RESIN	%	GAS	FUSE NO.	IMPULSE BREAKDOWN DATA TIME (μs)	IMPULSE BREAKDOWN DATA VOLTAGE (kV)	AVERAGE ARC VOLTAGE (kV)
None		SF_6	127	20	17	5.08
None		Air	99	20	18	5.3
None		Air	97	20	20	5.54
Polyethylene (Stratified)	10	Air	159	20	21.5	5.66
Acetal (Delrin*)	10	Air	155	19	23	5.73
None		Air	95	25	23	5.67
Acetal (Delrin*)	30	Air	167	25	29	5.68
Acetal (Delrin*)	20	Air	166	24	29	5.85
Polyethylene	2.5	Air	119	31	12	5.2
Acetal (Delrin*)	10	Air	153	29	25	5.75

*Manufacturer's trademark

The first set of experiments was confined to a small-rated fuse (60 amps) but tested in a high-power laboratory at critical currents. Four sets of identical fuses were constructed with 0%, 10%, 20% and 30% resin filler mixtures respectively. The tests were conducted to determine the maximum amount of resin which could be tolerated. The element design (0.05 mm thick, 2.67 cm diameter) and fuse construction are shown in Figures 2-13 and 2-15 respectively.

Tests were conducted at critical current (3.2 kA) with fully offset current wave. (3-3) Test voltage was 15.0 kV. Voltage was increased from earlier tests conducted at 12.5 kV with pure sand filler (Table 1-3) to examine if acetal resin would improve interruption capability by developing higher arc voltage.

Out of the samples tested, the filler mixture containing 20% acetal resin gave the best results. They successfully interrupted the critical current at 15.0 kV. Test results and average arc voltage are listed in Table 3-3. Other samples failed to interrupt or displayed restrike characteristics.

Table 3-3

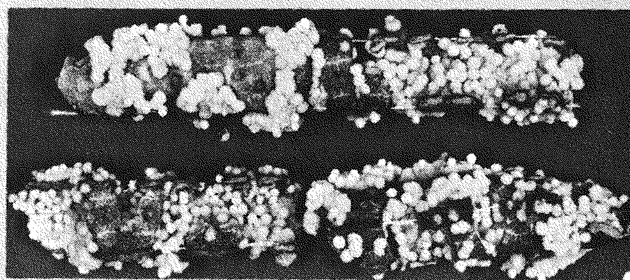
CRITICAL CURRENT INTERRUPTION TESTS ON 2.67 cm DIA. 0.05 mm THICK DIAMOND PATTERN CYLINDER FUSES

FUSE NO.	COMPOSITION % ACETAL RESIN	CLOSING ANGLE DEGREES	PEAK CURRENT kA	PROSPECTIVE CURRENT kA (RMS)	MELTING TIME ms	ARCING TIME** ms	AVG. ARC* VOLTAGE kV	REMARKS
177	-Nil-	21°	4.9	3.2	2.5	8.0	9.9	Failed
178	-Nil-	15°	3.9	3.2	2.6	7.0	9.96	Failed
179	-Nil-	19°	4.25	3.2	2.7	8.5	9.4	Failed
180	10.0	20°	4.9	3.2	2.6	8.0	10.43	Failed
181	10.0	15°	4.1	3.2	2.7	8.25	8.5	Failed
182	10.0	21°	4.6	3.2	2.7	7.25	9.45	Restrike
183	20.0	17°	4.05	3.2	2.5	7.5	11.29	Interrupted O.K.
184	20.0	10°	4.7	3.2	3.0	7.5	10.68	Interrupted O.K.
185	20.0	21°	4.6	3.2	2.7	7.5	9.75	Interrupted O.K.
186	30.0	15°	4.25	3.2	2.7	7.0	13.96	Restrike
187	30.0	21°	4.25	3.2	2.5	7.25	11.67	Restrike
188	30.0	17°	4.7	3.2	2.5	7.5	9.99	Interrupted

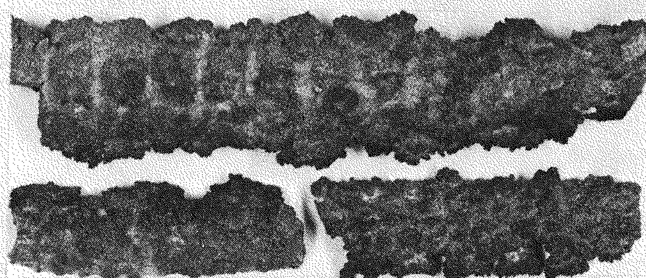
$$* \frac{1}{T_a - T_m} \int_{T_m}^{T_a} V \, dt$$

**Calculated for first half cycle

Fulgurites recovered from a 20% acetal resin mixture are compared with the fulgurite from a pure sand fuse in Figure 3-10. Clearly the fulgurite of 20% acetal resin mixture has a thin cross section, indicating a small arc energy corresponding to larger arc voltage. The convolutions also are all apart. Fulgurites recovered from the pure sand fuse show shorted convolutions and thicker fulgurite sections.



FULGURITES FROM A 20% ACETAL RESIN / SAND MIXTURE



FULGURITES FROM A PURE SAND FUSE

Figure 3-10

Average arc voltages have been calculated to first half cycle and compared in Table 3-3 for different fuses tested. It is observed that the arc voltage steadily increases with the addition of acetal resin, although the spread is fairly wide. Better average arc voltage will have better current limiting action and thus lesser let-through, which is an advantage of the addition of acetal resin.

Interruption capability of the fuses also improves with the addition of acetal resin. It appears that by selective gas generation the acetal resin improves interruption. Pure sand filler fuse #178 has developed a good arc voltage of 9.96 kV yet has failed to interrupt, whereas fuse #185, which has an average arc voltage of 9.75 kV, interrupted the test current (see mark "X" in Figure 3-4). This may be due to the gas dynamics generated from the ablation. End cap pressure confinement and restrike problems were definitely experienced with the 30% mixture; therefore, 20% was selected as an initial design.

Since the fuses have been tested at critical currents with a highly offset current wave, they represent the most severe arc energy conditions. The let-through in this case can be taken as the peak value for comparison with the available manufactured fuses. The let-through for a state of the art fuse with 60 amps current rating is about 1.3×10^5 amperes^2 second. The let-through for newly developed fuse is 0.85×10^5 amperes^2 second, which represents a 35% improvement and is a significant improvement.

ACETAL RESIN - ITS EFFECT ON LOAD CURRENT

The addition of acetal resin to the sand filler under load current and overload current conditions produces a new set of problems which must be evaluated before the acetal resin can be accepted. The resin will vaporize until equilibrium is reached. This requires a sealed fuse which is no longer a problem. Sealed fuses which operate in oil are already available. The vaporization is an additional heat-absorbing mechanism which can affect the fuse load rating. Finally, the vapor may be transported and accumulated to one end of the fuse due to a "heat pipe" effect.

In order to evaluate each of these problems, a series of experiments was conducted. The first test consisted of a measurement of the acetal vapor pressure under equilibrium conditions from 50°C to 175°C. 175°C represents an estimate of the element temperature at full load and was therefore chosen as an upper limit for the experiment. The measured vapor pressure is shown in Figure 3-11. The vapor pressure is a tolerable number and, although it requires a sealed fuse, the problem is not severe.

The second experiment was directed toward the melting characteristics. Due to the polymer vaporization, some of the heating energy which would normally go into the silver will go into the polymer and therefore alter the melting characteristics. To measure this effect, two sets of fuses were constructed (one with a pure filler and one with a 20% acetal filler) and their melting characteristics were measured. In both cases the fuses had a 0.05 mm thick, 2.67 cm diamond element. Voltage measurements across the fuse were taken every 30 seconds. Two typical curves at 110 amperes are shown in Figure 3-12. As can be seen, the melting time for the fuse with the composite filler is longer. This reflects energy going into vaporization and translates into a higher load rating. The melting time-current characteristics for the two sets of fuses are plotted on a log-log plot in Figure 3-13. Due to the linearity of the curve, only a few measurements were recorded. The acetal resin increases the load current rating by 6-7%. At first sight this appears to be a positive effect, but it could lead to a serious problem if the vapor is transported through the fuse away from the element.

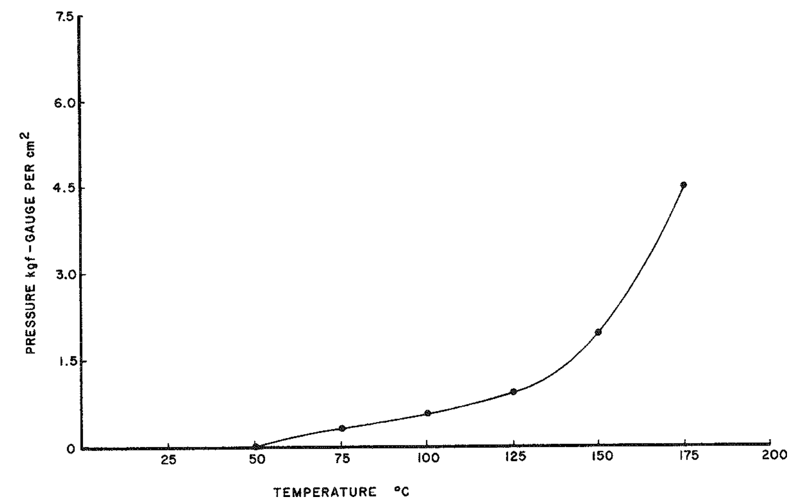


Figure 3-11. Vapor Pressure for Acetal Resin

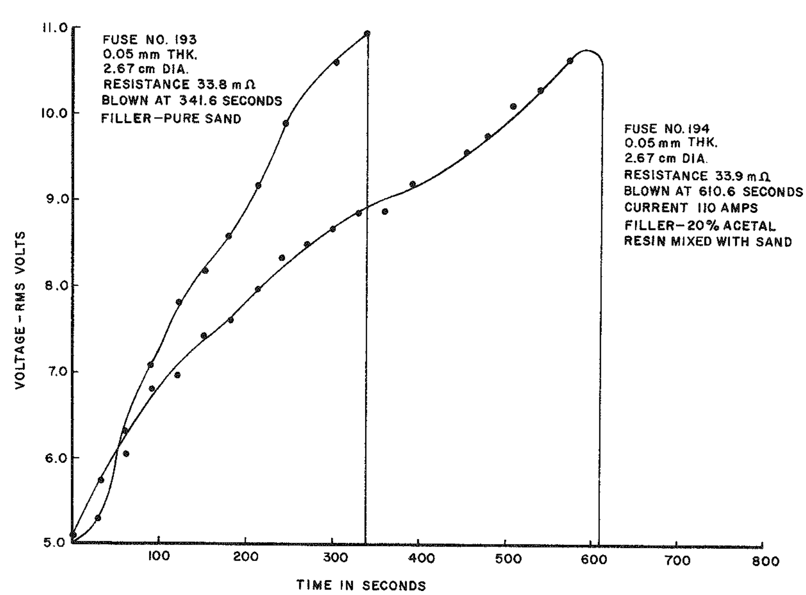


Figure 3-12. Comparison of Melting Time of Fuses With and Without Acetal Resin

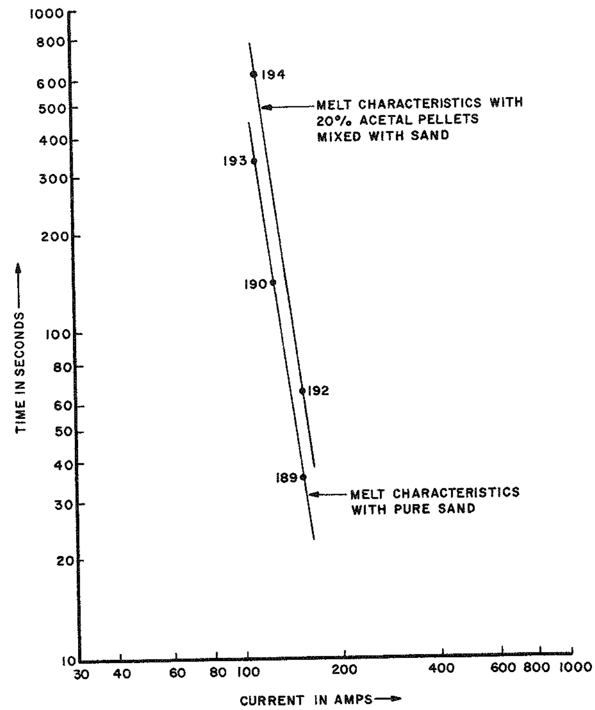


Figure 3-13. Fuse Melt Characteristics for 2.67 cm Dia. 0.05 mm Thick Silver Element Diamond Pattern Fuse With and Without Acetal Resin

To estimate the severity of the heat pipe effect, a fuse with 20% acetal resin was cycled at 150% rated current for one hour on and one hour off. The cycling was repeated three times. The fuse was opened and then inspected. During this experiment a fan was directed at the fuse to enhance the thermal gradient. After three such cyclic loadings, the acetal resin had collected in a ring at one end of the fuse, leaving a blackened sand residue at the remaining end of the fuse. A cutaway view of the fuse is shown in Figure 3-14.

Polymer vaporization is a major problem which requires more attention. Acetal resin was chosen because of its availability and relatively large diameter which was required in the test models to generate the large arc voltage. Other materials are available which have a higher melting temperature and therefore may not present a vapor problem. Vapor barriers inside the fuse may be a second approach to a solution. In either case, acetal resin demonstrates the potential benefits which can be derived from controlled gas generation but reveals some severe problems which must be solved before the technique can be employed.

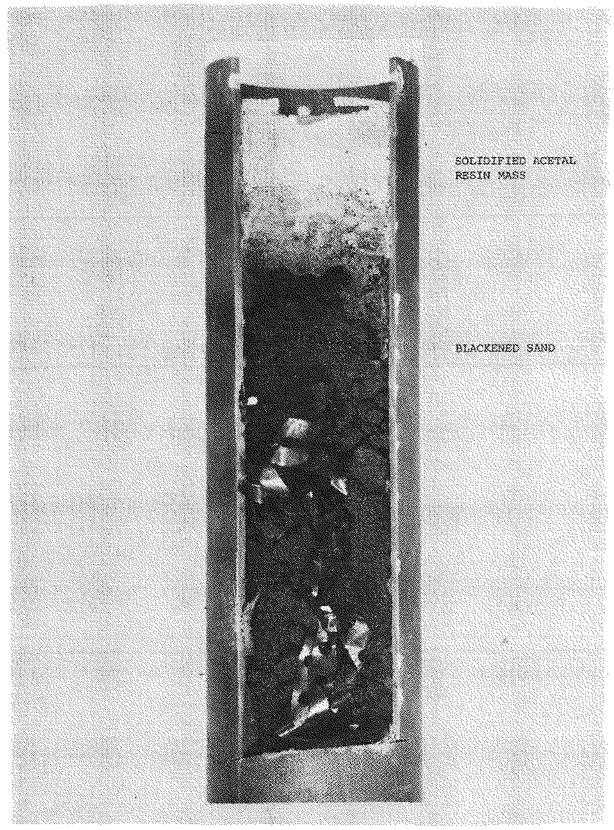


Figure 3-14. Cutaway View of Fuse with Composite Filler After Cyclic Overloads

REFERENCES

3-1 M. Hudis, "New Test Facility Examines Arc Interruption Technology," Allis-Chalmers Engineering Review 41, pp. 8-11, 1976.

3-2 H. W. Mikulecky, "Current-Limiting Fuse with Full Range Clearing," IEEE Trans. PAS 84, pp. 1107-1116, 1968.

3-3 H. W. Mikulecky, "Pre-Test Determination of Current for Maximum Thermal Arc Energy Release in Current Limiting Fuses," IEEE PES Summer Meeting Paper, F75-556-1, July 1975.

Section 4

HIGH-POWER LABORATORY TESTS

The 20% acetal resin mixture and different 200 A rated fuse elements were assembled as complete fuses and tested to determine interruption capability. The low current melt tests conducted in the previous experiment had shown the following two fuses to have the high current ratings approaching 200 amps:

- Fuse having an element thickness of 0.4 mm and diamond cylinder diameter of 2.67 cm.
- Fuse having an element thickness of 0.229 mm and diamond cylinder diameter of 4.0 cm.

The first series of tests was conducted to evaluate the relative performance of the two element designs at 7.2 kA (Allis-Chalmers' High-Power Laboratory). Additional tests at critical currents were then carried out at the Westinghouse high-power laboratory. The critical current for the two fuses is 25.2 kA and 21.2 kA respectively.

The results of the first series of tests conducted on these fuses are listed in Table 4-1. Fuses having a diameter of 4.0 cm and a thickness of 0.229 mm interrupted in all tests. Fuse #214, having a diameter of 2.67 cm and a thickness of 0.4 mm, failed to interrupt under the same test conditions. Oscillograms for the fuses are compared in Figure 4-1.

The average arc voltage, let-through, and the energy dissipated in the fuses has been calculated and listed in Table 4-1. The average arc voltage developed by fuses with a wider diameter is far superior. Fuse #220, with a diameter of 4.0 cm, has developed an average arc voltage of 20.4 kV. The average arc voltage developed by fuse #214, with a diameter of 2.67 cm, is 12.27 kV only. Thus by increasing the diameter of the diamond cylinder, a considerable improvement in arc voltage can be obtained. This is probably due to better distribution of energy within the wider fuse channel. The current limiting action is also better because of higher arc voltage.

Table 4-1

COMPARISON OF INTERRUPTION CAPABILITY OF 0.4 mm THICK AND 2.67 cm DIA. DIAMOND PATTERN FUSES WITH 0.23 mm THICK AND 4.0 cm DIAMETER FUSES

FUSE NO.	THICKNESS mm	CYLINDER DIAMETER cm	CLOSING ANGLE DEGREES	PROSPECTIVE CURRENT kA	MELTING CURRENT kA	PEAK CURRENT kA	PEAK ARC VOLTAGE kV	ARCING TIME ms	AVERAGE ARC VOLTAGE kV	ARC ENERGY IN FIRST HALF CYCLE MJ	LET-THRU IN FIRST HALF CYCLE $10^6 A^2 s$	REMARKS
214	0.4	2.67	8°	7.2	15.3	17.9	17.0	44.0	12.27	1.71	1.34	Failed. Caps blown apart
215	0.4	2.67	112°	7.2	14.0	14.5	22.95	30.0	10.4	1.32	1.09	Interrupted. Caps blown apart
220	0.229	4.0	10°	7.2	17.8	18.7	27.2	5.5	20.4	1.22	1.25	Interrupted. Caps blown apart
221	0.229	4.0	95°	7.2	9.35	10.2	14.5	6.5	9.07	0.33	0.55	Interrupted O.K.
222	0.229	4.0	162°	7.2	16.2	17.0	32.0	6.0	19.54	1.14	0.94	Interrupted. Caps blown apart

End caps in most of these tests were blown off, shearing the barrels. This results from the higher energy associated with higher current rated fuses. The arc energy dissipated in all these fuses is in excess of 1 MJ. For higher currents the end caps were epoxied to the barrels in addition to being secured with screws in an attempt to provide additional strength. The fuse assembly was designed to withstand a force of 7,000 lbs.

The next series of tests was conducted to examine the interruption capability of these fuses at critical currents at the Westinghouse high-power laboratory. Two sets of fuses were prepared, both having an element diameter of 4 cm. Two different thicknesses were chosen. The first was the same 0.229 mm thickness which showed good arc voltage development in the earlier tests; the second used a 0.3 mm thick silver element. The 0.3 mm thick fuse with the 4.0 cm diameter has a 200-ampere rating. Critical current for this fuse is 28.2 kA.

Fuse #239 (0.3 mm thick), which was tested at a prospective current of 27.0 kA, failed to interrupt. Failure was accompanied by the barrel bursting into pieces. Small pieces of unburnt silver were recovered scattered all over, indicating that the silver was not burnt to exhaustion.

Further tests were therefore conducted at lower currents of 10 kA (rms) on fuses 240 and 231 with silver element thickness of 0.3 mm and 0.229 mm respectively. The fuses interrupted, except that the end caps had blown apart after shearing the barrel at the ends.

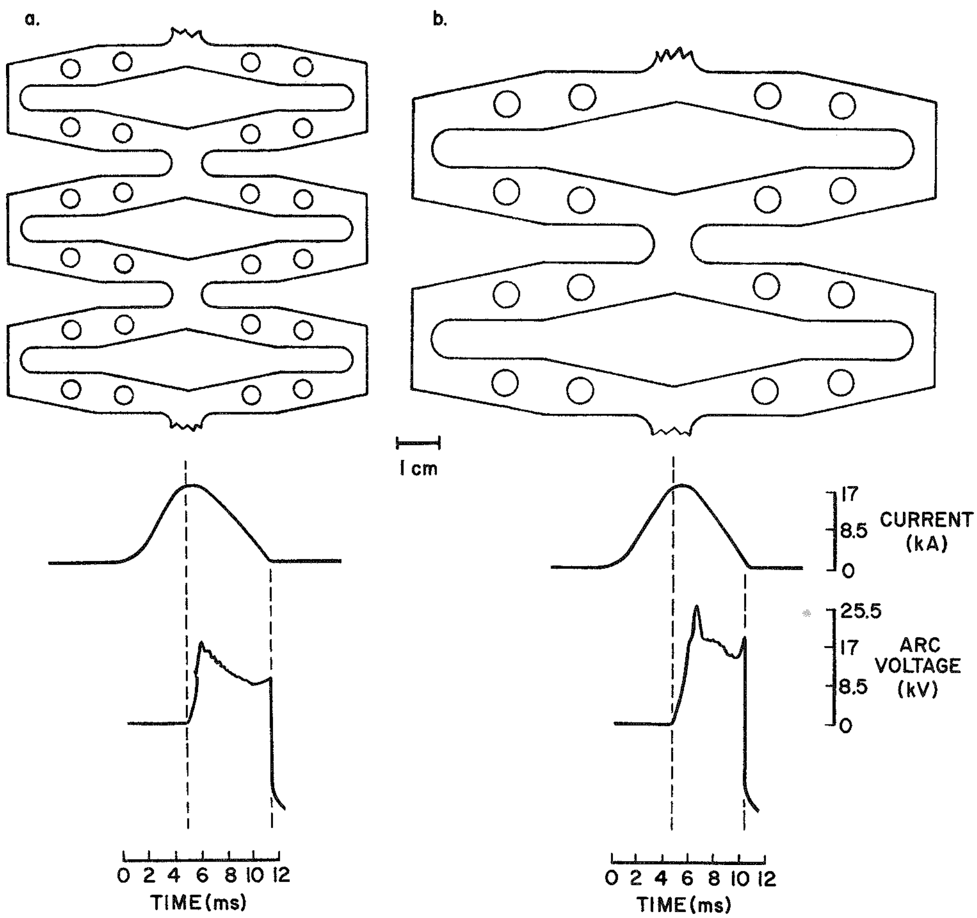


Figure 4-1. Comparison of Arc Voltage for 4.0 cm and 2.67 cm Diameter Elements

The results indicated that fuses with this test vehicle will not be able to withstand the forces which develop when tested for currents above some threshold value (10 kA). The arc voltages developed in the fuses were good initially but collapsed within a period of two or three milliseconds, indicating the fuses had failed, apparently by blowing apart, which results in an open-air arc with a small arc voltage.

The results of the tests conducted are tabulated and compared in Table 4-2. The arc energy dissipated in the fuses and the let-through within first half cycle were also calculated to give an insight into the possible mechanism of failure. Besides the arc energy, the instantaneous power dissipated in the fuse has also been calculated at different time intervals. The oscillograms of fuses 239 and 241, shown in Figures 4-2 thru 4-4, indicate that the fuses failed within two and three milliseconds of arcing period when the arc voltage has collapsed. The instantaneous power dissipation in the fuses at different time intervals was calculated and is shown for these fuses in Figures 4-5 thru 4-7.

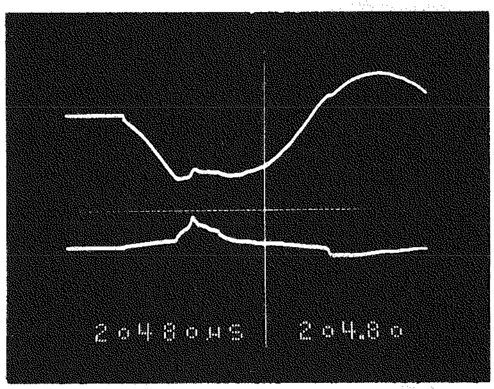
Table 4-2

HIGH-POWER INTERRUPTION TESTS ON 4.0 cm DIAMETER DIAMOND PATTERN CYLINDER FUSES WITH DIFFERENT THICKNESS

FUSE NO.	THICKNESS mm	PROSPECTIVE CURRENT kA	CLOSING ANGLE DEGREES	ARC START DEGREES	MELTING CURRENT kA	PEAK CURRENT kA	PEAK ARC VOLTAGE kV	ARCING TIME ms	MELTING TIME ms	ARC ENERGY IN FIRST HALF CYCLE MJ	LET-THRU FIRST HALF CYCLE $10^6 A^2 s$	REMARKS
230	0.229	12.5	6.0	117	18.8	25.6	25.6	78.0	4.0	1.36	3.17	Failed. Caps blown apart
231	0.229	10.0	6.	103	19.4	21.9	25.3	6.0	4.5	1.19	1.92	Interrupted. Caps blown apart
232	0.229	15.0	8	72	21.8	27.2	23.4	78.0	3.0	1.85	3.48	Failed. Caps blown apart
239	0.3	27.0	8	76	32.8	48.7	18.7	78.0	2.8	2.01	14.94	Failed. Barrel bursted
240	0.3	10.0	16	128	24.4	21.3	17.8	6.0	6.0	1.11	3.05	Interrupted
241	0.3	15.0	11	87	26.7	32.8	16.9	78.0	4.0	1.34	6.27	Failed. Barrel bursted

Energy dissipated in fuse #241 at the time of failure is not in excess of the energy withstood in fuse #240 (Figure 4-6). However, the instantaneous power dissipation far exceeds the levels withstood in other fuses. The peak power dissipation in fuses 239 and 241 is 808.5 MW and 553.8 MW respectively. In both cases the fuses failed. The peak power dissipation in fuse 240 is 345.6 MW. At this level the fuse interrupted.

The probable cause of failure and rupture of the barrel thus appears to be the high impulse forces accompanied with the abrupt transition from conducting to arcing caused by heavy power dissipation. This abrupt transition of the fuse from the conductive to arcing stage initiates pressure waves within the barrel, causing high impulse forces. Apparently the present test vehicle has failed to withstand these forces. This also appears to be consistent with the scattering of unburnt silver pieces observed all around. Scattering of unburnt silver pieces also indicates their potential to absorb greater energy, if delivered at slower rate.

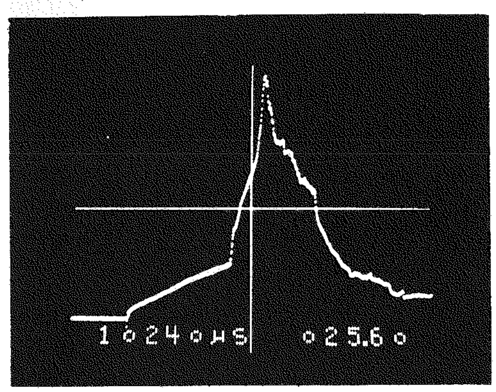


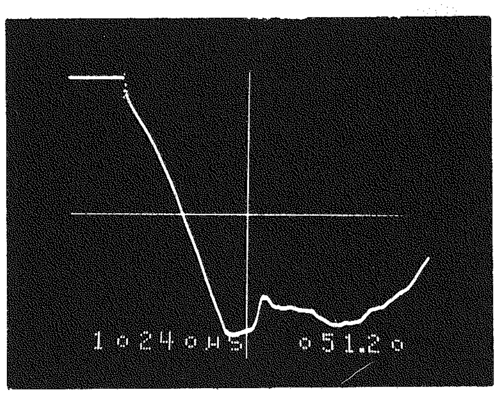
FUSE #239

ARC VOLTAGE AND CURRENT TRACE

PROSPECTIVE CURRENT: 27.0 kA (rms)
TOP TRACE CURRENT: 1080 AMPS/UNIT
LOWER TRACE ARC VOLTAGE: 958 VOLTS/UNIT

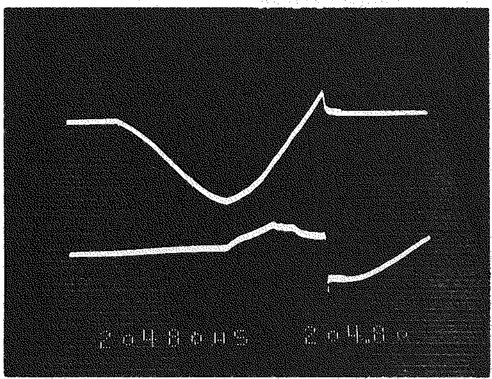
ENLARGED ARC VOLTAGE TRACE
958 VOLTS/UNIT





ENLARGED CURRENT TRACE
1080 AMPS/UNIT

Figure 4-2. Current and Arc Voltage Traces for Fuse #239

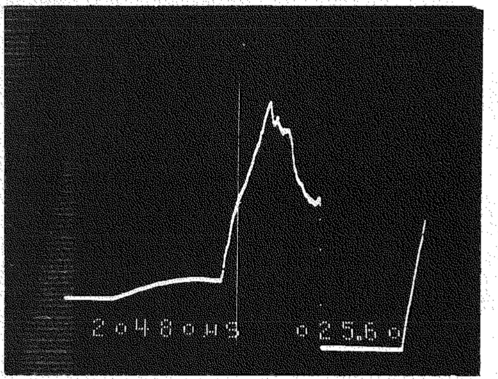


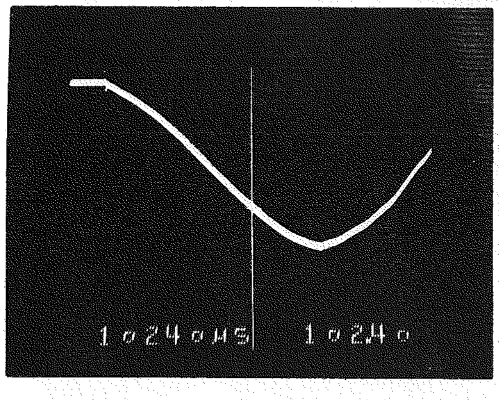
FUSE #240

ARC VOLTAGE AND CURRENT TRACE

PROSPECTIVE CURRENT: 10 kA (rms)
TOP TRACE CURRENT: 505 AMPS/UNIT
LOWER TRACE ARC VOLTAGE:
958 VOLTS/UNIT

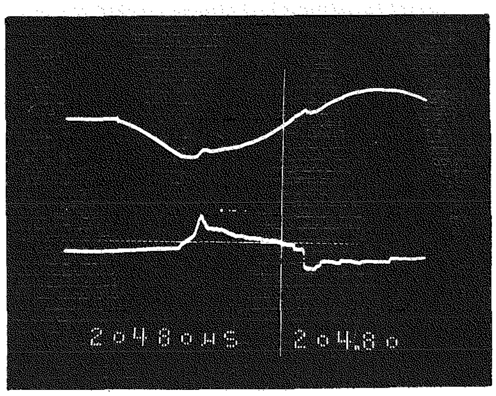
ENLARGED ARC VOLTAGE TRACE
958 VOLTS/UNIT





ENLARGED CURRENT TRACE
505 AMPS/UNIT

Figure 4-3. Current and Arc Voltage Traces for Fuse #240

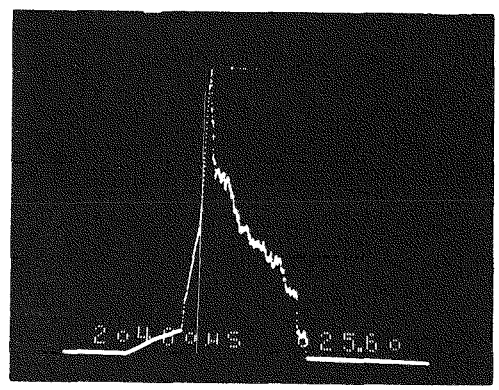


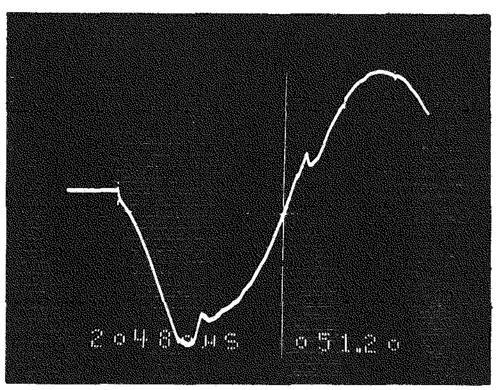
FUSE #241

ARC VOLTAGE AND CURRENT TRACE

PROSPECTIVE CURRENT: 15.0 kA (rms)
TOP TRACE CURRENT: 1080 AMPS/UNIT
LOWER TRACE VOLTAGE: 958 VOLTS/UNIT

ENLARGED ARC VOLTAGE
958 VOLTS/UNIT





ENLARGED CURRENT TRACE
1080 AMPS/UNIT

Figure 4-4. Current and Arc Voltage Traces for Fuse #241

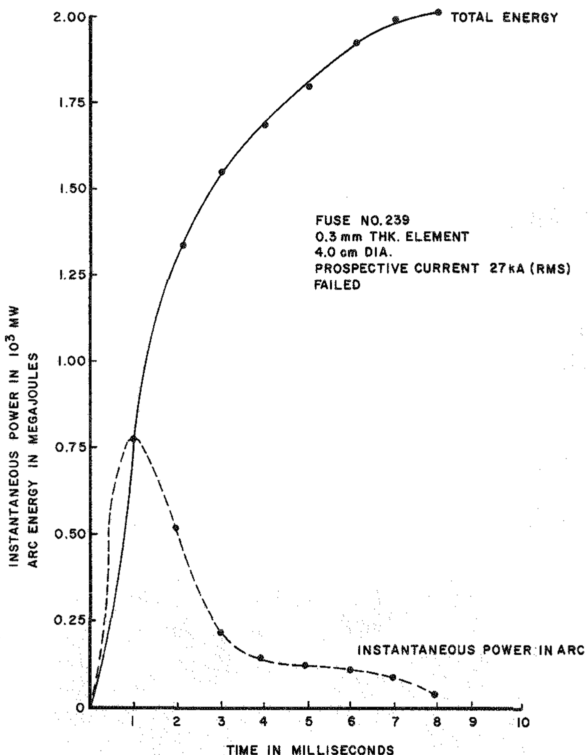


Figure 4-5. Energy and Power Dissipation in Fuse 239 at Different Time Intervals

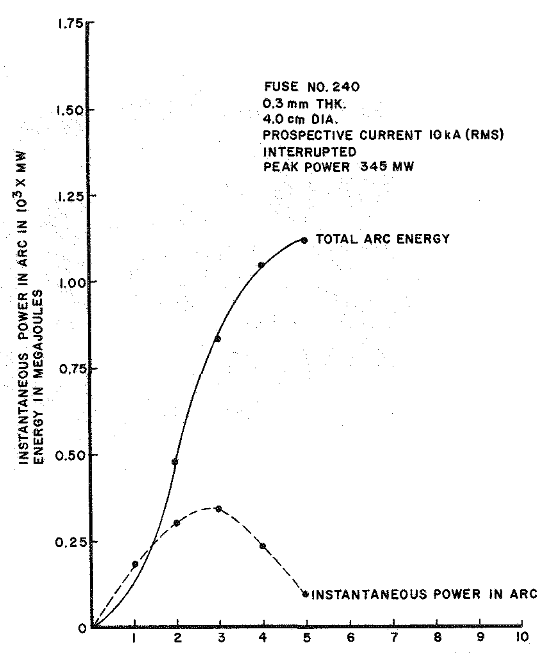


Figure 4-6. Energy and Power Dissipation in Fuse 240 at Different Time Intervals

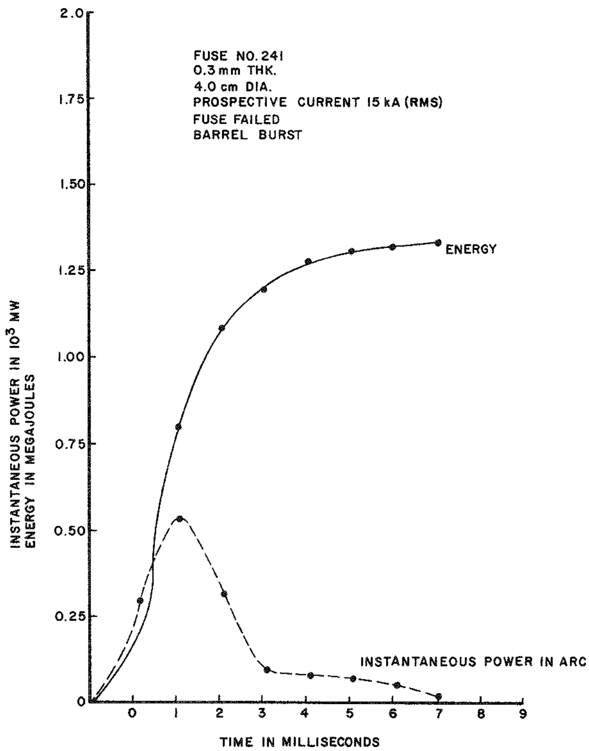


Figure 4-7. Energy and Power Dissipation in Fuse 241 at Different Time Intervals

The impulse forces associated with higher rated current fuses have to be analyzed so that a fuse vehicle with adequate strength can be designed. Once such a fuse vehical is developed, it may be possible to develop a fuse with a 200-amp rating in a single barrel.

Section 5

CONCLUSIONS

Current limiting fuse technology can be significantly improved. Commercially available fuses are based on years of development and have demonstrated significant progress; however, considerable improvement is possible. The three new concepts studied in this work have demonstrated the following potential technology which can be applied to current limiting fuses:

- New element design concepts which will increase the heat transfer by over 20%.
- New element design concepts which will increase the arcing gradient by over 10%.
- New filler compositions which will further increase the arcing gradient by over 30%.

With this level of demonstrated improvement and no technical limit identified, major rating improvements are certainly possible. A 200-A, 15 to 34 kV fuse in a single barrel appears obtainable.

Although this work has demonstrated significant fuse technology progress, it has also uncovered a number of problems associated with larger ratings which require attention before new fuses can be developed. The magnitude of the average arc voltage is important in determining the magnitude of current limiting action, but equally important is the arc voltage wave shape. The arc voltage should be weighted at the beginning of the arcing cycle to produce maximum current limiting action. All of the designs developed under this work have been aimed in that direction and worked extremely well up to at least 60- to 70-amp fuses. At the 170- to 200-amp level, the design produced an excessively abrupt arcing transition which resulted in a severe shock wave. This shock wave cannot be contained in a typical 100-A fuse barrel and is typical of the problems which require additional work. These do not appear to be difficult problems but were not properly anticipated and must be addressed before major new progress can be made.

Appendix A

CAPACITOR BANK LABORATORY

The capacitor bank laboratory is based on a compound capacitor bank which can store energy up to 0.25 MJ and provide up to 20 kA rms with synthetic recovery voltage of 100 kV peak. The compound circuit contains two main capacitor banks, an isolation breaker, independent spark gaps, and a variety of timing generators and pulsing supplies. It is supported by time delay units, current level detectors, pulsed power supplies, high-frequency voltage dividers, current transformers, current shunts, and appropriate measuring instruments. One capacitor bank is designed to provide high currents at relatively low voltages to maintain an arc. The second is designed to provide high dielectric probing voltages at low current to simulate system recovery voltage.

A typical compound circuit connected to test a fuse is shown in Figure A-1.

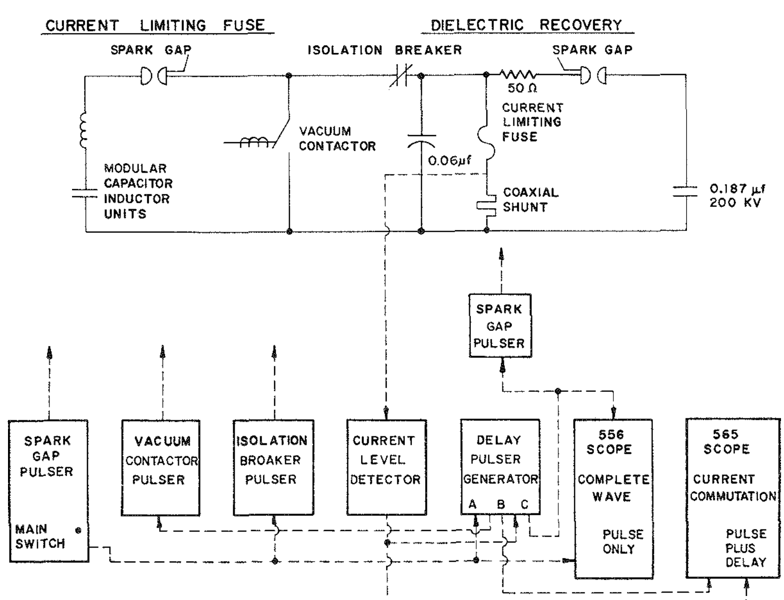


Figure A-1

In testing a current limiting fuse, the arc voltage exceeds the capacitor bank charge voltage by design and distorts the current wave shape into a decaying exponential which never crosses current zero. Under this condition, a current level detector cannot be used to establish a reproducible timing reference.

Through the use of a vacuum contactor, a well-defined current zero can be obtained. At a predetermined time after the main bank is triggered, the vacuum contactor is triggered. When the contactor closes (4 $\pm$ 0.1 ms after it is triggered), current in the fuse and the isolation breaker is reduced rapidly (40 to 100 MA/s). This provides a reproducible current ramp plus a well-defined energy limit (fuse arc energy) for the experiment. The current level detector is then used at the 1- to 10-A level to provide the required timing reference.

The dielectric probing voltage from the high-voltage capacitor bank is applied after a predetermined delay from current zero. The timing reference for the delay is provided by a current level detector. The time delay is typically in the microsecond range. By varying the delay time and repeating the experiment, a curve of breakdown voltage versus time delay is generated for the model under test. Comparing curves for various model configurations provides a measure of the relative merits of the different configurations.

Appendix B

PATENT LITERATURE INVESTIGATION

At the outset of the fuse study, patents on file in the Patent Office, Washington, D.C., were investigated for prior art. The classes of patents investigated were those deemed to possibly contain prior art on application of cylindrical elements, gas impregnation, and polymeric fillers or additions to current limiting fuses.

The investigation was quite comprehensive but by no means exhaustive. The following patent classes comprised the primary field of investigation:

- 337-158: Current limiting devices (e.g., high-voltage fuses)
- 337-159: Comprising fuse link or element structure or arrangement
- 337-110: With arc suppression or blowout means
- 337-250: With gas expulsion means; venting, cooling or deionizing
- 337-273: With arc suppression or extinguishing means
- 337-152: Thin film.....
- 337-295: With particular geometrical shape or configuration
- 337-279: Deionizing gas- or vapor-generating material

Seemingly remotely related classes 337-21/114/157/203/204 were also investigated.

Scattered references to cylindrical elements were found. (USP's 2,761,931, 2,777,033 and 3,317,691 were typical.) In general, this art seemed to be applied to low-voltage fuses.

Gas impregnation appeared to be largely limited to expulsion and miniature fuses. One significant exception was found (USP 2,539,261). This patent proposed SF_6 filling of a fuse with no sand filler. Miniature gas-filled fuses with no sand are proposed in USP's 3,005,074 and 3,001,050.

The application of gas-evolving solid cores and solid attachments was rampant in the patented art, but only two references to organic gas-evolving filler components were found. The two cases (USP's 2,325,416 and 3,197,593) propose organic binders (not fillers) for the sand.

In conclusion, some priority for cylindrical elements was found in patented art; however, it was primarily related to lower voltage fuses. No significant prior art on gas-impregnated, high-voltage sand fuses was found. Finally, organic filler additions seemed to emphasize binders rather than granular organic additives for gas evolution. Incisive references to the concepts proposed in this project were not uncovered.