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SOME CONSIDERATIONS IN DESIGNING HEAVY CAPACITY FUSES

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The conditions governing the operation of the open link fuse and the enclosed fuse are radically different. That such a difference exists is due largely to the presence in the latter of a confining case of relatively small dimensions and of a material, the porous filling, which acts in two capacities: first, to disintegrate the vaporized metal; secondly, to condense or cool it and render it non-conducting.

The filling, on account of its porosity, allows the expanding gases to escape in every direction and their continuity is thus broken up. Furthermore, the gases coming in contact with a substance, which is at a temperature many hundreds of degrees lower than that of the gases, are condensed and cooled and thereby lose their conducting power.

This feature is wholly absent in the open link fuse. The gases formed at the rupture simply expand in the atmosphere, and a continuous stratum of conducting vapor is formed between the two terminals of the cut-out in which the fuse is mounted. There is nothing present to disrupt, break up, or condense this vapor other than the air, which can act only in a slight degree and relatively slowly; and in this condition we find the explanation of the tendency shown by the open link fuses, whether multiple or single strip, to arc most violently when subjected to a short-circuit.

On the other hand, the gases so formed in the open link fuse are dissipated with greater or less rapidity into the surrounding atmosphere, and since there is no confining casing, no opportunity exists for the violent explosive action which

will occur as a result of the expansion of the metal vapor in the enclosed fuse, if it is not properly designed.

The conditions to be met in the design of an enclosed fuse are therefore materially different from those imposed by the open link fuse. We not only have to suppress the arc but we have to handle the tremendous expansive force of the vaporized metal within a comparatively confined space.

Further, the radiation of the heat from the metal of the link takes place in an entirely different manner. With the open link the heat dissipation is directly from the surface of the metal. In the enclosed fuse, the heat dissipation must take place by conduction through the porous filling to the surface of the tube, so that in enclosing a fusible link and surrounding it with porous material we have modified practically all the conditions of operation.

The most serious difficulty that we have to contend with in the design of the larger capacity fuses is that of explosion, and this difficulty becomes greater as the capacity is increased. The problem is largely one of which we term "volume ratio and distribution;" that is to say, the relation which the volume of the fusible link bears to the volume of the enclosing tube and the distribution of the metal in the filling. Were it possible to carry out the same relationship in the large capacity fuses as that employed in the small capacity fuses, the problem would be too simple and would possess few features of technical interest. It is obviously impossible, however, to maintain this same ratio on account of both cost and dimensions; it is necessary, therefore, to devise other means which, while tending to reduce the volume of fusible metal to the lowest possible point, will so facilitate the ready escape and condensation of the hot metallic gases as to render the operation of the fuse quiet and reliable under all conditions.

Consider more in detail what actually takes place when an enclosed fuse is blown on short-circuit. As the rush of current occurs, the metal is raised through its melting point to its boiling point and the current continues to flow through the fuse for a brief interval on the conducting vapor path of the volatilized metal. It is extremely important that the temperature of these gases should be lowered with the greatest possible rapidity to a point where their conducting power ceases to exist, in order to bring about a reduction in the time of operation of the fuse, which is of tremendous importance in

reducing the internal pressures developed and in preventing explosion.

To emphasize this characteristic more forcibly, consider that the maximum running temperature of the porous filling would be slightly less than the melting point of the metal of the fuse link, say approximately 315 degrees cent., were zinc employed and the fuse running at its full load capacity. When a short-circuit occurs, the metal of the link is suddenly raised to a temperature of at least 1000 degrees cent. and as the pressure in the tube becomes greater this temperature is increased. The relatively low temperature of the filling, however, immediately tends to cool these hot gases and convert them from a conducting medium into an actual insulator. Therefore, the sooner we can bring the hot gases into contact with the filling, or conversely, the sooner we can bring all the filling into action as a condenser, the more rapid will be the extinction of the arc within the fuse and the rupture of the circuit.

These considerations show that as little metal as possible must be used in the link and, further, its surface must be so extended as to provide every facility for the hot gases to escape and so distribute the metal within the mass of the filling that each particle of it shall be brought promptly into action.

All these conditions are effectively met by employing what is known as the "multiple link" or one of its modifications. It is quite a simple matter to obtain an increased link area of 100 per cent or more by this method, which will permit of a reduction of at least 18 per cent in the total volume of the metal necessary for a given capacity, according to the design.

Reference to Chart 1, giving an end-section through three types of fusible links, will illustrate how readily this may be accomplished. In Fig. 1 we have an end-section of the widest practical single-strip link which could be used in a given tube. In Fig. 2 is shown how the surface may be readily extended 100 per cent without occupying a greater width, and with a further advantage that the metal is more widely distributed within the filling, rendering this far more effective and rapid in its action. At the same time the metal is brought closer to the radiating surface, which will also affect the total amount of metal necessary for a given capacity of a fuse. In Fig. 3 we have another arrangement of the same link which would also be effective. The mathematical consideration of the effect of

a change in position of the conductors within the enclosing casing is interesting.

Applying the equation given in *Watson's Physics* on the transference of heat, and bearing in mind that this applies more strictly to transference between parallel surfaces and where the flow takes place in parallel lines, one can work out an equation which, with a proper value of the factor D , representing

Chart No. 1.

Fig. 1.

Fig. 2.

Fig. 3.

Length 3 inches

Area Fig. 1 = 6 sq. in.

Area Fig. 2 = 12 sq. in.

Area Fig. 3 = 12 sq. in.

the distance through which the heat is transmitted, bears out the author's hypothesis, thus :

$$Q = \frac{K A (T_2 - T_1) t}{d} \quad (1)$$

Where Q = the quantity of heat in calories,

K = a constant for any one substance which is independent of the thickness, area, or the difference in temperature, but changes

with the substance used. In this case it refers to the porous filling and the tube,

d = the distance through which the heat is transmitted,

t = the time in seconds in which a given number of heat units would pass from one surface to the other.

T_1 and T_2 are the temperatures respectively of the two surfaces between which occurs the transmission of heat, in this case the temperature of the fuse casing at the surface and the temperature of the fuse link,

A = the area or average cross-section through which the heat passes. Transposing, we get the equation:

$$\frac{Q}{t} = \frac{K A (T_2 - T_1)}{d} \quad (2)$$

and representing the calories per second, Q/T by Q' , the equation becomes :

$$Q' = \frac{K A (T_2 - T_1)}{d}. \quad (3)$$

It is desirable to transform this equation into electrical units.

One calorie per sec. = 4.189×10^7 ergs per sec.

10^7 ergs per sec. = 1 watt.

Therefore, 1 cal. per sec. = 4.189 watts.

From this it follows that

$$Q' = \frac{I^2 R}{4.189} \quad (4)$$

Substituting this equivalent in equation (3)

$$\frac{I^2 R}{4.189} = \frac{K A (T_2 - T_1)}{d}, \quad (5)$$

in which $I^2 R$ = the total watt loss in the fuse.

Now, transposing and reducing to simpler form

$$I = 2.045 \sqrt{\frac{K}{R} \frac{A (T_2 - T_1)}{d}} \quad (6)$$

Since K and R are both constant for any given filling and fuse, we may represent $\sqrt{\frac{K}{R}}$ by K' and reduce the formula to a simpler form,

$$I = 2.045 K' \sqrt{\frac{A (T_2 - T_1)}{d}} \quad (7)$$

As already pointed out, the value d must be determined in each case to meet the condition of divergent heat rays; but once determined, an examination of this equation shows that any variation in this factor, that is to say, any change in the position of the link, affects the current flow. This is further proved by tests of the fuses themselves which will be described later.

It will be apparent that in order to get the most satisfactory operation of an enclosed fuse, and one of the smallest possible dimensions for a given capacity, all the porous filling should be brought into service when the fuse is subjected to an excessive overload or short-circuit.

From this it is clear that the shorter the distance the gases have to pass in order to bring into action the maximum amount of filling, the greater will be the rapidity of condensation of the gases and the quicker will the arc be interrupted. To show what an important bearing a proper subdivision and distribution of the metal of the link has in accomplishing this result, consider the fuse sections shown in Chart 2, where in Fig. 1 we have a diagrammatic section through the center of a five-wire multiple fuse drawn three times larger than its actual dimensions. This is divided accurately into five segments, each segment, representing the space which must handle the gases evolved from one element of the link. The circle in the centre of each space represents accurately the proportionate diameter of the wire for a certain capacity of fuse and its relation to the enclosing space. The lines numbered from 1 to 24 represent the mean path or distance that the vapors have to travel in that specific direction in order to bring into action the total amount of filling. It will be understood that in actual practice the number of lines or paths would be materially greater, but for the present discussion any number which would divide up the enclosing space into reasonably even proportions will be sufficient. The length of these lines has been accurately measured and their average length ascertained and found to be, as given in the diagram, 0.192 of an inch in the actual fuse, or in the diagram three times that length. In Chart 2, Fig. 2 we have a similar diagram of a flat-strip link of the same capacity. The space through which the gases will have to pass has been divided into an equal number with those of the multiple link and their average length determined. In this case the average length is found to be 0.363 of an inch, or with the flat

Chart No. 2.

Average length of vapor path=192"

Fig. 1.

Average length of vapor path=363"

Fig. 2.

link the gases have to pass through an average distance 89 per cent greater than in the five-wire multiple link. In other words, the time which must elapse before all the filling can be brought into action to condense the vapor is nearly double, with the result that a larger amount of energy is absorbed by the fuse, the current flows longer through it and the breaking or rupturing of the current becomes far more difficult. This furnishes another reason why an explosion will take place with a single-strip link and will not take place under similar conditions with a multiple link. With the single link in a given period of time a much smaller quantity of filling can be reached by the gases, with the result that the condenser or cooling action is not sufficiently rapid to prevent the pressure reaching a disruptive point, and the fuse explodes. With the multiple link, according to the above comparison, practically twice the mass of filling is brought into action in the same period, and the cooling rate is so rapid that explosive pressures are not developed. That this theory is correct is shown both by the oscillograph records referred to later, and by actual test of the fuses themselves.

To ascertain definitely the actual reduction in metal volume for any given capacity of fuse, obtained by proper subdivision of the link, an extended series of calibration tests were made on a set of fuses under identically the same conditions. These fuses were all made up in tubes of the same size and fitted with the same size terminals, the lengths of the links being the same. Reference to Chart 3 gives tabulated data for the reduction in metal secured with both the round wire link and the flat strip link, showing clearly the effective reduction in metal volume obtained in this way. Reference to Chart 4 gives the tabulated results of another series of tests which show an interesting comparison of the gain in capacity brought about by the increase in surface of the links and the proper distribution of the metal. The areas referred to are the actual areas of the fusible portion of the link and do not include the copper terminals which, as previously stated were identical in each fuse and consequently could be disregarded.

Having taken up the theoretical consideration of the subject and the calibration tests supporting some of the deductions, it is desirable now to consider the actual operation of the fuse under short-circuit. To permit of a full consideration of the phenomena shown at various intervals during the blowing of the

No. of Fuse	Style of Link.	Fuse Link Construction	Size of Link.	Volume Ratio	Amperes	Reduction in Metal Volume.
83	Single Wire		Diam. .164"	1.344%	80	Unit for Wire Links
106	2 Wire Multiple		Diam. .108" Each.	1.166%	80	13.22%
80	5 Wire Multiple		Diam. .063" Each.	.9919%	80	26.2%
88	Single Flat Strip		.063" x .3125"	1.253%	80	Unit for Strip Links.
86	Single Flat Strip		.028" x .625"	1.114%	80	11.1%
104	2 Strip Multiple		.0258" x .3125" Each	1.026%	80	$\frac{18.1\%}{\text{Under No. 88.}}$ 7.8% Under No. 86.
105	5 Strip Multiple		.0095" x .3125" Each	.9447%	80	$\frac{24.6\%}{\text{Under No. 88.}}$ 15.2% Under No. 86.

Chart 3

No. of Fuse.	Style of Link.	Fuse Link Construction	Size of Link.	Area	Ampere Capacity
81	Single Wire.		Diam. .141"	1.33	60
96	2 Wire Multiple		Diam. .10"	1.88	73
80	5 Wire Multiple.		Diam. .063"	2.96	80
91	Single Flat Strip.		.100" X .1562"	1.537	65
90	Single Flat Strip.		.075" X .208"	1.856	67
87	Single Flat Strip.		.050" X .3125"	2.175	70
85	Single Flat Strip.		.025" X .625"	3.90	75
89	Single Flat Strip.		.0215" X .728"	4.50	75
97	2 Strip Multiple		.025" Thick .3125" Wide.	4.05	78
84	5 Strip Multiple		.025" Thick .125" Wide.	4.50	80
98	5 Strip Multiple		.0125" Thick .25" Wide.	7.875	83

Chart 4

fuse under those conditions, an oscillograph was used. The resultant curves are given in Figs. 5 to 16, and the actual record of the tests, together with a drawing of an end-section of the links used in each case, with other important data relating to the test are given in Chart 5. The tests consisted in subjecting fuses, similar in every detail of construction, except as relates to the fusible portion of the link, to direct short-circuit across the bus-bars of a 6000-ampere-hour battery fed by one or more 500-kw. generators. The potential coil of the oscillograph was connected across the fuse rather than across the circuit, in order to show clearly the variations in the volts' drop at different intervals. An examination of these several curves

FIG. 5.—Five-wire multiple link 0.063 diam. capacity; 80 amperes.
vol. ratio = 1 per cent

gives a most interesting and instructive history of the complete cycle of events occurring within the fuse during its operation, all within a period of time considerably under 0.05 seconds.

Referring to curve of Test IX, Fig. 12, as a good illustration, this may be analyzed as follows: This curve exhibits the operation of a five-strip multiple link fuse of 1 per cent volume ratio, 80 amperes capacity. Following the current curve, it will be seen that during the period $J A$ the current is zero. At the instant A , the switch was closed and the current instantly rushed through the fuse, rapidly increasing in value until at D it had reached its maximum. It then begins to die away until at C it has become zero again, or in other words, the fuse has

opened the circuit. Referring to the voltage curve from *K* to *Y*, the voltage as measured across the fuse is practically zero, that is to say, it was zero at *K* but at the beginning of the current flow, there was of course, a slight rise. This is, however, so small as not to be visible on the curve and for all practical purposes the voltage may be regarded during the interval *K Y* as zero. At the instant *Y*, the voltage begins to go up with great rapidity until it practically reaches its maximum at *I*; it then continues at almost even value until just before the rupture of the current, occurring at *C*, a slight inductive kick is noticed at *F*, after which it sharply declines

FIG. 6.—Single flat strip 0.028 x 0.625 wide. Capacity 80 amperes;
vol. ratio = 1.12 per cent

and becomes constant at *M*, *MO* being the full voltage of the circuit across the fuse.

Referring to the current curve, note the rapid rise of the current value from the point *A* to *E*. During that period, there was practically no voltage across the fuse. The actual time during which this rise in current was occurring, represented by the distance *AB*, is 0.0038 sec. It is during this interval that the fuse link is being raised to its melting point, the total energy impressed on the fuse being extremely small. From the point *E* on the current curve to its maximum value at *D*, the metal is being converted into vapor, and a correspond-

ing rapid rise in voltage will be noted, showing the enormous increase in the resistance of the circuit. At *D*, the vapor begins to condense, or, in other words, lose its conductivity, and as the conductivity of the vapor path diminishes, the current falls. The voltage, however, continues to rise slightly, due to the same cause but remains practically constant from the point *I* until just before reaching the point at *F*. During this period the current is falling rapidly, and the total time or duration of fall is found to be 0.012 seconds. The maximum current which passes through the fuse is found to be 8415 amperes and the voltage at the same instant, found by measuring the height *HL*, was 304 volts, so that the

FIG. 7.—Single flat strip 0.050 x 0.3125 wide. Capacity 70 amperes; vol. ratio = 1 per cent

power input into the fuse at the instant *G* is 2,558,160 watts, apparently an enormous amount of energy, but practically an instantaneous value. By integrating it is found that the average watts were 1,925,000 during the period that power was absorbed by the fuse. This period of energy input, is represented by the distance *BC*, and is found to be actually 0.0146 sec. from which is derived a value of 28,600 watt-sec. or a little over 27 B.t.u. The total period of operation, or the time *AC*, which elapsed after the switch was closed, until the circuit was opened, was but 0.0184 sec.

Referring to the curve, Test X, that of a single flat strip link fuse, it is noted that the time during which the link was

being melted as represented by the distance AB , was practically the same as that of Curve IX of the previous test, but the significant feature lies in the relatively slow decline of the current value and the prolongation of the period during which energy was being absorbed by the fuse or the period BC . This time is actually 0.0246 sec. or an increase of 68 per cent in the period of operation of the fuse during which arcing was going on. By integrating the curve in precisely the same manner as that of Test IX, the average watts were found to be 2,360,000 and this value multiplied by the time, gives 58,000 watt-secs. or 57 B.t.u., an increase of the total energy input in excess

FIG. 8.—Single flat strip 0.030 x 0.625 wide. Capacity 83 amperes; vol. ratio = 1.19 per cent

of 102 per cent or more than double the total energy absorbed by the multiple strip fuse.

A similar comparison of the other curves bears out in a most striking manner the important influence which the extension of the link surface and its proper distribution within the filling has in reducing to a large degree the total energy absorbed as well as the duration of the period of energy input. Comparing the results it will be found that the single link fuses invariably absorb more total energy.

The average energy input of the multiple link fuses tested was but 22,587 watt-seconds as compared with an average

its rate of escape that the bursting pressure would be rapidly reached.

I would briefly summarize the results of the other tests as shown in tabulated form in Chart 5 and the analyses of the other curves may be briefly summarized as follows:

Tests I and II (Figs. 5 and 6) compare the operation of a five-wire multiple link fuse and a single-strip flat link fuse of the same ampere capacity. By reference to Chart 5 it will be seen that the operation of the single flat link fuse was explosive and dangerous, whereas the multiple link fuse operated quietly. Comparison of these curves confirms this most forc-

FIG. 10.—Five-strip, multiple link 0.0125 x 0.250 wide. Capacity 83 amperes. Vol. ratio = 1 per cent

bly. It will be noted that the period *A B*, during which the metal was being raised to its melting point, was practically the same for both fuses, but the period *B C*, during which energy was being absorbed by the fuse, is extended in a most pronounced manner in the single link and that the total energy absorbed was about 120 per cent greater.

Test III (Fig. 7) showing the operation of a single flat strip fuse of the same volume ratio as Test I but of a smaller ampere capacity, exhibits an extension of the period of energy input *B C* even in a more pronounced manner. The total energy absorbed in this fuse was nearly 140 per cent greater than with the multiple link.

In Tests IV and V (Fig. 8) we compare the operation of the five-strip multiple link fuse and the single-strip link of the same ampere capacity with the five-wire multiple link of the earlier test. Unfortunately the film record of Test IV was torn so that it was impossible to compare the curves. The record shows, however, that the multiple strip operated quietly, while the single strip exploded and one may judge of the characteristics of the curve of the multiple strip by reference to Test VII (Fig. 10) which was the curve made from a fuse of identically the same construction. The same characteristics are here presented as in Test I.

In Test VI (Fig. 9) is shown the operation of a single wire

FIG. 11.—Two-strip multiple link 0.025 x 0.3125 wide. Capacity 78 amperes. Vol. ratio = 1 per cent

link fuse. This curve is particularly interesting as showing the effect of concentrating a mass of metal in as compact form as possible, thereby reducing to a minimum the avenues of escape of the gases within the filling. The rise of the current wave is more pronounced than in any of the other single link fuses, the current here reaching a maximum of 10,642 amperes. While the period of energy input, *BC*, is relatively short. This is due to the fact that this fuse exploded with greatest violence and the current was actually ruptured by the explosion. This is indicated by the very pronounced inductive kick shown on the curve, the rise in potential at the instant of rupture being about 450 volts.

In Test VIII (Fig. 11) is shown the operation of a two-strip multiple link of slightly less capacity than that used in Test VII, its operation being most satisfactory in every way.

Tests IX, X and XI (Figs. 12, 13 and 14) give the comparative operation of two single-link fuses and a five-strip multiple link at 600 volts as distinguished from 500 volts heretofore used. Again the multiple link operated quietly, whereas the two single-link fuses exploded.

Test XIII (Fig. 15) records the behavior of the curve of a fuse, where the explosion did not interrupt the current promptly but where the arc was maintained for a brief interval. The varia-

FIG. 12.—Five-strip multiple link 0.025 x 0.125 wide. Capacity 80 amperes. Vol. ratio = 1 per cent

tions in the voltage during the period of arcing are here most pronounced.

In Test XV (Fig. 16) is shown the operation of a five-strip multiple link with a slight inductive resistance in the circuit. In comparison with other multiple link curves, the prolongation of the period *AB* is most marked with slower and less abrupt rise of the potential. The fuse operated perfectly although giving indications of the phenomena shown.

Another important consideration is the concentration of the energy at one point in a single-strip fuse as compared with its division in the multiple-link fuse. An interesting illustration

of this particular feature is found in Tests I and II. The fuse of Test I was a five-wire multiple link, the total resistance of which was 0.0017 ohms or the resistance of each element was 0.0085 ohms. The maximum current flow through this fuse, the record shows was 7600 amperes, from which it is obvious that the energy required for raising the metal to the boiling point of each element was 19,650 watts or a total for the fuse of 98,250 watts. Compared with the single-strip link of Test II, the resistance of which was somewhat lower on account of its greater volume ratio, being 0.0015 ohms, the maximum current flow was seen to be 8910 amperes, giving a total power input of 123,700

FIG. 13.—Single flat strip 0.028 x 0.625 wide. Capacity 80 amperes. Vol. ratio = 1.12 per cent

watts. In other words, 25,000 more watts were absorbed by the single link fuse at the period of maximum current flow than by the multiple link, and further than that all of this energy was developed at one plane at the center of the fuse, whereas with the multiple link but 19,650 watts was developed in each element; that is to say, there was over six times as much energy developed at one point of the single link fuse as in the multiple link.

Now under such conditions it must be realized that there exists in the flat link fuse a hole or tunnel through the filling, being the space formerly occupied by the metal of the link, which is

momentarily filled with a conducting vapor. The conductivity of this vapor is dependent very largely upon its density. In this concentration of a relatively large amount of vapor within an extremely confined space, and consequently of relatively great density, is found one explanation for the greater current flow seen in every instance in the single-strip link. With the multiple-link fuse we have five tunnels distributed at wide intervals within the tubing, the energy in each one being but one-sixth that in the single tunnel of the other fuse. Moreover, it has been shown that with the single link fuse, the vapor

FIG. 14.—Single flat strip 0.063×0.3125 wide. Capacity 80 amperes.
Vol. ratio = 1.26 per cent

has to travel approximately twice the distance in order to bring all the filling into action as a condenser, and consequently requires more time than with the multiple fuse. Therefore, with the single link fuse, there is a rapid accumulation of pressure and a pronouncedly greater current flow, or an accumulative effect resulting in the disruptive action noted.

The statement may be made in making these comparative tests, that possibly the most efficient form of single link fuse is not used, and that the area might be extended by using a greater width and folding up the edges, etc. In this connection it should be pointed out that such modifications could hardly

affect the results, since if such a peculiar form of single link fuse were employed, the same form could, of course, be used in the elements of the multiple strip for comparison, and the gain,

FIG. 15.—60 amperes, 600-volt. Single flat-strip link

both in area and distribution, would remain relatively the same. Further than that, it is difficult to conceive of any arrangement of the single link whereby all the mass of the filling could be so promptly and effectively brought into action.

FIG. 16.—Five-strip multiple link 0.025 x 0.125 wide. Capacity 80 amperes. Vol. ratio = 1 per cent

Two other possible causes contributing towards the explosive action of a fuse have been suggested, one, in the presence within the filling of a certain percentage of moisture and within the casing of a certain amount of air which, it was claimed, was

Test Number	Fuse Link Construction	Capacity Amps Volts	Volume Ratio of Fuse Link	Maximum Amperes	Time of Melting A. B.	Time of Arcing B. C.	British Thermal Units	Operation.
I		80 500	1%	7600	.0052	.0135	16.6	Quiet and satisfactory. Cartridge uninjured.
II		80 500	1.12%	8910	.0052	.0243	36.55	Explosive and dangerous. Cartridge injured at one end.
III		70 500	1%	8170	.0045	.0302	39.88	Explosive and unsatisfactory. Cartridge injured at one end.
IV		83 500	1%	—	—	—	—	Quiet and satisfactory. Photographic record lost. Cartridge uninjured.
V		83 500	1.19%	9570	.0059	.0253	48.78	Explosive and dangerous. Cartridge injured at one end.
VI		80 500	1.35%	10642	.0055	.0166	32.8	Explosive and very dangerous. Cartridge burst.
VII		83 500	1%	8420	.0048	.0132	22.9	Quiet and satisfactory. Cartridge uninjured.
VIII		78 500	1%	8170	.0052	.0118	18.9	Satisfactory. Cartridge uninjured.
IX		80 600	1%	8420	.0034	.0146	27.0	Satisfactory. Cartridge uninjured.
X		80 600	1.12%	9390	.0042	.0246	54.94	Explosive and dangerous. Cartridge burst.
XI		80 600	1.26%	9650	.0048	.0163	35.8	Explosive and very dangerous. Cartridge burst.
XIII		60 600	—	6520	.0035	.0243	44.42	Explosive and very dangerous. Cartridge burst. Base broken.
XV		80 600	1%	—	—	—	—	Quiet and satisfactory.

Chart 5.

suddenly and rapidly expanded by the heat of the arc. An examination of the filling of the ordinary fuse will show that there can be no material amount of air, the heating of which would occasion the violent explosions resulting from short-circuit, particularly when it is considered that the metal generally used for the link expands over 2400 times when converted from its metallic form to vapor. By actual measurement it is found that the total volume of air present in the average enclosed fuse is in the neighborhood of 19 per cent of the filling used.

The presence of water might cause serious disturbance were there a sufficient amount of it converted into steam, but this would require the heating of the entire mass of filling to a high temperature; and to raise it to this temperature in the extremely short interval of time which is required to operate the fuse, would call for the application of a tremendous amount of heat energy. Of course if the arc should be maintained, the filling would rapidly reach such a temperature, but the condition under consideration is one where the fuse explodes when it is short-circuited, and as there can be no prolonged maintenance of the arc under this explosive action, which would affect the filling, it could not be heated in that manner and the only heat which could be applied to that particular purpose is that absorbed by the fuse in converting the metal of the link into its vapor. Actual measurement was made of the percentage of moisture present in the filling, both before and after a fuse had been subjected to a severe short-circuit which it had handled satisfactorily. Starting with an initial amount of 5 per cent, nearly 3 per cent remained, showing that but a little over 2 per cent of the total moisture had been driven off; namely, that portion of the moisture present in the filling which was quite close to the metal of the link.

While there are unquestionably various methods by which relatively the same effects may be produced as by the use of the multiple link, such, for example, as the well-known cigarette fuse or the cylinder link, it will be seen that these are but the amplification of the same principles; namely, extreme extension of surface and such an arrangement of the metal that the greatest possible contact with the filling is provided, to increase to the greatest degree the avenues of escape of the gases.