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THE SHOCK HAZARD ASSOCIATED WITH THE EXTINCTION OF FIRES INVOLVING ELECTRICAL EQUIPMENT

by

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1. Introduction

The fighting of fires in, or near, electrical equipment carries the risk of electrical shock to the personnel operating the fire-fighting equipment. A shock may be caused either by accidental contact with live conductors, or by the extinguishing agent conducting a current which subsequently passes to earth through the body of the operator. The second hazard is made greater as higher voltages come into use for electrical transmission and distribution, as for example, in the supergrid which transmits power at 275 KV.

This note is concerned with the hazard associated with the conductivity of the extinguishing agent, and is intended to collate and review the information on this subject which is available at the present time. In the main, the work which has been carried out has been concerned with hose streams of the type likely to be used on large fires, and therefore the most likely to come into contact with electrical installations at high voltages. Some work has been done using hand extinguishers, and these investigations are discussed.

2. Electrical Conductivity of Extinguishing Agents

In examining the problem of the electrical shock hazard it is necessary to examine the properties of the commonly used extinguishing agents and to determine which are sufficiently conductive to be potentially dangerous. The extinguishing agents in common use are:-

1. Water
2. Foam
3. Carbon dioxide
4. Dry chemicals
5. Vapourizing liquids

2.1. Water

The conductivity of water exhibits a very wide range of values from that of highly purified water, which has a specific resistance of 10^6 ohm. cm., to sea water which has a specific resistance of approximately 20 ohm. cm. Water from public supplies, which is derived from rivers, lakes or wells, contains a number of salts in solution, the ions of which are dissociated, thus making the water electrically conductive. The conductivities found in public supplies varies, in general lying in a range of specific resistance from 1000 ohm. cm. to 4000 ohm. cm. Table I gives representative values of specific resistance, taken from the literature on the electrical shock hazard when using water as the extinguishing agent.

In addition to the substances which occur naturally in water, it is also necessary to consider the additives which are employed for specific purposes, such as wetting agents, anti-freeze compounds, and salts which are present in the streams from portable extinguishers, of the soda-acid type, and extinguishers containing alkali-metal salt solutions ("loaded stream" extinguishers).

Wetting agents are surface-active agents consisting generally of a mixture of organic compounds[(10)]. They can be arranged into three main classes - anionic, cationic, and non-ionic, of which only the latter does not ionise in solution. Hence if an agent is employed which is anionic or cationic, the resulting solution may have a considerably greater conductivity than the water in the absence of wetting agent.

Anti-freeze solutions are most commonly made by using calcium chloride as the freezing point depressant, together with a corrosion inhibitor. This is an aqueous solution of a salt, which will be dissociated into ions, and hence will have a very much higher conductivity than the water alone. A portable extinguisher of the soda-acid type, projects a liquid stream which contains sulphuric acid and sodium bicarbonate and sodium sulphate in solution, all of which dissociate into ions thus making the water much more conductive. The "loaded-stream" extinguisher contains a proprietary solution, although it is known that potassium salts form part of its composition[(11)]; in some extinguishers of this type the solution is expelled by reaction with an acid, so that in general the emergent stream of water is probably of much higher conductivity than water from a public supply.

2.2. Foam

The foams used for fire-fighting purposes are of two types - chemical foam and mechanical foam. Chemical foam is formed by the reaction of two aqueous solutions, usually aluminium sulphate and sodium bicarbonate together with a foaming agent and stabiliser. Mechanical foam is formed by the incorporation of air, by physical turbulence, with a water solution containing a foam-forming compound. These compounds can be the protein type, made up of high molecular weight polypeptides, together with polyvalent metallic salts, or the synthetic type, made up of compounds of synthetic detergents. The conductivity of the foam-forming solutions will depend on the concentration of free ions, and this may result in a conductivity significantly higher than that of water from a public supply.

2.3. Carbon Dioxide

The discharge from a carbon dioxide extinguisher consists partly of carbon dioxide vapour, and partly of particles of solid carbon dioxide (dry ice). For practical fire-fighting purposes the discharge is non-conducting.

2.4. Dry Chemicals

These extinguishing agents are based on a mixture of powders generally with sodium bicarbonate as base, together with additives to improve flow and storage properties. The powder is discharged from the extinguisher as a cloud of particles, and can be regarded as non-conducting for practical purposes[9].

2.5. Vapourizing Liquids

These agents are in general, compounds formed by the replacement of the hydrogen atoms in the simple hydrocarbons (methane, ethane) by one or more of the halogens, i.e. fluorine, bromine, and chlorine. The liquids formed do not ionise and are therefore non-conducting; the gaseous compounds are stored in liquid form under pressure, becoming gaseous upon discharge, and hence are also non-conducting.

3. The Electrical Shock Hazard

In a consideration of the problem of the electrical shock hazard it is essential to adopt a criterion for practical fire-fighting which gives a very wide margin of safety to the personnel involved. The problem of what constitutes a dangerous shock is complicated by the widely varying susceptibilities of individuals to electric currents. It is well established that it is the magnitude of the current passing through the body which governs the severity of the shock, although the duration of exposure to the current also determines its effect, the shock becoming more severe the longer the time of exposure[3][11]. The current flowing through the body is not directly proportional to voltage, since body resistance is a function of the voltage to which it is exposed[5]. Up to 50V the resistance of the body (between hand and foot) is greater than 4000 ohms, but as the voltage increases the resistance falls as puncture of the skin develops, until a minimum level is reached for voltages greater than 1000V. Hence higher voltages are more dangerous than would be anticipated on a proportionate basis. The frequency of the voltage producing the shock is also important[12], with frequencies in the range 20-70 c/s being the most dangerous.

The following table[4] gives a subjective indication of the effect of currents of various magnitudes.

Current magnitude	Physiological effect
0-0.9 mA	Not noticeable.
0.9-1.2 mA	Only felt at point of contact.
1.2-1.6 mA	Slight tingling sensation in hand.
1.6-6 mA	Shaking and feeling of cramp (with some people pain), first in the wrist and lower arm, and finally at the shoulder.
6-8 mA	Hands stiff and cramped, difficulty in releasing electrode.
13-15 mA	Pain hardly bearable, and release only possible with great effort.

Over 15 mA	Release impossible.
Over 20 mA	Generally injurious to health if heart lies in current path.
50-100 mA	Lower limit of fatal effect.

The lower limit for a fatal shock may be taken as 50 mA to allow for the wide variation in individual susceptibility(11). Under conditions of continuous exposure the maximum current to which an individual may be safely exposed is as low as 5 mA(11).

As a standard for practical fire-fighting a level of current has to be chosen which gives a large safety margin. The safe level has generally been taken as the lowest limit which can be appreciated. Some workers have taken 3 mA as the safe level(3)(8), but in general a current of 1 mA is regarded as the current which is just perceptible.

4. Solid hose streams

A considerable amount of work has been carried out to examine the risk arising from the use of solid hose streams near electrical equipment. This is an important problem because where large fires are being fought with hose streams there may be overhead lines in the vicinity which are at high voltage.

4.1. General considerations

The current which will flow along a solid stream of water incident on a conductor will be dependent on the resistance of the stream and on the voltage at the conductor. The current, i, is given by the following expression:-

$$i = \frac{\pi d^2}{4} \cdot \frac{u}{\rho l} \qquad \text{........ (1)}$$

where u is the voltage between conductor and earth

d is the diameter of the nozzle orifice

l is the distance between nozzle and conductor

ρ is the specific resistance of the water

In practice the above relationship is modified by the form of the stream. After a certain distance the stream is no longer completely solid, and begins to break up into discrete drops, causing a rapid rise in electrical resistance. Additionally, the diameter of the stream is less than that of the nozzle due to hydrodynamical effects, and its length is greater than the distance between the nozzle and the conductor.

Equation (1) predicts that the stream current is directly proportional to the voltage of the conductor. For a given nozzle diameter and stream length the current will be less than that predicted, because of the increase in resistance due to the effects mentioned above (see Figure (1a)). At high voltages there will be some arcing which will produce a current more nearly approaching that expected from the unbroken stream, giving rise to the hypothetical curve shown in Figure (1a), the form of which is in good agreement with the work of Buffet et alia[2], as illustrated in Figure (2a).

The current in the stream would be expected to be inversely proportional to the stream length (for a particular voltage and nozzle diameter), which gives the rectangular hyperbola shown in Figure (1b). In practice, however, after a certain distance the stream is completely broken into drops and its effective resistance is very large, giving a very low value of current. Some experimental curves are shown in Figure (2b), due to Buffet et alia, which show good agreement with the anticipated form of the relationship.

The current is predicted by equation (1) as being proportional to the square of the diameter of nozzle, for a given voltage and stream length. For a short stream length the practical relationship would be expected to be close to the theoretical, because the stream is unbroken; the current is somewhat lower than predicted because the diameter of the jet is less than that of the nozzle orifice (see Figure (1c)). At longer stream lengths there is no current flow at small diameters because the stream is completely broken before reaching the conductor. The curve therefore intersects the diameter axis as shown in Figure (1c). This prediction is in agreement with experimental observations as shown in Figure (2c), the results being due to Buffet et alia.

The way in which the resistance of the jet changes with stream length has been studied in detail by Thom[7]. He used a coefficient, α, suggested by Koch[6], given by:-

$$\alpha = R\Big/\frac{4\rho l}{\pi d^2} \qquad \ldots\ldots\ldots (2)$$

where R is the measured resistance of the stream.

Thom considered the stream could be divided into three zones, which are:-

(i) a straight compact zone, in which the water is in the form of an unbroken jet

(ii) a zone of expansion, in which the water is beginning to break into drops

(iii) a broken zone in which the water consists entirely of discrete drops.

The curves in Figure (3) show the variations in α observed. The value of α (and hence of resistance) increases relatively slowly at first as the stream length increases while the jet remains reasonably compact, but then increases at a very rapid rate as the expansion zone is encountered. When the broken zone is reached the value of α becomes very large and then increases relatively slowly with further increases in stream length. For the public supply water used by Thom the value of α in the broken zone was in the region of 1000, and for sea water α was as large as 100,000.

In addition to the factors considered in equation (1), the water pressure and the nozzle design have an important influence on the current in the stream, in that they affect the form of the jet by varying the positions at which the zones referred to above can occur. Thom has demonstrated that the internal design of the nozzles can have a considerable effect on the stream resistance under otherwise standard conditions. Buffet et alia investigated the effect of pressure in some detail, and found that the stream current varied with pressure in a complex manner, the form of the variation depending on stream length, nozzle diameter and conductor voltage. In their experiments they varied the pressure until the maximum current value was observed, for particular values of conductor voltage, nozzle diameter, and stream length, thus ensuring that the worst conditions were encountered.

4.2. Safe operating conditions

It was stated in Section (3) that the current through a man holding a branch should be limited to 1 mA. In practice a current flowing through the hose stream will flow to earth through the hose and its associated appliance, and through the branch man, the resistances of which are electrically connected in parallel. The current flowing through the body of the branch man will therefore depend on his body resistance, on his resistance to earth, and on the resistance to earth of the hose and appliance. To simplify the problem, and to establish the greatest factor of safety, it is generally assumed that the whole of the current flowing down the hose stream will flow through the branch man, i.e. the resistance of the hose line and appliance to earth is infinite, and the resistance to earth of the branch man is zero.

4.3. Review of results available

A number of investigations have been carried out by workers in various countries. Although there were variations in the measurement techniques, the experimental procedure was similar in all the work, and consisted of directing a hose stream at a conductor or metal target, (e.g. a cable or plate, sphere, etc.) energised at various voltages, and measuring the effective current flowing along the stream to earth, for various experimental conditions. The experiments have been performed on nozzles of various diameters (and presumably of different designs), using water delivered at various pressures, and for water of differing conductivities.

The principal investigations are summarised in Table II, which also gives details of some of the more important ad hoc experiments.

The work of Buffet et alia[2] forms the most comprehensive investigation to date. The authors give a table of recommended safe operating distances, for nozzles of 7, 18, and 30 mm diameter (0.28, 0.71 and 1.18 in). The table is based on a safe current of 1 mA, and is applicable for voltages up to 150 kV to earth;* the table is reproduced in Table III.

Sprague and Harding(3) conducted an investigation for nozzles of greater than 1 in diameter. A table of safe distances is given for nozzles of $1\frac{1}{4}$ in diameter, or less, based on a safe current of 3 mA. The table covers a wide range of water resistivities (500 - 6,000 ohm cm), but is unduly restrictive in that it does not recommend the use of hose streams on conductors at a voltage greater than 13,200 V to earth. This table is given in Table IV.

Fitzgerald(8) gives his results in terms of the stream lengths which gave a current of 3 mA. He gives a table of recommended distances for nozzle diameters of $\frac{5}{8}$ in and less (reproduced in Table V), for a water specific resistance of 1,530 ohm cm, and for voltages to earth of up to 130 kV. He does not recommend the use of fire streams of diameters greater than $\frac{5}{8}$ in, which, in view of other work, is unrealistic, and arises because he limited his stream lengths to a maximum of 30 feet. For voltages up to 600 V, he states that solid streams from nozzles up to $1\frac{1}{4}$ in diameter can be used, providing a minimum distance of 5 feet is maintained.

An account of work done by Caldwell is given in a paper by Walker(13). A table of safe distances is given for $1\frac{1}{8}$ in and $1\frac{1}{2}$ in diameter nozzles, for voltages up to 30 kV. This table is quoted in other papers,(1)(14)(15), and is reproduced in Table VI. There is no indication of the criteria used in drawing up the table, and the specific resistance of the water used is not given. A table is also given by Walker for sea water, but no indication is given as to the criteria used in compiling it, and no experimental results are given. Both these tables appear to be rather hypothetical in view of the limited scope of the experiments.

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*It should be noted that the working voltages quoted for transmission lines are voltages between lines, and the voltage to earth is $1/\sqrt{3}$ of these values.

Apart from the papers mentioned above, extensive investigations have been conducted by Thom[7], Baatz[15] and Sarvas and Ponni[16]. These papers do not give any firm recommendations about safe distances to be employed but contain useful information. Some of the results are included in Figure (4) which gives a general plot of safe distances collected from a number of sources. The details of these experiments are given in Table II.

Tests have also been carried out at the Croydon Electricity Station[1], at Birkenhead, (quoted in a paper by Reanney[17]), and by Brown[18]. The details available on these experiments are given in Table II, together with the deductions made.

4.4. Discussion of experimental evidence

Correlation of the various experiments is extremely difficult because of the wide variation in nozzle diameters and design, in the conductivity of the water used in the experimental technique, and in the criterion of the safe current employed. As a general rule it can be said that complete safety is obtained if the conductor is situated in the region of the stream where it is completely broken into discrete drops. In this zone the resistance of the stream is high (approximately 1000 times as large as a solid stream of water from a public supply[7]), and is independent of the conductivity of the water used[7]. In practice, however, the distance at which the stream is completely broken will depend on the design of the nozzle and on the water pressure used; an added difficulty is that the distance is difficult to determine by direct observation.

Most of the measurements of current carried out by various workers were probably made in the expansion zone of the stream, where the jet is partly broken into drops, but not completely composed of discrete drops. In general, it can be stated that the safe distance must be increased as the diameter of the nozzle becomes greater, because of the lowering in resistance due to the greater area of the jet cross-section. Also the safe distance must be greater the larger the conductor voltage, because of the increase in stream current arising from direct proportionality to the voltage, and also from arcing at higher voltages[2].

In Figure (4) the safe distances recommended in a number of investigations are plotted against the voltage of the conductor to earth; these distances are based, in general, on direct measurements of current in hose streams. A number of distances corresponding to a current flow of 1 mA are also plotted on the graph, taken from papers in which no specific recommendations are made. Considering nozzle sizes of 1 in and over, the work of Sprague and Harding[3] shows good general agreement with the distance recommended by Caldwell[13]. The safe distances given by Sprague and Harding are generally lower than those given by Buffet et alia[2], only approaching the same values for low values of conductivity. Direct comparison with Caldwell's values is not possible because no criterion of safe current is given and the water conductivity is not known.

The results of Fitzgerald[8], for nozzle diameters of $\frac{5}{8}$ in and less, are in good agreement with those of Buffet et alia for 18 cm nozzles. Although Fitzgerald uses a criterion of 3 mA for safe current, compared with 1 mA for the work of Buffet et alia, he bases his distances on a lower value of specific resistance (1530 ohm cm).

The Croydon tests[1] show a fair measure of agreement with other work, as do the isolated results reported by Reanney[17] (Birkenhead tests) and by Sarvas and Ponni[16]. The value of Brown[18] for a $1\frac{1}{4}$ in nozzle is rather lower than the other values, but he does not quote a water conductivity.

Results quoted by Baatz[15] for small nozzles are lower than the recommended values of Buffet et alia, but the latter values are based on a margin of safety.

The general conclusion, from a study of the experimental work by different workers, is that the results of Buffet et alia give criteria for the minimum safe distances to be employed, which are generally more severe than those adopted by other workers; this probably stems from the fact that they used a criterion of safe current of 1 mA and took the maximum currents observed over a wide range of water pressures. The corrections for varying water conductivity made by Sprague and Harding, and by Fitzgerald, do not appear to be justified, since if the current is as low as 1 mA, the conductor is almost certainly in the expansion zone of the jet and quite small changes in stream length would result in large changes in resistance(7).

5. Spray nozzles

The general conclusion from work carried out on spray nozzles, similar in nature to that for solid streams, is that the current conducted by the spray is small. The work of Thom(7) showed that the current conducted by the spray is of the same order as the leakage current due to ionisation of the air surrounding the conductor. These currents are of the order of tens of microamps, for example, in the course of Thom's work a conductor at 35.2 kV to earth, when sprayed with a cupric solution (specific resistance 113 ohm cm) from a nozzle at 0.8 m, produced a current of less than 100 μA. Consequently there is no danger to personnel holding a spray nozzle, from the point of view of shock due to a current being conducted by the spray, and the problem reduces to the maintenance of a distance which is sufficient to eliminate the possibility of accidental direct contact with live conductors.

Recommended safe distances of approach are given by Thom (quoting a table given by Appel and Bono which has no reference), Buffet et alia, Fitzgerald, and by the Chicago Fire Department(11).

These distances are tabulated in Tables VII, VIII, IX and X and are plotted in Figure (5). The distances recommended by Fitzgerald, and those recommended as a result of the Chicago tests show a good measure of agreement. The distances given by Buffet et alia are significantly lower at higher voltages, as also those quoted by Thom, which are lower at all voltages. In the latter case it is not clear whether the voltages quoted are line voltages or voltages to earth; if they were line voltages then the distances would show better general agreement with the distances given by other workers.

As a general principle it seems reasonable to adopt a minimum distance of approach, such as the 4 ft recommended by Fitzgerald, and to avoid the small distances given by Thom at voltages in the region of 10 kV. The distance can be increased for higher voltages, but what contributes a safe working distance is rather arbitrary, and dependent to a large extent on the general layout of the installation constituting the hazard. The increase in the recommended safe working distance with conductor voltage, shown in Figure (5), is probably not necessary, since the danger of accidental contact is not dependent on the voltage.

6. Portable extinguishers

The problem of the danger arising from the use of portable extinguishers containing water is similar to that arising from the use of a jet from a hose. The diameter of the nozzle is much less than those encountered with hose nozzles, and on representative modern extinguishers is approximately $^3/_{32}$ in. The greatest hazard arises from the fact that portable extinguishers often contain solutions which are highly conductive, e.g. soda-acid, "loaded stream", and anti-freeze solution (see Section 2); at short range, with a solid stream, these solutions may result in a dangerous current being conducted.

For extinguishers containing water from a public supply there is probably very little danger up to 1 kV, even at distances as small as 1 foot. For example, for water of specific resistance 2,000 ohm cm the resistance of a 1 ft length of water stream, of $^3/_{32}$ in diameter is 1.37 MΩ. The current flowing under a potential of 1 kV is 0.73 mA, which is well within the safe limit of 1 mA adopted. The order of magnitude is comfirmed by work carried out on Nu-swift extinguishers[9], where a current of approximately 1.9 mA was found at a distance of 20 cm, for water of the same conductivity.

Extinguishers containing highly conductive solutions present a much more difficult problem. The specific resistance of anti-freeze solutions may be as low as 9.3 ohm cm[9], resulting in a current of 157 mA for a potential of 1 kV, with a stream $^3/_{32}$ inch in diameter at a distance of 1 ft. This may be a lethal current, and presents a serious danger to the user. This order of current is also confirmed by the work on Nu-swift extinguishers[9], in which a current of 200 mA was observed at a distance of 20 cm. This type of extinguisher must therefore be used at a distance at which the jet is sufficiently broken up into discrete drops to restore the current to below 1 mA. Information on this point is sparse, but in the work done on Nu-swift extinguishers the current along the liquid stream had fallen to a negligible value at a distance of 1 m, indicating that the jet was sufficiently broken up at this distance. Other work[20] has shown that even at voltages as high as 30 kV (a.c. 50 c/s), using fresh water, there was zero potential at the extinguisher nozzle at 4 feet distance. Using sea water (specific resistance 25 ohm cm) at 440 volts a.c. and 800 volts d.c., the nozzle potential was zero at distances of 3 feet and over. In general, from the limited evidence available, the stream appears to be sufficiently broken at distances of 3 - 4 feet. More evidence, however, would be required to confirm this distance, which may vary considerably with the type of extinguisher employed.

The general conclusion is that with extinguishers containing highly conductive solutions a minimum distance of approach is required, certainly not less than 4 feet, for voltages up to 1 kV. Extinguishers containing water from a public supply may be used at shorter distances (for voltages up to 1 kV) from the shock hazard point of view, but from general considerations of safe approach to electrical apparatus a similar distance to that required for the highly conducting medium is advisable. For voltages greater than 1 kV the distance of approach should be increased, in accordance with the general recommendations given by workers on hose streams, c.f. Buffet et alia for nozzles of 7 mm (0.276 in) in diameter.

7. Foam

The ratio of the specific resistance of a foam to that of its generating solution shows a practically linear increase with the expansion factor of the foam[20], and appears to be independent of the nature of the foaming agent and of the specific surface of the foam. This finding has been confirmed on theoretical grounds[21].

The general conclusion is that a foam stream would have a resistance higher than that of a solid stream of generating solution, but in view of the widely varying resistivities possible with such solutions[20], it seems reasonable to apply similar restrictions to the use of foam streams as to the use of solid streams of water.

Conclusions

(1) The maximum current which should be permitted to pass through the extinguishing medium to the fire-fighting equipment is 1 mA. This ensures that this is the maximum current which can pass through the body of a man operating the equipment.

(2) (a) The work done by various experimenters on hose streams is difficult to correlate because the precise form of the stream is dependent on pressure of water supply, on nozzle diameter, and on the internal design of the nozzle. It is therefore difficult to give a general rule as to the length of streams for which the current is below the safe limit.

(b) In general, the safe distance must be increased with increasing nozzle diameter and conductor voltage.

(c) The results of Buffet et alia give rise to recommended safe distances which appear to give the greatest margin of safety when their results are compared with those of other workers. The recommended safe distances are given in Table III, covering voltages up to 150 kV to earth, and applying to a range of nozzle diameters, up to 9/32 in, between 9/32 in and 23/32 in, and between 23/32 in and $1\frac{3}{8}$ in.

(3) Water sprays do not conduct electrical currents of dangerous magnitudes. The limitation on the safe distance is that of the minimum distance of approach to equipment at high voltage.

(4) (a) Portable extinguishers, containing a highly conductive solution, may contribute a serious hazard even at comparatively low voltages of up to 1 kV. A dangerous current can be conducted by the stream if the extinguisher is used at distances of less than 4 feet. There is a paucity of information as to whether the stream is sufficiently broken at this distance, and further information is required to determine if the distance is adequate.

(b) Portable extinguishers containing water from the public supply can be used safely at distances down to about 1 foot, for voltages up to 1 kV. From the viewpoint of accidental contact with live components, however, a minimum distance of approach should be adopted.

(c) For voltages greater than 1 kV safe distances should be adopted in accordance with work done for hose streams for smaller nozzle sizes.

(5) The same limitations should be placed on the use of foam streams as for hose streams of water.

(6) There is no electrical hazard, from the point of view of current conducted by the extinguishing medium, in the use of carbon dioxide, dry chemicals, or vaporising liquids, but minimum distances of safe approach to electrical equipment must be maintained.

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Table 1

Specific Resistances of Water from Public Supplies

Authority	Specific resistance (ohm cm)
Tests carried out at Croydon Electricity Station[1]	2100
Buffet, Maruelle, Moigne, and Roussel[2]	2930, 3180, 3600 (at 21°C)
Sprague and Harding[3] (Survey of water supplies in State of Indiana)	Range: 710-5400 Deep wells: 1000-2000 Lake and river: circa 4000
Estorff and Weber[4]	2780
Report on Spray Appliances by Danish Power Association[5]	1320 at 9°C 1260 at 20°C
Koch[6]	455
Thom[7]	"Soft" water: 1850 Sea water: 20
Fitzgerald[8]	4570 at 8.5°C. A minimum value of 1530 is given for results of a survey of water in State of Ontario
Report on tests with Nu-Swift dry powder and water type extinguishers[9]	Darmstadt supply: 2000

Table II

Details of Experimental Work on Solid Hose Streams

Observer	Nozzle Diameters	Voltages to Earth	Water Pressures	Details of Water Used	Other Information	Experimental Observations	Remarks
Buffet et alia (2)	7-33 mm	115 V) a.c. 460 V) and d.c. 3 KV a.c. 6 " " 12 " " 60 " " 150 " " (a.c. supply at 50 c/s)	0-15 kg/cm^2	Dhuys : 2930 ohm cm Avre : 3180 " " Seine 3600 " " (All at 21 °C)	A useful elementary theoretical consideration is given of the effect of stream length, nozzle diameter and voltage.	The effect of alternating and direct potentials is studied, and also the influence of flames, fumes and water vapour. A detailed examination is made of the effect of voltage, stream length, nozzle diameter and pressure, on the current along the hose stream.	A table of recommended safe distances is given for nozzles of 7, 18, and 30 mm diameter. This table is based on a safe current in the hose stream of 1 mA, and is applicable up to 150 KV. The currents used are the maxima observed over the pressure range.
Sprague and Harding (3)	1 in. 1$\frac{1}{8}$ in. and 1$\frac{1}{4}$ in.	440 V-100 KV (a.c. at 60 c/s)	30, 50, and 70 lbf/in^2	Purdue University water mains: 1900 ohm cm at 63°F	A survey showing the wide range of water resistivity in Indiana State is given.	The effect of voltage and stream length in the hose stream current was examined in detail.	A table of recommended safe distances is given for a 1$\frac{1}{4}$ in diameter nozzle, for a range of water resistivities from 500-6000 ohm.cm. The table is based on a safe current of 3 mA, and an upper limit of 13,200 volts is advocated.
Thom (7)	7, 14, 18 mm	15,63 KV line voltages (a.c. at 50 c/s)	2-16 kg/cm^2	Rhone : 1825 ohm cm Cupric solution (2% copper sulphate 2% agricultural lime) : 113 ohm cm (both at 20°C) "Soft" water : 1850 ohm cm Sea water : 20 ohm cm (both at 18°C)		The effect of pressure, voltage, nozzle design and stream length on the stream current is examined.	An interesting discussion is given of the variation of stream resistance with variation in stream length. No specific general recommendations are made. Resistance in broken zone of stream is shown to be independent of water conductivity.
Fitzgerald (8)	$\frac{1}{2}$ in.-1$\frac{1}{4}$ in.	600 V-130 KV (a.c. at 60 c/s)	30-100 lbf/in^2	Toronto city: 1800 ohm cm (at 8.5°C)	A survey was carried out on Ontario water from various locations, and a minimum resistivity of 600 ohm cm was found	The effect of nozzle size and stream length on the hose stream current was examined.	A table of recommended safe distances is given for nozzles up to $\frac{5}{8}$ in. diameter, assuming a safe current of 3 mA, up to a maximum of 130 KV. The use of nozzles larger than $\frac{5}{8}$ in. is not recommended. The safe distances are applicable to a water pressure of 100 lbf/in^2 and a water resistivity of 600 ohm cm.

Table II

Details of Experimental Work on Solid Hose Streams (Continued)

Observer	Nozzle Diameters	Voltages To Earth	Water Pressures	Details of Water Used	Other Information	Experimental Observations	Remarks
Baatz [15]	8, 12 mm	10, 20, 30 60, 110 KV (a.c. at 50 c/s)	3.5, 6.5 atm.	Stuttgart: 1667 ohm cm.	Effect of area of cross-section of conductor varied, and also comparison made with a plate, and of jet directed vertically downwards.	Effect of stream length, nozzle diameter, voltage and pressure on stream current.	Graph given showing distance between nozzle and conductor for a current of 1 mA, under various conditions.
Caldwell (see Walker [13])	1⅛, 1½ in.	5-30 KV	Pressure was varied but range not given.	Not given		Resistance of varying hose stream length measured over voltage range.	A table of recommended safe distances is given for voltage up to 30 KV. No criterion of safe current is given, and the basis for the table is not clear. A similar table is given for sea water, which appears to be largely hypothetical.
Croydon tests [1]	⅝-1⅜ in.	132 KV (line voltage, a.c. at 50 c/s)	100-190 lbf/in^2	2100 ohm cm		Resistance of hose stream measured for various stream length.	Safe working distance of 40 ft. recommended from nozzles of ⅝ in. diameter and less. Safe working distance of 60 ft. recommended for nozzles of ¾ in. diameter and greater. No criterion of safe current given, but distances are presumably based on assumption that stream is broken.
Reanney [17] (Birkenhead tests)	⅝ in.	11 and 30 KV (a.c. at 50 c/s)	60-80 lbf/in^2	Not given			No shock felt for ⅝ in. diameter nozzle at distance of 30 ft.
Brown [18]	1¼ in.	11 KV (a.c. at 60 c/s)	60 lbf/in.^{2}	Not given		The safe distance was that at which no current flow could be detected.	For a 1¼ in. diameter nozzle it was concluded that it was safe to operate at 30 ft distance with "fresh" water, and 40 ft. with sea water.
Sarvas and Ponni [16]	10-28 mm	500 V and 12 KV	4-14 atm.			Current in hose stream was measured at various stream lengths, pressures and nozzle diameters.	For nozzles up to 17 mm diameter the safe distance for 20 KV line voltage is 7 m, and for 500 V line voltage it is 2 m.

Table III

Safe distances recommended for hose streams by Buffet et alia(2)

Voltage between conductor and earth	Diameter of nozzle orifice		
	7 mm	18 mm	30 mm
115 V (a.c.)	0.50 m	1.00 m	2 m
460 V (d.c.)	0.75 "	3 "	5 "
3 KV (a.c.)	2 "	5 "	10 "
6 " "	2.5 "	6 "	12 "
12 " "	3 "	6.5 "	15 "
60 " "	4.5 "	12 "	22 "
150 " "	6 "	15 "	25 "

The table is reproduced below in English units for ease of reference, the distances being quoted to the nearest 0.1 ft.

Voltage between conductor and earth	Diameter of nozzle orifice		
	9/32 in(1)	23/32 in(1)	$1\frac{3}{8}$ in(1)
115 V (a.c.)	1.6 ft	3.3 ft	6.6 ft
460 V (d.c.)	2.5 "	9.9 "	16.5 "
3 KV (a.c.)	6.6 "	16.4 "	32.8 "
6 " "	8.2 "	19.7 "	39.4 "
12 " "	9.9 "	21.4 "	49.3 "
60 " "	14.8 "	39.4 "	72.3 "
150 " "	19.7 "	49.3 "	82.0 "

(1) These are the nearest fractional inch equivalents of the metric sizes.

Table IV

Safe distances recommended for hose streams by Sprague and Harding(3)

Volts	Water resistivities (ohm cm)							
	500	1000	1500	2000	3000	4000	5000	6000
440	11	7	5.5	4.5	3	3	3	3
1100	30	18	14	12	8.5	6.5	5.5	5
2200	*	30	23	20	15	12	9	8
4400	*	35	31	28	23	19	16	15
6600	*	*	34	33	30	26	23	22
13200	*	*	*	*	33	31	29	28
22000	*	*	*	*	*	*	*	*
Nozzle pressure: 50 lbf/in^2 Nozzle size: $1\frac{1}{4}$ in.								

*At these voltages the stream should not be permitted to come into contact with the conductor.

The distances in the table are in feet, and the voltages quoted are relative to earth.

Table V

Safe distances recommended for hose streams by Fitzgerald(8)

Voltage to earth (volts)	Minimum safe distance for $\frac{5}{8}$ in solid stream nozzle (ft)
2,400	15
4,800	20
7,200	20
8,000	20
14,400	25
16,000	25
25,000	30
66,500	30
130,000	30
Nozzle pressure: 100 lbf/in^2 Water resistivity: 1,500 ohm cm	

Table VI

Safe distances recommended for hose streams by Caldwell (see Walker)(13)

Voltage to earth (volts)	Safe distance (ft)			
	$1\frac{1}{8}$ in nozzle		$1\frac{1}{2}$ in nozzle	
	Fresh water	Sea water	Fresh water	Sea water
1,100	6	25	9	30
2,200	11	25	16	30
3,300	15	-	22	-
5,500	18	-	27	-
6,600	19	30	29	35
11,000	20	30	30	35
22,000	25	30	33	40
33,000	30	35	40	45

Table VII

Safe distances recommended for spray nozzles in paper by Thom(7)

Voltage of installation (volts)	Distance (metres)
up to 7,500	0.15
7,500 to 15,000	0.30
15,000 " 25,000	0.42
25,000 " 37,000	0.60
37,000 " 50,000	0.80
50,000 " 73,000	1.10
73,000 " 88,000	1.30
88,000 " 110,000	1.60
110,000 " 132,000	1.92
132,000 " 154,000	2.22
154,000 " 187,000	2.65
187,000 " 220,000	3.10

Table VIII

Safe distances recommended for spray nozzles by Buffet et alia(2)

Voltage between conductor and earth	Safe distance (metres)
115 V (a.c.)	0.50
460 V (d.c.)	0.75
3 kV (a.c.)	1.00
6 " "	1.00
12 " "	1.20
60 " "	1.50
150 " "	2.00

Table IX

Safe distances recommended for spray nozzles by Fitzgerald(8)

Voltage to earth (volts)	Minimum safe distance (feet)
2,400	4
4,800	4
7,200	4
8,000	4
14,400	4
16,000	4
25,000	6
66,500	8
130,000	14

Table X

Safe distances recommended for spray nozzles as a result of Chicago Fire Department tests(11)

Voltage to earth	Minimum safe distance (feet)
19 kV	4
38 "	6
76 "	8
127 "	14

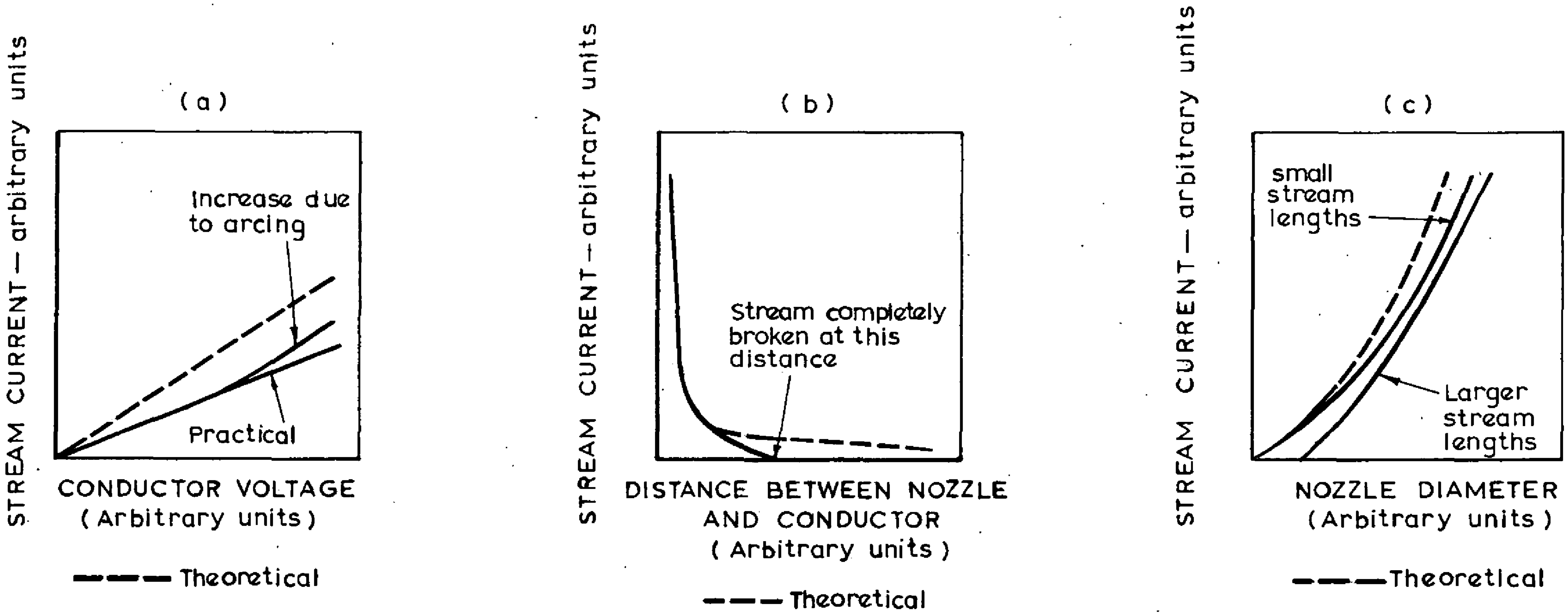


FIG.1. HYPOTHETICAL RELATIONSHIPS BETWEEN STREAM CURRENT AND THE PRINCIPAL VARIABLES

1/5201 F.R.529

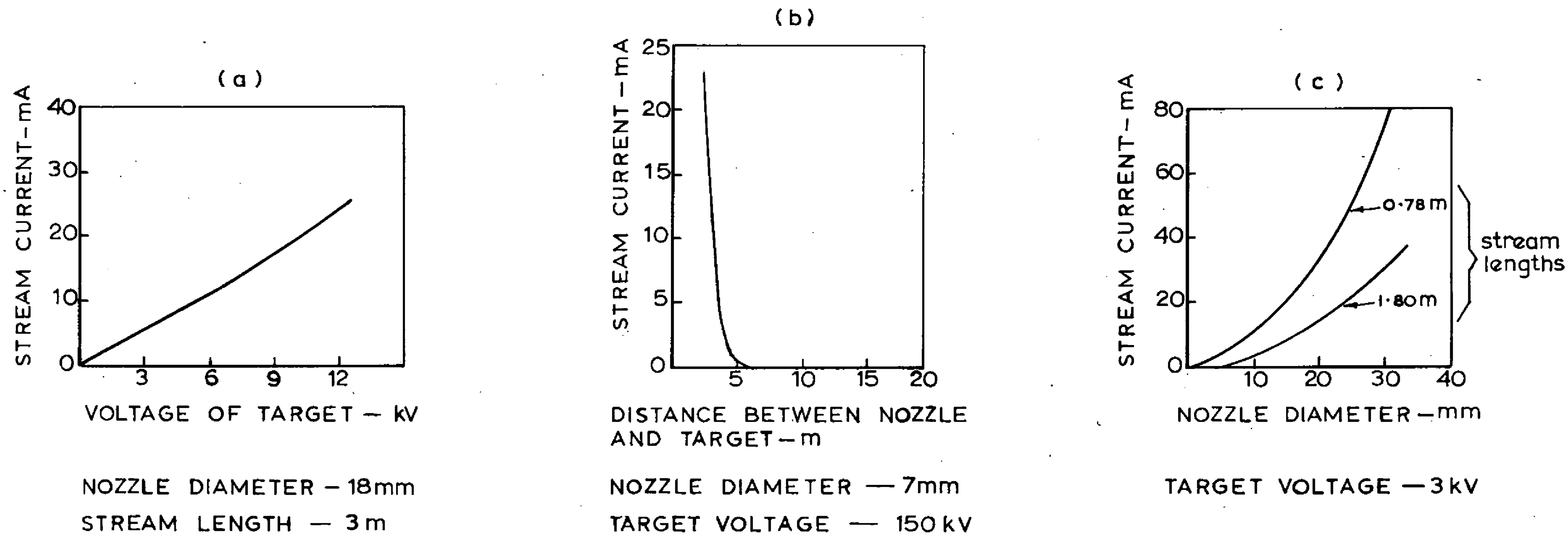
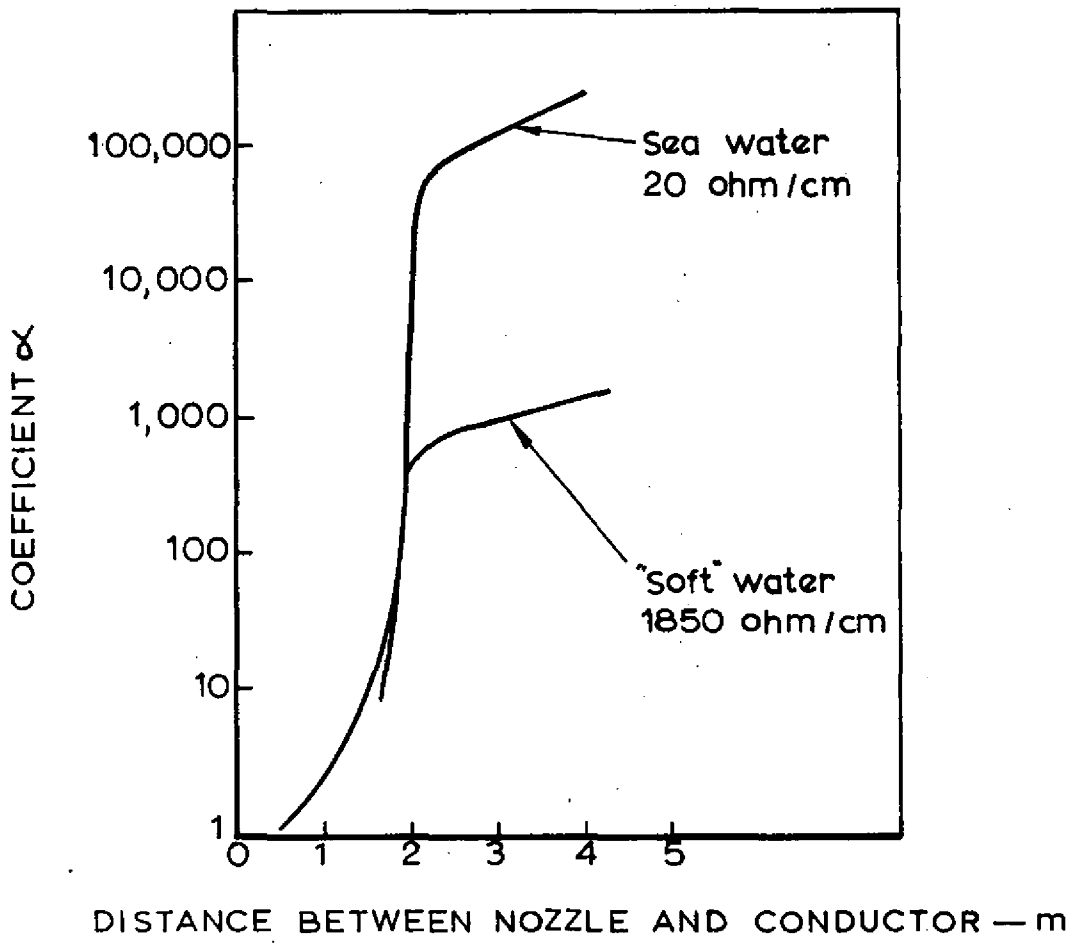


FIG. 2. EXPERIMENTAL RELATIONSHIPS BETWEEN STREAM CURRENT AND THE PRINCIPAL VARIABLES

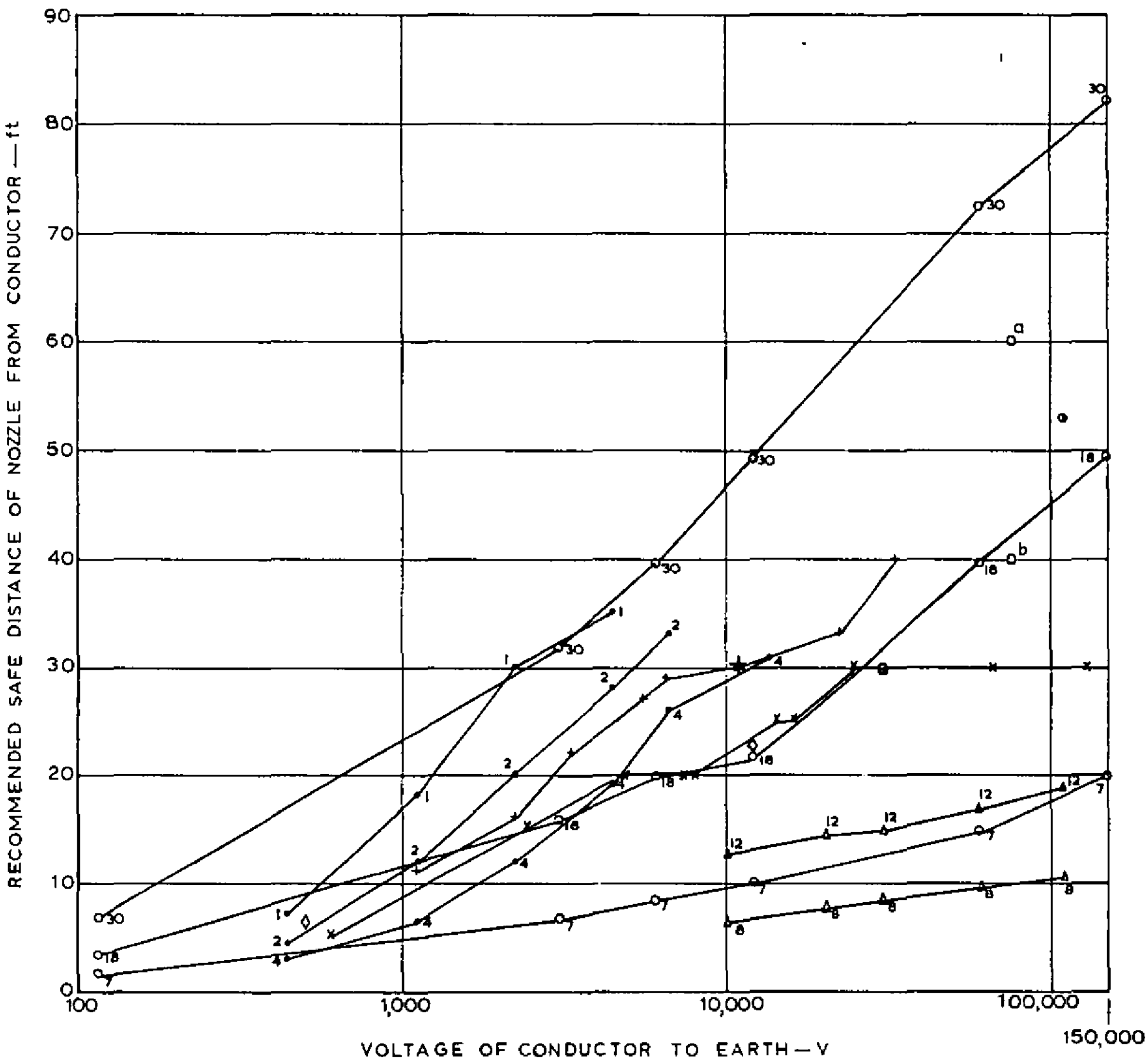


CONDUCTOR VOLTAGE — 8·75 kV

PRESSURE — 5kg/cm^2

FIG.3. VARIATION OF COEFFICIENT ∝ WITH DISTANCE BETWEEN NOZZLE AND CONDUCTOR

1/5202 F.R.529



30 ○ 18 ○ 7 ○ BUFFET ET ALIA (30mm, 18mm, 7mm nozzle diameter)

1• 2• 4• SPRAGUE AND HARDING (1000, 2000, 4000 water specific resistance, nozzle 1¼ in. diameter)

× FITZGERALD (nozzles ⩽ ⅝ in. diameter)

+ CALDWELL (nozzle 1½ in. diameter)

12△ 8△ BAATZ (12 mm, 8mm nozzle diameters)

a□ b□ CROYDON TESTS (a - nozzles ⩾ ¾ in. diameter; b - nozzles ⩽ ⅝ in. diameter)

◊ SARVAS AND PONNI (nozzle 17mm diameter)

▲ BROWN (nozzle 1¼ in. diameter)

■ REANNEY (nozzle ⅝ in diameter)

● DANISH POWER ASSOCIATION (nozzles up to 24 mm diameter)

FIG. 4. VARIATION OF SAFE DISTANCE WITH CONDUCTOR VOLTAGE FOR SOLID STREAM NOZZLES

2/294 F.R.529.

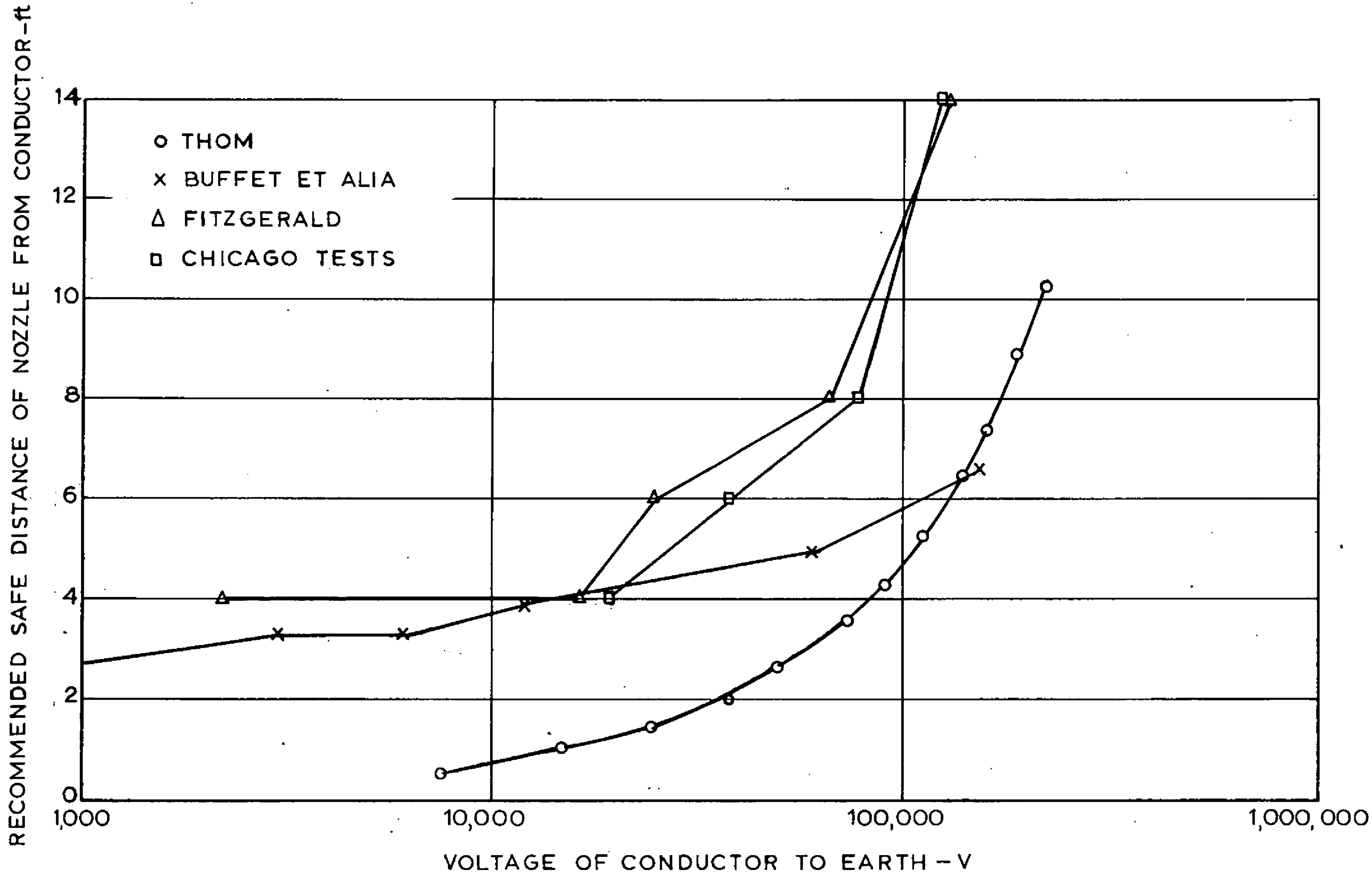


FIG. 5. VARIATION OF SAFE DISTANCE WITH CONDUCTOR VOLTAGE FOR SPRAY NOZZLES