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Insulators for 1000 to 1500 kV systems

BY P. J. LAMBETH

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[Plates 16 and 17]

In areas of heavy pollution, the risk of flashover at working voltage as a result of conducting layers on the surface is likely to be the limiting criterion for insulator length. Performance is being evaluated in natural pollution to determine whether or not values used at lower voltages may be linearly extrapolated to 1000 to 1500 kV.

To carry the large conductor bundles, insulators will need a heavy mechanical rating. Very strong resin insulators with fibre-glass cores can be produced. Such insulators can have greater leakage path in a given length than conventional porcelain or glass, and hence give a reduced overall length. Another method of reducing length is to use a porcelain with a resistive glaze; this improves performance in pollution both by drying the surface and suppressing discharges.

In substations and on lines, assemblies of individual post and string insulators will be used to give improved mechanical characteristics and reduce the height of substation structures and line towers for reasons of amenity and cost.

1. INTRODUCTION

Either switching surges or pollution may be the limiting criterion for determining the length of outdoor insulators for u.h.v. systems, but in this country where many u.h.v. lines and substations would need to be near the coast and subject to saline pollution it can be safely assumed that a substantial proportion of any system would need to be designed to take account of pollution.

Other papers in this report are devoted to various aspects of flashover caused by switching surges, flashovers which are governed more by the characteristics of the air gaps than the insulators.

In this paper therefore the object has been to consider the general problems caused by pollution, the particular problems of insulators for u.h.v. systems, the methods of pollution testing insulators for these very high voltages, and lastly the means by which the size of u.h.v. insulators might be limited to relatively modest values.

2. POLLUTION BEHAVIOUR OF INSULATORS

If a high-voltage insulator is exposed to atmospheric pollution either industrial, or coastal, the surface is coated eventually with a layer usually containing salts, which becomes partially conducting when it is wetted. The wet layer passes a current and heat is dissipated in the surface film. The effect of this is to raise the temperature and hence the conductivity, but at or near boiling-point, evaporation reduces the thickness, although the surface conductivity remains fairly constant until the salts begin to come out of solution. When this happens a local instability sets in, usually at a point where ie (current density \times electric stress) is a maximum, and power dissipation and resistance rapidly increase until a dry insulating band appears around the insulator. This band cannot withstand the full voltage on the insulator, and the air gap across it breaks down, causing discharges. The concentration of current at the roots of the discharges

causes the dry band to widen until sparking occurs infrequently. Such a quasi-stable situation can be maintained in practice for a long time and the bursts of current associated with sparking across the dry bands are characteristic of the behaviour of most insulators in polluted localities even though flashover may never take place. Where an insulator consists of several identical units in series it is common for dry bands to form on most units (see figure 7). However, if the resistance of the polluted layer in series with the discharge is low enough the discharge is unstable, that is, current drawn from the supply increases if the discharge extends over the wet surface.

Broadly speaking the discharge will be unstable if

$$E_d + I(dR(x)/dx) < 0,$$

where E_d is the electric stress in the discharge, I is the current, $R(x)$ is the resistance of the wet layer between the roots of the discharge and the electrode and x is the length of the discharge (Hesketh 1967). In the simplest uniform one-dimensional case this becomes equivalent to stating that the discharge is unstable when the field in the arc becomes less than the field in the wet layer (Hampton 1964). Since

$$E_d = AI^{-n}$$

we can deduce a relationship of the form $E_c \propto \sigma_c^{-n/(n+1)}$, where E_c is the critical stress on the insulator, and σ_c is the corresponding surface conductivity.

When the discharge is unstable it extends across the layer. This is a circuit instability and occurs at the same stress whether the resistive layer is liquid or solid (D. Marsh 1973, personal communication). The speed of extension is relatively slow, some metres per second, and the mechanism of propagation is still not well understood. Experiments have shown that, while propagating, the discharge is in electrical contact with the surface through filamentary lateral discharges. Speed of propagation is generally higher for a positive than for a negative discharge, and speed increases with the degree of instability (Boylett & McLean 1971).

From laboratory work on the processes of flashover a number of laws can be derived for the behaviour of insulators subjected to pollution. However, to determine the actual behaviour of full-scale insulators more realistic tests must be made. These can be carried out by energizing insulators in natural conditions over long periods and noting their performance. Though such tests are essential they are expensive and time-consuming, and not precisely reproducible. Consequently, artificial pollution tests have been developed which simulate the essential features of natural conditions, and have been validated by reference to insulator behaviour in natural pollution.

One such test, the salt-fog method, in which insulators are subjected to an artificial swirling fog of salt water droplets, was originated in the United Kingdom at C.E.R.L. (Ely & Lambeth 1964) and developed in collaboration with Electricité de France and E.N.E.L. (Lambeth *et al.* 1968). The severity is a function of the salinity of the solution to which the insulators are subjected and the test voltage, and performance is judged either by the maximum salinity of fog which an insulator will withstand at a given voltage for an hour, or by the voltage at which flashover occurs at a given salinity, when the voltage is raised in small steps over a long period.

From tests on a large number of different types of insulators a number of the laws governing the behaviour of insulators in pollution have been derived (Lambeth *et al.* 1973). The most important are listed below:

- (1) Length and flashover voltage for a uniform insulator are directly proportional for the same severity.
- (2) Flashover stress (E) and salinity (S) are generally related by an expression $E \propto S^{-p}$ where p is 0.2 to 0.3.
- (3) For insulators of the same broad design the flashover voltage increases with the leakage path over the surface of the insulator.
- (4) Performance is generally improved by inclining the insulator from the vertical.
- (5) Performance deteriorates as insulator diameter increases up to about 500 mm.
- (6) Flashover voltage is reduced as the duration of the voltage application is increased.

3. SPECIAL PROBLEMS OF ULTRA-HIGH VOLTAGES

The laws governing pollution behaviour have been derived mainly from tests on insulators for systems below the ultra-high voltage range. Some work has been done using artificial test techniques on insulators long enough for u.h.v. systems, but until adequate measurements have been made of the characteristics of u.h.v. insulators in naturally polluted atmospheres, there must remain some doubt about the validity of the artificial test techniques at the highest voltages.

For example, figure 1 shows the results of tests on a representative range of insulator types by workers in a number of countries using a variety of artificial pollution techniques. Nearly all show almost constant flashover stress as a function of length, that is proportionality between flashover voltage and length. Kawai's kaolin/salt slow-wetting test, however, shows a drop of up to 20% in flashover stress on standard cap-and-pin insulators as length is increased from 1 to 9 m (figure 1*h*) and even more alarming reductions for shorter strings in earlier tests (figures 1*d* and 1*f*). As length is perhaps the most critical factor in u.h.v. system design it is worth while considering possible reasons for non-proportionality. If all segments of an insulator have the same electrical parameters, e.g. the same dry band widths and wet-surface conductivities, then proportionality should be ensured. However, a slow wetting process can give a non-uniform wetting. This arises because the dry-weather voltage distribution on a long insulator is largely determined by stray capacitance and is therefore non-uniform. Consequently as humidity increases condensation occurs preferentially on the lower-stressed units which remain cooler. Discharge over the more highly stressed parts of the insulator will occur first, and the discharge effectively bypasses an appreciable section of the insulator making total flashover possible at a lower voltage than if the insulator were completely wet, with a more uniform conductivity. The important question is whether, with such light wetting the conductivity can be high enough to make this the condition which gives the minimum flashover voltage for a given solid pollution deposit. At the other end of the scale of wetting there is the possibility of non-proportionality for a completely different reason. On a large insulator, such as a bushing, rain is collected more-or-less uniformly, but cascades downwards, so that at any instant the layer increases to a maximum at the bottom. Heavy rain is usually considered innocuous because of its washing action, but large quantities of water can easily result in the gaps between the sheds of insulators being bridged, and hence give a reduced effective leakage path. Sparking between sheds is noticeable during live-washing tests on 400 kV post insulators, and may be the cause of flat voltage/salinity characteristics in salt-fog tests on insulators with closely spaced sheds. The taller and wider the insulator, the more likely it is that non-uniformity of resistance, and inter-shed bridging will have a significant effect on its behaviour.

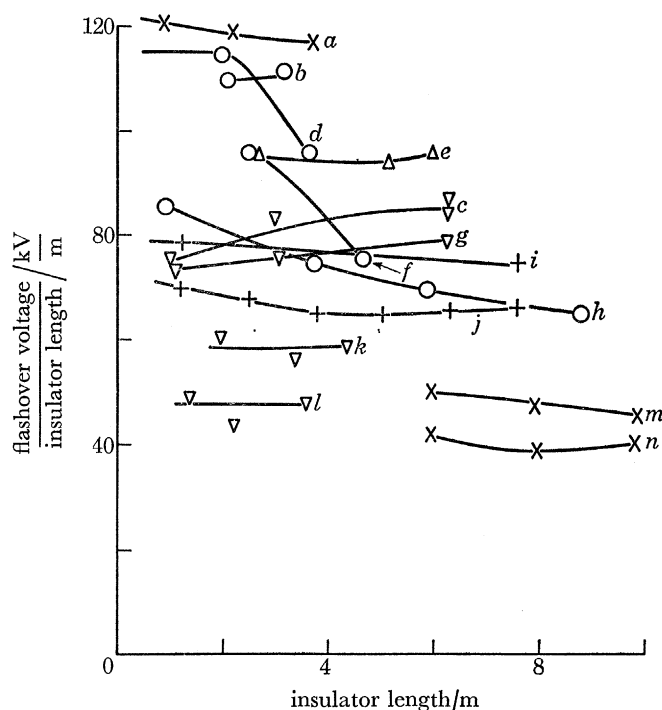


FIGURE 1. Flashover voltage against length for constant pollution severity:

source	insulator type	test method
(a) NGK (1968)	antifog cap and pin	{ kaolin/salt layer kaolin/salt: slow wetting salt fog
(b) Kawai (1970)		
(c) Lambeth <i>et al.</i> (1970)		
(d) Kawai (1970)	standard cap and pin	{ kaolin/salt: slow wetting prewetted cement kaolin/salt: slow wetting salt fog kaolin/salt: slow wetting
(e) Aleksandrov <i>et al.</i> (1965)		
(f) Kawai (1970)		
(g) Lambeth <i>et al.</i> (1970)		
(h) Balderston <i>et al.</i> (1972)		
(i) Heise & Köthe (1964)	long rod (NVKL 75/27)	} prewetted methyl-cellulose
(j) Heise & Köthe (1964)		
(k) Ely (1971, private communication)	barrel: antifog shed	} salt fog
(l) Lambeth <i>et al.</i> (1970)	barrel: plain shed	
(m), (n) Tagaki <i>et al.</i> (1968)	bushing: plain shed	kaolin/salt layer

Mechanical problems will be particularly important at u.h.v. levels. Lines are likely to have heavier conductors, and insulators of double the highest mechanical rating used in this country today (380 kN or 40 tonf, ultimate tensile strength) are likely to be needed. On tension, and terminal towers about four times this rating may be required. It is quite feasible to use assemblies of two or four strings in parallel, and many lines in this country do use assemblies of 190 kN strings but such large numbers of units would be required that the reliability of individual units would have to be extremely high. Alternatives to conventional glass and porcelain insulators are resin-bonded fibre-glass rods on which developments are in progress. These can be several metres in length and have sufficient mechanical strength to take the full loads required. The number of separate units required could then be only 2% of conventional cap-and-pin types: the reliability required of a unit would therefore be less.

Substation insulators for u.h.v. present more problems, both electrical and mechanical, than

line insulators. Because the posts required to withstand switching surges at 1500 kV system voltage may be 10.5 m high (UHV *ad hoc* Group 1972) even in clean areas, it becomes impracticable to use single free-standing posts because the strength of porcelain is inadequate. Conventional alternatives are rigid assemblies such as inverted 'V' or tripod posts. Even these are rather weak, and expensive, and a more practical solution is a 'Maypole' post (figure 2, plate 16) in which a single rigid member is used, pivoted at top and bottom so that it acts as a strut, and restrained by four insulating guys using line insulators. Since porcelain is a rigid material, and much stronger in compression than in tension, the strut can be highly loaded. The line insulators form catenaries, and make the whole assembly flexible and thus able to withstand impulsive forces. The complete assembly is relatively cheap. However, it is bulky, and it seems likely that substations for ultra-high voltages will be much more compact as well as cheaper if they are metalclad and insulated with compressed gas, such as sulphur hexafluoride. Even so, outdoor bushings will be required to connect such a substation to the overhead lines. Such bushings are likely to be very costly. They must be designed with large diameters to withstand the radial stress imposed by differences between the internal capacitive voltage distribution determined by the foils, and the uncontrolled external voltage distribution given by the pollution layer. The porcelains will probably be held in compression by the central conductor, but if inclined to the vertical the bending moments will be very high. The problem of water cascading mentioned earlier may need special precautions in areas of severe pollution.

4. NATURAL POLLUTION TESTING AT BRIGHTON

To study the problems of pollution behaviour at alternating voltages up to 1500 kV (system) an insulator testing station at Brighton has been extended to provide facilities for testing of line and substation insulators (figure 3, plate 16). The site is heavily polluted, as it is located on the southern arm of Shoreham harbour and directly exposed to winds from the sea which is only 50 m away.

A key question already referred to, which can only be resolved by natural pollution testing, is whether or not proportionality holds between insulator length and flashover voltage for the same pollution severity. Hence, similar, but shorter, insulators are also energized at voltages of 250 to 400 kV for comparison with those at ultra-high voltage.

The u.h.v. insulators are arranged on two gantries parallel to the coastline, 40 m high by 43 m wide. Each can contain up to eight line-insulator assemblies. The total can be made up of four nearly horizontal tension sets, eight angled insulators (halves of 'V' insulator assemblies), two or four vertical sets and up to two vertical posts. In addition the busbar is supported by two 'Maypole posts' (figure 2). Space is available for further posts or novel insulator assemblies as required.

The busbar is energized by a single-phase 900 kV transformer with a rating of 3 MVA (figure 4, plate 17), fed by a low-impedance regulator to give a continuously variable voltage output. The short-circuit current is over 30 A at maximum voltage. The test transformer has a centre-tapped secondary winding connected to the tank so that it is energized at half the output voltage. The tank is supported on 12 multiple-cone posts, and the connexions to the busbar and earth are made via 450 kV bushings, each with a leakage path-length of 21.5 m.

The testing technique to be used is new, and involves both automatic adjustment of the test voltage and increase in the insulator lengths. The procedure is as follows:

Each insulator has connected to it a number of special explosive fuses, designed to disconnect when a flashover occurs (figure 5). When a fuse operates the length of the insulator is automatically increased by about 15 %, and each subsequent flashover increases the insulator length further.

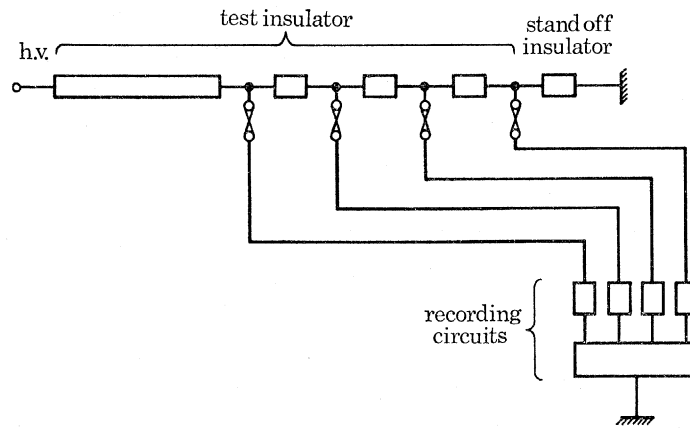


FIGURE 5. Testing circuit for 1500 kV insulators at Brighton.

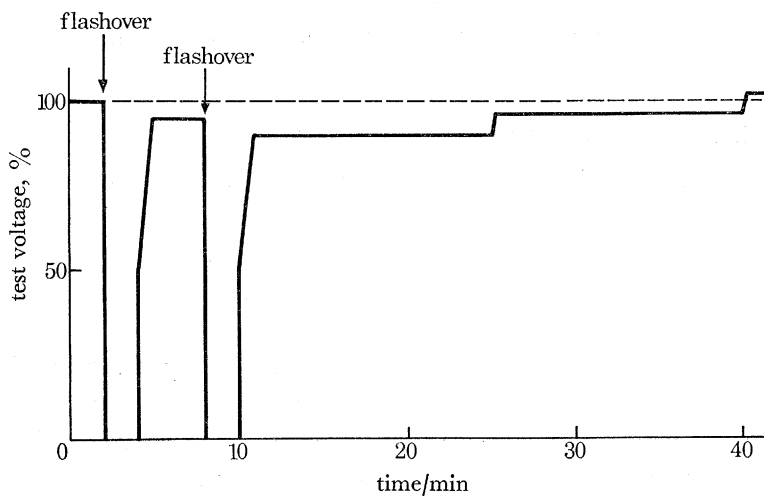


FIGURE 6. Test voltage variations in response to flashovers.

The circuit breaker controlling the transformer will also trip on a flashover. The regulator automatically then runs down to half setting. Two minutes later the circuit breaker closes at the reduced voltage, and the regulator is automatically run up to a predetermined value, usually 95 % of the previous test voltage. If no further flashovers occur the voltage is increased after about 15 min to a value slightly above the original one. This final value is chosen so as to keep the long-term mean stress on all the test insulators constant. Thus if there are 10 insulators, each fused to give a 15 % increase for a flashover, the voltage would be increased by 15/10, i.e. 1.5 %. If there is another flashover while the voltage is still depressed from the first one, the voltage after re-energization is raised to only 90 % of the original value, and then increased to its long-term value in two steps after 15 and 30 min (figure 6). The more flashovers which occur in a short time, the lower the voltage, so that flashovers may be obtained at the lowest stress possible during any period of bad weather. Afterwards the voltage is increased by stages to

a higher value to give a constant long-term mean insulator stress, and hence consistent testing procedure. Two insulators are regarded as controls; they have fuses giving increases of only 5%. These will be used as 'bench marks' against which the performance of the other insulators can be judged, so that the importance of profile, position and orientation can be assessed. The frequency distribution of flashover stress in terms of the control will give the frequency distribution of the limits of severity, and thus long-term performance can be inferred. Comparing flashover stresses in the u.h.v. range with those for the same insulators at the lower voltages will show whether or not flashover stress is a function of voltage.

Testing has only recently started but already indications of the discharge characteristics are available. The appearance of the site at night when the insulators were polluted and wet is shown in figure 7, plate 17. The frequency of discharges (figure 9) is similar to that recorded at lower voltages in both natural and salt fog tests, although the duration of the pulse train may be rather longer at the higher voltage. The current waveform for a single-cycle during a discharge is similar to that of lower voltage insulators (figure 8).

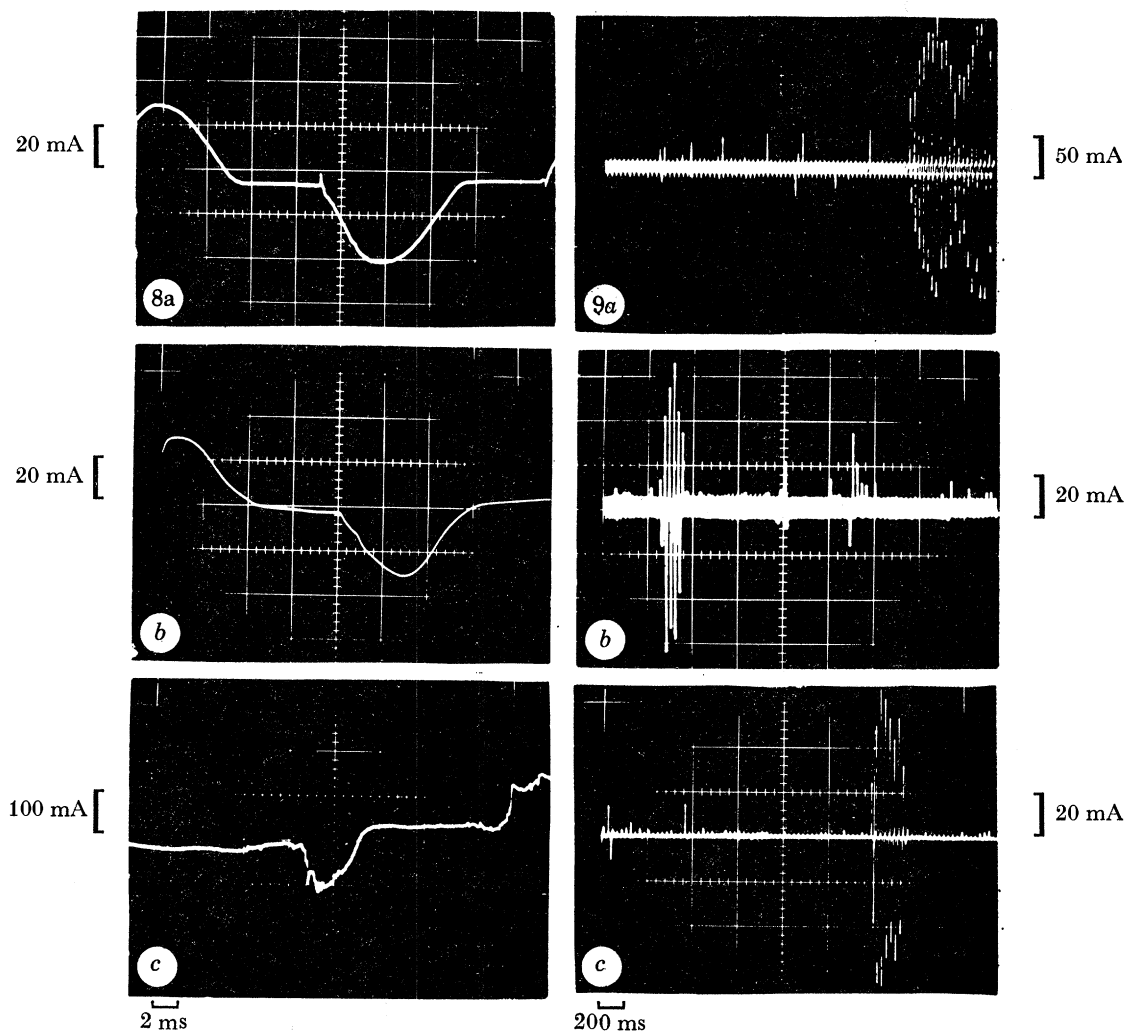


FIGURE 8. Discharge current waveforms: (a) 1100 kV duplex 'V' insulator: natural pollution at Brighton; (b) 550 kV bushing: natural pollution at Brighton; (c) 400 kV post insulator: salt fog test.

FIGURE 9. Discharge current pulses: (a) 1100 kV duplex 'V' insulator: natural pollution at Brighton; (b) 550 kV bushing: natural pollution at Brighton; (c) 400 kV post insulator: salt fog test.

5. METHODS OF IMPROVING INSULATOR PERFORMANCE IN POLLUTION

5.1. *Improving insulator geometry*

One way to obtain a better insulator in a given height is to increase the length of the leakage path. For ratios of leakage path/overall length up to about 3, increases in leakage path are beneficial. Above this value, using the conventional materials – porcelain or glass, it becomes difficult to form profiles without reducing air clearances between the sheds so low that sparking occurs between the sheds, especially when there are drips on them, rather than over the surface. For porcelain line insulators the optimum design appears to be an antifog disk unit, such as the

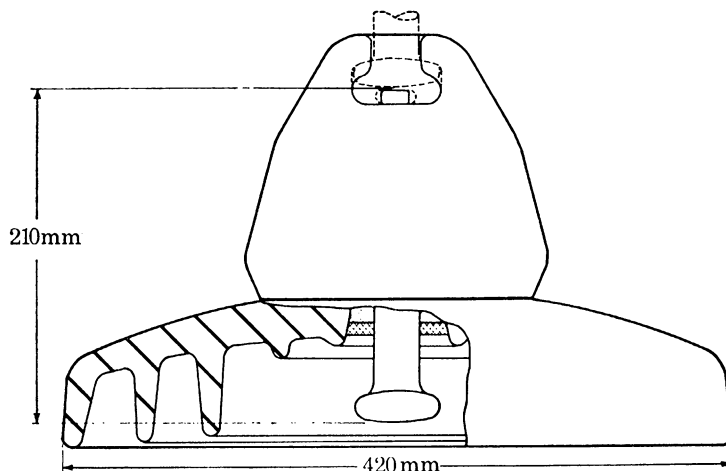


FIGURE 10. Line insulator, 380 kN u.t.s.

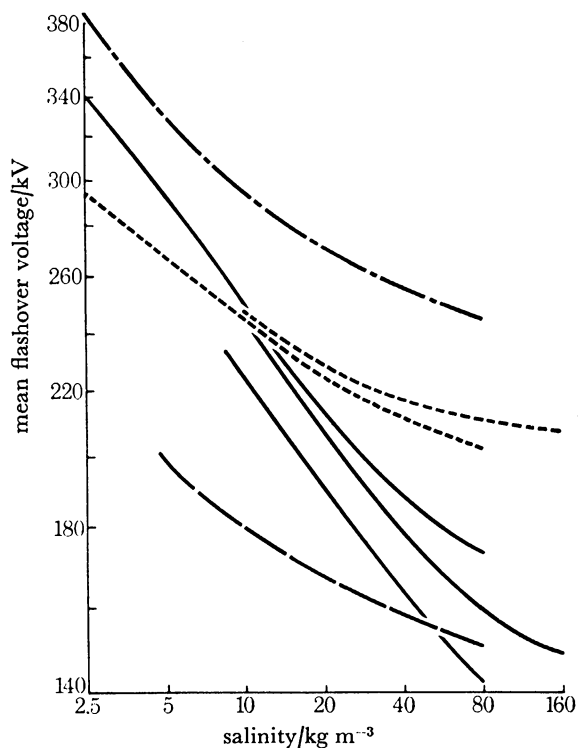


FIGURE 11. Salt fog performance of 2.94 m high barrel porcelains. — — —, plain alternate long and short; — — —, 3-skirt antifog; —, plain; — —, 2-skirt antifog.

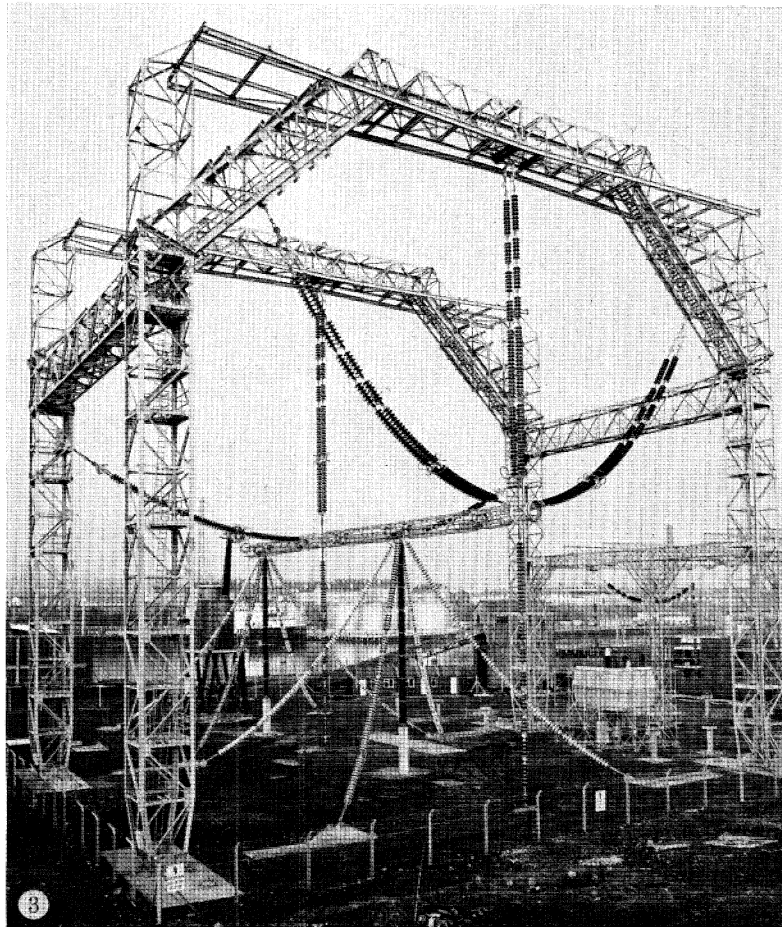
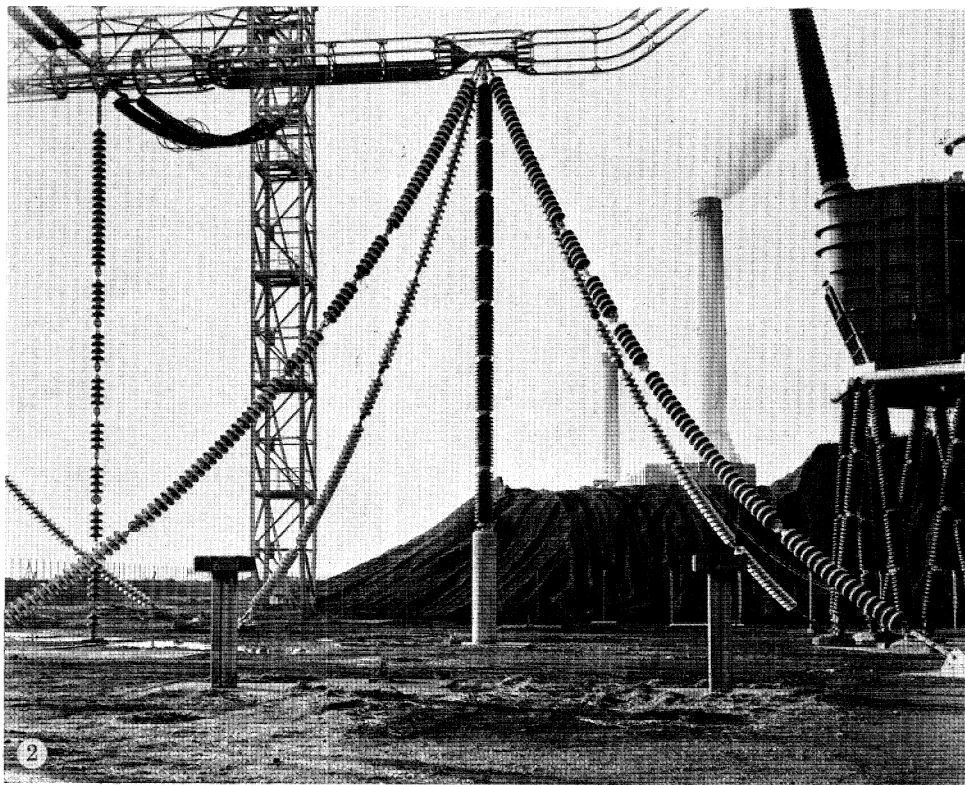


FIGURE 2. A 'maypole' post designed for 1500 kV system, 75 kN working load.
 FIGURE 3. 1500 kV insulator testing equipment at Brighton.

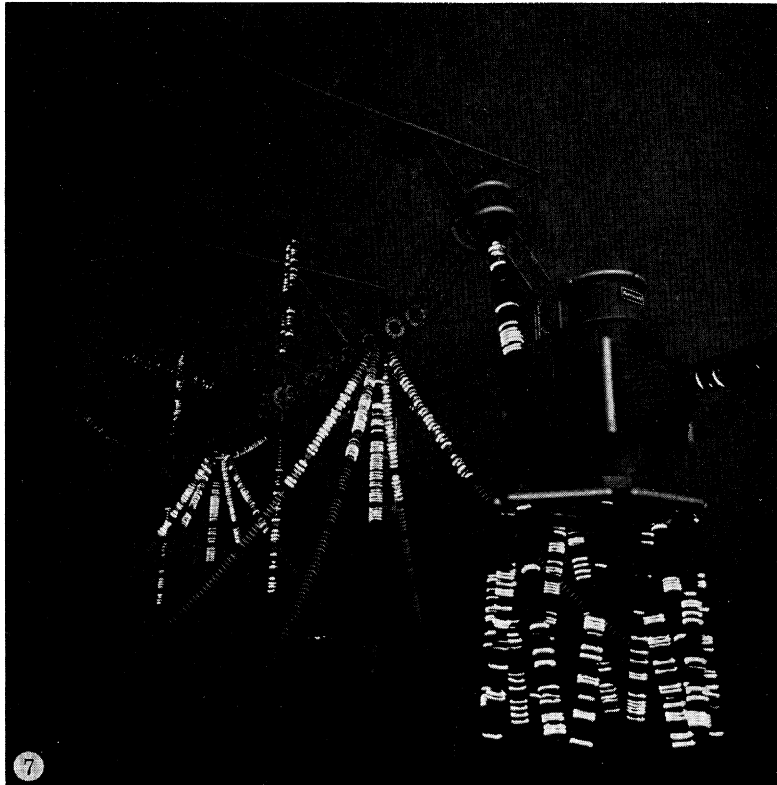
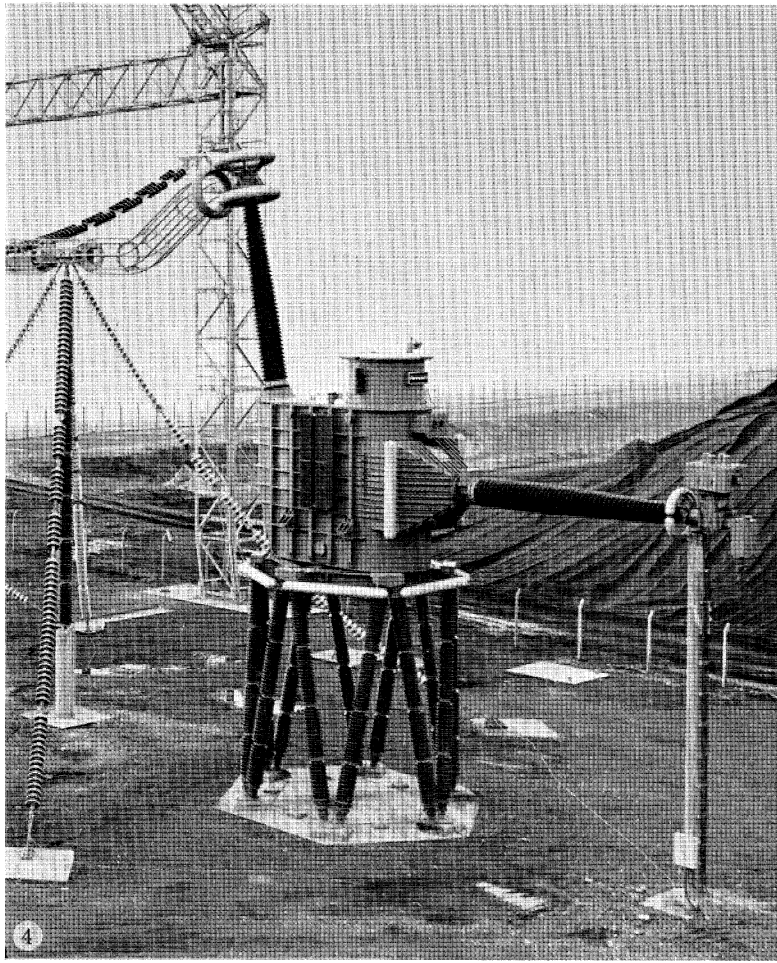


FIGURE 4. 900 kV testing transformer.

FIGURE 7. Discharges on insulators at night: voltage $1100/\sqrt{3}$ kV.

type shown in figure 10 with a leakage path/length ratio of 2.9 at a rating of 380 kN u.t.s. Similar limitations apply to porcelain rod insulators, but resin-bonded glass-fibre rods can easily be designed with ratios of leakage path to overall length of 8 or 10. Staggered shed sizes ensure that the air breakdown path is always reasonably long in relation to the leakage path in parallel with it.

For post insulators similar principles apply. Profiles in porcelain with leakage path ratios of up to 3.5:1 have been produced with alternate long and short plain sheds which give good performance especially in heavy pollution (figure 11). There is perhaps little further improvement to be made by mere change in profile on practical porcelains.

One further option which is open to line designers is to use units in assemblies which give longer insulator length in a given clearance. 'V' assemblies are obvious examples, and in addition to giving about 40 % more effective length than a single vertical string such assemblies also limit conductor swinging. Further increases in length can be obtained by extending the insulator along the line of the conductor. However, such arrangements tend to be both costly and mechanically complex.

5.2. *Reducing the deposit*

Atmospheric deposition can be reduced by aerodynamic design, but this is only practicable for vertical insulators, and it tends to be of second-order importance except for special situations. Better exposure to the cleaning effects of rain is probably more worthwhile in this climate.

Water washing is an effective method of removing the deposit, but it needs to be done so frequently where pollution builds up quickly, as on the coast, that it must be carried out without interrupting the supply. Live washing introduces a hazard to the system, when the pollution on the insulator goes into solution and flashover may occur because of cascading water bridging the gaps between the sheds. The gaps should be large, and it may prove desirable to fit special water deflecting sheds either of metal or plastic on u.h.v. posts (Ely, Lambeth & Looms 1973). Because of the large distances involved a washing system would require a high-pressure jet sweeping across the insulator, to counter possible wind deflexion, and rising slowly at the same time to remove the pollution from the bottom of the insulator before the whole surface is wetted.

5.3.1. *Grease*

The most effective ways of getting a good pollution performance are to render the pollution layer ineffective. Greasing the surface does so because particles are absorbed into the grease, and the water is forced into discrete droplets and thus does not form a continuous film over the surface. Recent developments in hydrocarbon-based grease have produced a material which can be sprayed on when molten, giving a soft layer which will not melt or slide at high ambient temperatures, but which will melt to engulf dirt if sparking occurs.

Such a layer will last for several years in a heavily polluted area before it needs changing. Nevertheless, the large areas of u.h.v. substation insulators would require such long outages for greasing that it seems unlikely that it will be widely used.

5.3.2. *Resistive glaze*

It has been known for many years that another way to render the pollution layer innocuous is to employ a 'stabilized' insulator, i.e. an insulator with a resistive glaze coating passing about 1 mA or more (Forrest 1942). The presence of this resistive glaze layer changes the pollution flashover process in a number of important ways.

There is a continuous heating of the surface, whether the wet pollution layer is continuous or not. Consequently the dry band widths are not severely limited, as they are with a normal insulator, but tend to grow much larger. During the drying process discharges can be completely suppressed even when the pollution layer conductance is between one and two orders of magnitude greater than that of the glaze (Lambeth 1971).

Resistive-glazed insulators therefore perform excellently in pollution when continuously energized. However, when energized suddenly in a cold wet state the heating effect is temporarily lacking, and if the pollution layer is sufficiently conducting to permit a discharge to occur, flashover may follow within a few cycles, just as if the insulators were unstabilized. However, since the short-term flashover voltage of a normal insulator is perhaps 30 to 100 % greater than its long-term flashover value substantial savings in leakage path can be achieved with resistive-stabilized insulators.

In fact, the main problem still encountered after many years' work on the glazes is their relatively short life. Where current flows between the glaze and the wet layer over it electrolysis takes place. Electrolytic attack can also occur at the electrodes when water is present. Prolonged small discharges can be produced also by salt concentrations. Damage from these causes can eventually erode the glaze, cause continuous sparking and destroy the insulator. The latest glaze to be developed is based on tin-oxide and is less easily damaged than materials used before.

No resistive-glazed insulator can be expected to last indefinitely, but acceptable working life may be achieved using tin-oxide glaze, provided that the glaze is thickly and uniformly applied, with bands of higher-conductivity near the electrodes, especially if the glaze/electrode junctions are protected from moisture. Best results are likely for insulators of a basically cylindrical shape, such as substation posts.

6. FUTURE PROSPECTS FOR U.H.V. INSULATOR DESIGN

To summarize the prospects for u.h.v. outdoor insulators, it seems likely that there will be developments of ultra-strong (800 kN) rod insulators with fibre-glass cores and plastic coatings, with complex long-creepage shed profiles in 'V' assemblies for overhead lines, as well as conventional antifog cap-and-pin porcelain units. Substations for the highest voltages are likely to be mainly indoors with only a few essential bushings. If not resistive-glazed such insulators will need to be either greased or washed live in heavily polluted situations, and complex washing systems with water deflectors fitted to the insulators would be justified.

The work was carried out at Central Electricity Research Laboratories and this paper is published by permission of the Central Electricity Generating Board.

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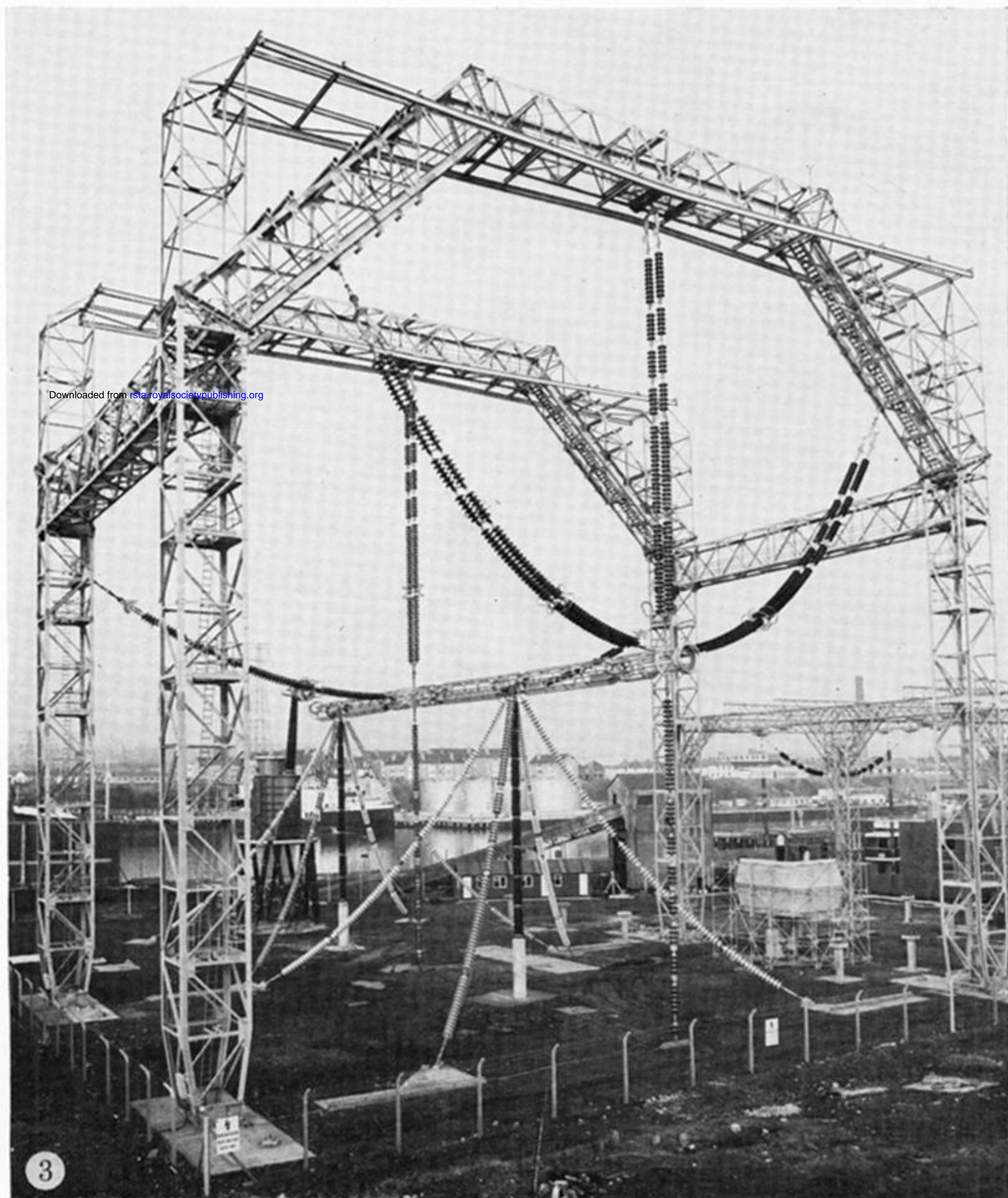
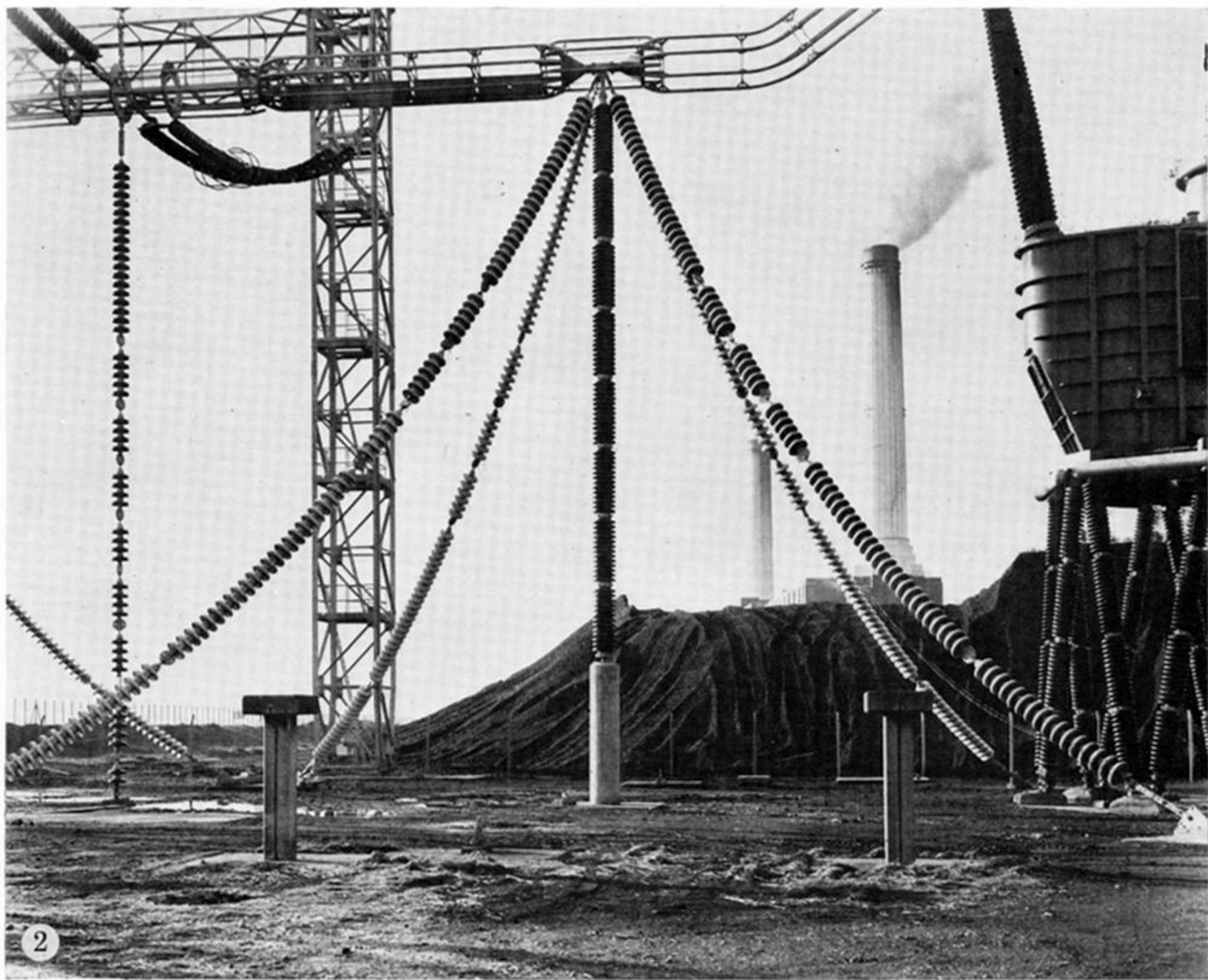


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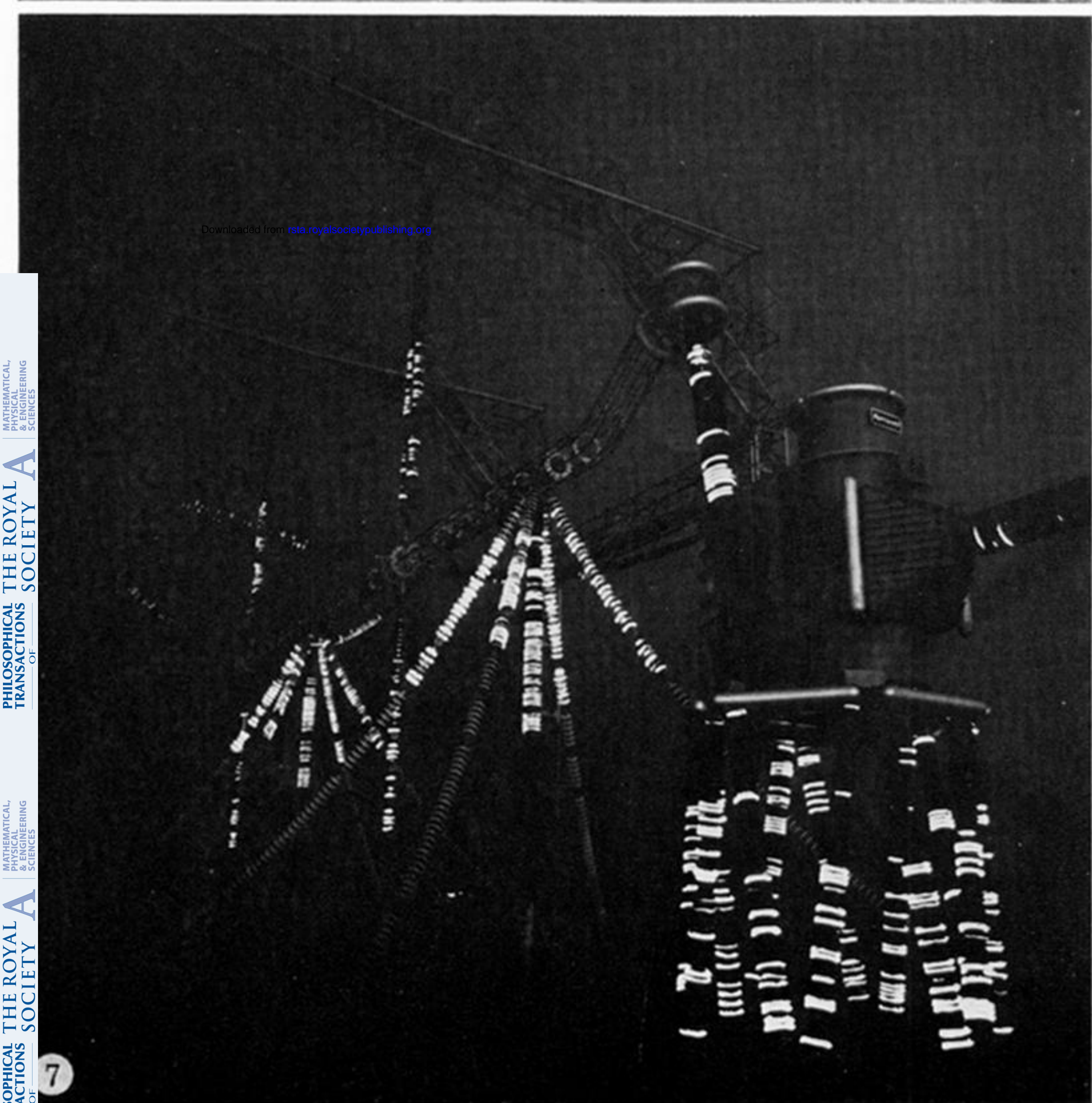
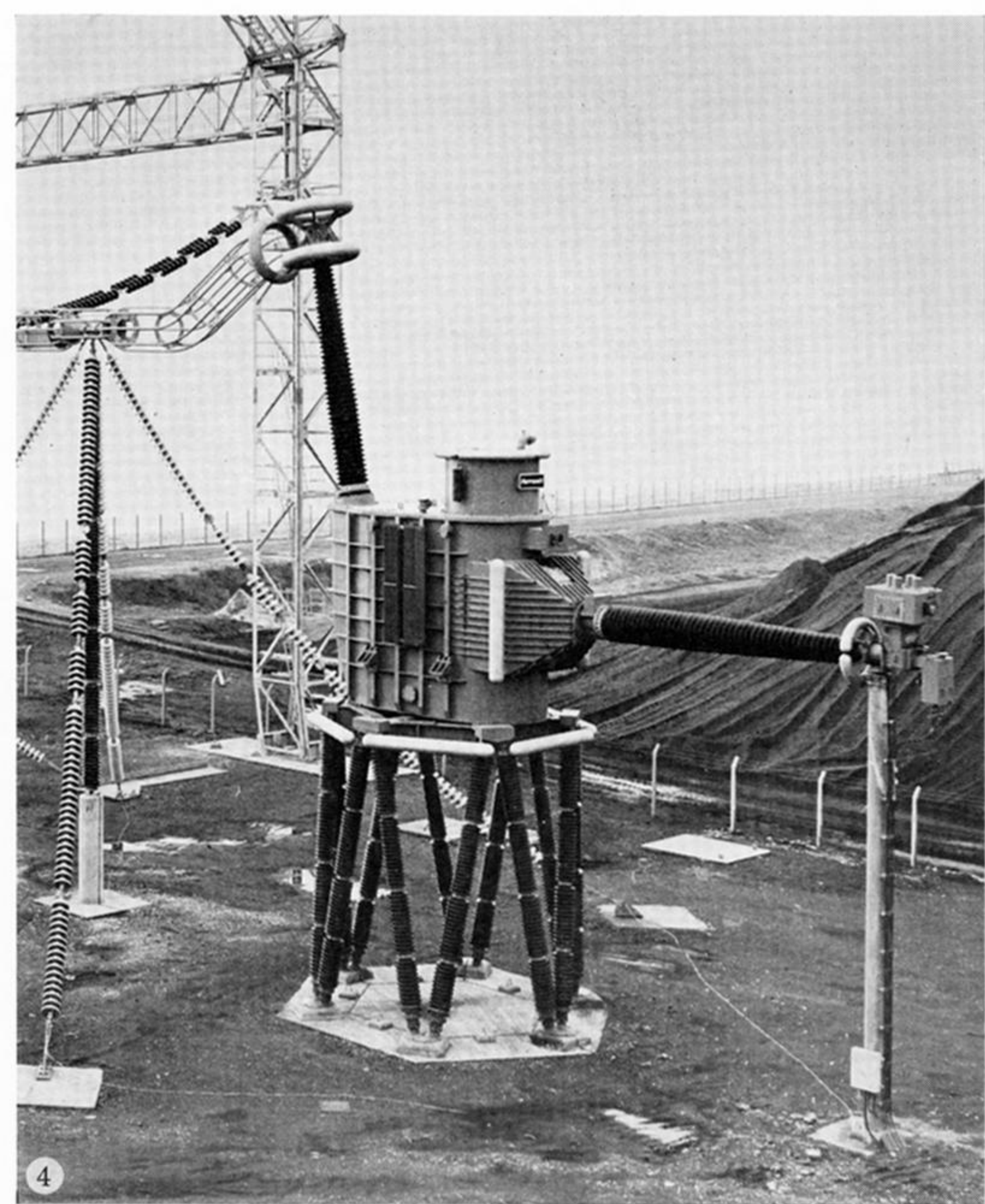


FIGURE 4. 900 kV testing transformer.

FIGURE 7. Discharges on insulators at night: voltage $1100/\sqrt{3}$ kV.