SF$_{6}$ Switchgear for Outdoor and Indoor Switching Stations

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III. SWITCHGEAR

SF_6 switchgear for outdoor and indoor switching stations

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The increasing production of electrical energy has led to an even more rapid increase in the breaking capacity of high-voltage circuit-breakers.

Based on a careful evaluation of the known interrupting principles the advantages of SF_6 as an interrupting and insulating medium are explained.

The results of investigations on SF_6 plasma properties, gas flow problems and dielectric phenomena, which have a direct bearing on the design of SF_6 interrupter units and SF_6 metalclad switchgear, are presented.

The present development situation is discussed: it covers outdoor circuit-breakers for 230 to 420 kV, metalclad substations for 110 kV and recent designs for voltages up to 1300 kV.

1. Introduction

In 1970 a total of about 5×10^{12} kW h were generated in the world. With an annual rate of increase of 7 %, which doubles the figure every 10 years, about 40×10^{12} kW h will be generated by the end of this century. Figure 1*a* shows the generation of electrical energy in several countries

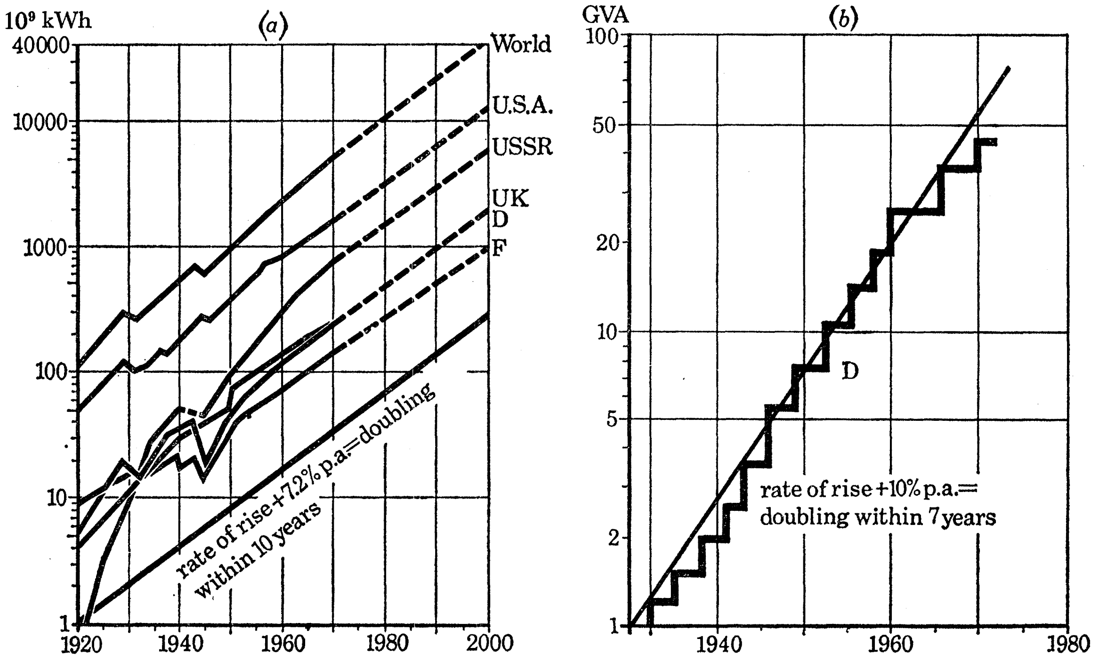

Figure 1. (*a*) Generation of electric energy in the world and in several countries. (*b*) Development of the breaking capacity of high-voltage circuit-breakers in the Federal Republic of Germany.

and in the world in general. Compared to the increase in generated power, the breaking capacities of circuit breakers show an even faster rise. In figure 1*b* the continuous line indicates a growth rate of 10% per annum. This development is essentially determined by two factors: first, the growth in generating capacity and, secondly, the increasing trend toward interconnexion of systems.

The main functions of a circuit breaker are to carry the rated current when closed, and to provide effective insulation against the operating voltage, and also against overvoltages, with its contacts either open or closed. In addition, it should be able to fulfil switching functions under all conditions of operation and fault. When a breaker interrupts heavy fault currents, which today may attain values as high as 60000 A, the temperature inside may rise up to 30000K. Circuit breakers of the latest design are capable of interrupting currents under these conditions with an arc duration of between 5 and 20 ms. The breaker, which may have been carrying its rated current for several months, is expected to operate correctly at all times.

Oil circuit breakers, minimum oil breakers, air-blast breakers, vacuum breakers and sulphur hexafluoride (SF_6) breakers are in use today (Rieder 1970). Thorough analyses of SF_6 as an insulating and arc-quenching medium, of which an account is given below, have shown the outstanding properties of this gas, which have revolutionized the design of high-voltage circuit breakers. These properties, as compared with those of other arc-quenching media, have made it possible to increase the rating of the interrupters, and to decrease the noise level. SF_6 is particularly suitable for use in metalclad switchgear which is steadily gaining prominence under the aspects of high compatibility with the environment (Boeck & Troger 1972).

2. DESIGN FEATURES AND MODE OF OPERATION OF AN SF_6 CIRCUIT BREAKER

Figure 2 shows a section through a pole of a modern SF_6 puffer-type breaker with two interrupter units for an operating voltage of 245 kV and a breaking capacity of 15 GVA. The 420 kV switchgear uses four breaking units with a breaking capacity of 35 GVA. The essential parts of the breaker are a hydraulic drive system, an operating linkage and modular size interrupter units of an extremely simple and rigid design.

Figure 3 illustrates the mode of operation of a puffer-type breaker. The drawings show the contacts in the closed position, opening of the contacts with the gas being initially compressed, the instant of arc extinction with the hot gases flowing through the hollow contacts, and the fully open position. Among the known puffer-type breakers this design has the following outstanding properties:

A relatively small contact clearance is used by taking full advantage of the high dielectric strength of the SF_6 gas. Together with a short contact travel from contact separation to the extinguishing position this results in a small arc energy, high extinguishing ability and short interrupting time. A wide clearance between the arc and the insulation material, the transport of plasma and arcing products to regions with zero or low dielectric stress and a contact clearance not bridged by insulation material make use of the full dielectric properties of the SF_6 gas during and after arc extinction.

These SF_6 breakers create no environmental problems: they are hermetically sealed so that no gas is emitted, and the noise level is therefore very low.

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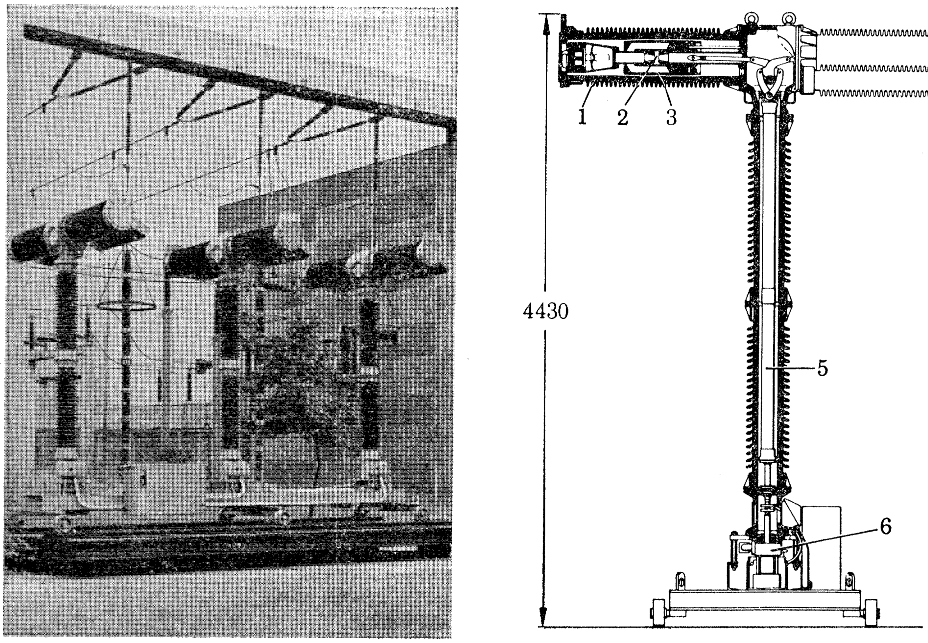

FIGURE 2. 245 kV circuit-breaker, 15 GVA. Pole assembly of SF_6 puffer-type breaker. (1) Interrupter unit; (2) double-flow contact system; (3) blast piston with moving contact; (4) grading capacitor; (5) insulating rod; (6) hydraulic drive system.

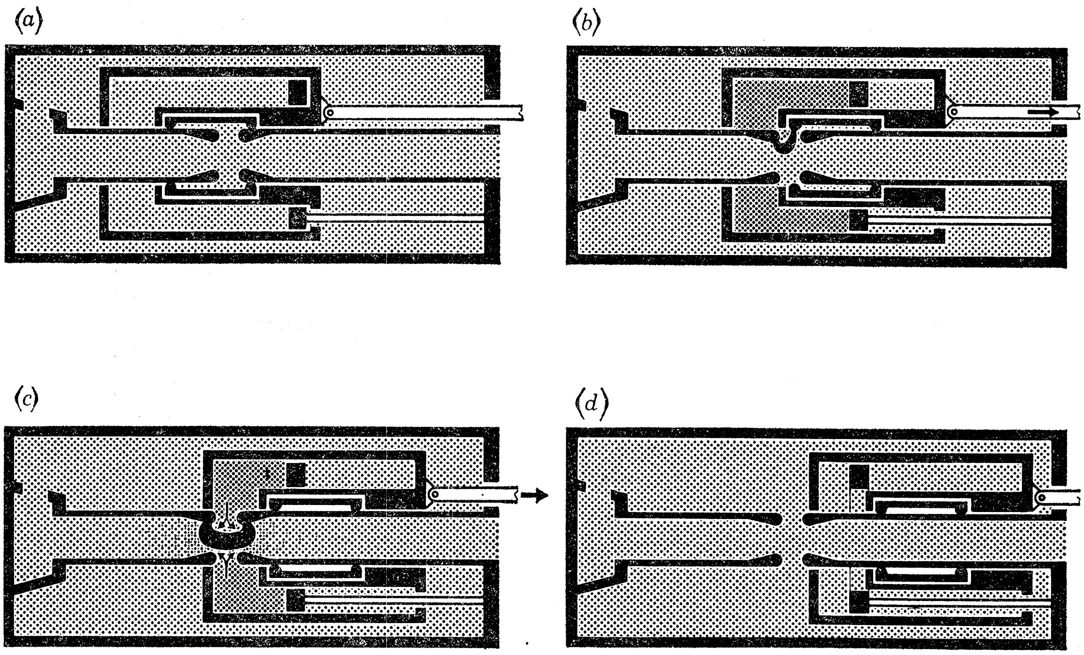

FIGURE 3. Operation of a SF_6 puffer-type circuit breaker. Four different interrupting positions are shown. (*a*) 'Closed': equal pressure conditions in the interrupter. (*b*) Contacts just opened: gas in the puffer chamber being compressed by the moving cylinder and fixed piston. (*c*) Contacts at breaking distance: the compressed SF_6 flows through the nozzles, cools and interrupts the arc. (*d*) 'Open': equal pressure conditions in the interrupter.

3. Basic features of the SF_6 breaker design

SF_6 is about five times heavier than air. It is chemically very stable, odourless, inert and non-toxic.

The gas has a high dielectric strength and outstanding arc-quenching characteristics. It has thus been possible to increase the rating of switchgear units and to drastically reduce the size of switchgear installations.

In SF_6, the arc voltage remains low until immediately before current zero so that the arc energy does not attain a high value. Moreover, the arc time constant for SF_6 is also very low. Furthermore, SF_6 and its decomposition products are electronegative, permitting electron capture at relatively high temperatures. Thus the dielectric strength rises rapidly and enables the breaker to withstand the recovery voltage even under extreme switching conditions.

3.1. *Dielectric properties of* SF_6

Under usual test or field conditions, the dielectric strength of SF_6 in an almost homogeneous field and at atmospheric pressure is about two and a half times that of air. At a pressure of 300 kPa, the dielectric strength of SF_6 roughly equals that of insulating oil and also that of air compressed at 1000 kPa (Oppermann 1972).

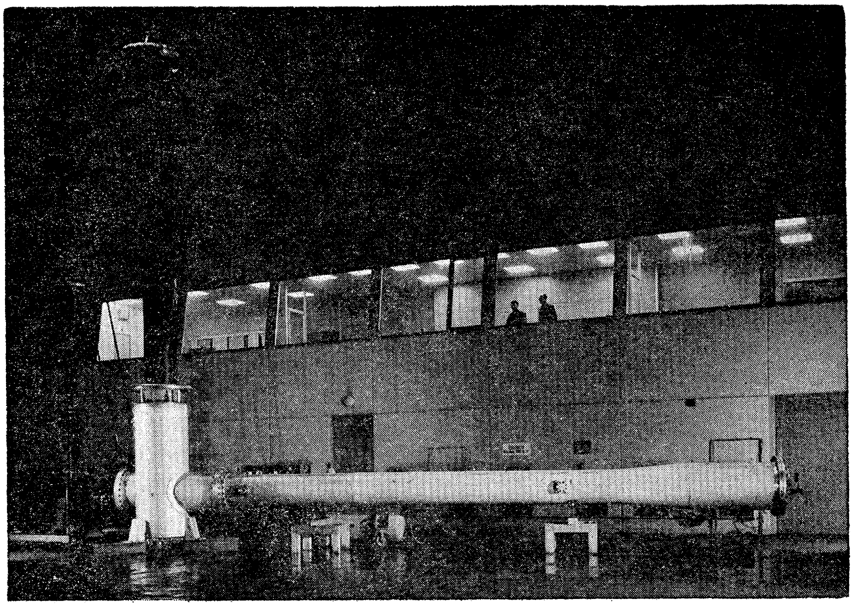

Figure 4. Test arrangement, compressed SF_6-gas insulation, air-SF_6 bushing and SF_6 test tank for 765 kV equipment.

In order to develop the optimum shape and arrangement of the component parts the electric fields have been calculated, thus effectively backing up the experimental work. Where digital computers are available, this also applies to complicated fields and component parts of intricate shape (Knörrich & Koller 1970). With such carefully designed parts the insulation is free of internal discharges up to values that are well above the operating voltage.

However, as regards the practical use of SF_6, allowance must be made for additional influences. Examples are surface conditions and pollution effects, as well as a volume effect which is inversely proportional to the dimensions. However, these problems can be eliminated by selecting the appropriate material and configuration of the component parts.

Figure 4 shows an arrangement by means of which such tests with compressed SF_6 gas were carried out at power-frequency voltages up to 850 kV and lightning impulse voltages up to 1800 kV.

The test voltage was applied to the horizontal high-pressure SF_6 tank via the vertically arranged air-to-SF_6 bushing. The 6 m insulation length required in air is much greater than the clearance in the gas tank with diameters between 600 and 800 mm. Various electrode configurations and insulators have been installed in this tank and examined under all the pertinent conditions.

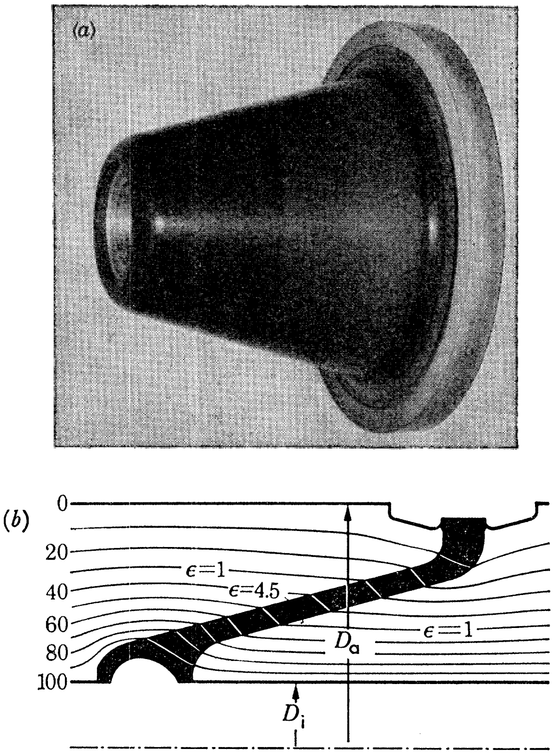

FIGURE 5. Supporting insulator for compressed SF_6-gas insulation: (a) supporting insulator; (b) potential distribution.

Figure 5 shows as an example a 765 kV insulator for coaxial insulation arrangements together with the potential distribution graph as calculated by a computer. The considerably reduced dimensions for compressed SF_6 gas insulation can best be compared by means of the following example.

For an insulator with an overall height of 160 mm, the impulse and power-frequency withstand voltages are shown in figure 6*a* as a function of the SF_6 pressure. At a pressure of 350 kPa the withstand voltages are almost equal those for outdoor post-insulators measuring 2100 mm (figure 6*b*). Not only the flashover distance, but also the creepage length can be considerably reduced in SF_6, because only outdoor insulators must be designed for the anticipated degree of pollution. Thus the mean electrical field gradient of 2 to 5 kV/cm for outdoor post insulators increases to above 50 kV/cm under compressed SF_6.

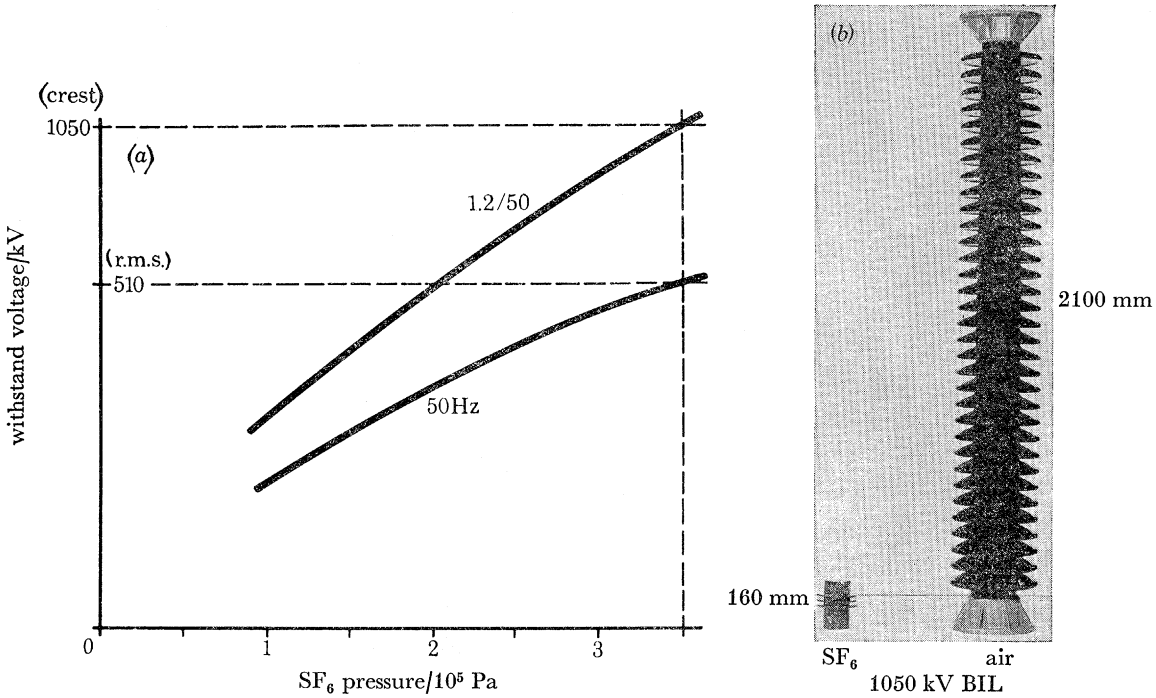

FIGURE 6. (*a*) Insulator in SF$_6$: impulse and a.c.-withstand voltages. (*b*) Comparison of 245 kV insulators in SF$_6$ and air, 1050 kV BIL.

3.2. *Analysis of SF$_6$ arc characteristics*

The understanding of the insulating and arc quenching properties of SF$_6$ presumes the knowledge of its physical qualities up to a temperature of 30 000 K, e.g. the gas and particle density, electrical conductivity, thermal conductivity, specific heat and speed of sound. These quantities had been determined by means of spectroscopic analyses (Motschmann 1966, 1967, 1968; Frie 1967). These methods can also be used for the investigation of a.c. arcs (Hertz, Motschmann & Wittel 1971). Thus it was possible to determine the temperature distribution and arc diameter as a function of time.

Figure 7 shows two examples: (*a*) the temperature curve under conditions of decreasing current, and (*b*) the temperature decay of an abruptly interrupted experimental arc of 200 A below. Similar measurements, together with high-speed pictures taken of breaker arcs and the corresponding electrical values, helped to further explain the arc-extinction process (Hertz 1970).

Figure 8 shows a typical series of high-speed photographs taken of an SF$_6$ arc burning in a twin-nozzle arrangement. The peculiar pattern of the frames results from the recording method, where the image of the arc is decomposed into small stripes by means of glass fibre bundles, recorded with a rotating drum camera, and again recomposed optically (Hertz 1969). The time resolution is very high, up to 500 000 frames/s. It can be seen, however, that starting at the left-hand nozzle, a brightly illuminated area moves into the space between the contacts. This area can be identified as a jet of metal vapour emitted from the electrode. The bottom part of the figure shows a twin-trace rotating drum camera picture of a cross-section perpendicular to the axis – in the lower trace through a monochromator for filtering out the 515.3 nm copper spectral line and in the upper trace the normal picture in integral light. Such bursts of metal vapour

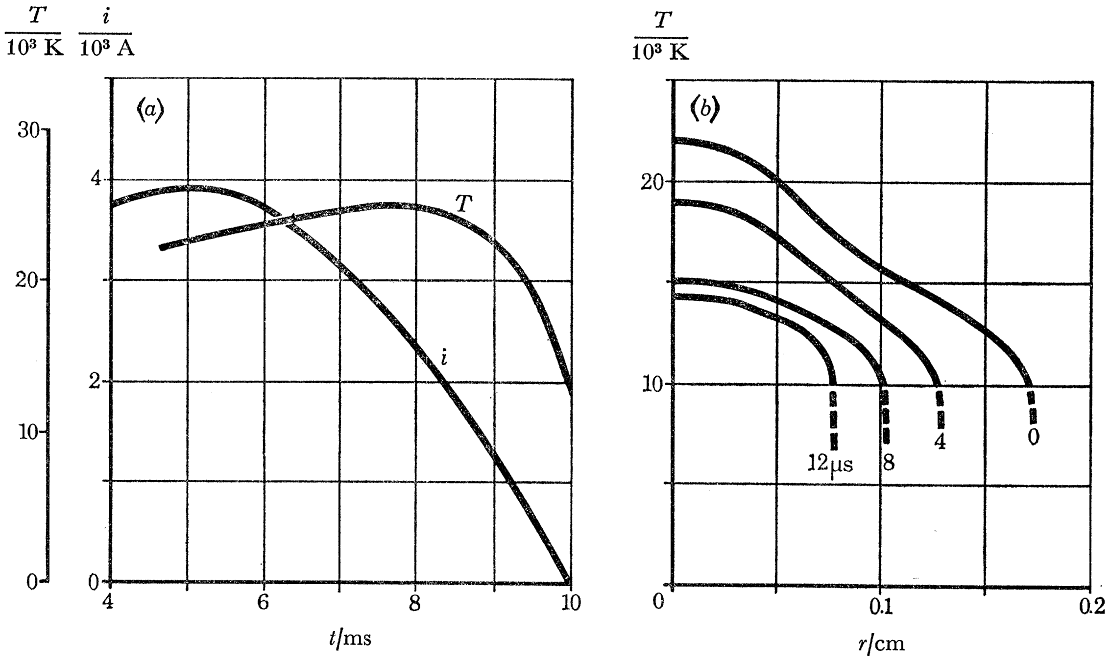

FIGURE 7. Investigation of the temperature of non-steady arcs by line-intensity measurements. (*a*) Current and temperature in the axis of an a.c. SF_6 arc. Flow at sonic velocity; pressure 3×10^5 Pa. (*b*) Collapse of the temperature profile $T(r)$ of an abruptly interrupted SF_6 arc (200 A). The arc was observed at the nozzle exit of a model arrangement.

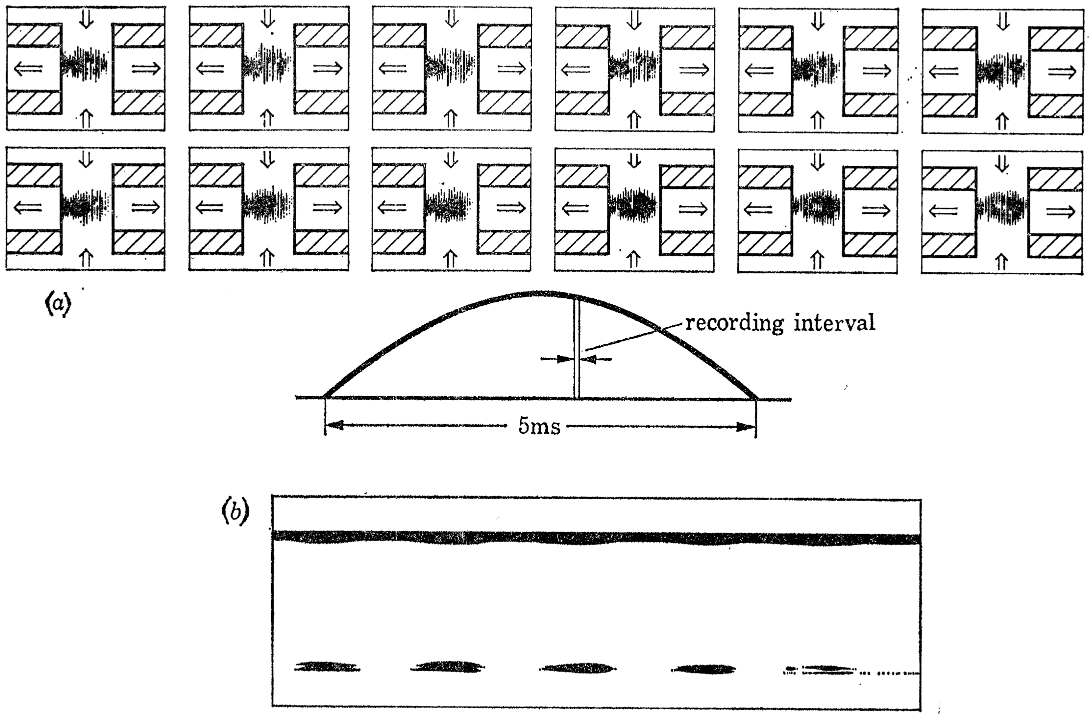

FIGURE 8. High-speed framing pictures of an a.c. arc in flowing SF_6. (*a*) High-speed (5×10^5 frames/s) light fibre camera pictures of a 100 Hz, 1000 A arc in flowing SF_6. Double nozzle arrangement. (*b*) Presence of metal (Cu)-vapour jets proved by means of a twin-trace rotating drum camera picture of a cross-section perpendicular to the axis: upper trace, integrated light; lower trace, light of the spectral line 515.3 nm shows periodic Cu vapour bursts.

have an adverse effect on arc extinction in circuit breakers. They can be avoided by a suitable design of the nozzle arrangement.

The reasons for the superior performance of SF_6 as an arc-quenching medium, which was revealed by the above investigations, are as follows (Hertz 1969, 1970):

(1) SF_6 has a low dissociation temperature ($\approx$ 2000 K), which permits arcs to be cooled to this relatively low temperature not only by normal thermal conduction but also – even without any flow or turbulence effects – by the transport of reaction energy. Air, on the other hand, has a dissociation temperature of 7000 K and cooling by the transport of reaction energy already ceases at this level so that further cooling is slowed down accordingly.

(2) SF_6 and almost all its decomposition products are electronegative and have an affinity for electrons. During cooling the dielectric strength of the break therefore rises more rapidly than with air, for example.

3.3. *Flow analysis*

Arc extinction very much depends on cooling by the gas flow and on the particular flow conditions (Kopplin, Rolff & Zückler 1971). For instance, micro-turbulence effects increase thermal conduction. However, bigger vortices, which might be found due to centrifugal forces, should always be avoided because they reduce the gas pressure and the dielectric strength of the break. The flow conditions in the interrupters and their effect on arc extinction have therefore been thoroughly investigated by employing, for example, the schlieren method, pressure and velocity

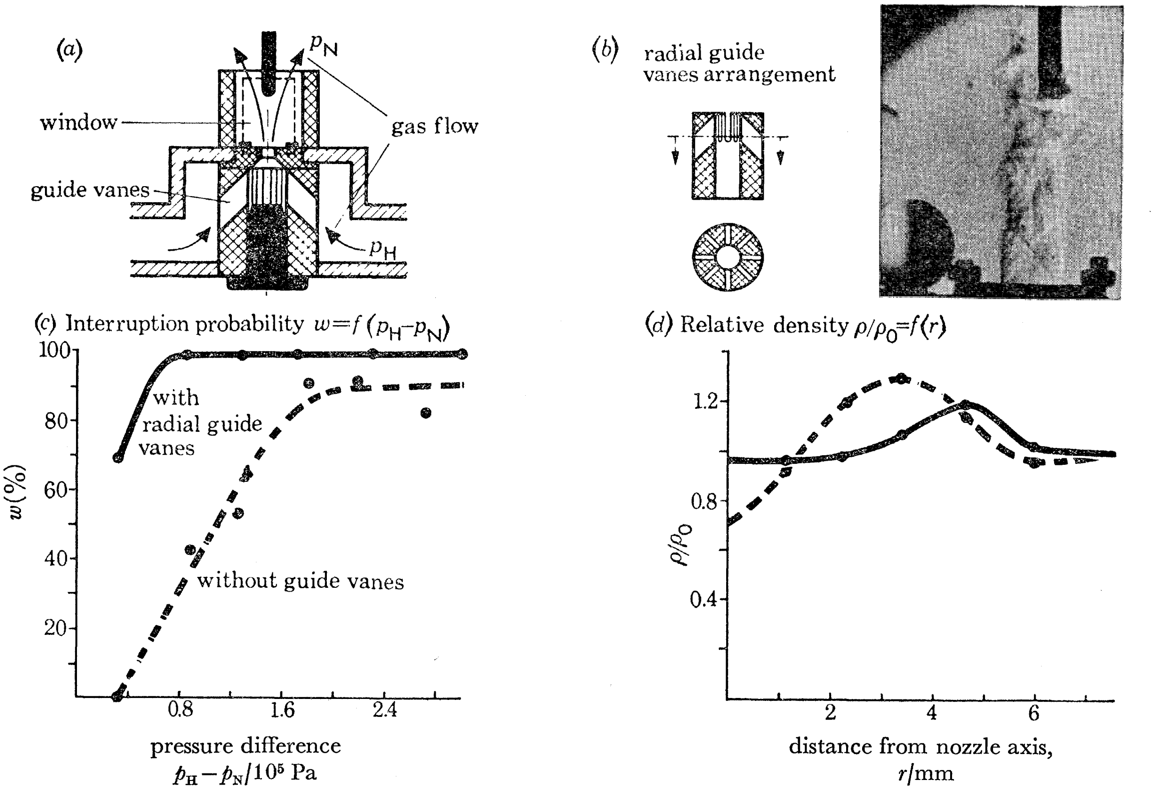

FIGURE 9. Breaker flow investigations. A model breaker (*a*) with replaceable guide vanes generating different flow conditions was investigated by the schlieren method (*b*) and interruption tests: breaking probability depending on the pressure difference at the nozzle (*c*). The evaluation of the schlieren pictures enables the determination of the radial density distribution in the nozzle (*d*).

measurements (Zückler 1967), holographic methods and experiments carried out on interrupter models.

Figure 9 shows an example of breaker flow investigations. The performance of an experimental breaker with replaceable guide vanes for producing various flow conditions was examined by the schlieren method and by breaking test operations. Schlieren pictures permit the determination of the radial density distribution which is caused by the differing flow conditions. They also explain the higher density in the nozzle axis and the high dielectric strength and arc-quenching capability with radial guide vanes which suppress vortices in the nozzle axis.

Examples of flow model investigations are shown in figure 10.

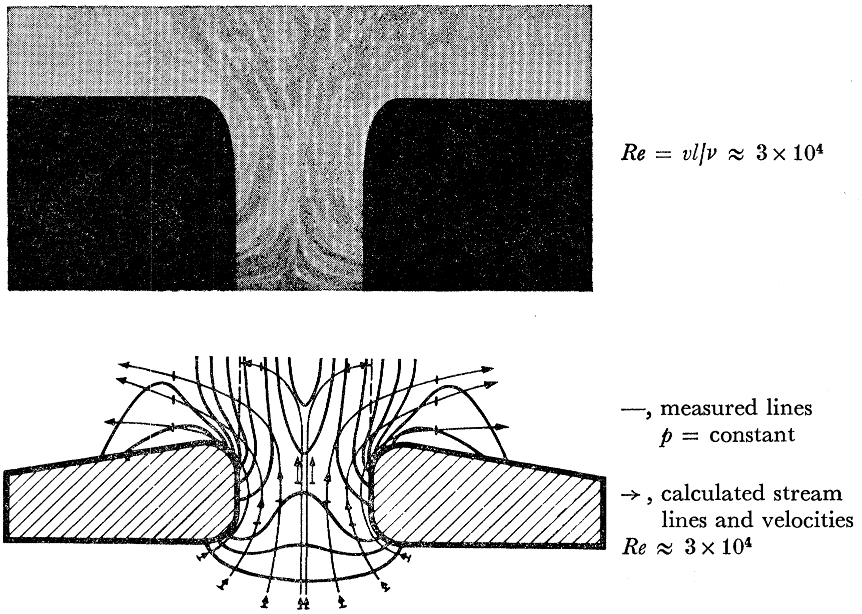

Figure 10. Flow-model investigations. The flow through nozzles can be investigated by model experiments. The pictures show the investigation of the same twin-nozzle by means of different methods – above: water flow; below: gas flow.

At the top of the picture, the flow pattern for a twin nozzle arrangement has been made visible by means of a water flow. The flow lines appear on the photograph as traces of small reflecting particles which are carried along and which are illuminated by a narrow band of light. In the lower half of the picture, the gas flow pattern in the same nozzle is illustrated as it appears in theory after taking readings of the pressure distribution by means of probes.

As the Reynolds numbers are very similar, the flow patterns are the same.

Experiments of this type and their theoretical evaluation provided the basis for an interrupter design which takes into account the knowledge of gas flow effects and dielectric properties.

4. Practical experience

When SF_6 is decomposed by an arc, only a small amount of fluorine is lost by reacting with metal vapours. This results in the formation of decomposition products. Appropriate and adequately large filters are used which absorb the decomposition products as well as moisture. The SF_6 system is effectively sealed off from the surrounding so that a nearly ideal SF_6 atmosphere exists, as regards corrosion and isolation. For additional safety, insulation materials have been selected with optimum performance under the worst possible conditions of moisture penetration and decomposition rates.

In some research institutes and industrial laboratories recourse can be made to more than fifteen years' experience with SF_6 and its application. Not a single case is known in which SF_6 proved detrimental to health, not even in the high-power experimental stations where switchgear units are sometimes tested at a high frequency of operations and at the highest breaking currents up to their limiting capacity (Handke, Mathing & Richter 1972; Pflaum 1971).

5. SF_6 SWITCHGEAR SUPPLIED

In addition to the uprating of switchgear units, there has been a breakthrough in the design of space saving switchgear installations in recent years: SF_6 circuit breakers have been built for more than 10 years and metalclad switchgear with SF_6 insulation since 1967. At the end of 1972, roughly 500 circuit breakers for 125 to 420 kV and 50 metalclad switchgear installations comprising more than 220 units for 125 to 170 kV were manufactured and supplied by Siemens.

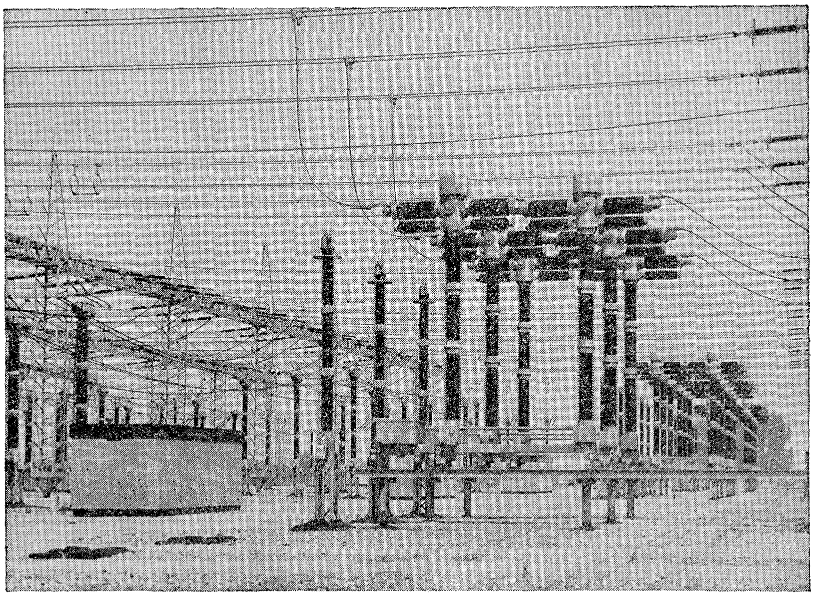

Figure 11. Conventional switchgear with SF_6 circuit-breakers for 420 kV.

Figure 11 shows a conventional outdoor substation with SF_6 circuit breakers for 420 kV with four breaking units and figure 12 an SF_6-insulated metalclad substation for 125 kV with one breaking unit and 5 GVA.

6. RECENT RESULTS AND PROSPECTS OF FUTURE DEVELOPMENT

On the basis of the results obtained so far, and in view of the fact that future development looks promising, a paper dealing with switchgear for a maximum operating voltage of 1300 kV has been drafted for CIGRE (Müller 1971; Boeck & Troger 1972).

In figure 13 a comparison is made between SF_6-insulated switchgear and a conventional

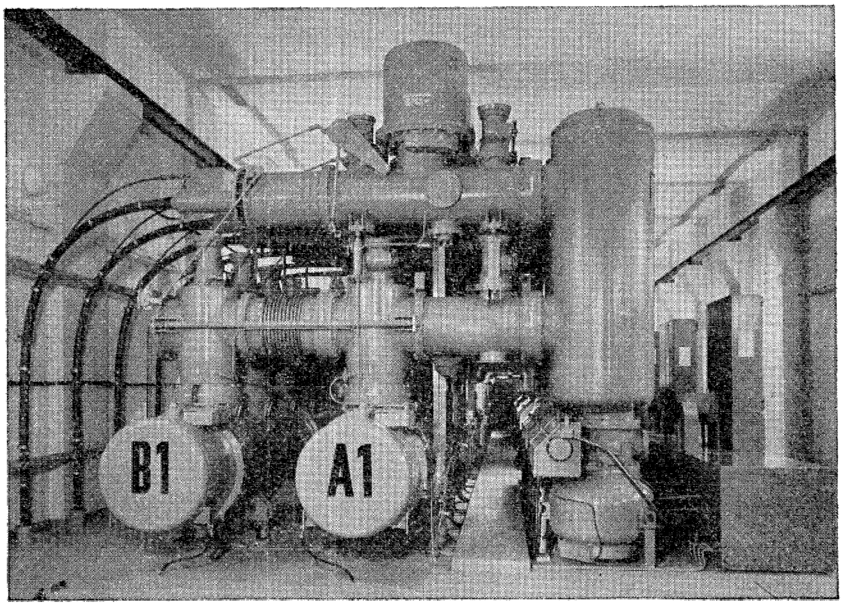

Figure 12. SF_6-insulated switchgear for 125 kV.

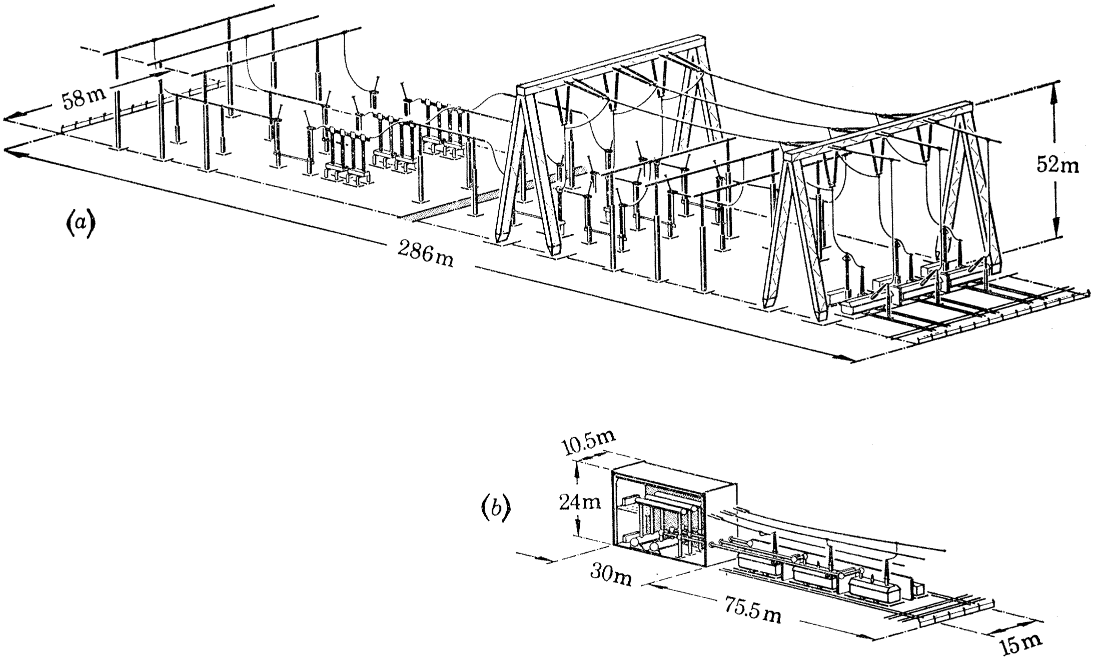

Figure 13. 1300 kV switchgear, transformer feeder 3000 MVA, single busbar with auxiliary bus. (*a*) Conventional switchgear: area requirement 16700 m^2, volume 887800 m^3; (*b*) SF_6 insulated switchgear: area requirement 1500 m^2, volume 36000 m^3.

design for 1300 kV. SF_6-insulated tubular bus systems for power transmission will moreover be used to an increasing degree. The first bus system of this type ordered in Europe, will be installed by Schluchseewerke-A.G. of Germany in 1974. The project consists of two parallel 420 kV bus systems in an underground pumped-storage station. The total length of single phase tubular bus is 4000 m.

Metalclad substations and transmission lines will make it possible to apply still higher voltages and currents even in the power centres of large cities and industrial areas. The results already obtained, indicate that the problems which had been existing for many applications of very high voltage levels can now be solved. Also the growing interest in preserving our environment, which in many cases has still remained unspoilt, will add impetus to the implementation of the new designs (Olsen & Rimpp 1971; Troger *et al.* 1972).

Thus the new technique of SF_6 switchgear, which I have tried to describe very briefly, will represent an essential contribution for solving the problems of energy transport and distribution of our time.

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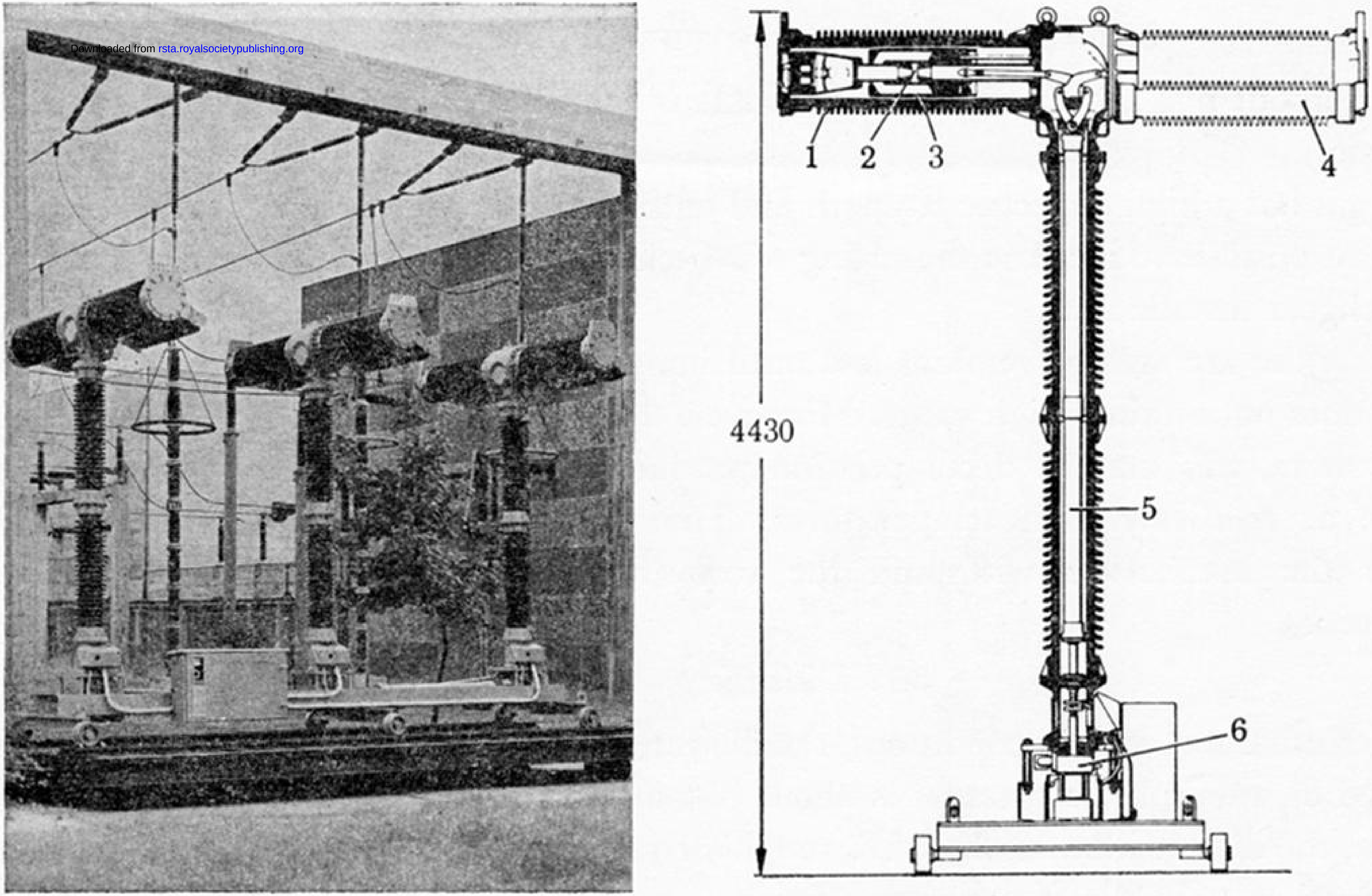

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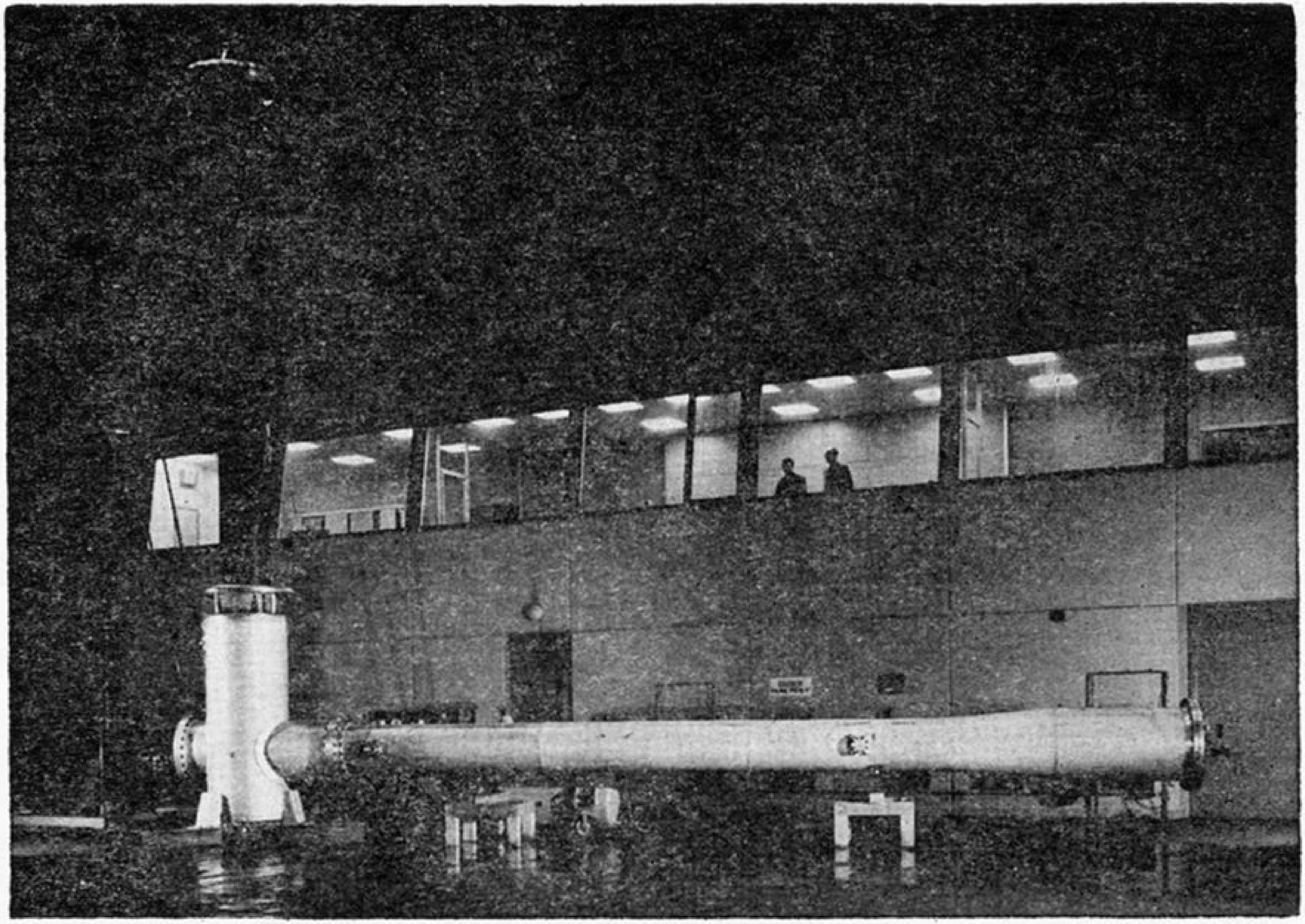

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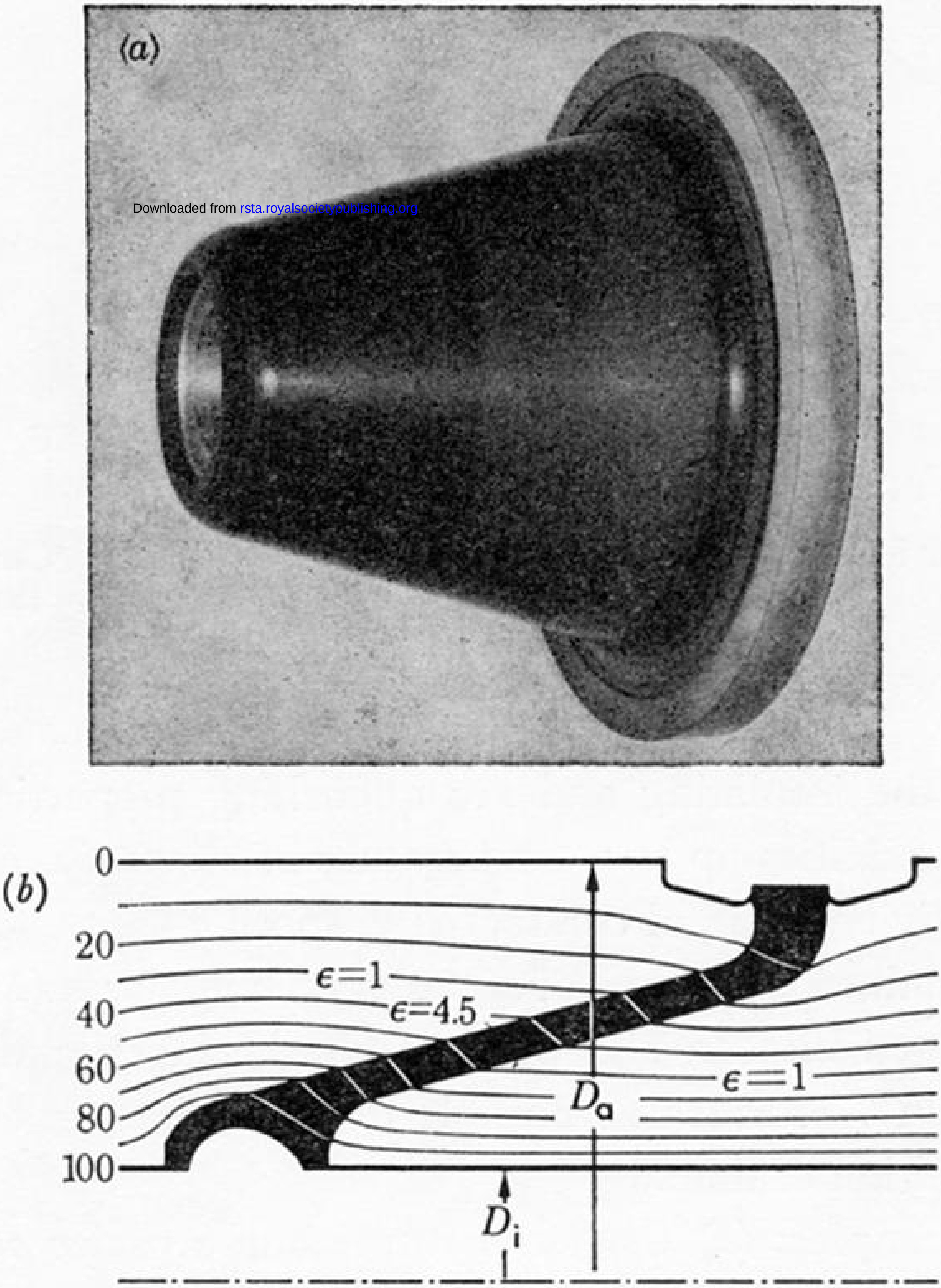

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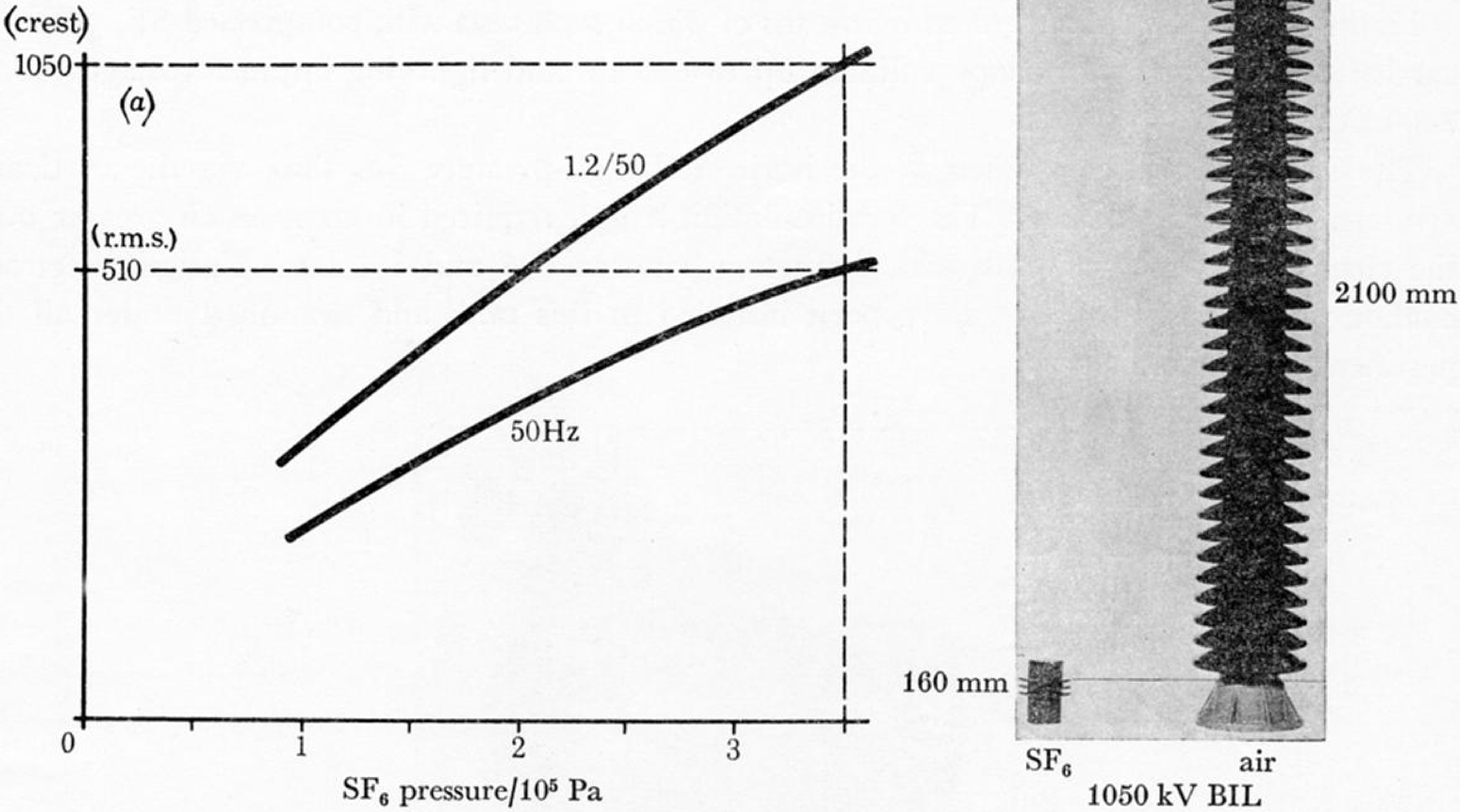
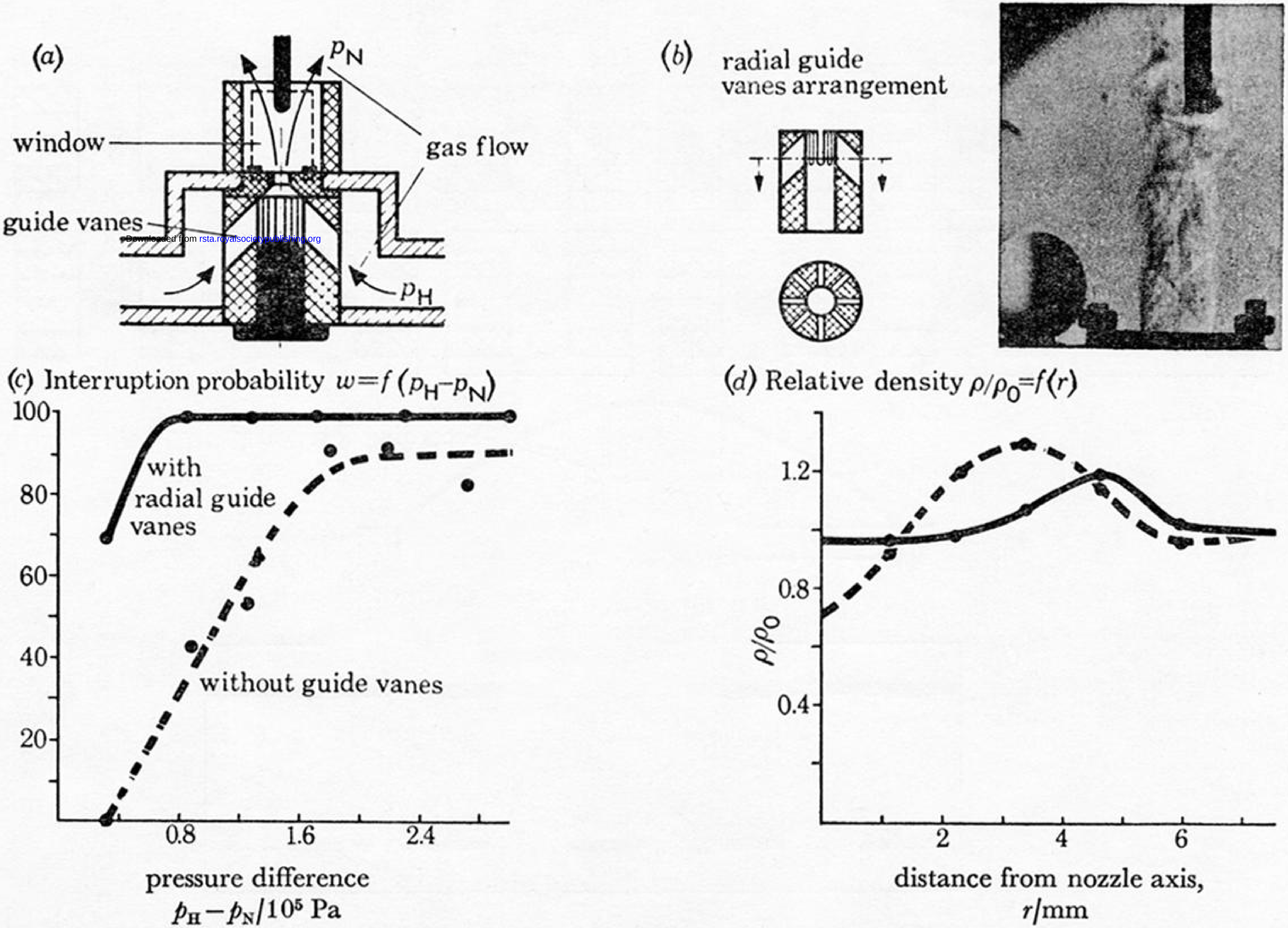


FIGURE 6. (*a*) Insulator in SF$_6$: impulse and a.c.-withstand voltages. (*b*) Comparison of 245 kV insulators in SF$_6$ and air, 1050 kV BIL.



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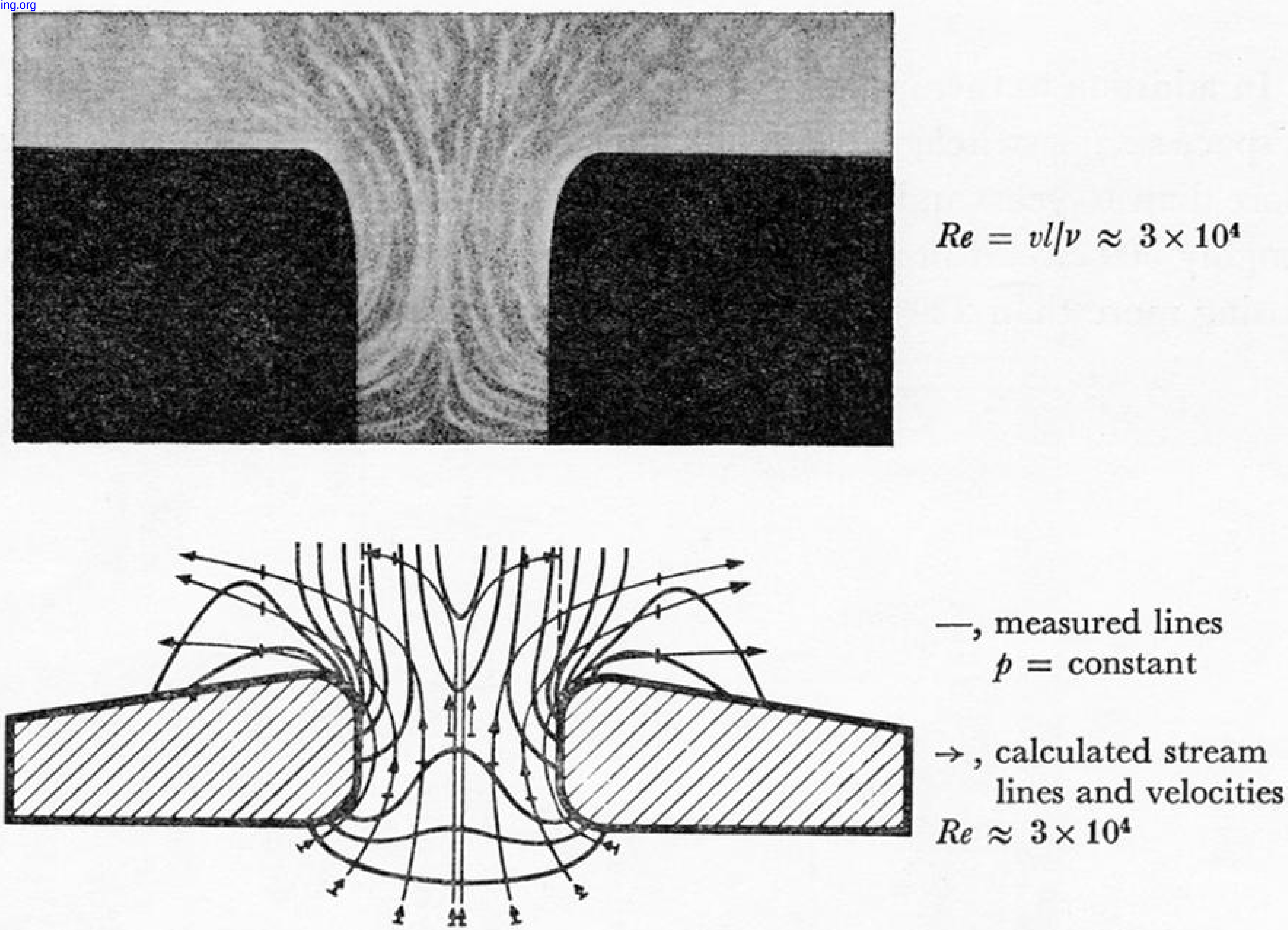

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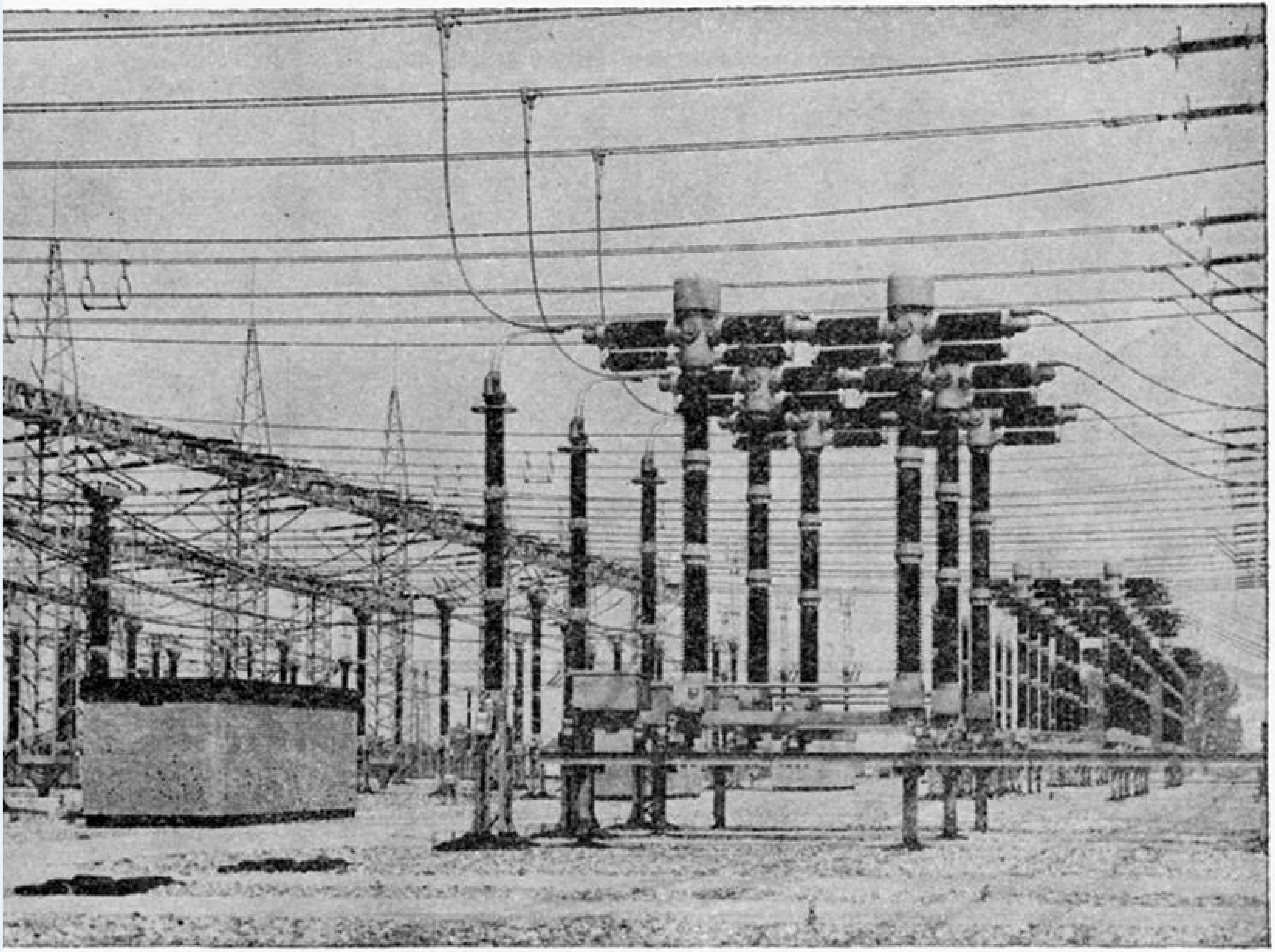

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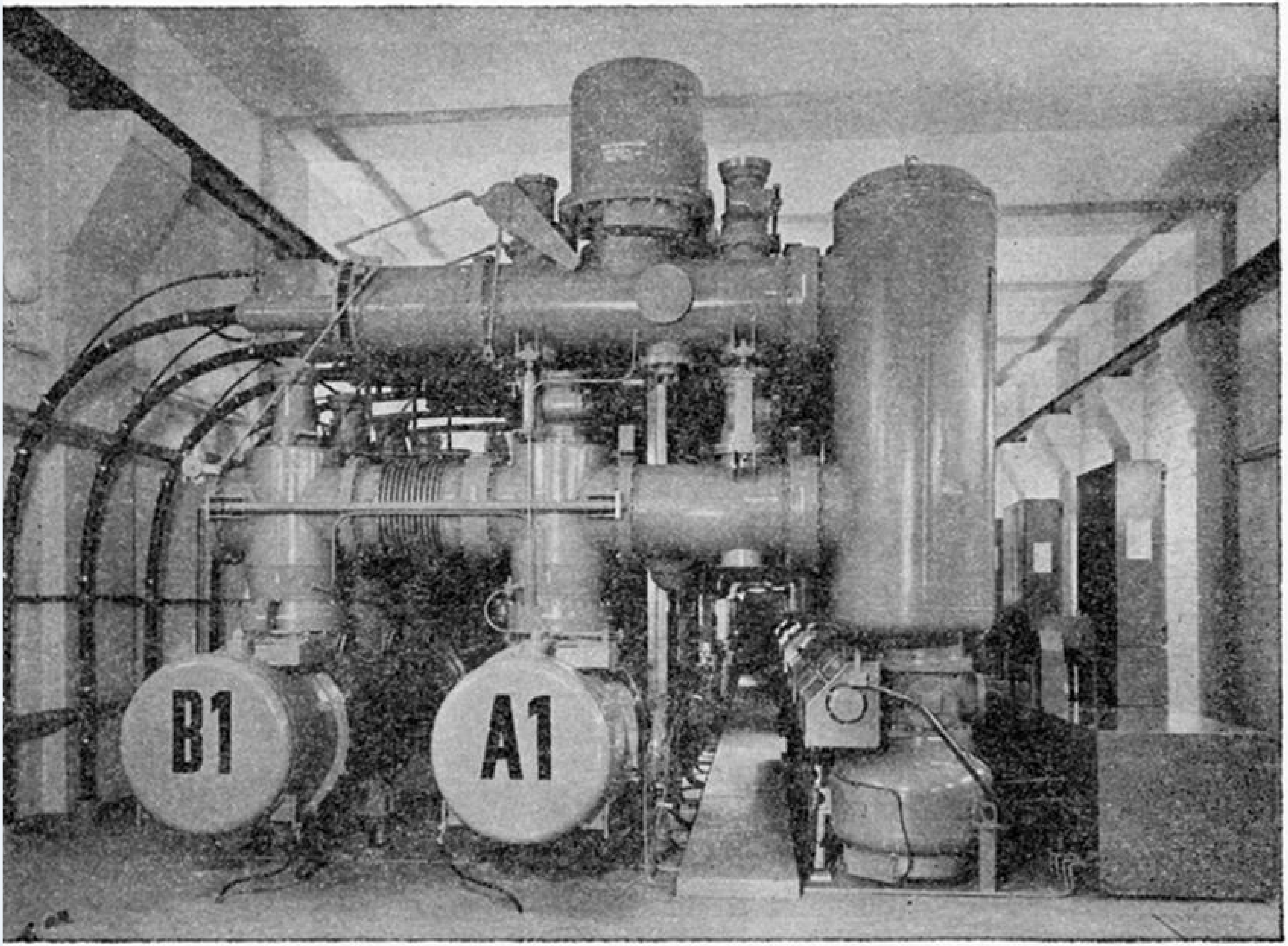

FIGURE 12. SF_6-insulated switchgear for 125 kV.