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# A Review of the Development of the Vacuum Interrupter

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# A review of the development of the vacuum interrupter

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[Plates 12 and 13]

The basic physical processes occurring in vacuum arcs are described, and it is shown that reasonable agreement exists between theory and practice as to the interrupting ability to be expected of vacuum interrupters.

Designs of interrupters and contacts for both low and high current applications are reviewed, together with the properties of materials required.

The advantages and disadvantages of this method of circuit interruption in power systems are discussed, together with the present applications of these interrupters.

Finally, an attempt is made to predict the pattern of future development of interrupters and of their applications.

## 1. Reasons for the vacuum interrupters

The vacuum interrupter has fascinated the circuit breaker designer for many years, primarily because of its manifest advantages, which are:

(*a*) It is entirely self-contained, needs no supplies of gases or liquids, and emits no flame or smoke.

(*b*) It requires no maintenance, and in most applications, its life will be as long as that of the circuit breaker in which it is applied.

(*c*) It may be used in any orientation.

(*d*) It is not flammable.

(*e*) It has a very high commutating ability and needs no low ohmic resistors or capacitors to interrupt short-line faults.

(*f*) It requires relatively small mechanical energy to operate it.

(*g*) It is silent in operation.

These advantages have undoubtedly been the driving force which has spurred the development of vacuum interrupters forward.

The main disadvantage of the vacuum interrupter was that its cost has been somewhat higher than that of conventional interrupters, but present evidence is that not only can this be reduced, but that consequential savings in the rest of the switchgear will result from the use of vacuum interrupters.

Figure 1 shows a typical vacuum interrupter in schematic form. It consists of an evacuated envelope which contains a pair of contacts (one of which can be moved), surrounded by a shield to condense metal vapour, which would otherwise coat the internal surface of the insulating envelope.

The envelope, shown in the figure as glass-ceramic, may be made of any suitable material, such as glass, porcelain or alumina, generally as used in electronic tubes. The contacts are made of one of a number of highly specialized alloys, and shaped to control the arcing process. The stem of the moving contact is sealed with a metal bellows (usually stainless steel), so that a pressure of $10^{-4}$ to $10^{-5}$ Pa ($10^{-6}$ to $10^{-7}$ Torr) may be maintained for many tens of years. This is achieved by rigorous degassing and cleaning during construction of the interrupter, and by the fact that ultra-low gas content contact metals act as very efficient getters.

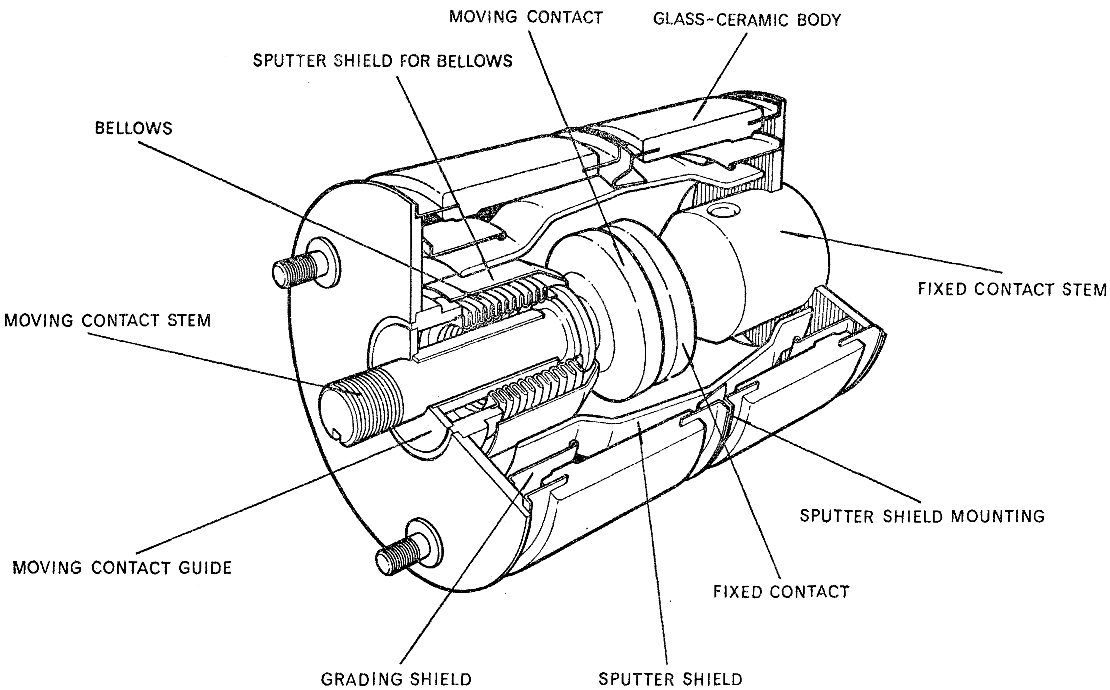


FIGURE 1. Typical vacuum interrupter.

## 2. HISTORICAL REVIEW

There was interest in the theoretical possibility of interruption in vacuum even in the nineteenth century, but the first demonstration of real interrupting ability was by Sorensen & Mendenhall of the California Institute of Technology in 1923/26. They interrupted 900 A at 40 kV. Technical difficulties prevented the manufacture of sealed interrupters, and interest ebbed and flowed periodically thereafter. Small switches for a few amperes at a few kilovolts were developed in the 1930s, and interrupters capable of handling between 2 and 4 kA at 15 to 20 kV were available by the end of the 1940s, but no vacuum interrupter could interrupt power system fault currents (Selzer 1971).

In 1953, the General Electric Company of the U.S.A. and the Electrical Research Association in the U.K. both started serious work, the Electrical Research Association to study the processes of arcing and arc extinction in vacuum, and the General Electric Company to develop an interrupter for power circuit breakers. By 1960 the Electrical Research Association (Reece 1963) had progressed as far as was possible with the rather limited resources available, but some of the basic physics of the vacuum arc and of arc extinction was understood in so far as was necessary for the further development of interrupters. Current chopping, which had troubled the early interrupters, was understood and could be controlled, and the principle of multi-fingered contact (since developed for high current interrupters) had been demonstrated. A contact designed for vacuum contactors, now in commercial use, which gave very low chopping levels and very long life had also been developed.

In 1962 the General Electric Company (Cobine 1963) announced the development of the first power interrupter capable of interrupting 12.5 kA at 15.5 kV.

In the U.K. a 15.3 kA 132 kV vacuum circuit breaker was tested in 1967. This used eight interrupters in series per phase, and four circuit breakers were installed and commissioned in 1968. These were, and still are, the highest rated vacuum circuit breakers in service in the world, and they have given very satisfactory service now for $4\frac{1}{2}$ years.

Figure 2, plate 12, shows one of these circuit breakers. Four interrupters, each individually rated at 15.3 kA, 16 kV, 1200 A, are contained in each half of the head of the T. The interrupters are immersed in $SF_6$ at a pressure slightly above atmospheric, and capacitors are used for control of voltage distribution. The circuit breaker interrupts short line faults and switches transformers without the use of resistors.

The interrupters are operated by mechanical linkages from the spring mechanism in the cubicle. The circuit breaker has two-cycle performance.

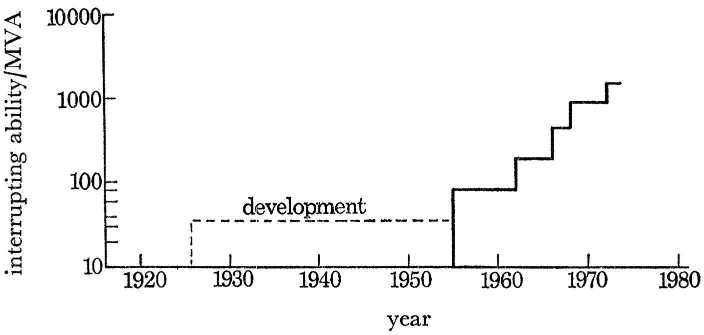


FIGURE 3. Growth of interrupting ability of vacuum power interrupters.

In 1968, 33 kV interrupters were produced both in the U.S.A. and the U.K. and the largest interrupter now commercially available is rated at 40 kA 38 kV.

The pace of development in interrupting ability has been exceedingly rapid. Figure 3 shows that if the 1923 experiments, which did not lead to commercial interrupters, are neglected, in ten years the interrupting ability of power interrupters has risen from 80 to 1600 MVA single phase.

## 3. Arcing and interruption processes

The vacuum arc is able to make the transition from a good conductor to a good insulator, which must occur at current zero, much more rapidly than high-pressure arcs.

The arc which forms when two plain butt contacts are separated in vacuum is either diffuse or constricted, depending very largely on the magnitude of the current. At peak currents below 10 kA the arc is diffuse, but is constricted at higher currents. The diffuse arc has a very high interrupting ability (measured in terms of the product of the rate of fall of current and the rate of rise of recovery voltage), while the constricted arc has almost no interrupting ability at all.

The rapid surge of progress in vacuum interrupters in the 1960s, shown previously, depended mainly on the development of contact geometries which prevented the high current arc remaining in the constricted regime right up to the current zero.

The diffuse vacuum arc consists of a number of small separate arcs in parallel each having a positive voltage–current ($v$–$i$) characteristic, and each developing from a cathode spot on the negative contact.


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Figure 4, plate 12, shows a vacuum arc burning between 45 mm diameter copper electrodes, separated by an 8 mm gap. The lower electrode is the cathode. The exposure is 40 μs and the instantaneous current about 3000 A. A few flying droplets of liquid copper can be seen in the gap, and on the extreme left of the anode a hot globule of copper, melted during the previous peak current (8 kA) period, can be seen. In the original colour photograph it can be seen that this globule is surrounded by a halo of glowing copper vapour, excited by the electrons from the cathode spots.

The cathode spots can be seen clearly on the negative electrode, although it will be appreciated that they are highly overexposed in the photograph, because of their high brightness.

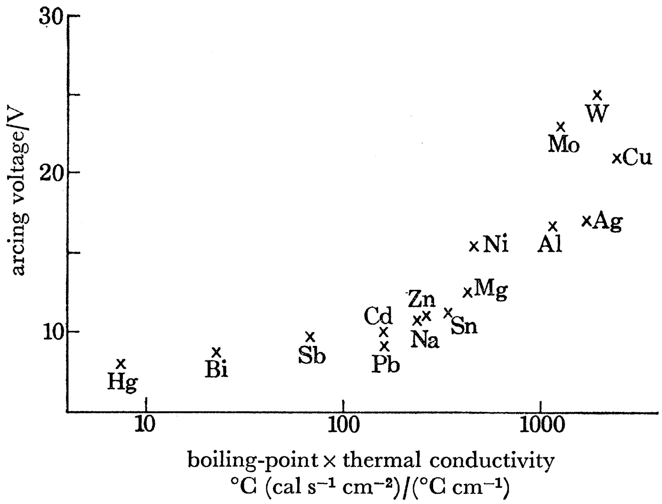


FIGURE 5. Effect of thermal properties of cathode on arcing voltage.

The spots repel each other (retrograde motion) and move about on the cathode. Each spot emits electrons and metal vapour and the current density, although difficult to measure, is of the order of $10^6$ to $10^8$ A/cm$^2$. Just in front of each spot there is a high-pressure region, the pressure being maintained by the local magnetic pinch at a value of $JI\ 10^{-8}$ atm, which may be above 1 atm, and from this region there streams towards the anode electrons (the main current carriers) at $10^8$ cm/s and neutral metal vapour and positive ions, both at about $10^6$ cm/s. Thus the positive ions move in the same direction as the electrons, and this, and the lack of collisions in the tenuous plasma, allows the low current vacuum arc to burn with effectively zero voltage gradient in the arc column.

The voltage at which a low current diffuse vacuum arc burns depends almost wholly on the cathode material. Figure 5 shows how the arcing voltage is related to the product of boiling-point and thermal conductivity. The boiling-point is, of course, a measure of the temperature needed in the spot to produce the metal vapour necessary for the production of positive ions, and the thermal conductivity affects the rate at which heat is lost from the spot into the adjacent relatively cold metal. Associated with arc voltage is arc stability, which influences the tendency to current chop. A metal with a low arcing voltage supports a stable arc with a low chopping level, and a metal with a high arcing voltage leads to high chopping level. Recent developments in 2-phase alloys and with sintered materials have led to contact materials with chopping currents much below those of either constituent.

Because of the very high velocity of the metal vapour towards the anode, where it condenses, the vapour density falls very rapidly at current zero. Indeed, the density is such that a good (from the electric strength viewpoint) vacuum is reached at or possibly even before the current zero, and the final interruption process involves electrons and ions only, with neutral particles playing an almost negligible role.

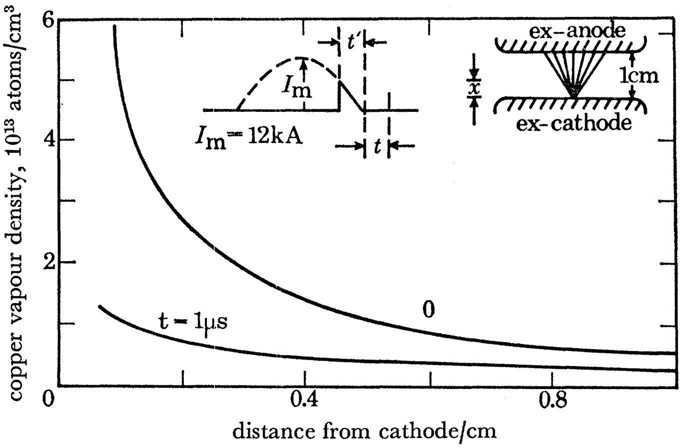


FIGURE 6. Vapour density between plane parallel copper contacts after current zero: current concentrates to single cathode spot at $i = 100$ A.

Figure 6 shows estimated vapour densities around current zero for a 12 kA peak copper arc between large flat contacts 1 cm apart. It has been assumed that at a time ($t'$) before current zero, when the current is equal to 100 A, the penultimate cathode spot is extinguished. One cathode spot then carried the current down to current zero. The vapour density has been estimated on a basis of a mean vapour velocity of $10^6$ cm/s, with a Maxwellian distribution of velocities.

The figure shows that even at the instant of current zero ($t = 0$) 90% of the gap has a density below $6 \times 10^{13}$ cm$^{-3}$, and since the critical density between the electrodes for a breakdown will be approximately $10^{14}$ cm$^{-3}$, most of the gap is effectively clear of vapour at the instant of current zero. The singularity at $x = 0$ is due to the extremely small size of the cathode spot.

In fact, the picture of interrupting ability given by figure 6 is probably pessimistic because: (*a*) the actual vapour distribution is probably more concentrated about the mean than in the Maxwellian distribution; and (*b*) very accurate oscillograms have shown that even when interrupting fault currents the cathode spots tend to be extinguished just before $i = 0$, probably when $i \approx 1$ A.

That extremely high interrupting abilities in terms of $-\mathrm{d}i/\mathrm{d}t \times \mathrm{d}v/\mathrm{d}t$, are achieved by vacuum interrupters is shown by figure 7. This figure shows a drawing (not to scale) of an oscillogram of a small vacuum interrupter with molybdenum contacts (the interrupter being about 50 mm diameter × 150 mm long) interrupting direct current by the injection of an artificial current zero. The interrupting ability of $4 \times 10^{18}$ V A s$^{-2}$ is far greater than that of other types of interrupter.

Had this behaviour of the vacuum arc been maintained up to the higher currents, power vacuum interrupters would undoubtedly have been available before 1962. However, when the current rises above about 10 kA, a magnetic constriction process sets in. The increasing vapour density due to the larger number of cathode spots, and the collisions between electrons (pursuing cycloidal paths under the influence of the self-magnetic field) and the metal vapour particles sets up losses, and a voltage gradient is now built up. Once the total arc drop reaches approximately 40 V or so, positive ions, which previously penetrated all the way to the anode by reason of their initial kinetic energy of approximately 40 eV, now fail to reach the anode because of the work done on them by the electric field, and an ion starved region develops just in front of the anode. This constriction and resulting ion starvation causes high and fluctuating voltages (somewhat akin to the ion starvation effects in the anode arms of mercury arc rectifiers). The high voltage and local high current density rapidly lead to the formation of a boiling anode spot producing a sufficiently dense vapour cloud for ions to be formed by collision right up to the anode (Mitchell 1970).

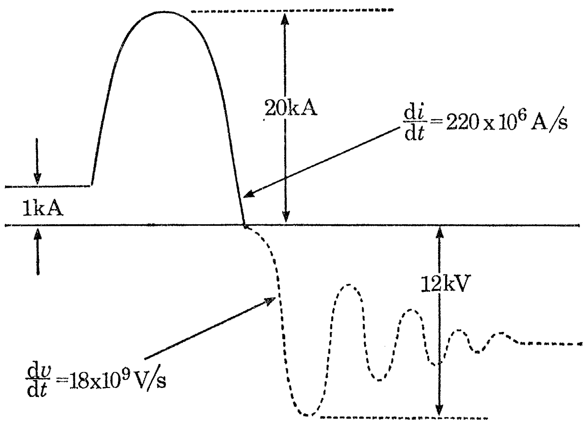


FIGURE 7. Interruption in a vacuum.

The cooling thermal time constant of a cathode spot is of the order of a microsecond, because of its very small size. An anode spot, on the other hand, the diameter and depth of which varies according to how long the constricted arc has been allowed to remain in the one place (but which is always several orders of magnitude larger than a cathode spot), may have a cooling time constant ranging from hundreds to many thousands of microseconds.

Thus if a large anode spot is formed, and continues to emit metal vapour copiously at current zero, there is no possible chance of interruption occurring.

The major step in the development of vacuum interrupters was to produce a contact geometry which would either prevent constriction of the arc at high currents, or if it did not do that, would ensure that the constricted arc reverted to the diffuse form sufficiently soon before the current zero for any large heated areas on either electrode to cool to an acceptable vapour pressure before the current zero, so that the interruption was achieved by the diffuse arc.

This has been done in at least two designs of contact. In the 'spiral petal', developed and used by the General Electric Company of the U.S.A., the arc is allowed to constrict, but is kept in motion around the periphery of the contacts, so that no large, deep, overheated spots are allowed to develop.

Figure 8 shows the geometry of the 'spiral petal' contact. The contacts are essentially disk shaped, slightly coned on their cooperating faces, so that when they are closed contact is established at or near the centre of the disks. A series of spiral slots are cut into the outer portions of the disks, the spirals being opposite handed in the two disks.

When the contacts separate, an arc is drawn in the centre of the disks, and if the current is high it remains constricted. However, the system is of course magnetically unstable, and any slight perturbation of the magnetic field causes the arc to move rapidly to a point on the periphery of the disks, where it forms a U-shaped loop between the disks. Once at the periphery the magnetic blow-out effect of the petals between the slots causes the constricted arc to move around the edge of the contacts. Thus although at the edge of the contacts the surface is melted, the movement of the arc prevents areas with long thermal time-constants being formed, and the arc reverts to the diffuse form before the current zero.

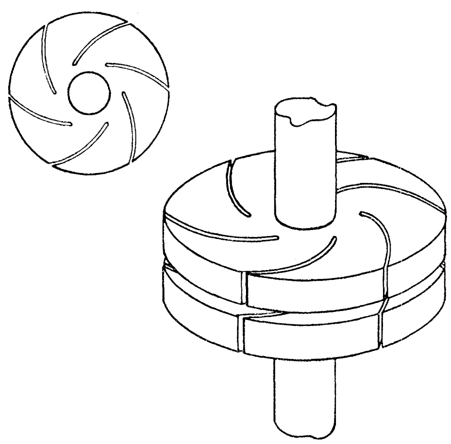

FIGURE 8. Spiral petal contact.

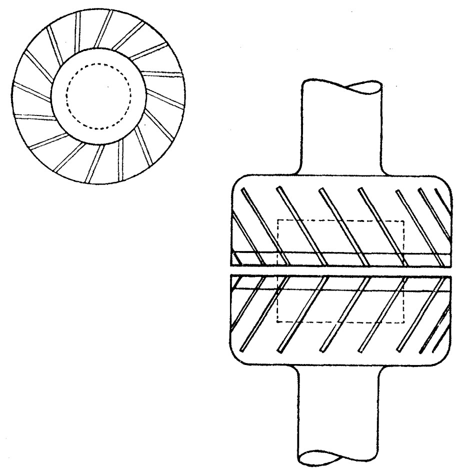

FIGURE 9. Contrate contact.

In the contrate contact, on the other hand, developed by Associated Electrical Industries and used by Vacuum Interrupters Limited, the arc is maintained in a quasi-diffuse form even during the peak current period. Figure 9 shows the contrate contact to be cup-shaped, contact being made between the rims of the cups. The sides of the cups are slotted in a helical fashion, the helices being of opposite hands in the two contacts.

When these contacts separate, arcs are formed at a number of points around the periphery of the contact, and these spread into a complete ring of arc. The arcing voltage is considerably less than in the case of the spiral petal contact, and the large number of contact points around the periphery increases the normal full load current rating of the contacts.

There are many other points which can be mentioned only in passing.

Contact materials, often two-phase alloys, have had to be developed so that they do not weld (difficult in ultra-clean conditions), have acceptably low gas contents and chopping levels and yet have low resistivities and high mechanical strength, so that they can withstand both high voltages and repeated mechanical operations.

Ultra-clean methods of assembly have been needed, since a vacuum interrupter does not have an electron beam to clean it up, but may have to carry current for many years, and then suddenly have to interrupt tens of kiloamperes. This condition is in many ways more onerous than that of high-power electron tubes. In figure 10, plate 13, an operator can be seen loading components into a furnace in a clean area, and the extreme precautions needed to maintain cleanliness during manufacture are apparent.


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## 4. Future development

The vacuum interrupter is at present more expensive than the interrupting devices in other circuit breakers, and its cost is very sensitive to production volume. There is therefore a vicious circle to be broken before these interrupters can be really widely applied.

It must, however, be remembered that the switchgear user pays for a complete circuit breaker, and the greater cost of the interrupters may be offset by simplifications in the circuit breaker itself arising from their advantageous properties.

For vacuum interruption to become commercially successful, each application must meet two conditions. These are: (*a*) the market for the prospective application should be large; (*b*) the type of equipment must be such that the use of vacuum interrupters will lead to cost savings in the rest of the circuit-breaker unit.

A very careful study of the switchgear market has shown that metal-clad distribution switchgear appears to satisfy both of these conditions in the U.K. (Reece & Ellis 1971). The market is large, some 10000 circuit breakers per annum, and the circuit breaker, which at present has certain features needed to allow maintenance, can be simplified and cheapened by the application of vacuum interrupters (Armstrong 1972; Headley 1972).

The lesson to be drawn from this is that what is required at present is not necessarily a move to ever larger and higher voltage interrupters, which must of necessity be expensive, in an attempt to penetrate a rather small market, but the development of interrupters especially designed for use in 11/15 kV metal-clad distribution switchgear which can be manufactured at the lowest possible cost: this is being done. Figure 11, plate 13, shows three interrupters for 125, 250 and 500 MVA at 11 kV, developed as part of this programme for use in metal-clad distribution switchgear: it is expected that a considerable market will develop over the next few years.

In the field of high-voltage circuit breakers the position is rather less clear. The performance of the 132 kV 3.5 GVA vacuum circuit breakers in service has shown that the only problems are economic, and the customer would like more of this type of circuit breaker. The dilemma is that the competition, i.e. bulk oil, oil minimum, compressed air and SF6 can offer unit voltages from 75 to 150 kV per interrupter compared with at the best 38 kV for vacuum. To cheapen high-voltage vacuum circuit breakers, we must use less interrupters per phase, but this means making less interrupters in total of the particular type, having a higher voltage rating; both these restrictions increase the price of the interrupter. The only solution that can be seen to this particular problem lies in the results of research and development leading to interrupters having a greater interrupting ability per unit volume, so that although the rating increases the cost does not.

To summarize, the evidence is that the vacuum interrupter, which has already taken a large share of the high-voltage air-break contactor market, may next make a significant inroad into the distribution switchgear field, and this will happen in the next few years.

The further outlook is more uncertain: the few 132 kV vacuum circuit breakers installed are giving good service, and vacuum interrupters have been considered for e.h.v. metal-clad switchgear. It is, however, almost certain that further progress in research and development will be required to increase both voltage and current ratings and particularly to reduce specific volumes and specific weights before vacuum interrupters can effectively challenge the whole of the switchgear field.



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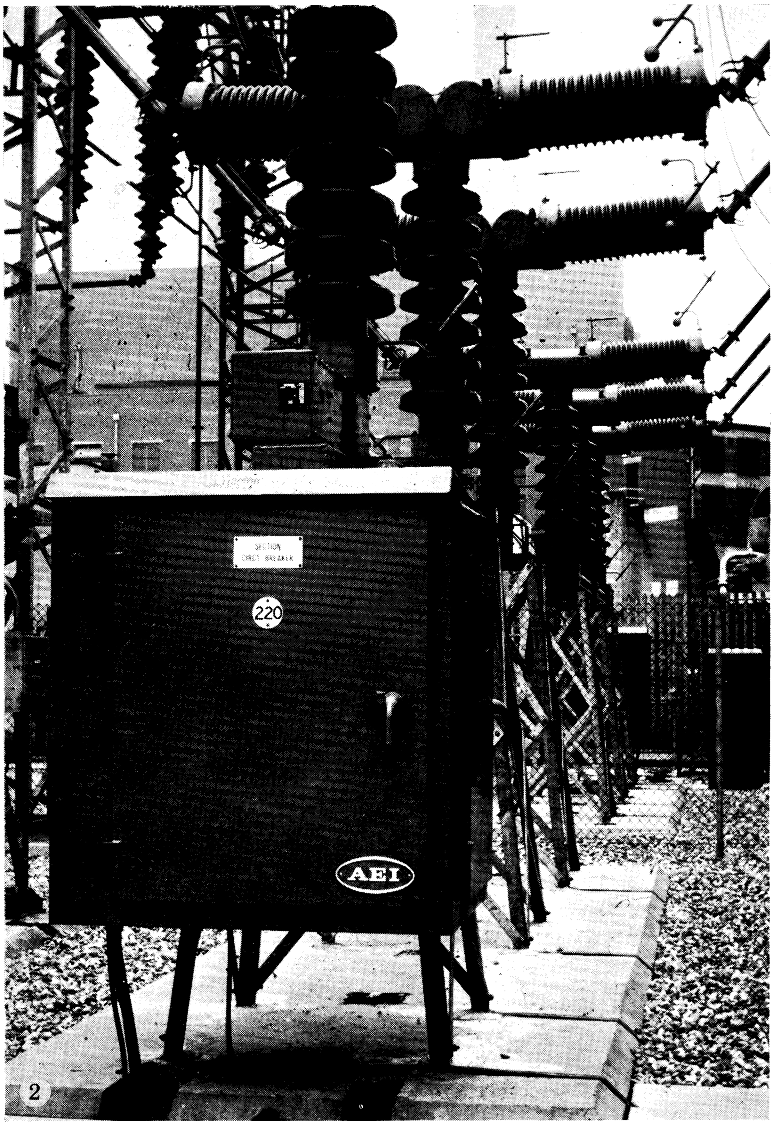


Figure 2. A 15.3 kA 132 kV vacuum circuit breaker.

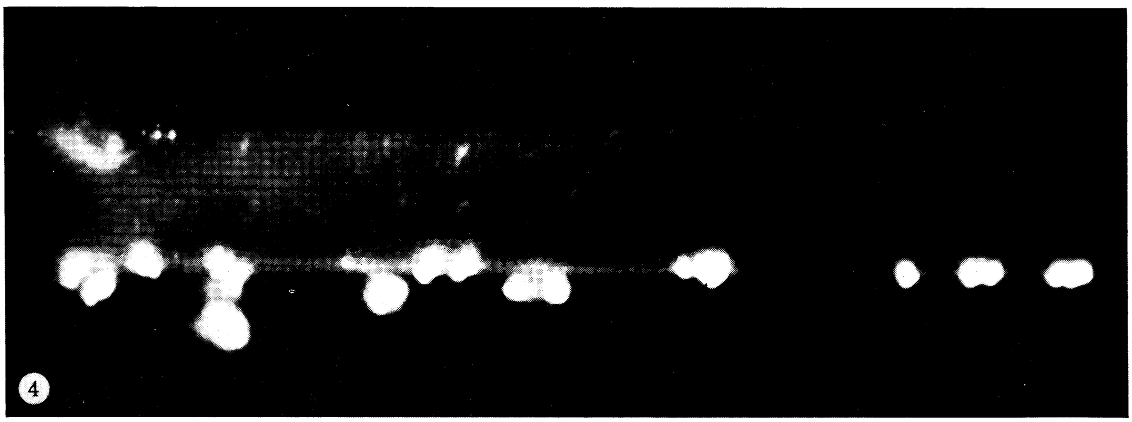


Figure 4. A diffuse vacuum arc.

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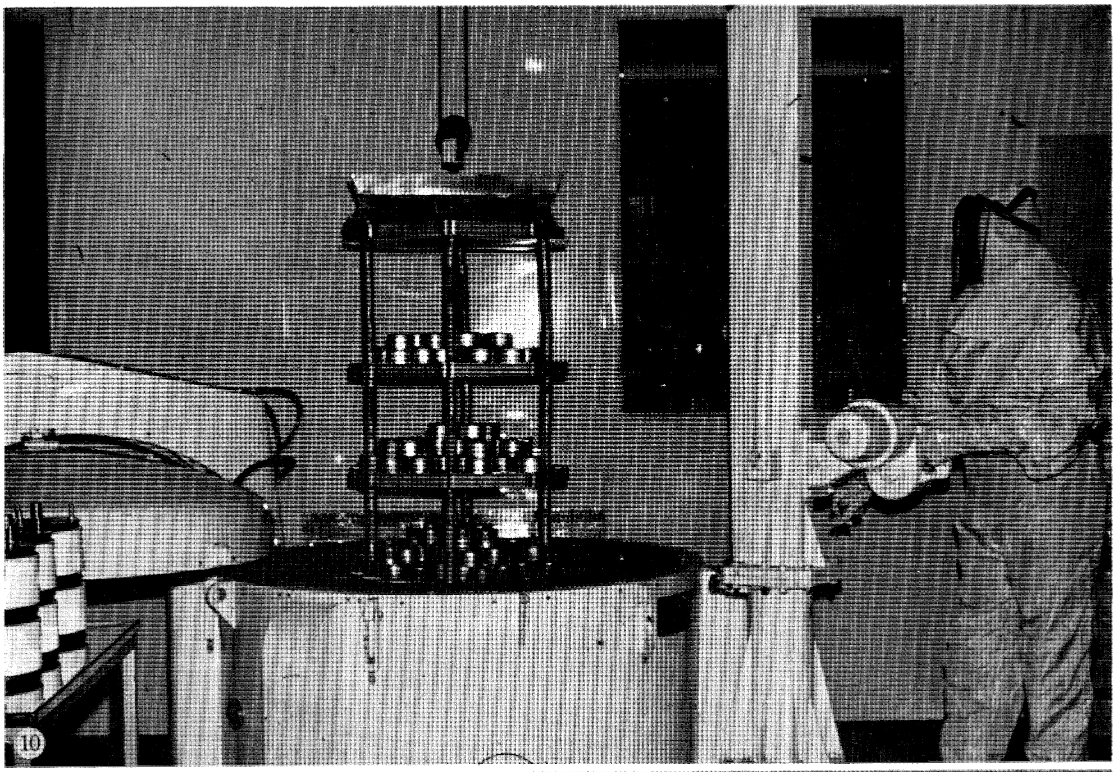

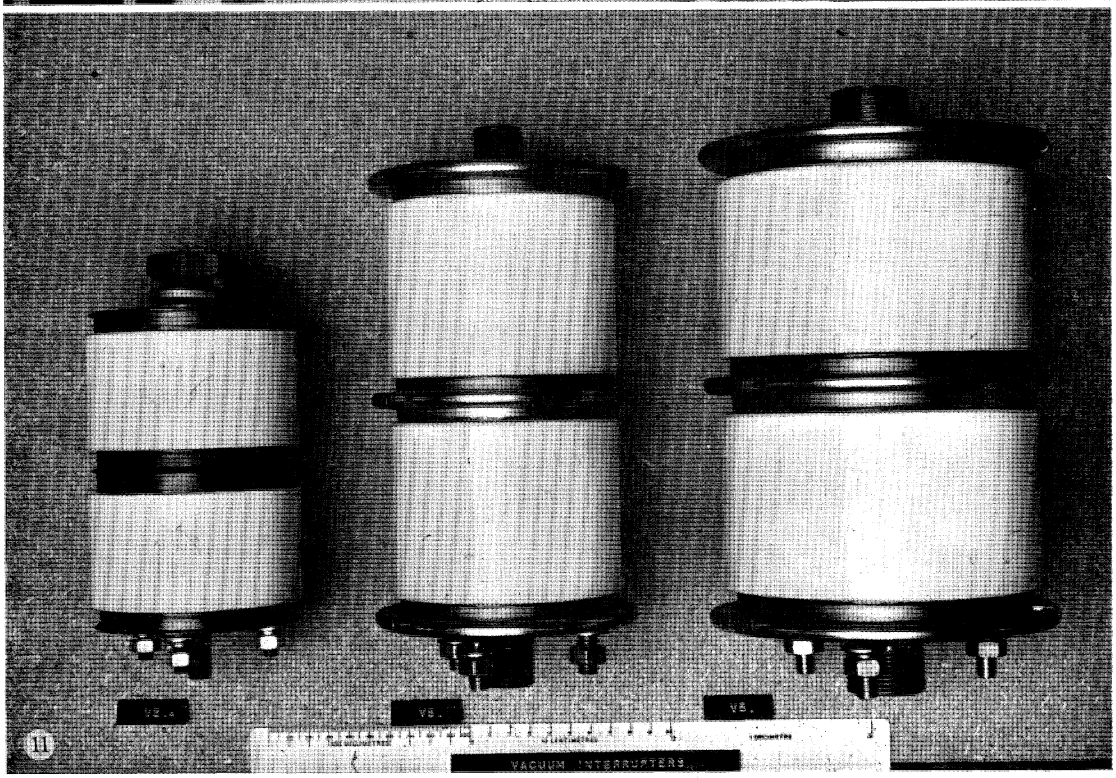

FIGURE 10. An operator loading components into a furnace in a clean area.

FIGURE 11. Three interrupters for 125, 250 and 500 MVA at 11 kV.



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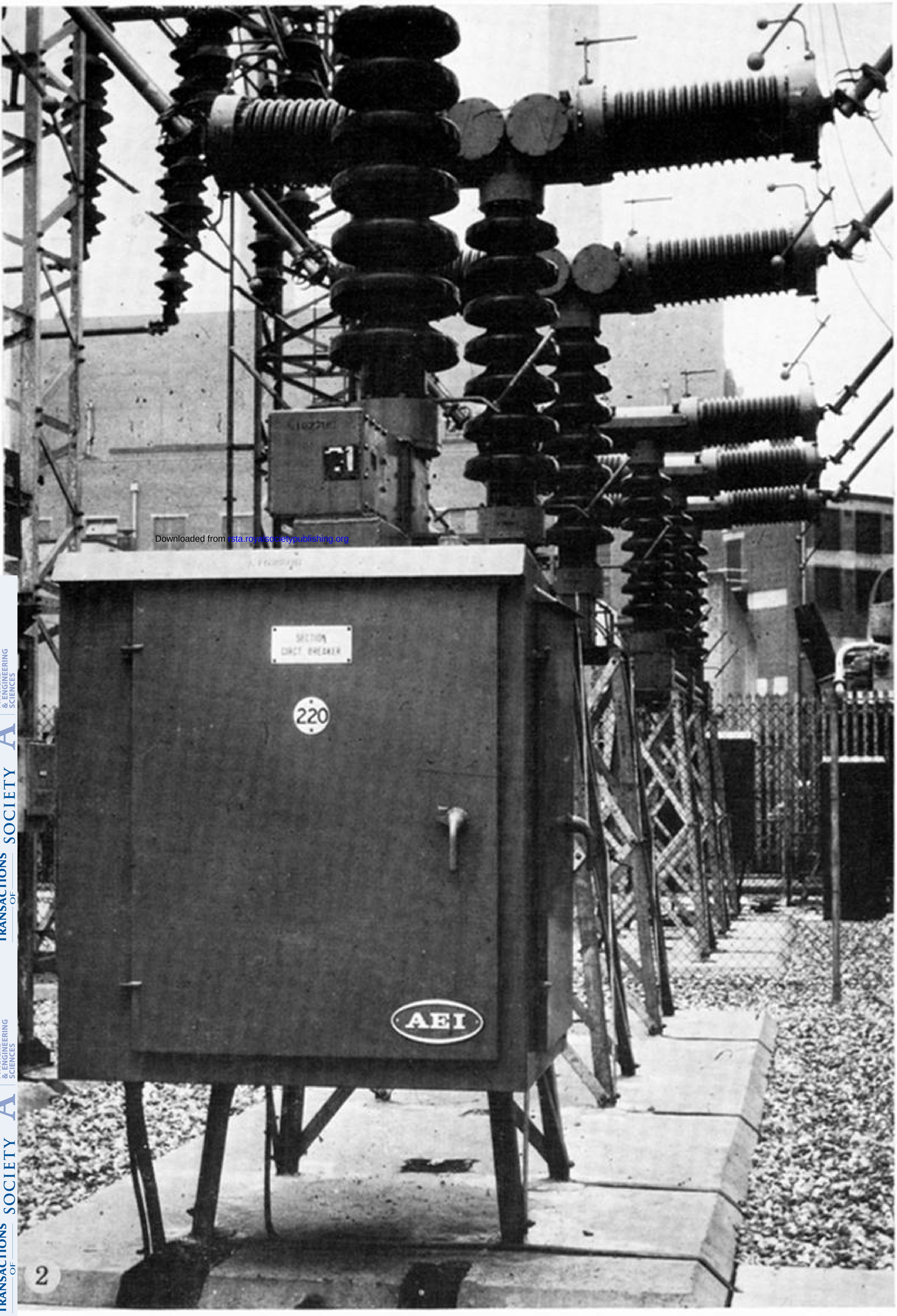


FIGURE 2. A 15.3 kA 132 kV vacuum circuit breaker.



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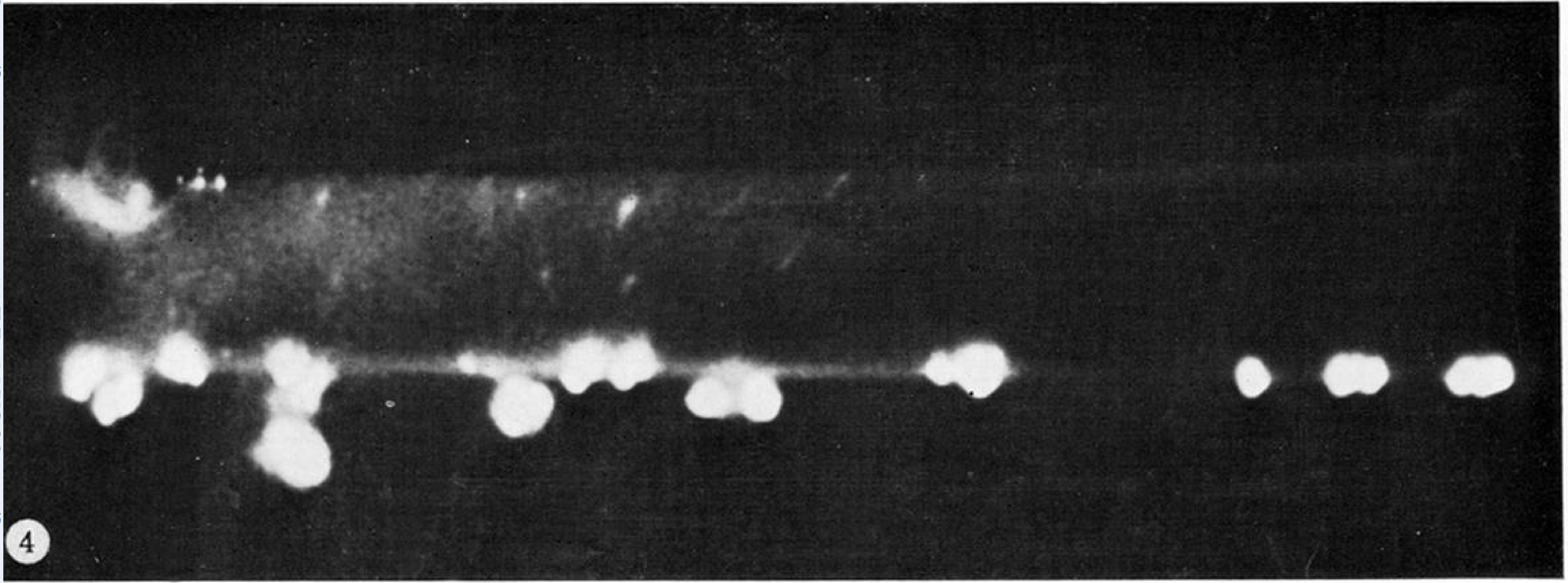
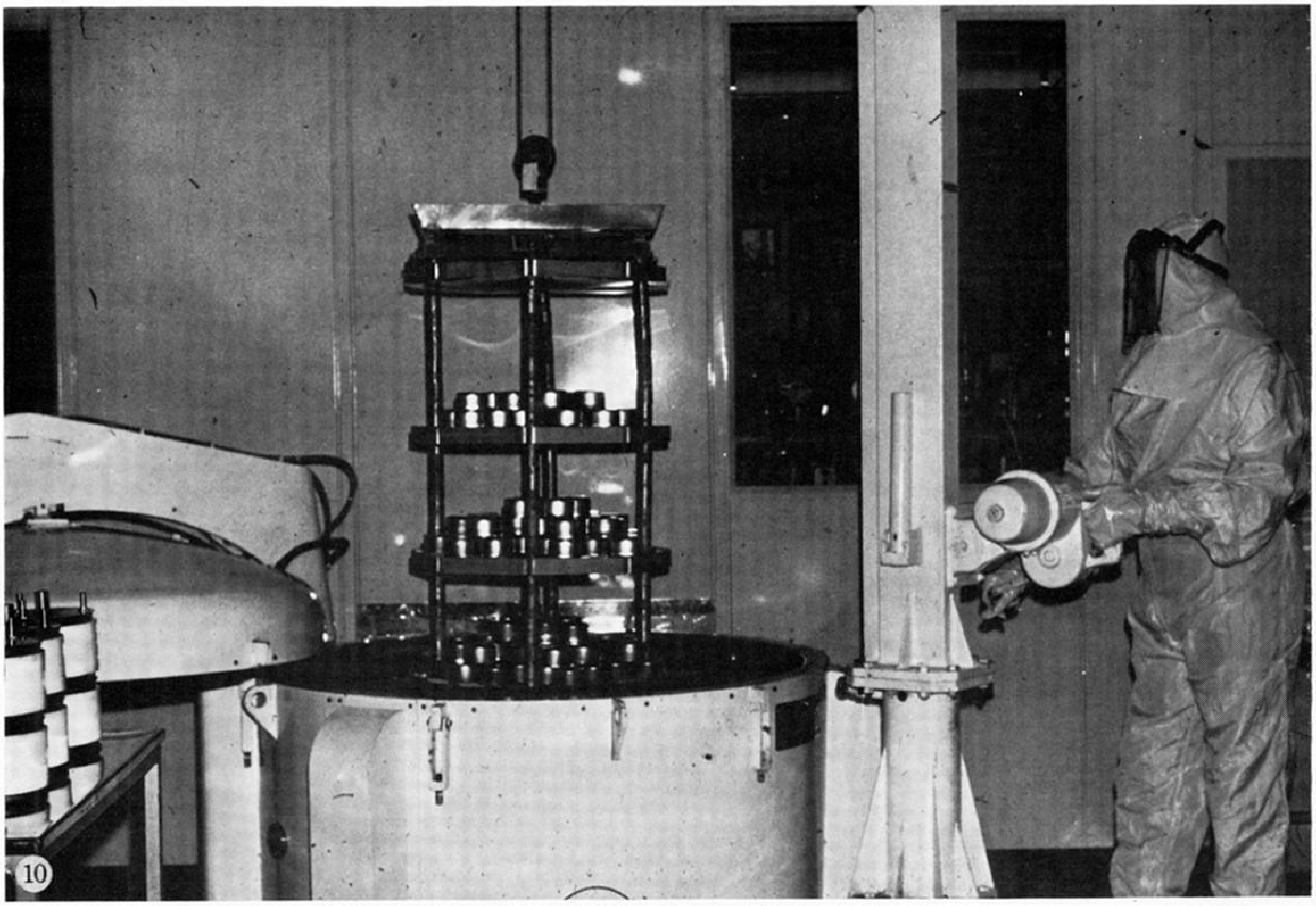



FIGURE 4. A diffuse vacuum arc.



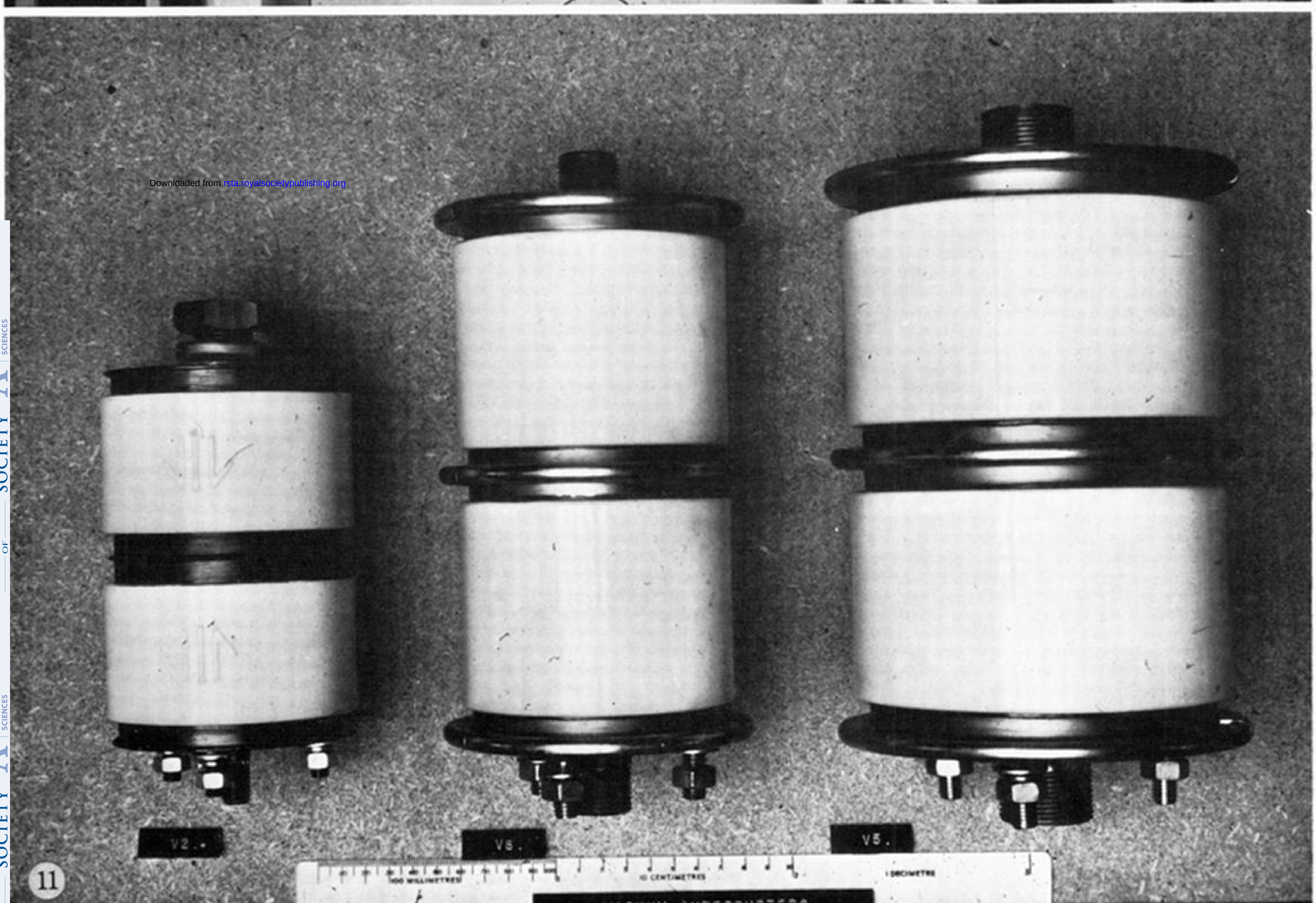






FIGURE 10. An operator loading components into a furnace in a clean area.

FIGURE 11. Three interrupters for 125, 250 and 500 MVA at 11 kV.