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Superconducting Machines - A New era for the Electrical Power Industry

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Superconducting machines – a new era for the electrical power industry

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[Plate 8]

This paper outlines the development of superconducting d.c. machines at I.R.D. where most of the work to date has been undertaken. Particular emphasis will be placed upon the industrial applications for these machines and the paper contains illustrations of the superconducting marine propulsion systems now under construction.

The object of the presentation is to demonstrate that superconducting d.c. machines are now available for industrial application after a relatively short period of development.

The paper also indicates the substantial advantages to be gained from the successful development of superconducting a.c. generators. The work which is necessary before these machines may be put into production will be discussed by consideration of the principal problem areas.

Finally, conclusions are drawn on the present status of superconducting machines and the changing attitudes in industry towards this new technology.

The case for superconducting machines

The status of superconductors has been steadily increasing from the advent of the high-field alloys some 13 years ago, through to the fully stabilized niobium–titanium about 8 years ago, to the fine filament, intrinsically stable materials which are now available. The numerous possibilities for the applications of superconductors have been discussed for many years, but until now they have never been taken too seriously by the majority of those responsible for shaping the future pattern of industry; and now is the time for substantial investment to usher in a new era for the electrical power industry.

The applications for superconductors cover electrical power transmission, rotating electrical machines, magnets for a variety of purposes including levitated transport and the control of high-energy nuclear particles, and numerous other less explored possibilities; of all these, none is more important or likely to bring the same degree of benefit as rotating machines.

D.c. power is used in increasing quantities for aluminium smelting, chlorine production and copper refining. Since large conventional d.c. generators are virtually non-existent this power is usually obtained from transformer rectifier plant. However, superconducting d.c. generators are feasible with ratings up to at least 200 MW and, if they are given the opportunity to be developed, will be the cheapest source of d.c. power by a considerable margin. D.c. motor drives are called for in many applications, but the limitations of conventional machines have restricted the number of installations now extant. In some instances, size, mass and economics have dictated the use of a.c. motors, with some complexity of control systems and sacrifice of fine speed control. These restrictions do not apply with superconducting d.c. motors; indeed, superconducting d.c. motors may be produced with ratings and torques far in excess of those possible with conventional designs, and apart from replacing conventional drives (in steel rolling mills for example), they may thus be employed in applications where previously d.c. motors were not available. At the present time the most important in the latter category is ship propulsion which is discussed later.

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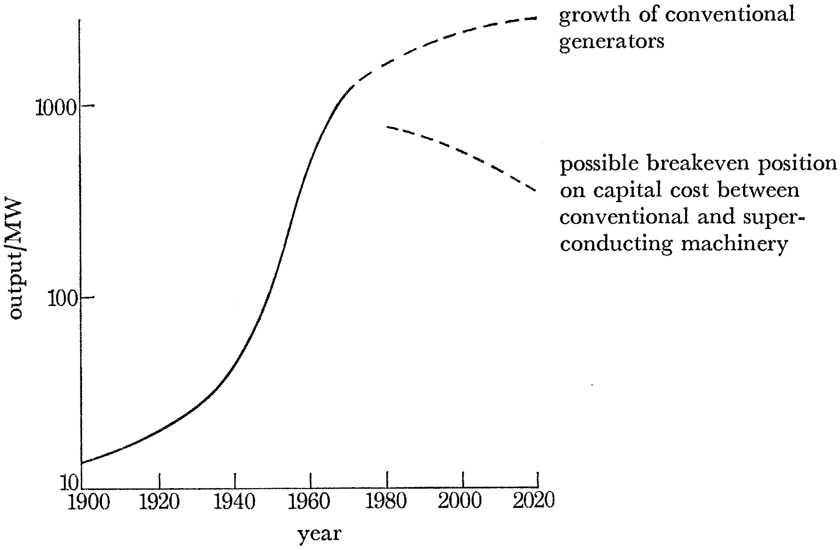

FIGURE 1. Growth of a.c. generator ratings.

The unit ratings of a.c. generators for central power stations have been increasing as shown in figure 1, and this trend is virtually certain to continue. It will continue in fact until conventional designs have been stretched to their limit, but it is not at all clear where this limit lies; it could be as high as 2000 MW, but reliability near the limit is an important question. It is possible to demonstrate that the limit for superconducting a.c. generators is much higher than 2000 MW, probably at least 5000 MW, but of course reliability has to be proven. However, there are a number of reasons why there is an outstanding case for the development of superconducting a.c. generators with a rather more than casual approach, and these are:

(1) The fact that they are capable of being developed to the highest ratings that are likely to be required in the future and the reasonable probability that, because the design limit is well removed, they may be more reliable than the conventional designs near their limit.

(2) On pessimistic estimates the manufacturing costs are (certainly for ratings in excess of 1000 MW) significantly lower than conventional generators.

(3) On reasonable estimates they appear to be more efficient than conventional generators.

Of course, there is the overriding requirement that, on reasonable engineering judgement, the development problems of the superconducting generators are not insuperable; it is the concensus of informed opinion that this is the case.

SUPERCONDUCTORS

There is no space for a long account of superconductors, but a few words on their performance are appropriate. Figure 2 shows the current density which may be achieved in niobium–titanium as a function of the flux density in which it is located. The average current density in a machine winding will be lower than indicated because it is desirable, if possible, to employ a combination of copper and superconductor. The copper serves to increase the thermal capacity of the winding and prevent possible damage in the event that the stored energy is released into the winding. Figure 3 shows a multifilament niobium–titanium superconductor manufactured by I.M.I.; the number of filaments may be varied to meet the required current

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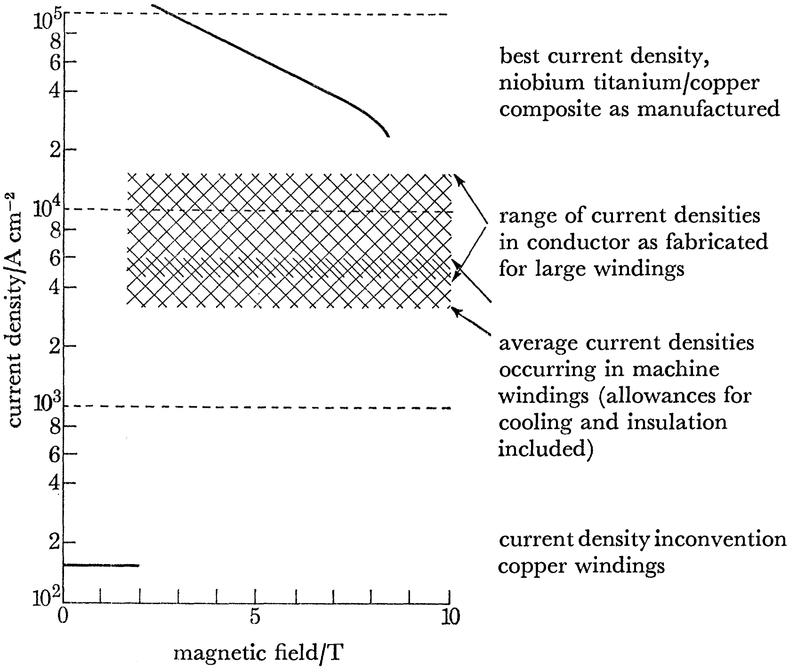

FIGURE 2. Characteristics of niobium titanium/copper composite superconductor.

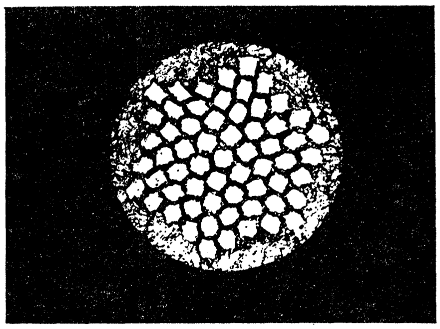

FIGURE 3. Multifilament niobium titanium/copper composite superconductor (×100).

rating. If it is necessary to change the current in a winding at a rapid rate, say 10% per second or more, it is necessary, in order to reduce the eddy currents, to include cupro-nickel in the copper matrix and also to twist the filaments. Niobium–titanium is the most widely used superconductor; it is suitable for electrical rotating machines and is available commercially. It is necessary to operate Nb–Ti at no more than about 5 K and this presents no difficulty with a liquid helium immersed winding. Niobium–tin is also being developed in filamentary form and may be operated at a higher temperature (about 9 K); this is an advantage for a.c. generators, but the material is brittle and windings are more difficult to fabricate.

One important feature of the available high field superconductors is that they cannot be used for alternating currents, or at least, nothing approaching power frequencies; the very best that might be achieved is about 1 Hz. Fortunately, this is not a stumbling block for electrical rotating machines because all of the benefits of superconductors may be obtained by employing them only for the d.c. excitation windings of both a.c. and d.c. machines.

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The benefits of using superconductors for electrical machines

The ability of a superconductor to carry very high currents enables the iron magnetic circuit of electrical machines to be eliminated. The consequences of this are that the magnetic flux density may be increased above the saturation level of iron and the mass of the machine is reduced. Consider the homopolar machine shown in figure 4; with an iron magnetic circuit the design specification would be approximately as follows:

ampere turns in winding	5×10^4
power consumption in winding	20 kW
machine flux (from both windings)	3 Wb

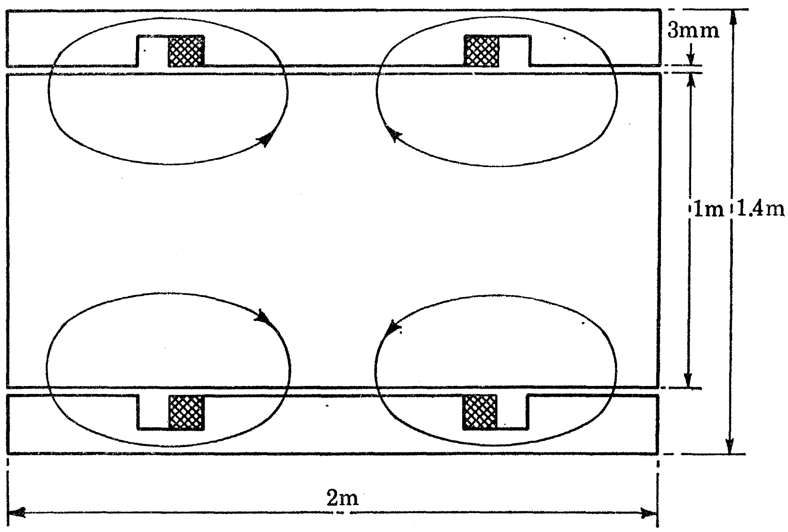

Figure 4. Diagram of drum type homopolar machine.

If the iron is removed, the ampere turns required to produce the same flux becomes 2×10^6 for each winding; if the winding is still made of copper, the power consumption runs into megawatts, but with superconductor it is zero. Furthermore, with the superconductor the machine flux could be increased several times over. The result is a more powerful and lighter machine.

In a large, conventional, a.c. turbogenerator, most of the rotor excitation ampere turns are required to drive the flux across the two airgaps and only about 10 % of the ampere turns are required to drive the flux through the iron. Let us suppose that we remove the iron and increase the ampere turns so that the flux density remains the same. The 'equivalent airgap' of the machine now rises from about 80 mm to something like 1200 mm, or by a factor of 15; thus, the ampere turns required rises from about 1.4×10^5 to 2×10^6, and the rotor copper loss rises from 0.3 % of machine output to about 67 % of machine output. This simple example illustrates that an all-copper machine is not practical, and an ironless machine can only work if the requirement for millions of ampere turns on the winding is met by the use of superconductors. Also, of course, the flux density of the excitation winding may be increased by a factor of three or four, and some of the restrictions on specific machine output such as iron saturation and stator diameter can be removed, enabling machines to be built which are considerably shorter and lighter than those available today.

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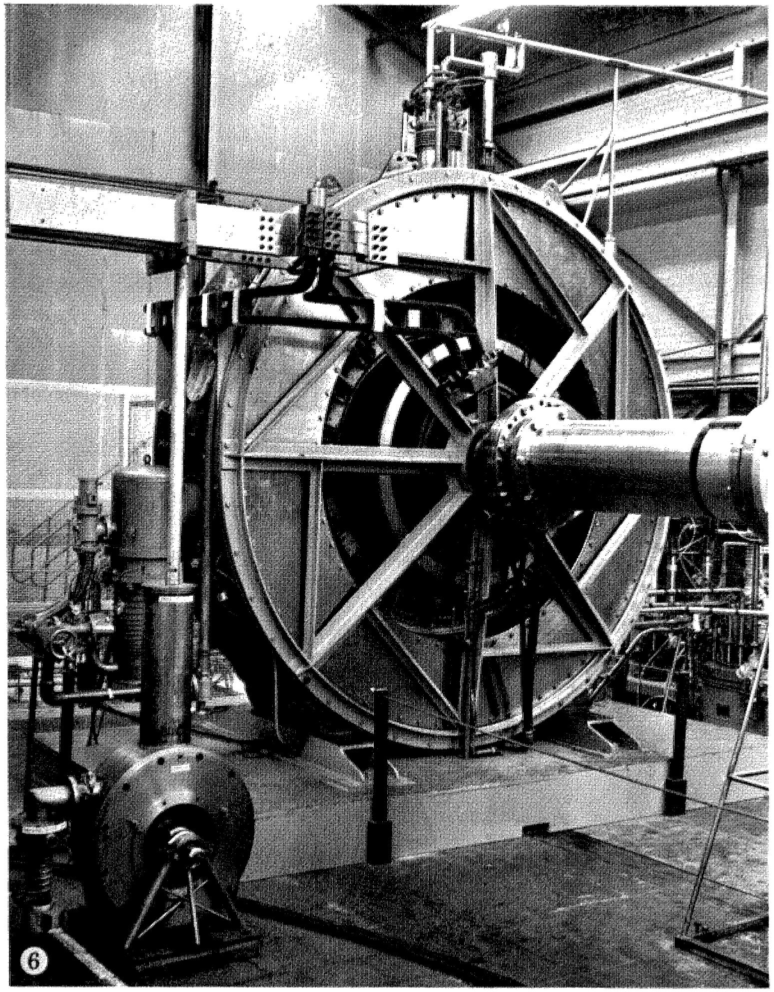

FIGURE 6. The 2.4 MW, 200 rev/min superconducting d.c. Fawley motor with the 37 kW model motor in the foreground.

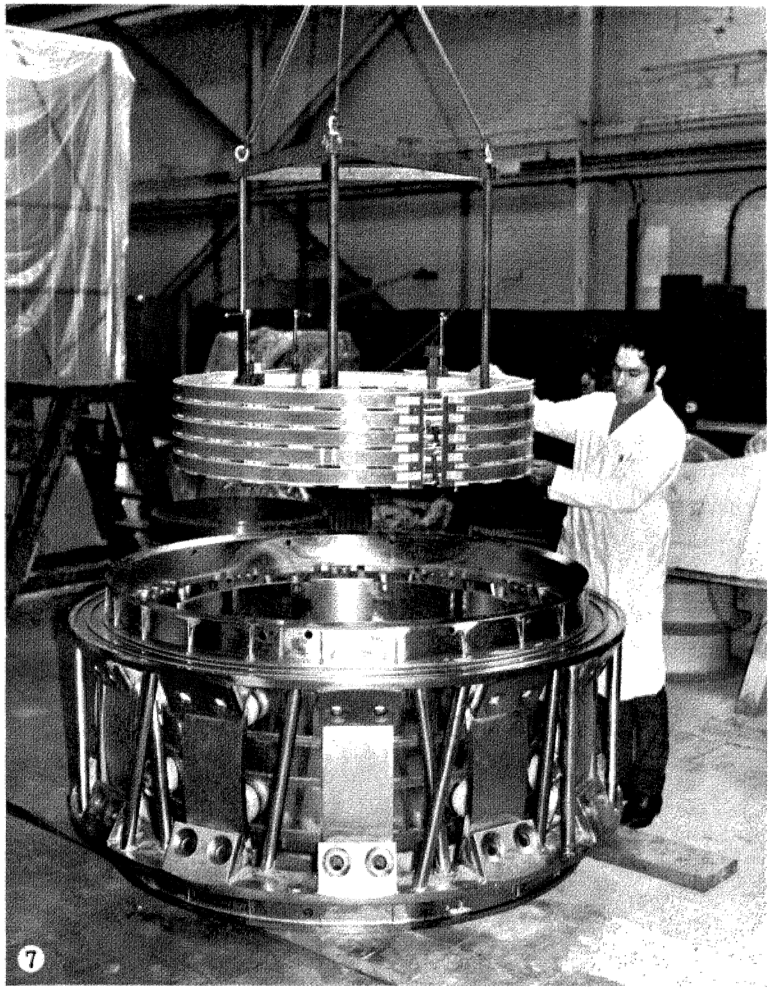

FIGURE 7. Superconducting d.c. generator field coils being fitted into coil support structure.

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Increased output has meant, in the past, increasing length, which in turn brings major mechanical problems. Hence, one of the most outstanding benefits to be had from superconducting a.c. generators, in addition to the lower cost and reduced mass, is a substantial reduction in machine length.

Superconducting d.c. motors and generators

Figure 5 shows in schematic form the superconducting homopolar machine; this is not described in detail because full details have already been published. The important features are the protection of the low-temperature superconducting winding from heat inleak by conduction and radiation, a good method of current collection from the sliprings of the armature, the possible need for a magnetic screening winding (also superconducting), and a reliable helium refrigeration system. Figure 6, plate 8, shows the world's first superconducting machine (37 kW), built at I.R.D. in 1966 on behalf of MoD(N), and the 2.4 MW, 200 rev/min Fawley motor, built by I.R.D. with the support of the National Research Development Corporation and tested with the close cooperation of the C.E.G.B., particularly the staff at Fawley Power Station.

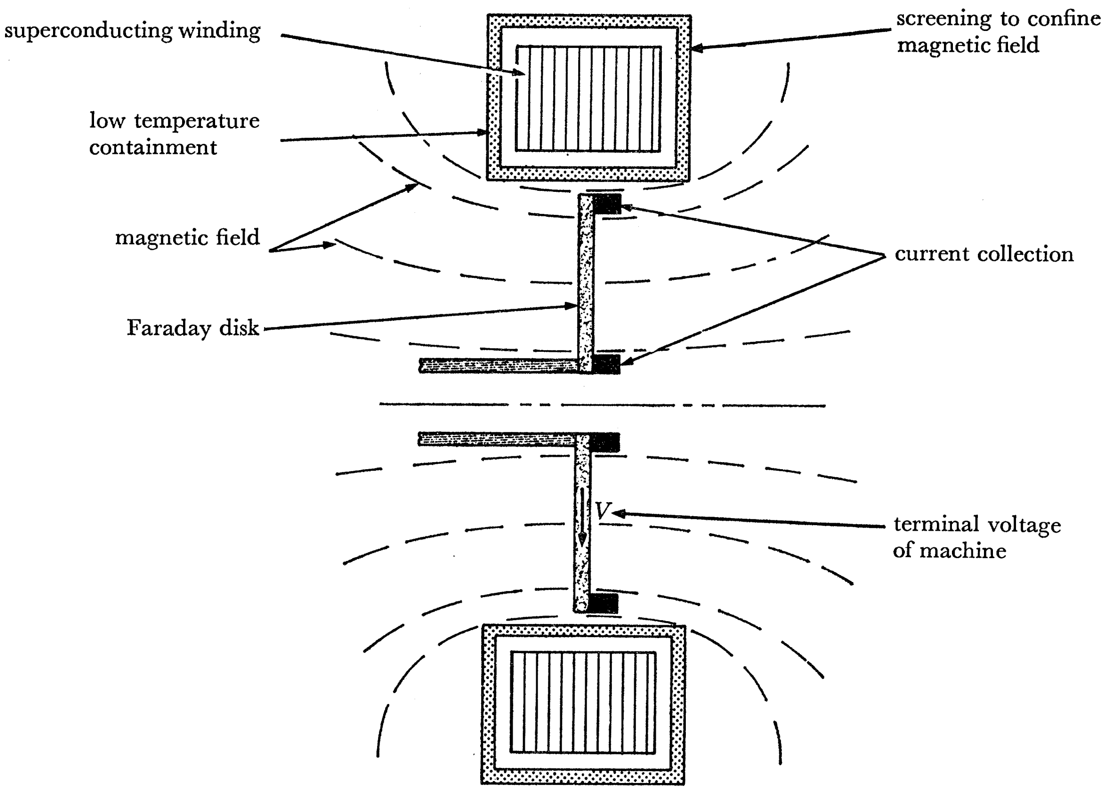

FIGURE 5. Schematic of homopolar machine indicating important design features.

At the present time I.R.D. is engaged, on behalf of MoD(N), in the construction of a superconducting marine propulsion system comprising a superconducting generator and superconducting low speed motor. The system, now nearing completion, employs many design improvements over the Fawley motor; for example, the superconducting windings are encapsulated in epoxy resin, and the new metal-plated carbon fibre brushes, developed at I.R.D. will

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be used. The equipment will be fitted into a ship for trials after tests at I.R.D. Figure 7, plate 8, shows some of the field coils of the generator.

The advantages of an electrical propulsion system are that better control and manoeuvrability are obtained but, more important, that the prime mover (the work is directed primarily at gas turbine driven ships) and the generator may be located at the most convenient position in the ship to give a better layout (to give more cargo space) and better accessibility (for overhauling or changing the prime mover). The change from steam turbine to gas turbine (with reduction gears) brings about a significant reduction in machinery mass and space, but the further change to gas turbine with superconducting electric propulsion brings a flexibility of design with substantial attendant benefits which are still not completely optimized or quantified.

Superconducting propulsion systems of the type now being developed at I.R.D. will benefit large container ships, large tankers, ferry boats, ice breakers, and deep sea tugs in addition to military vessels. Other applications for superconducting d.c. machines which are now ripe for development are drives to steel-rolling mills (and certain other steel mill drives) large boiler feed pump and fan drives for power stations, and numerous other drives in mining, cement production, etc. Also, for the d.c. power supplies mentioned earlier, the backlog of design, development and test experience makes it possible for the manufacture of pre-production prototypes to be initiated. There is a strong case for allowing the manufacture of a number of machines for different applications to proceed in parallel.

Superconducting a.c. generators

Superconducting a.c. generators have been under development at I.R.D. since 1968. The essential features of a superconducting a.c. generator (figure 8) are a rotating superconducting, excitation winding, a screen to prevent time varying magnetic fields (due to armature currents) from influencing the excitation winding, a stator (or armature) winding located in a non-metallic support structure, and a screen to confine the excitation field inside the machine.

The deletion of the magnetic iron circuit is highly desirable because of the reduction in mass and cost, but it does result in the machine windings 'seeing' the full magnetic field and, hence, being subjected to the full machine torque. It is not possible in a general discussion to give a detailed presentation of the machine design, but a brief appraisal of the basic problems is necessary.

Although all of those engaged upon the development of these machines are agreed on the basic concept, there are many variations in detail. Perhaps the most significant 'free choice' is whether to protect the machine environment from the rotating field with iron or with an eddy current screen. The approach preferred by I.R.D. at the present time is the eddy current screen, but this is not critical at the present stage of development. The first major problem to be solved is the prevention of an excessive quantity of heat reaching the superconducting winding; I.R.D. prefers to support the winding within a stainless steel cylinder, all at the low temperature, and to support the cylinder with 'cone-ends' shown schematically in figure 8. An alternative design suggested by another manufacturer is for the cylinder to be made from glass fibre. The cone ends are cooled with helium gas which is available after liquid helium has cooled the winding; the gas rises to ambient temperature after cooling the cone ends and is then returned to the helium liquefier. The superconducting winding must be extremely well supported in the cylinder and protected from thermal radiation from the rotor screen by a shield cooled to about 80 K by

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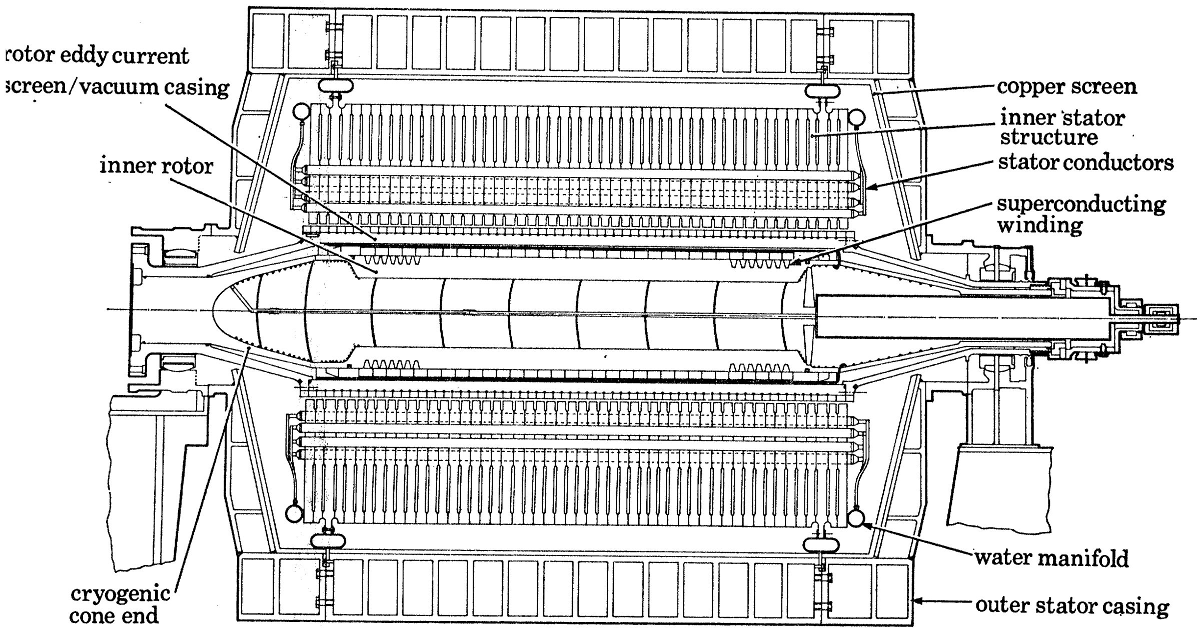

FIGURE 8. General arrangement of a superconducting a.c. generator.

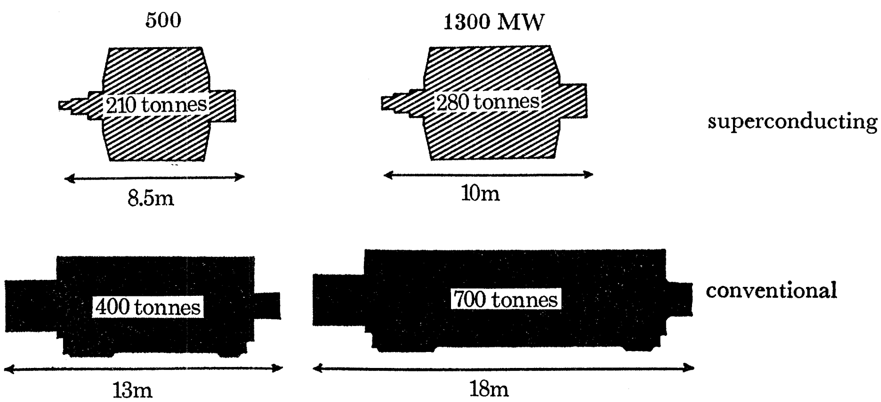

FIGURE 9. Comparisons of sizes and masses of 500 and 1300 MW conventional and superconducting a.c. generators.

helium taken from an appropriate point of the flow down the cone ends. An alternative design is to allow the rotor screen to operate at about 80 K (possibly higher); in this case a separate thermal radiation shield is not required, but a careful optimization is necessary on the refrigerator because of the additional thermal load of the rotor screen. Major sources of heating of the latter are the eddy currents due to the negative phase sequence current in the stator winding; the I.R.D. designs allow for this to be as high as 10 %, but it could possibly be made less with reasonable safety. The flow of helium to the winding must be carefully designed because the pressure increase as the helium moves from the axis to the winding will cause a rise in temperature; there are a number of ways of dealing with this problem, for example expanding the helium at the larger radius before the helium enters the winding.

The stator or armature winding is subjected to the full magnetic field and must be subdivided and, of course, cooled to remove the heat due to the load current and the eddy current.

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There is considerable freedom in selecting the radius of the stator winding, and in the present I.R.D. design the radius is quite large for a number of reasons: (*a*) to allow a higher total rating without exceeding accepted specific ratings; (*b*) to accept the machine torque more readily; (*c*) to increase the transient reactance of the winding.

A new type of stator winding has been evolved at I.R.D. which overcomes many of the problems encountered with the end windings of conventional machines. One of the problems to be solved is that of the non-metallic stator support structure that is subjected to the rotational stresses which give rise to hysteretic heating; possible materials are laminated wood of the 'Permali' type and glass fibre reinforced or carbon fibre reinforced materials. It will be necessary to construct a test rig to determine the fatigue properties of the various materials. The eddy current environmental screen requires careful optimization to reduce the losses; if the space is available, the losses are reduced by increasing the screen diameter, and an acceptable design appears quite feasible. The eddy current screen losses are lower with a 4-pole machine and this may well be the choice beyond perhaps the 1300 MW rating.

It is considered that a reasonable programme for the development of these machines is: (i) complete sufficient rig work to allow a detailed design to be undertaken; (ii) construct and test a 60 MW experimental machine designed to highlight as many as possible of the problems of full size machines; (iii) proceed to the manufacture and test of an intermediate rated machine of about 600 MW; (iv) start pre-production trials with a 1300 MW (perhaps higher) rated machine.

Figure 9 shows comparisons of sizes and masses for 500 and 1300 MW superconducting and conventional a.c. generators.

Conclusions

1. The technology of niobium–titanium superconductors has reached the point where the requirements of rotating electrical machines can be achieved.

2. The associated technology of helium refrigerators has the status necessary to give full support to the development of electrical machines.

3. Substantial benefits are available from superconducting d.c. motors and generators which are already at an advanced stage of development. The major factor which is preventing the widespread introduction of these machines to industry is operating experience and confidence, and this may be achieved only by the construction of pre-production machines for evaluation.

4. The superconducting a.c. generator provides the electrical power industry with a good opportunity to modernize and prepare for the continuing growth of power demand in a new era of electrical engineering.

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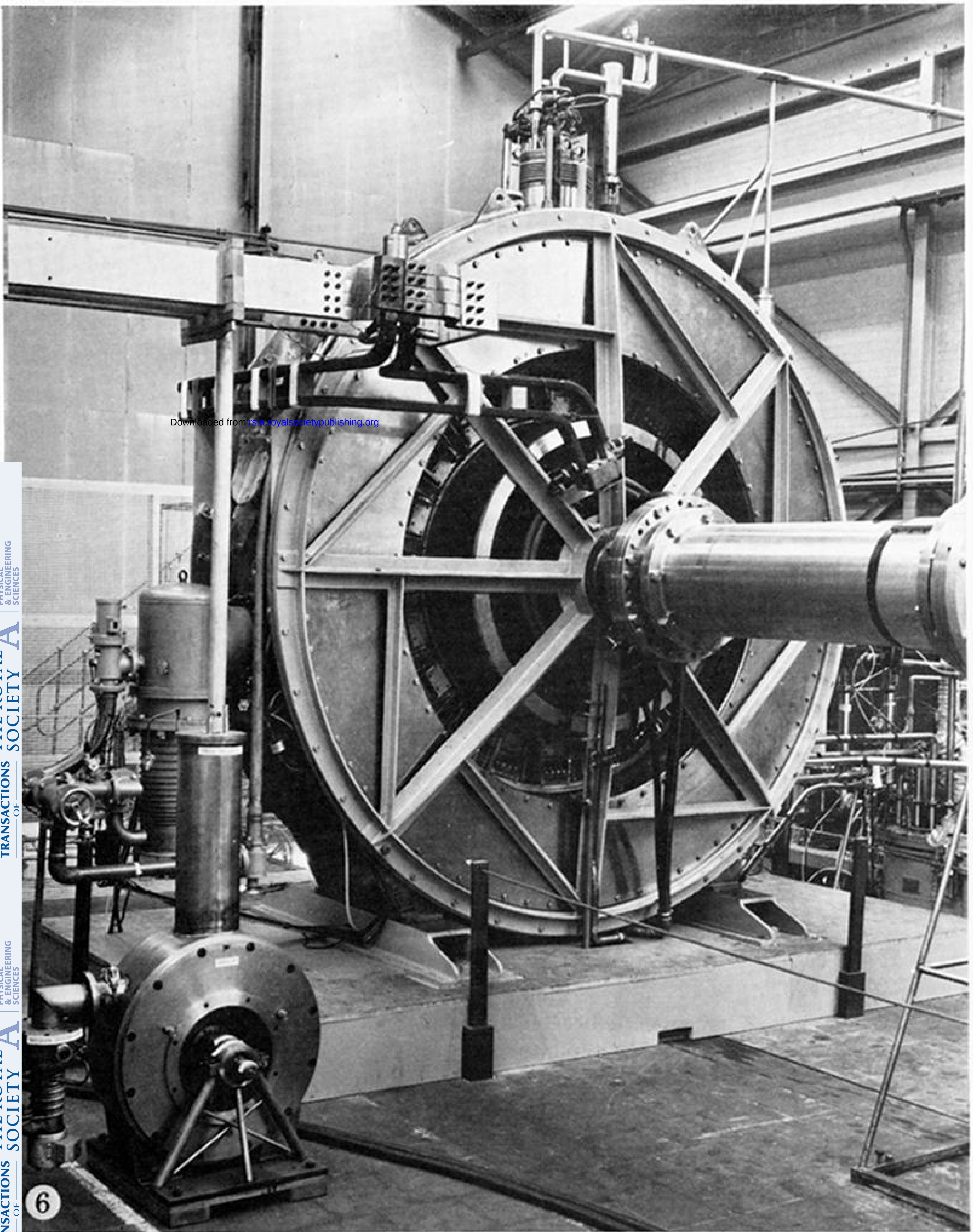

FIGURE 6. The 2.4 MW, 200 rev/min superconducting d.c. Fawley motor with the 37 kW model motor in the foreground.

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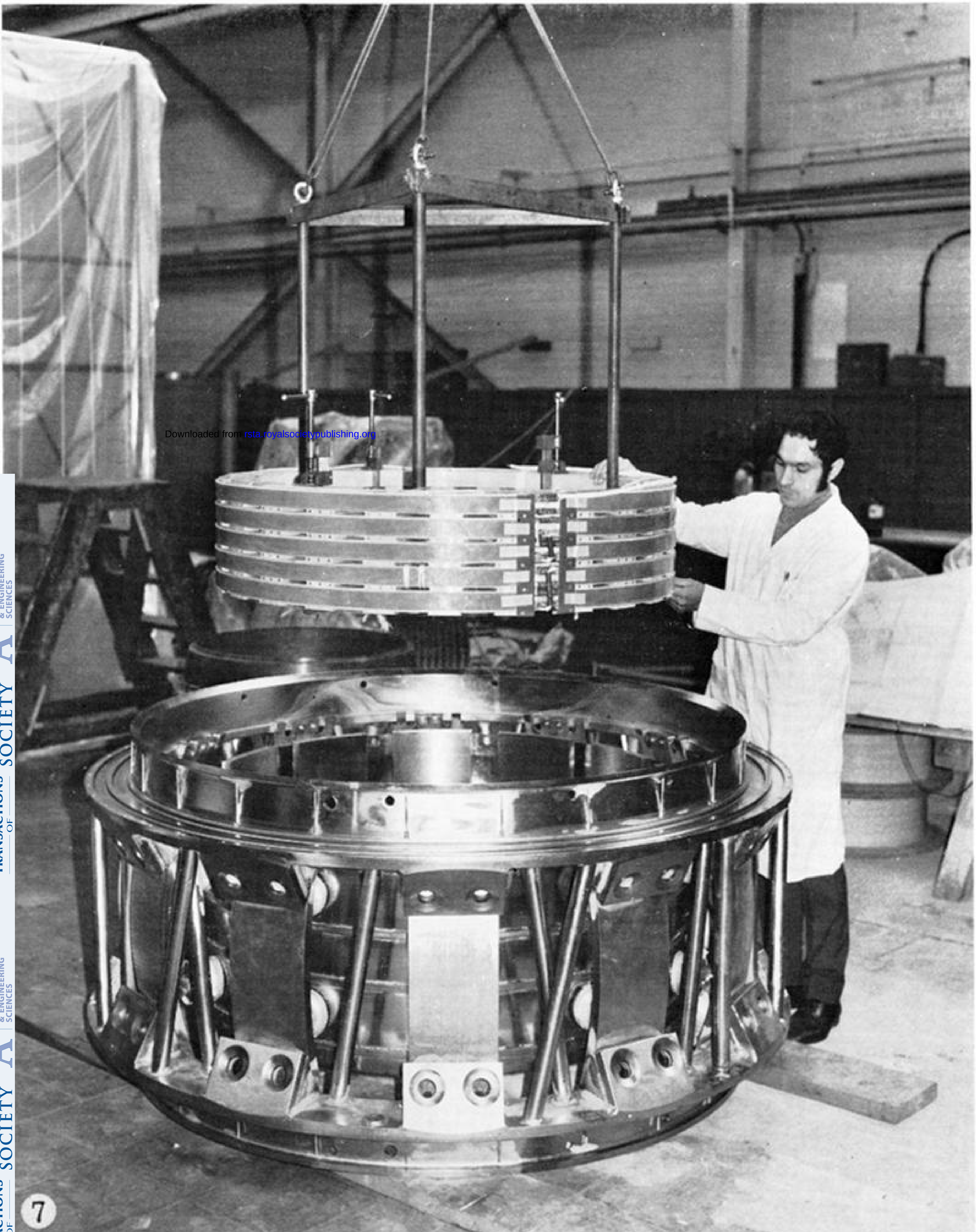

FIGURE 7. Superconducting d.c. generator field coils being fitted into coil support structure.

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