PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Growth of Turbogenerators

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The growth of turbogenerators

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[Plates 3 to 6]

The paper presents a general view on the growth of turbogenerator unit ratings. Evaluation of some of the parameters particularly important to growth of unit power output shows that further and substantial increase of unit rating is to be expected. Technological problems of increasing unit output are discussed for 2- and 4-pole generators, with mention of the possibilities and limitations of mechanical, electrical and thermal utilization. The present state of the author's company in turbogenerator manufacture is illustrated by short descriptions of the 722 MVA–3600 rev/min Cumberland generators for Tennessee Valley Authority and the 1333 MVA–1800 rev/min Cook generator for American Electric Power as well as the supercharged hydrogen-cooled generators and generators with complete liquid cooling for the gigawatt range. The prospects of using superconducting rotor windings to achieve highest unit power outputs in the future are discussed.

1. Introduction

Since 1898, when Charles Brown commissioned his first 6-pole 100 kVA turbogenerator at Brown Boveri (Abegg & Rauhut 1971), the unit ratings of these machines have increased to 1300–1500 MVA, a factor of increase of 15000 in 75 years. During the last 20 years there has been a steady increase of unit ratings from 150 to 600 MVA in Western Europe and even to 900 MVA in the U.S.A. The first 1500 MVA unit in the Biblis power station of the Rheinisch Westfälisches Elektrizitätswerk, manufactured by the Kraftwerksunion, and the 1635 MVA generator for the R.W.E. manufactured by the author's company, will close the unit rating 'gap' between America and Western Europe (see figure 1).

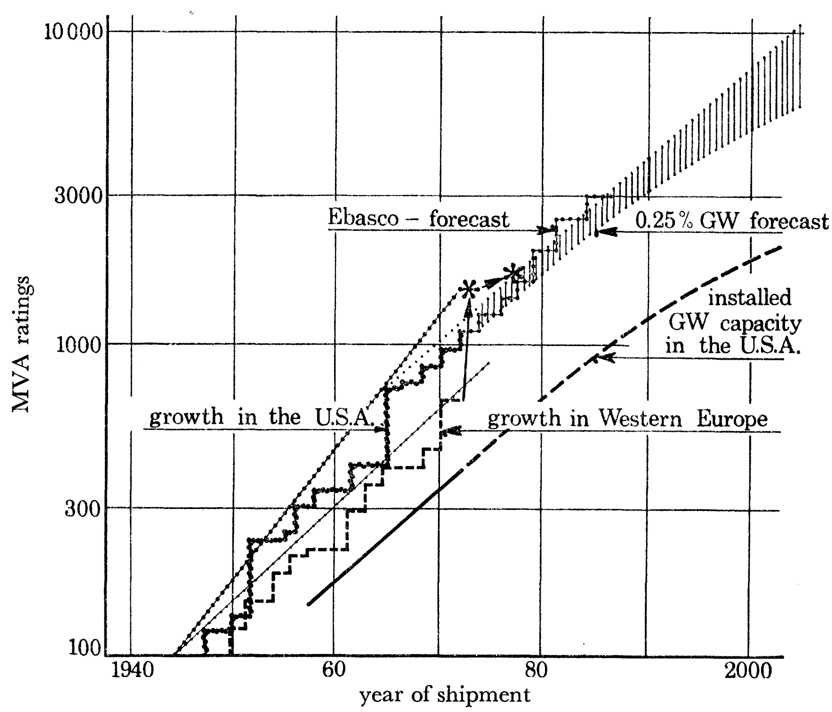

Figure 1. Prediction of turbogenerator unit ratings 1970–1990 (2000).

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In view of such growth rates of 7 to 11 % per year there arises the controversial question of what future growth of unit ratings to expect. In 1968, H. R. Bennet forecast 3000 MW units in the year 1987; that is a growth rate of 7 %. In the last 10 years the maximum MVA unit ratings have been around 0.25 % of the total installed GW capacity in the U.S.A. Prediction of future unit ratings, based on the forecasts (Kroms 1971) of the growth of American installed capacity, is more pessimistic, but agrees well with the estimate of G. Hurlbert in (Paramarcos 1972) (1984: 2000 MW, 1987: 2500 MW).

To make a realistic forecast the following six factors seem to be of greatest importance:

the increase of total energy consumption and the proportion of electric energy;

the trend towards grid interconnexions and the resulting future sizes of power systems;

the overall efficiency and the specific costs of power station as a function of unit rating;

the reliability and availability of the main energy converters: boilers and reactors, turbines and generators;

the environmental considerations; and

the technical development, manufacturing capacities, transport possibilities.

These parameters have partly a stimulating, partly a damping influence on the future growth of turbogenerators. Considering these influences a further but perhaps less rapid increase may be expected to about 1900 to 2000 MVA in the seventies and 2200 to 2500 MVA in the eighties. Prediction for 1990 or even 2000 with possible unit ratings of 3 to 5 GWA are still very uncertain. In what follows a general view will be given of the means, limits and possibilities in the technical and manufacturing field to increase unit ratings of turbogenerators with a maximum guarantee of adequate and safe electric power production in the future.

2. Technological problems in turbogenerators

The technological problems in turbogenerator design and manufacture are mainly connected with the growth of unit ratings and the increasing utilization of the available materials with regard to their mechanical, electrical and thermal behaviour. From better knowledge of the materials employed and of the loadings in the machine we can keep within the permissible limits and consequently avoid generator outages.

The following sections discuss some important problems in this connexion and draw conclusions and possibilities and limits for the further growth of turbogenerators.

(*a*) *Mechanical utilization*

Increased performance through better mechanical utilization is largely limited by two groups of problems: the available material properties and allowable stresses, particularly in the rotating parts; and the mechanical stability of the machine in which generator and turbine are to be considered as one unit.

The present-day quality of forgings limits the outer diameters of 2-pole rotors to about 1150 mm at 60 Hz and 1300 mm at 50 Hz; for 4-pole rotors these diameters are 1900 and 2200 mm respectively. For rotor end bells of austenitic steel, yield points up to 1.2 GPa (120 kgf/mm^2) are available so that, with suitable dimensioning of the rotor winding, no diameter reduction need be conceded for the end bells; rotor and end bell materials are, strengthwise, very well matched.

Although the forgers themselves strive to improve mechanical strength while maintaining magnetic properties and further progress is to be expected with fibre reinforced materials for end bells, we can scarcely expect a break-through to significantly increased rotor diameters in the near future. The only remaining way, mechanically, to increase unit output is to lengthen the rotor with the following consequences:

increasing rotor deflexion, magnetic pull and excitation of vibrations, particularly higher modes;

different behaviour with regard to vibrations between cold and warm rotor conditions and resulting thermal instabilities;

increasing vibrations of twice rotating frequency caused by anisotropy of the rotor body and its internal damping behaviour; and

instabilities due to the thermo-mechanical behaviour of the rotor winding and increasing influence of the mechanical damping of the rotor winding.

Apart from these, long rotors must run up through many critical speeds, which requires much time consuming balancing during manufacture and commissioning. The rotor should therefore be kept as short as possible.

With 4-pole rotors an additional problem arises: the production of mechanically homogenous forgings, weighing between 200 and 300 t, with minimum rejection risk. Due to large capital investments and technical progress in casting and forging, it is now possible to produce 250 t forgings from 500 t ingots suitable for 2000 MW rotors.

When forging design becomes impossible we may resort to a multi-block rotor construction, using a shrinking or welding technique or a combination of these.

The author's company recently produced a 4-pole multi-block rotor of 210 t finished mass and a total length of 20 m for a 1333 MVA generator by a shrinking process which has proved itself over 40 years in more than 300 rotors (Krick, Wälchli & Hiebler 1972). This rotor consisting of three main sections with 1750 mm diameter, shrunk by a central shaft, had a very low eccentricity and ran very smoothly up to its overspeed of 2160 rev/min (see figure 2, plate 3).

(b) *The electromagnetic utilization*

The electromagnetic utilization influences to a high degree the design and dimensions of: the stator core; the stator winding; and the rotor winding and its excitation. It also influences the operational electrical stability of the machine.

(i) *The stator core*

Through progress in the production of high quality core plate, the last 20 years have seen a 30 to 40% reduction in specific magnetization loss and, thanks to improved permeability, an increase of about 10% in allowable flux density (Abegg & Rauhut 1971). Grain orientation further reduces the specific iron loss to below 1 W/kg.

These improvements have allowed a decrease in the stator core outside diameter, which has eased the transport problem. However, the resulting reduction of the stator yoke increases the radial core vibration of twice nominal frequency, caused by the rotating magnetic field. The stator cores of highly rated 2-pole generators are therefore mounted on springs which reduce by a factor of 10 the vibrations transferred to the foundation (see figure 3). Increasing unit ratings bring difficult technological problems, not only in the active part of the machine, but also in the form of a number of parasitic side effects. Typical of these are end region problems, i.e. effects on the stator core ends, the stator end windings and their shields. With growing current loading the end region fields acquire considerable magnitude in all directions, penetrating active and passive parts and causing additional losses and heating, especially through concentration on places with discontinuities. This results in harmful secondary effects during normal operation, i.e. reduced efficiency and occurrence of hot spots in the core with the danger of burn-out, and during abnormal operation such as under-excited or asynchronous running.

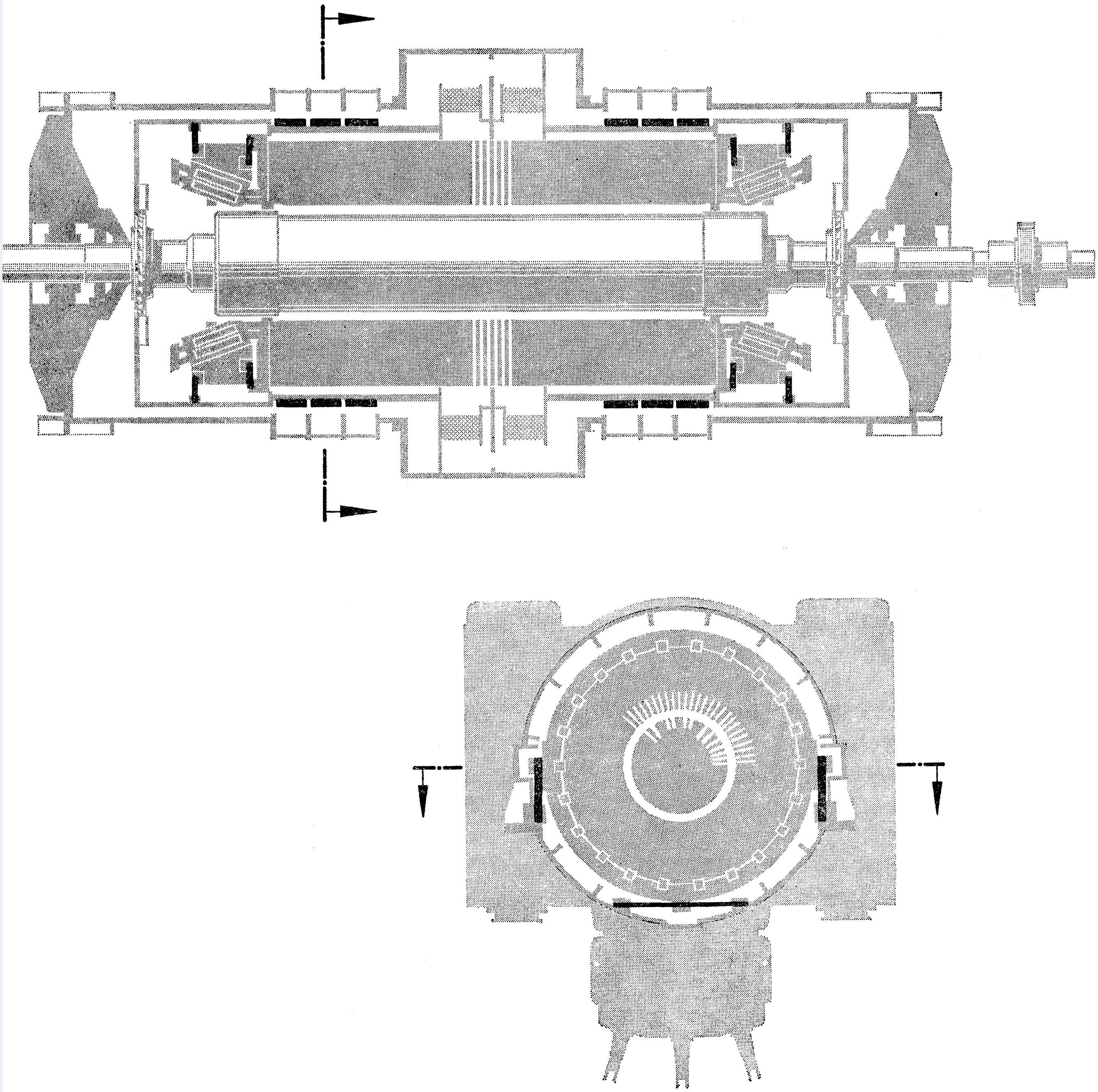

FIGURE 3. Springmounted stator core and end winding supports in 2-pole generators.

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Conventional stator core press plates, with or without shielding, have the disadvantage of a discontinuous transition from airgap to end region space with consequent local field concentrations and hot spots. For highly rated generators the author's company therefore uses conical end plates made of resin-bonded core laminations (see figure 5, plate 3). Measurements on generators up to 670 MVA show that the favourable introduction of the end field into the press plate results in relatively small loss densities in the end regions with a temperature rise of a few 10 °C (see figure 4).

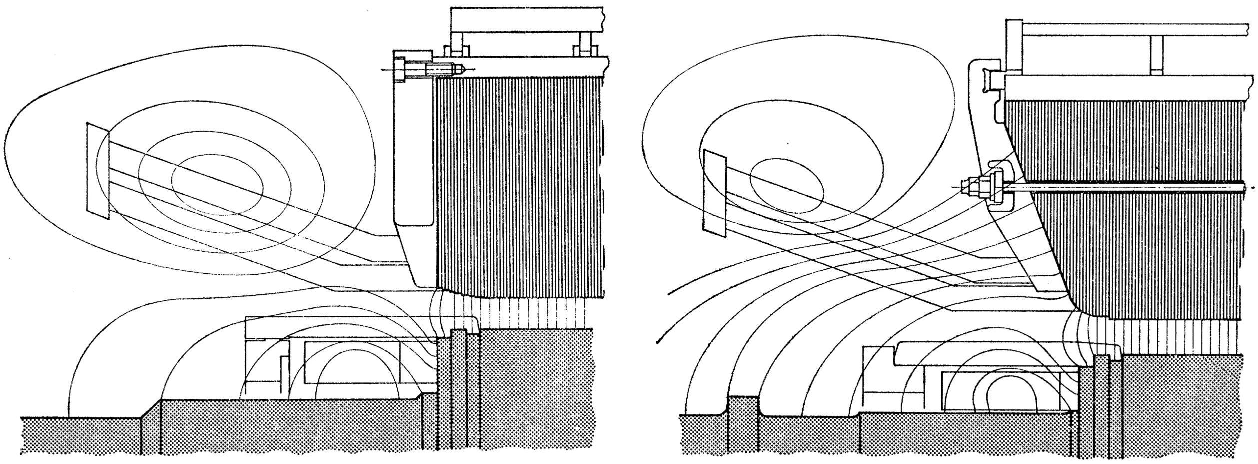

FIGURE 4. Longitudinal stray field distribution in the end region of turbogenerators at nominal rating pF = 0.85. On the right: conical laminated core end section, and on the left: solid pressplate with complete shielding effect.

(ii) *The stator winding*

With rising unit ratings the demands on stator windings resulting from higher dielectric, thermo-mechanical, vibration and short circuit loadings are increased considerably. Since its invention in 1912 the Roebelbar has firmly established itself as a simple and reliable conductor element. Of special advantage is the possibility of using the Roebel principle with liquid cooled conductors; this permits the construction of many forms of bar by the same production method (Müllner 1962). The Roebelbar will certainly continue to be used for generators in the gigawatt range (see figure 6, plate 4).

With increasing generator ratings standard pre-war insulations based on shellac and asphalt, partially gave trouble with creeping phenomena and tape separation. In the early 1950s a thermo-elastic insulation system based on formica–glass–epoxy was developed; this has outstanding dielectric and thermo-mechanical properties and has proved itself by its use in all big machines for over 15 years. Vacuum impregnation and moulding in special presses achieves an insulation wrap of excellent homogeneity, with high electrical and thermomechanical strength suitable for temperatures up to class F (155 °C). The extremely good discharge and ageing resistance allows for operation voltages up to 30 kV and even higher (Schuler 1970).

Despite the outstanding mechanical properties of modern insulations, the steady increase in vibration and short circuit loadings of the stator winding demands the greatest care in the design and construction of the stator winding system. In the last 20 years current loadings have increased by a factor of 2.5 and the product of current loading and current density by a factor of 10 (Abegg & Rauhut 1971). This has caused a considerable increase in the double-frequency vibration load on the stator bars, both in the slots and in the end winding regions.

Through improved techniques of wedging the bars in the slots, proved in 1:1 model tests, present-day current loadings may be even further increased with no bar vibration problems (see figure 7, plate 4).

The increasing magnetic fields in the end winding region cause greater circulation losses in the subconductors of the stator bar and excite vibrations which could mechanically damage the end windings. By twisting the stator conductors through 180° in the end winding portion in addition to the Roebel transposition of 360 or 540° in the slot, the effects of the three parasitic fields in the end winding regions can be compensated and the total stator conductor losses considerably reduced, in extreme cases halved (Vögele 1970 and figure 8).

The ability of the end winding to withstand vibration and short circuit forces is greatly enhanced by a special support system, the result of lengthy studies which allows axial expansion

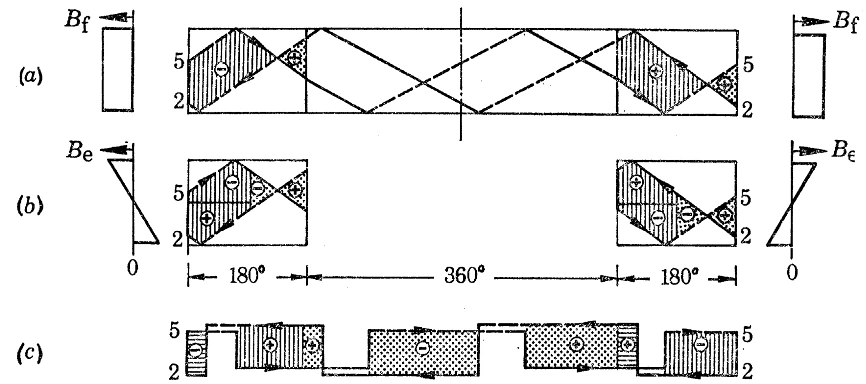

FIGURE 8. Roebel bar with 360° transposition in slot region and 180° transposition in overhang: (*a*) compensation only of constant component of non-inherent transverse field (B_f) in overhang; (*b*) compensation of the inherent transverse field (B_e) in the coil end; (*c*) compensation of constant component of radial field in overhang.

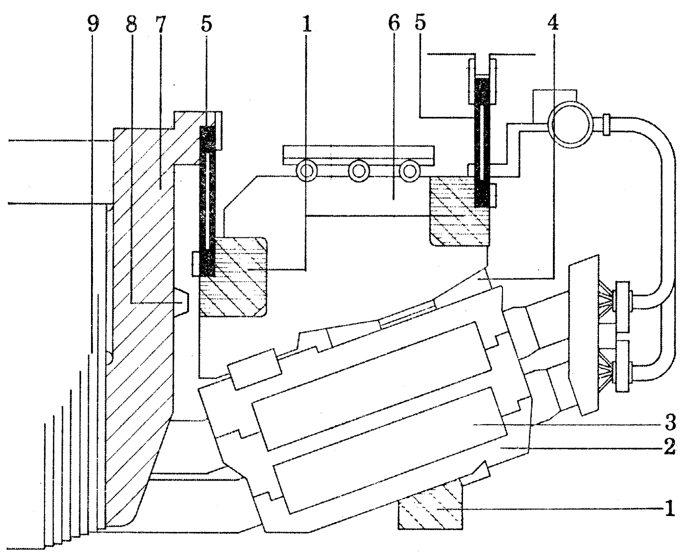

FIGURE 9. Principle of flexible end winding supports: 1, support rings; 2, plates and spacers; 3, end winding; 4, wedge with tension bolt; 5, spring leaves; 6, bracing plate; 7, core end press plate; 8, axial stop; 9, stator core.

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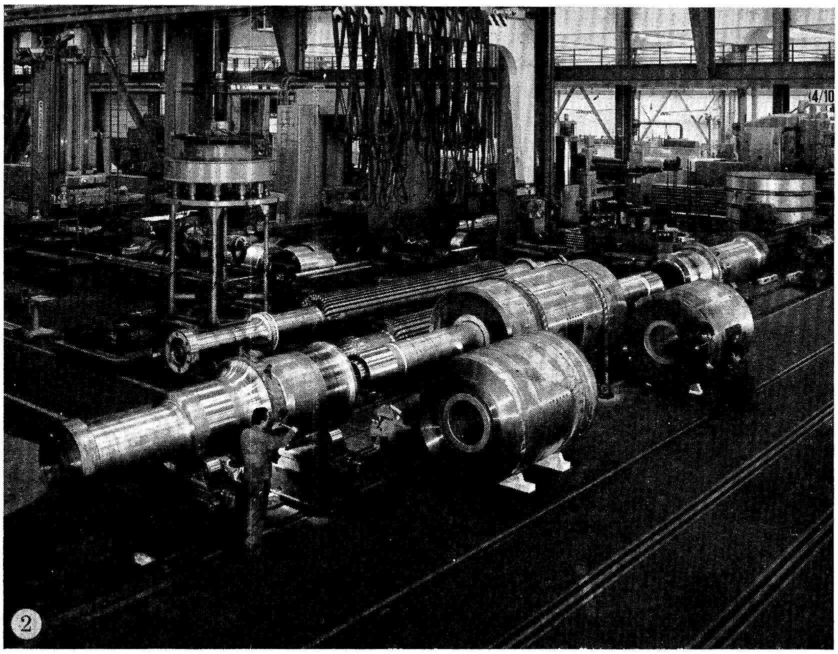

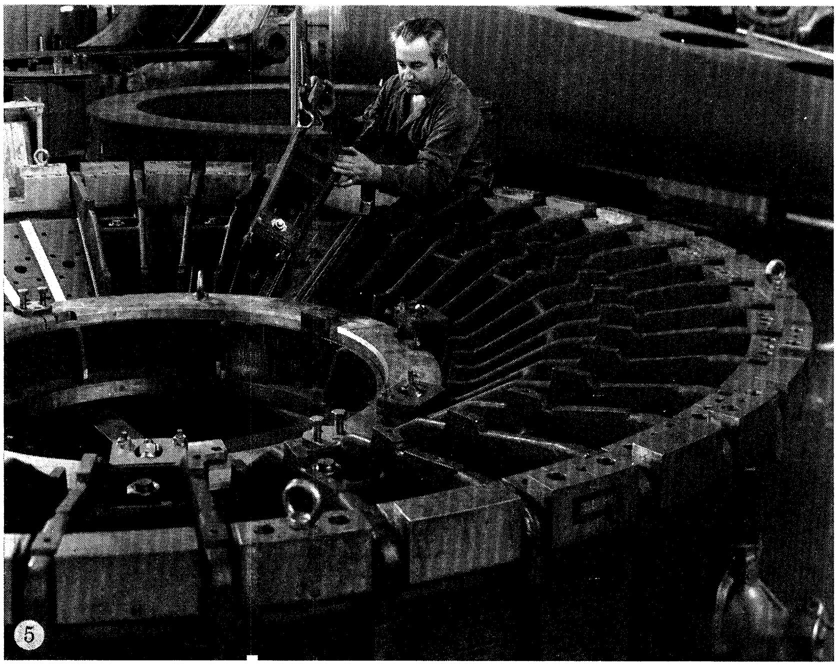

FIGURE 2. Multi-block rotor for 4-pole generators 1333 MVA/1100 MW consisting of one centre-body piece, two end-body pieces and a central shrink shaft with two shaft ends.

FIGURE 5. Conical core end section of resin-bonded stator laminations.

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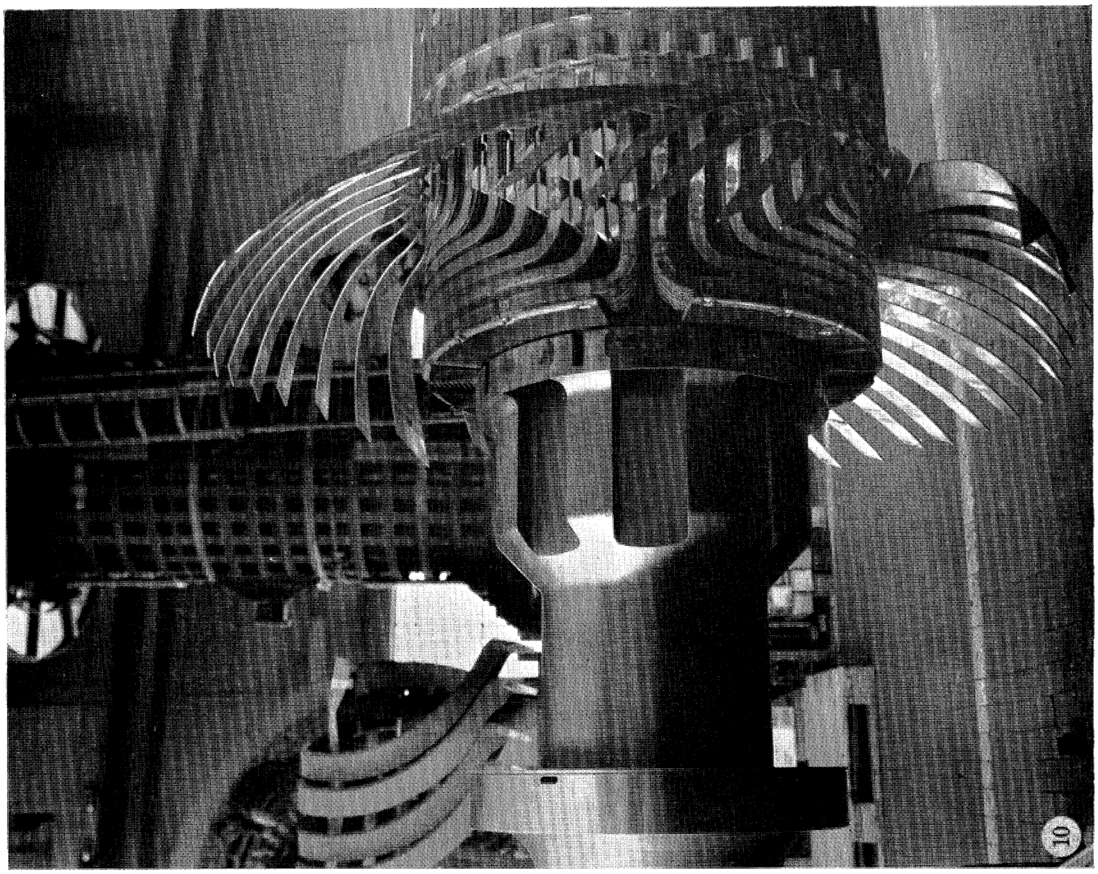
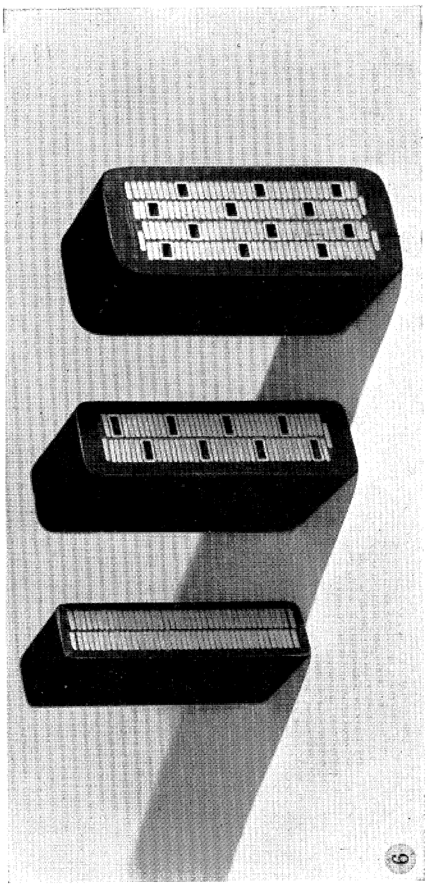


FIGURE 10. Damper winding for turbogenerators.



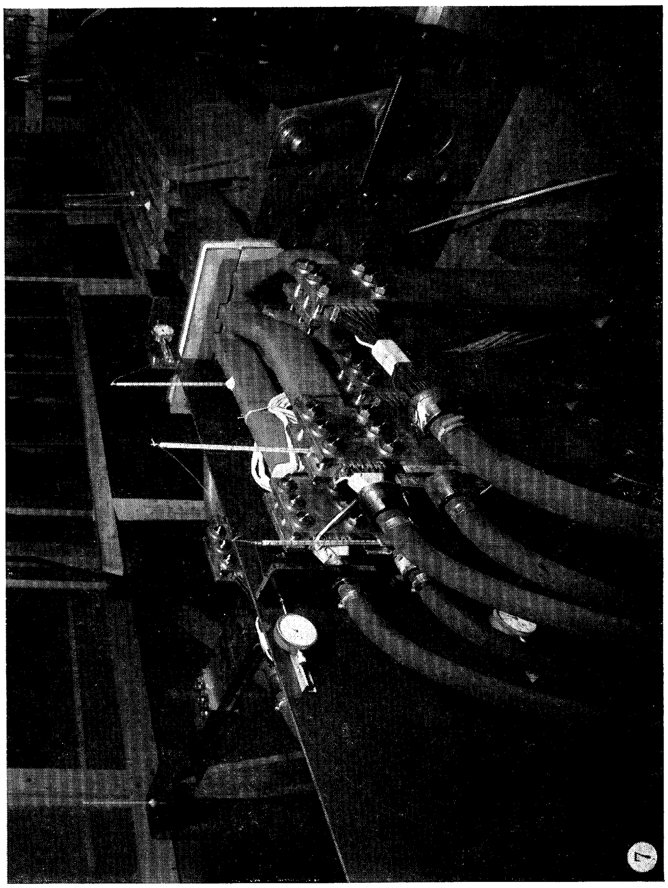


FIGURE 6. Roebelbars for indirect gas cooling and direct water cooling.

FIGURE 7. Full-scale model for testing of stator bars for turbogenerators of over 1000 MW.

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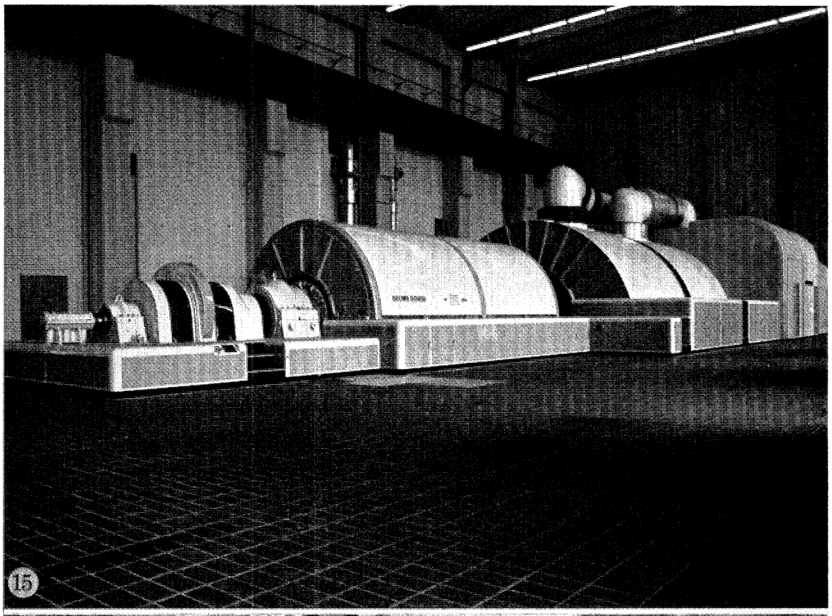

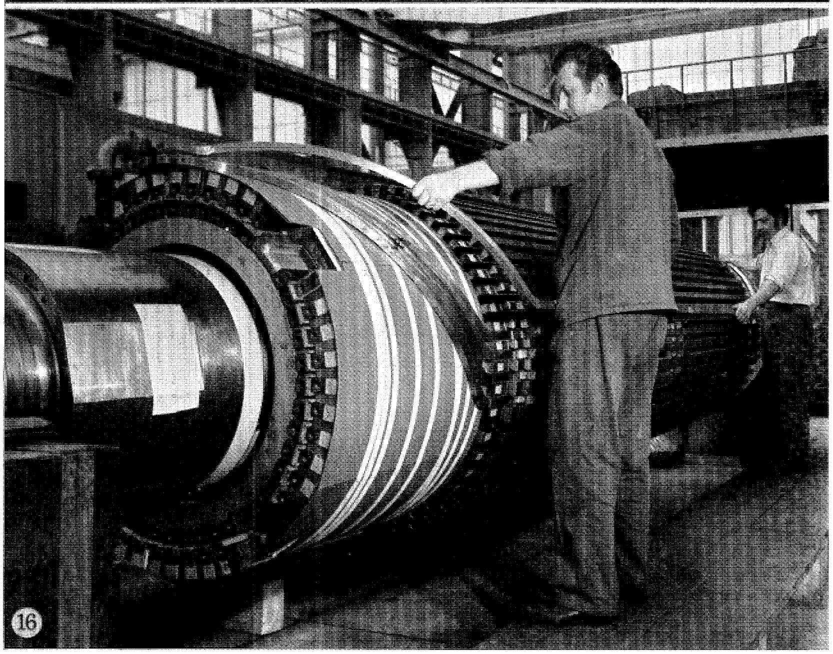

FIGURE 15. Turbine generator Skaerbaekvaerket with completely water cooled generator (330 MVA, 18 kV, 3000 rev/min).

FIGURE 16. Turbogenerator rotor with water cooled field and damper winding.

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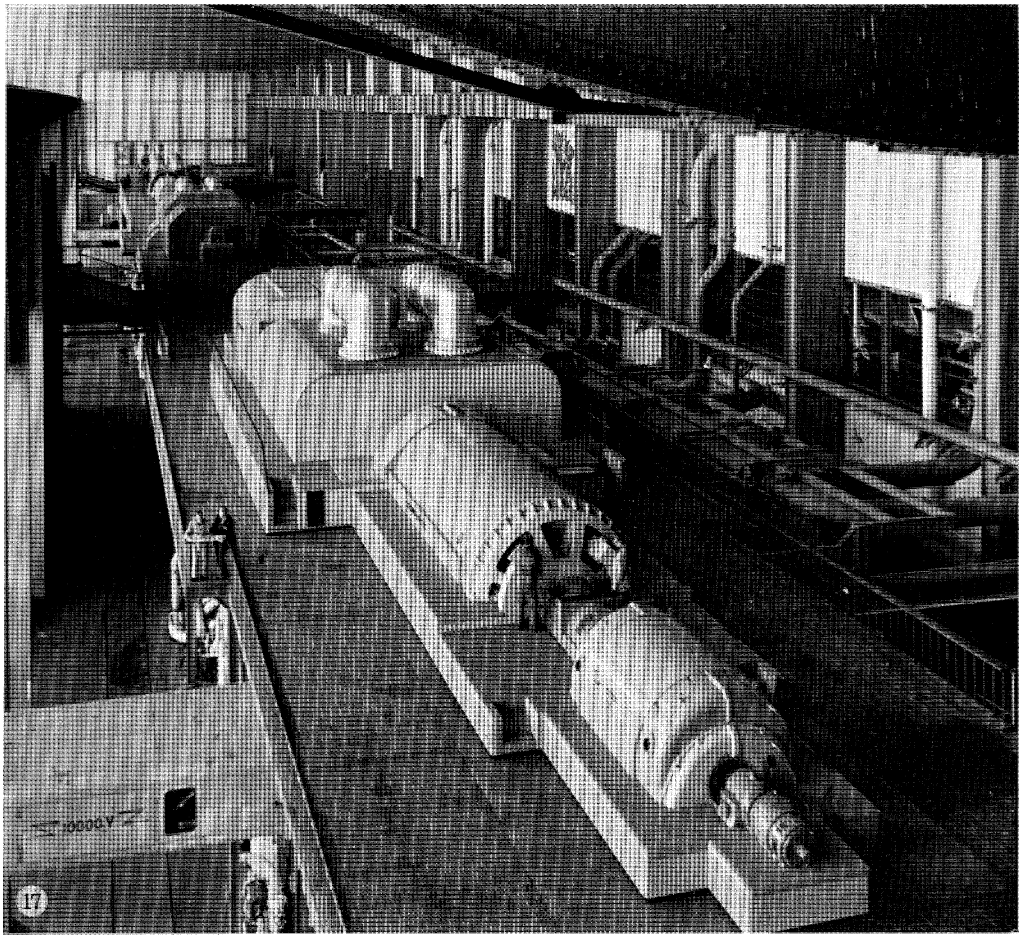

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FIGURE 17. Turbine generator Amer V with oil cooled generator core and stator winding (254 MVA, 12 kV, 3000 rev/min).

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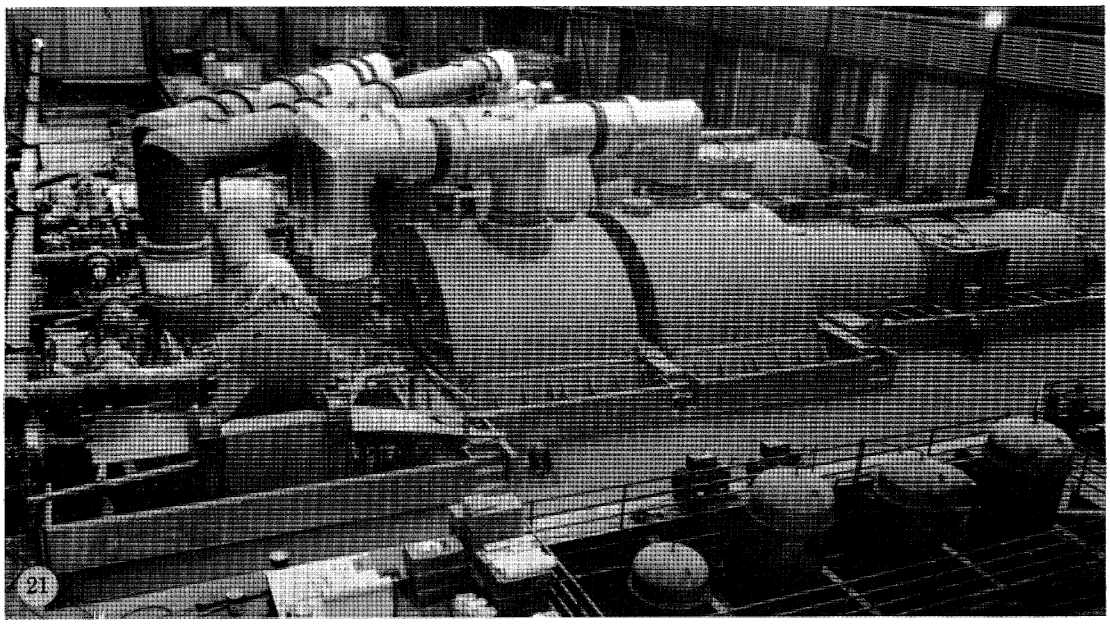

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FIGURE 21. Cross-compound turbine generator Cumberland of TVA 1300 MW, 60 Hz.

of the stator winding while securely supporting the end winding radially and tangentially (Herrmann 1965 and figure 9).

Resin impregnated support elements which adjust themselves to the winding contour form after polymerization a strong vibration resistant support network.

(iii) *The rotor winding and its excitation*

Whereas in the stator the dielectric problems are of great importance, the main rotor winding problem is to meet the extraordinarily high mechanical stresses (up to 200 MPa; 20 kgf/mm^2) that the winding copper and its insulation must support. The use of hard drawn, silver bearing

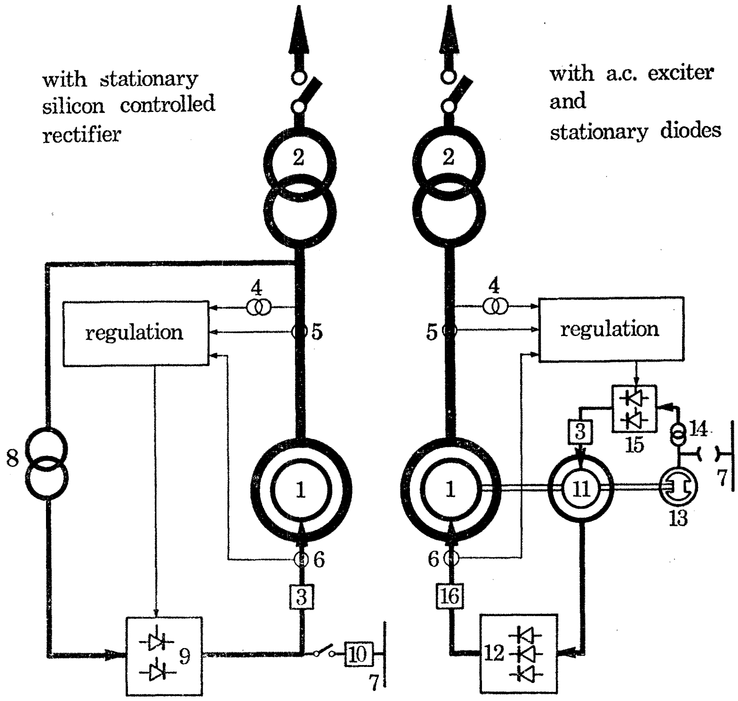

FIGURE 11. Excitation systems for large turbogenerators. 1, turbine generator; 2, unit transformer; 3, field discharge+overvoltage protection; 4, main voltage input; 5, main current input; 6, excitation current input; 7, auxiliary supply; 8, generator field transformer; 9, thyristor converter; 10, starting excitation device; 11, a.c. main exciter; 12, diode converter; 13, pilot exciter with permanent poles; 14, main exciter field transformer; 15, thyristor converter for main exciter field; 16, overvoltage protection.

copper and insulation of glass, asbestos and epoxy or Nomex, together with direct cooling systems have lessened the problem of thermo-mechanical creeping and will form the basis for further unit rating increases.

In its large generator rotors the author's company uses continuous damper windings to protect the rotor winding and end bells from the effects of system transients and to increase the negative sequence i_2^2t capability in the case of unsymmetric loads (see figure 10, plate 4).

Excitation whose power requirements is in the megawatt range requires special attention as unit ratings increase. Two principles are available: excitation by either rotating or stationary semiconductor rectifiers (see figure 11).

For turbogenerators of over 125 MW ratings, the author's company prefers excitation by stationary rectifiers, either fed directly from the generator terminals or from an a.c. exciter. For normal power systems with short-circuit durations of up to 1.5 s excitation from the generator terminals, through stationary thyristors and slip rings, is used. This has the advantage of high speed of response, short length of machine, low noise level and minimum maintenance requirements. For power systems with longer short-circuit durations, separate a.c. exciters with stationary diodes are employed giving reduced exciter response and a longer machine. Both of these systems can be used at even higher than present rating. Field currents in excess of 10 kA are transferred to the rotor by means of water-cooled slip rings with high reliability and minimum maintenance requirement.

(iv) *Electrical stability*

The static stability of a generator is strongly influenced by its short-circuit ratio. Whereas short-circuit ratios in the range 0.5 to 0.6 have been usual up till now in the U.S.A., the significantly smaller values of 0.35 to 0.4 for Western Europe, have given no stability problems. Further grid interconnexions and the use of faster turbine and generator regulating systems will permit lower short-circuit ratios of about 0.4 for large machines in the U.S.A. Worse utilization of generators for reasons of static stability will be necessary only when extremely long-distance power transmission is involved.

Increasing material utilization in large turbogenerators pushes up the subtransient and transient reactances which in turn reduces the dynamic stability. The transient reactances of 4-pole 2000 MVA units will be around 40 to 50 %, whereas those of 300 to 600 MVA 2-pole machines are about 30 %. The deterioration in dynamic stability of large machines can be offset by the use of quicker acting thyristor excitation systems with additional damping derived from pole angle deflexion. The dynamic stability problems would be greatly eased by the introduction of cryogenic generators with superconducting rotor windings, in which synchronous reactances are reduced by a factor of about 5 and the transient reactances again have values of about 30 to 40 % customary in generators of the MVA range with conventional cooling.

(*c*) *The thermal utilization*

Large turbogenerators have efficiencies approaching 99 %: we cannot therefore expect generators to contribute much to the further improvement of overall power station efficiency. Nevertheless, the battle against generator losses will continue unabated. 1 % loss in a 2000 MW generator amounts to a by no means insignificant 20000 kW of internal heating which can damage the machine and reduce reliability and which must be removed by suitable cooling processes. Steadily improving knowledge of the density and location of losses and progress in cooling techniques, from gases via liquids to cryogenics in the future, form the basis for impressive increases in unit ratings and in specific ratings per unit mass (see figure 12).

Through loss optimization and the change from gas to the 1000 times more efficient liquid cooling, specific ratings have doubled in the last 20 years, and will probably increase by a further 50 % in the next 10 to 15 years. Although practical experience on large liquid-cooled generators will push the unit rating limits to higher values, generator manufacturers are already considering what to do when the most effective liquid coolants are fully utilized. The main problem is with the rotor, and there are two possible solutions: increasing the admissible temperatures in the critical bottleneck, the rotor, or reducing the rotor temperatures by more efficient cooling systems.

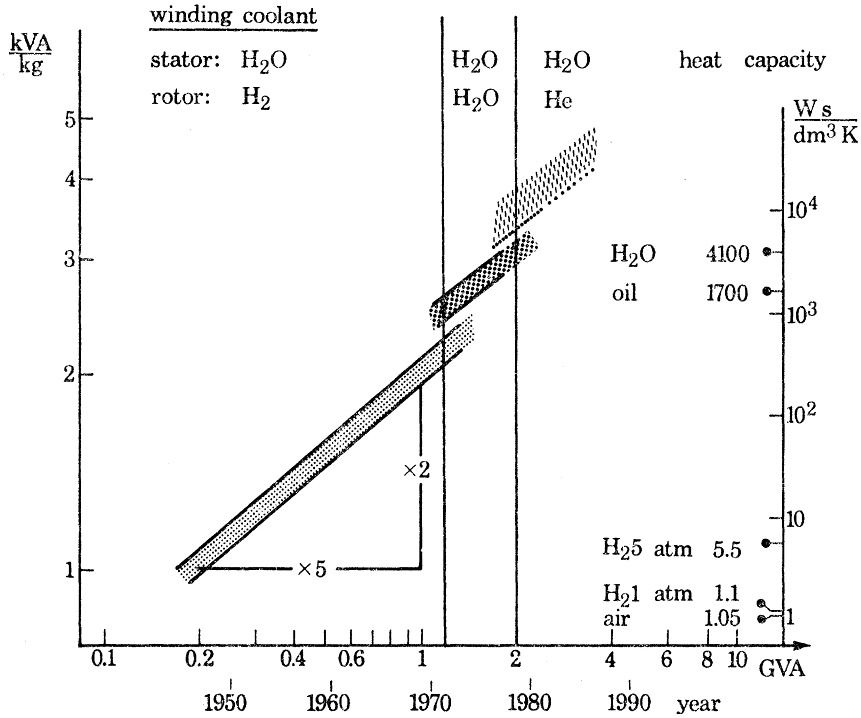

FIGURE 12. Growth of specific output (kVA/kg) of 2-pole generators, 60 Hz.

Higher rotor temperatures cannot be considered because of: difficulties in the development of insulation systems for higher temperatures and relatively high voltages with adequate mechanical strength; thermal stability of the rotor; and copper losses rising steeply with increasing temperature.

The use of lower rotor temperatures will be the only solution. But the costs of removing copper losses of more than 5000 kW with refrigerators will be so high that a break through to superconducting rotor windings with zero energy losses will be necessary. Possible specific ratings with superconducting rotor windings will depend very much on future developments in cryogenics, superconductivity and low-temperature materials. The studies of the author's company show that specific ratings will more or less follow the trend to date; in view of the mechanical limitations of presently available materials (brittle fracture) substantially greater improvement can scarcely be expected in the near future. Also I cannot endorse optimistic forecasts of substantial reduction of specific generator costs for superconducting machines. Considering the technical problems still to be solved I think that it will already be a real success if the electrical energy, required until the end of this century, can be produced by cryogenerators of approximately the same specific cost as present days' liquid-cooled machines.

Figure 13 shows the loss distribution as a percentage of the total losses for 2-pole 50-cycle generators of 1200 MVA/1000 MW, using various rotor cooling methods. The change from hydrogen to water cooling of rotor windings has allowed a lower temperature rise and a better balanced temperature distribution with even more than 20 % increase in rotor losses. Conventional water cooling of the stator winding can certainly cope with the increased stator winding losses from 24 % with hydrogen-cooled rotors to 30 % with water-cooled rotors. Despite increased utilization the fraction of losses in the stator core decreases from 9 % with gas rotor cooling to 8 % with water rotor cooling to 7 % with superconducting rotor windings;

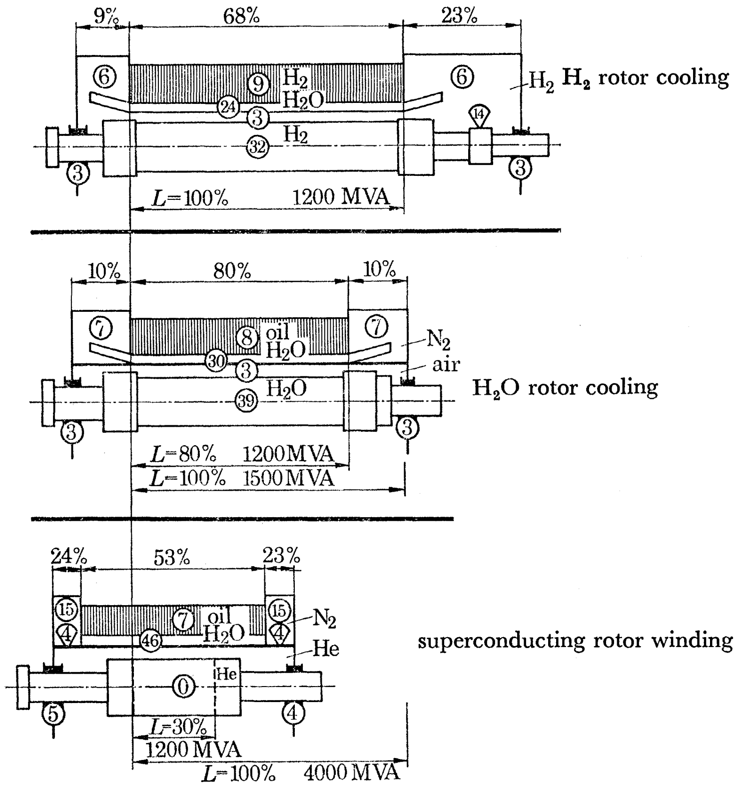

FIGURE 13. Basic dimensions and percentage loss distribution within 1200 MVA 2-pole generators, 50 Hz, with hydrogen and water rotor cooling and superconducting rotor winding. H_2 rotor cooling: (32) rotor Cu losses; (24) stator Cu losses; (9) stator iron losses; (3) surface losses; 2 × (6) losses in end winding regions; (14) ventilation losses; 2 × (3) bearing losses.

the corresponding increase of the loss share in the end winding region is clearly seen, increasing from 6 % through 7 % to 15 %, a clear indication of the increasing technical problems in the end winding regions with increasing unit ratings. The share of ventilation losses in the hydrogen cooled machine is 14 % and falls to almost zero in totally liquid cooled generators. Reductions in active machine length of about 20 % with liquid cooling and 70 % with superconducting rotor windings help to meet the demand for shorter, smoother running rotors.

Figure 14 shows the loss distribution in 4-pole 50 Hz generators of 1600 MVA/1400 MW with hydrogen, water and helium rotor-winding cooling.

In hydrogen cooled machines approximately 70 % of the total losses are removed by hydrogen; in liquid cooled and cryomachines practically all losses are removed by liquids.

The loss distribution in totally liquid cooled 2-pole generators according to the author's company design indicates three different intensity levels: the stator and the rotor windings with approximately 70 % of the total losses; the stator core and the end regions with about 20 %, and the surface and the bearing losses of about 10 %.

According to their intensity level these three regions are cooled by the most suitable agents: direct water cooling in the windings; direct oil cooling in the stator core and end plates; direct water cooling and nitrogen, as an inert gas, in the end winding regions according to the loss densities; water cooling of the inside of a glass-epoxy airgap cylinder which separates rotor and stator spaces, allowing the rotor to run in air with minimum ventilation and friction losses (Wiedemann 1968). The bearings have the usual direct cooling by oil.

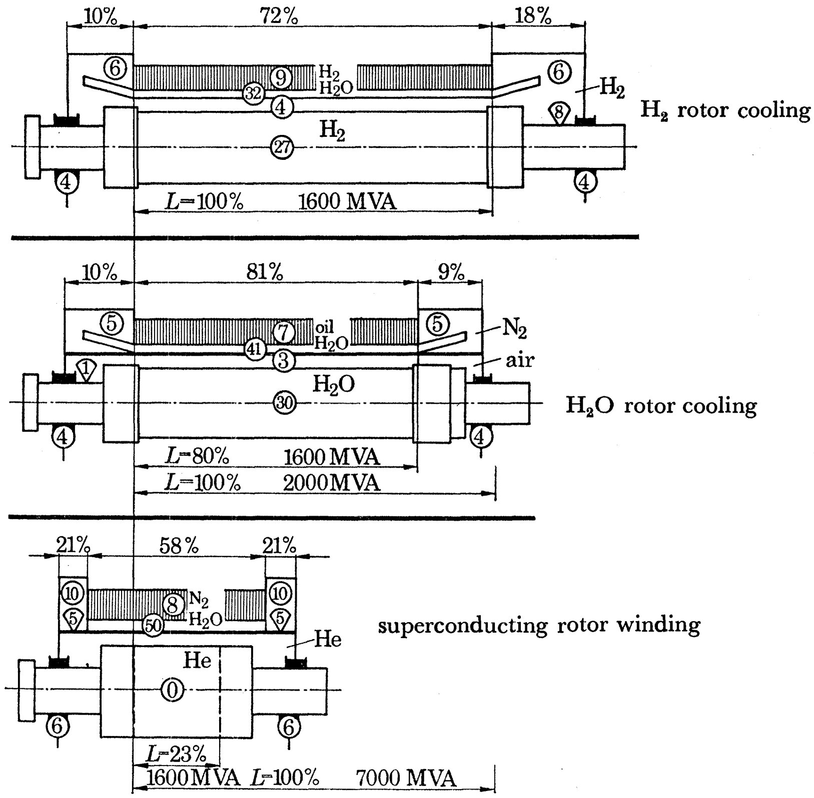

FIGURE 14. Basic dimensions and percentage loss distribution within 1600 MVA 4-pole generators, 50 Hz, with hydrogen and water rotor cooling and superconducting rotor winding.

The first Brown Boveri generator of 330 MVA, 3000 rev/min, with direct water cooling of the rotor was delivered in 1970 to Skaerbaekvaerket in Denmark (see figure 15, plate 5).

The main advantages of totally liquid cooling are:

Elimination of hydrogen with all its complications in design, manufacture and operation.

Simplification of stator casing, reduction of stator outside diameter and mass, thus facilitating the stator transport.

Excellent running behaviour of the rotor in both steady state and transient conditions, i.e. during power fluctuations and rapid starting. Prototype tests showed that even large amounts of leakage water do not effect the rotor vibrations.

No influence of rotor leakages to the stator, due to the airgap cylinder, thus no need to shut down the machine in case of unexpected leakage in operation.

Easy accessibility of the stator active parts even during operation (Noser & Pohl 1971; and figure 16 plate 5).

Tests with hydrogen, oil and water cooling of stator cores proved the superiority of oil as a coolant. The first Brown Boveri turbogenerator of 254 MVA, 3000 rev/min, with oil cooling of the stator core has given trouble-free service at the Amer power station in Holland for over 10 years (see figure 17, plate 6).

Oil has the following advantages over hydrogen or water as a core coolant: its heat capacity is similar to that of water, i.e. 1000 times better than hydrogen; it is electrically insulating and unlike water can be put in direct contact with the stator laminations; and in the event of core vibration oil serves as an excellent damping agent.

Running experience with the Amer generator has shown that the amount of oil leaking from the core is very small and due to the airgap cylinder does not interfere with machine operation. So, for the construction of reliable stator cores for generators in the gigawatt range, a design feature is available which has proved itself over several decades in transformer design up to the highest ratings.

The principle of using optimum cooling agents for every machine part leads in the future to cryogenerators with liquid helium cooled superconducting rotor windings. Superconductivity will permit the present flux density limit of 2 to 2.5 T in the rotor iron to be exceeded considerably and at the same time to forego the ferromagnetic properties of steel. This allows current loadings and power density to be increased considerably with practically no change in subtransient and transient reactances and no deterioration in electrical stability. Following the liquid cooling concept the author's company is evaluating the economics of superconducting generators and developing the technological bases for the production of future cryogenerators.

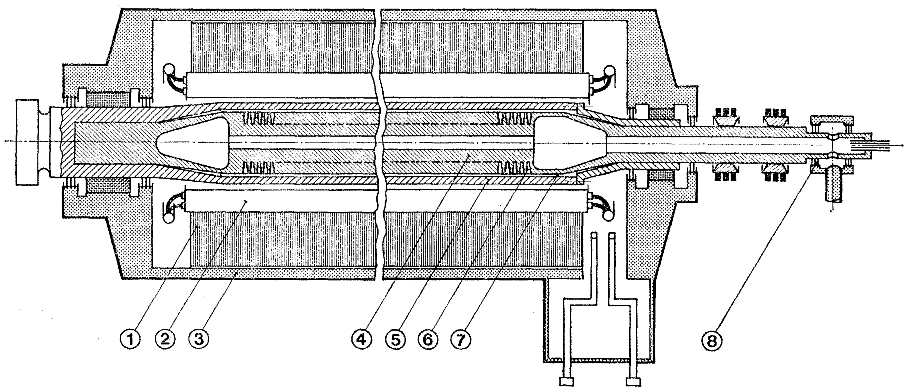

Figure 18. Basic design of a cryogenerator with superconducting rotor winding. 1, laminated iron shield; 2, stator conductors and supporting structure; 3, stator housing; 4, inner rotor; 5, damper cylinder (outer rotor); 6, superconducting winding; 7, rotor thermal insulation (vacuum); 8, rotor vacuum seals.

Figure 18 shows the basic lay-out of a cryogenerator with a superconducting rotor winding. The rotor is a rotating Dewar vessel containing a field winding of NbTi which is kept superconductive by liquid helium at 4 to 5 K. The cold rotor interior is thermally insulated in the radial direction by a vacuum space and a radiation shield and in axial direction by mechanical connexions to the shaft with a high thermal resistance. The rotor outer cylinder is designed as an electrical damping screen and protects the rotor winding from transient influences of the stator. The material and dimensioning of this cylinder poses special problems since it might also support high torques and radial and tangential forces on short circuit.

The stator winding lies completely in the air gap and is directly water cooled. It is fully exposed to high value tangential and radial fluxes and special measures are necessary to minimize the resulting winding losses. The stator winding support structure must be of a non-magnetic material and must resist high short-circuit forces and steady state fatigue loads.

A special problem is the shielding of the immediate surroundings from the strong magnetic fields; there are two possible solutions: the best rating per unit volume is achieved using a shield of laminated magnetic iron; minimum mass per unit volume by using a conducting, e.g. copper, screen which, however, reduces ratings per unit volume to about two-thirds.

The present studies indicate that the remaining technical problems should be solvable within a few years. However, only the future will show at what rating the economic transition from liquid cooling to cryo-cooling lies; the further development of conventional liquid cooling as well as progress in the field of superconductivity and cryogenics will be of decisive importance.

(*d*) *Manufacturing and transport problems*

Figure 19 shows the percentage reduction in material and manufacturing time to produce a total of 1000 MW with either 20 units of 50 MW, 5 units of 200 MW, 2 units of 500 MW or 1 unit of 1000 MW.

The curves illustrate that progress to increased unit ratings is consistent with present-day demands to economize on both raw material and skilled labour. As already mentioned, however, future cost savings in this way may be significantly smaller considering the steadily increasing demand for improved quality of materials and labour as well as for financial investments in research and development and in production facilities.

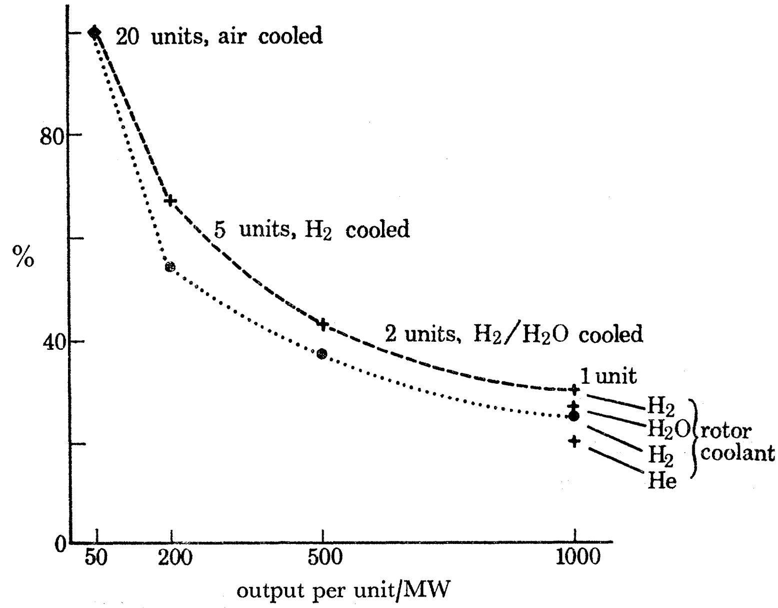

FIGURE 19. Material and manufacturing time required to achieve a total generator output of 1000 MW. +, total mass; ●, total manufacturing time.

Labour and material quality may be improved through: motivation to higher precision work with a high personal involvement of everybody engaged in the production process; and carefully devised systems of quality control which exclude faults and mistakes during manufacture, erection and commissioning.

Unfortunately experience and know-how, the base for such quality control systems, cannot be gathered from theoretical studies and model tests only. For new developments, full-scale prototype tests are essential. We are therefore most grateful to our progress-minded clients who are prepared to accept prototype machines incorporating features which establish future techniques; they do great service both to the industry and to the public in ensuring that the ever-rising energy demand is continuously and efficiently met.

The transportation of increasingly big and heavy generator parts put high demands on transport systems in the factory, in the power stations and for the transport companies. The transport capacity of railway lines in Europe is at present about 420 t with maximum outer dimensions of 4.2 m; this allows transportation of 4-pole generators of up to about 1700 MVA (see figure 20).

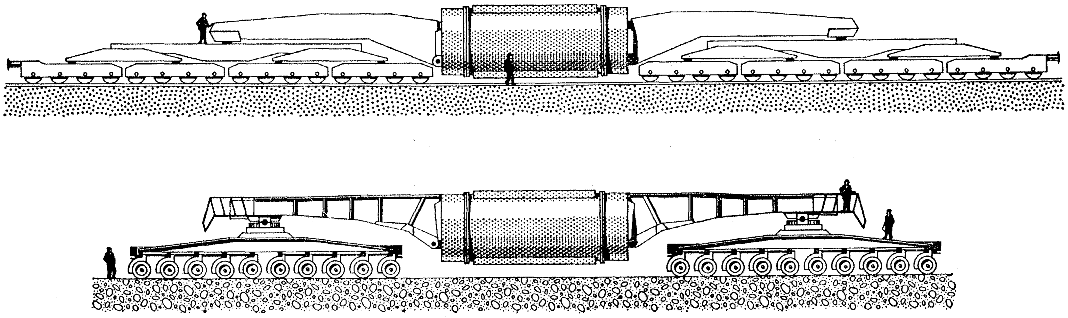

FIGURE 20. Transport facilities for generators: top, railway 'Schnabel' wagon for 420 tons; bottom, special truck for 600 tons by road.

In the U.S.A. a special truck is capable of transporting 600 t by road. The transportation problem is an important factor in the design of turbogenerators but in no way an absolute limitation. Various possibilities for the solution of this specific problem in the future are available, for example: manufacturing facilities situated on riversides with direct transport by roll-on/roll-off ships; multi-piece design of the stator similar to the well-known technique for $16\frac{2}{3}$ Hz railway generators (Abegg 1972); and final assembly in the power station as with large turbines.

3. Latest developments and realizations

On 17 June 1972 the first 1450 MVA, 3600 rev/min, cross-compound turbine generator (shown in figure 21, plate 6), reached the highest ever produced output of 1350 MW in the Cumberland power station of the Tennessee Valley Authority in the U.S.A.

The second set was commissioned in the beginning of 1973. The generator has conventional hydrogen cooling with water cooling in the stator winding (figure 22).

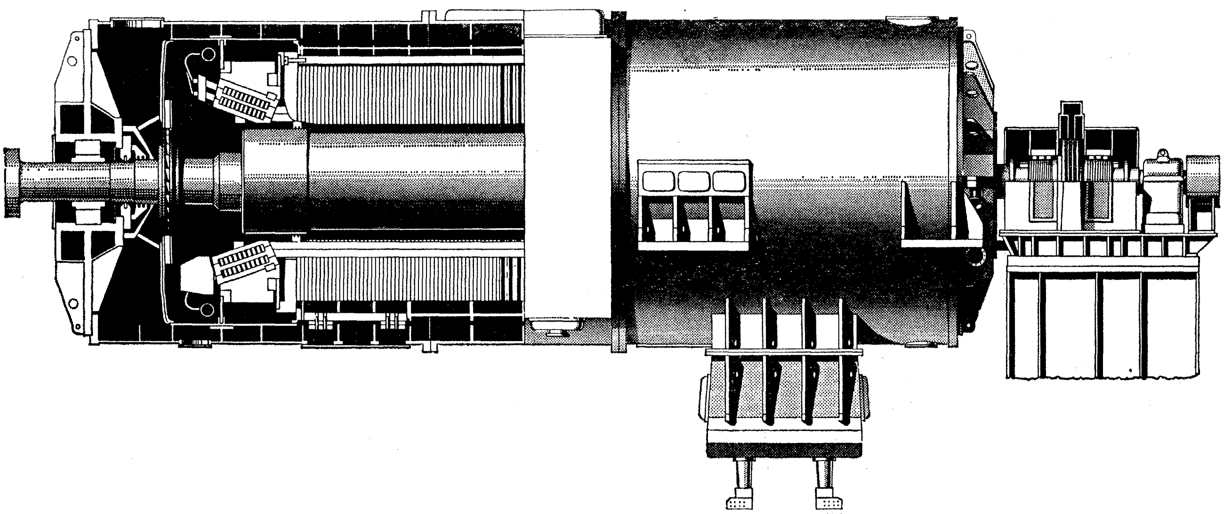

FIGURE 22. Two-pole generator 722 MVA, 22 kV, 3600 rev/min (stator winding: water cooled, rotor winding: hydrogen cooled).

Twenty-four similar generators for the American Electric Power, as well as for different power companies in Europe and Australia, are on the way in manufacture and erection.

For 2-pole generators of 800 to 1200 MVA a design for supercharged hydrogen cooling was developed with a 2-stage compressor on the slip-ring side (see figure 23). The active part could be dimensioned in an optimum way with regard to transportation by means of outside gas piping. In addition, the efficiency of the compressor was substantially increased.

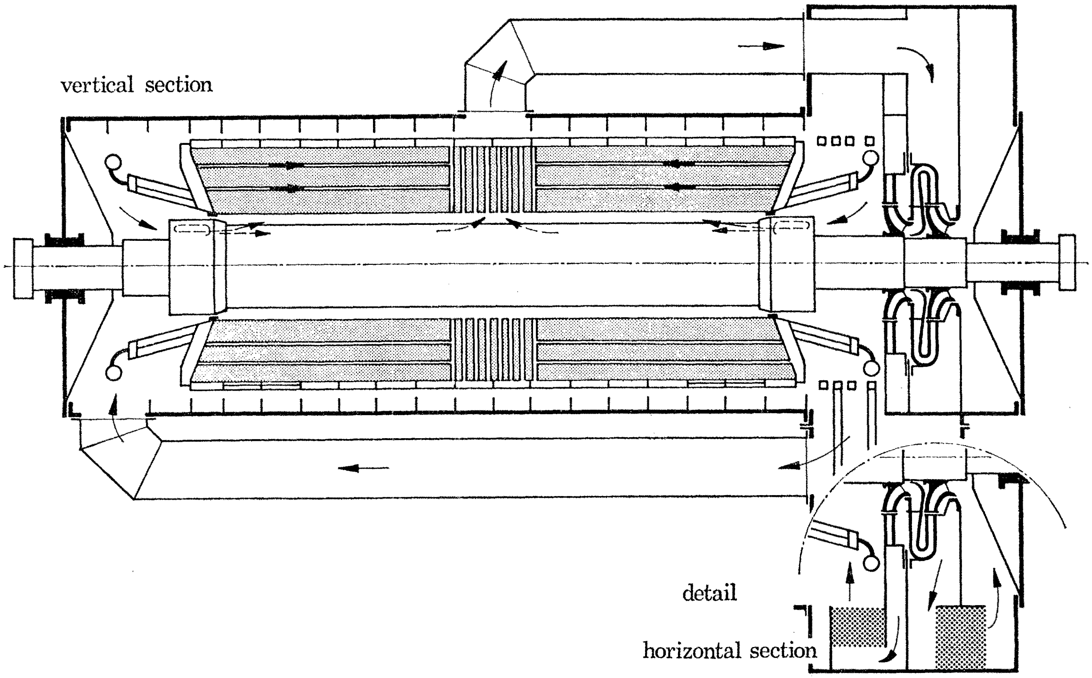

FIGURE 23. Two-pole generator 1200 MVA, 27 kV, 3000 rev/min (stator winding: water cooled, rotor winding: supercharged hydrogen cooling by a two-stage radial fan).

The first 4-pole generator of 1333 MVA, 1800 rev/min, for the American Electric Power Donald Cook power station at Lake Michigan is ready for shipment (figure 24). This generator is hydrogen cooled with water cooling of the stator winding, a design which may be used in 4-pole 60 Hz generators up to at least 1500 MVA.

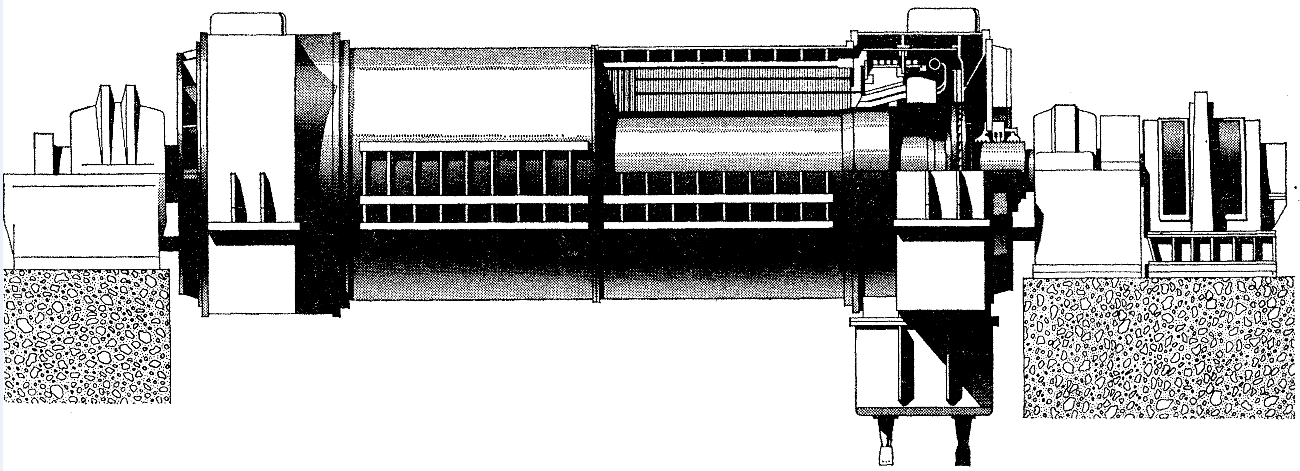

FIGURE 24. Four-pole generator 1333 MVA, 26 kV, 1800 rev/min (stator winding: water cooled, rotor winding: hydrogen cooled).

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For 2-pole generators larger than 1000 MVA and 4-pole machines larger than 1200 MVA total liquid cooling without hydrogen is of special interest.

Figure 25 gives the basic design of a 2-pole totally liquid cooled generator with pedestal bearings. Notable design features are that: an airgap cylinder separates the rotor from the stator compartment; the rotor, the windings of which are water cooled, runs in air at 0.5 atm; the stator compartment is filled with nitrogen, an inert gas minimizing occasional ionization effects; and the stator core is oil cooled, the stator winding conventionally water cooled.

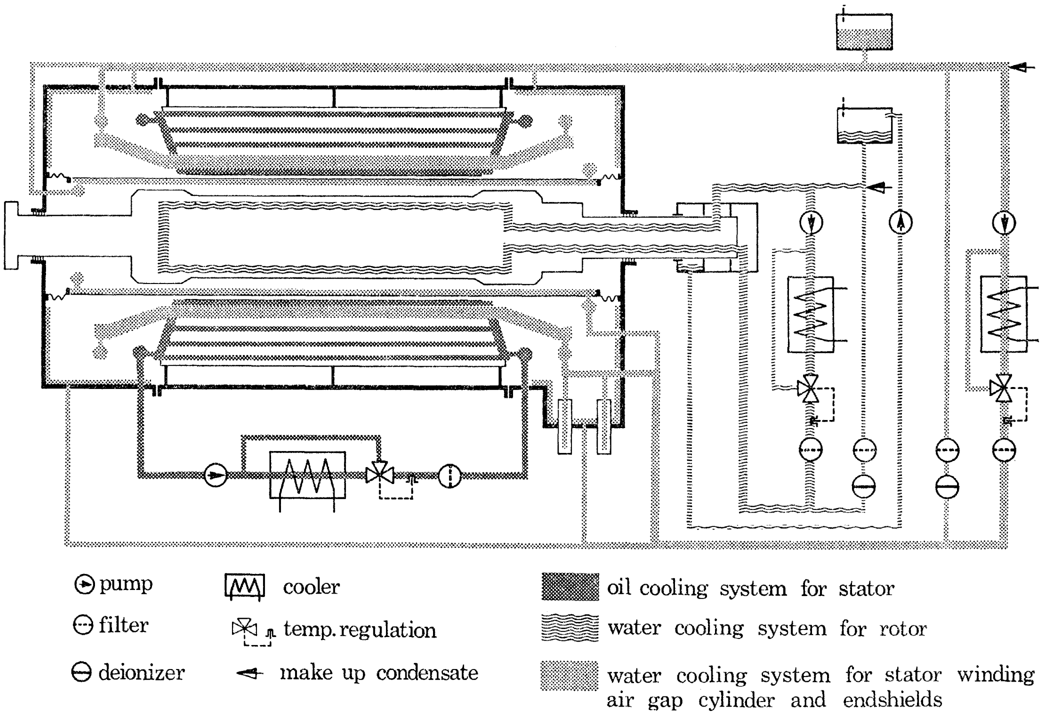

FIGURE 25. Totally liquid cooled generator (stator and rotor winding: water cooled, stator core: oil cooled).

This design will bring the unit ratings up to approximately 1700 MVA, 60 Hz, and 2000 MVA, 50 Hz, leading to cross-compound ratings of 3, 4 and 4 GVA (Krick *et al.* 1972).

With the same basic design unit ratings of 3 GVA in 4-pole generators may be attained. The largest turbogenerator ever built, a 1635 MVA unit for the Rheinisch Westfälisches Elektrizitätswerk, is manufactured according to this design.

Further increase of unit ratings may be expected in 2- and 4-pole liquid cooled generators with increasing operational experience and adequate further development. Totally liquid cooled turbogenerators will therefore give us the time necessary for the development and testing of the next machine generation: the cryogenerators with superconducting rotor windings.

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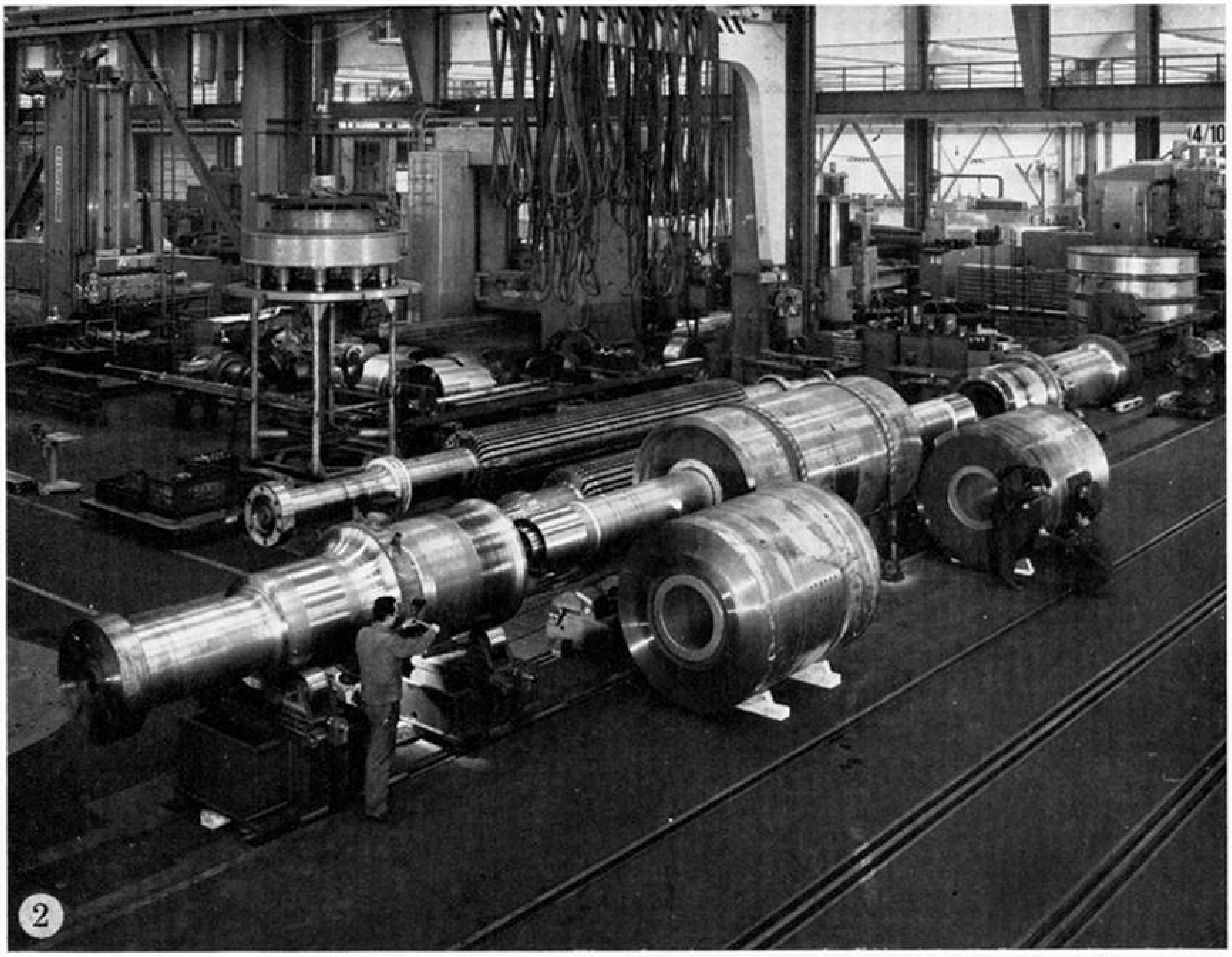


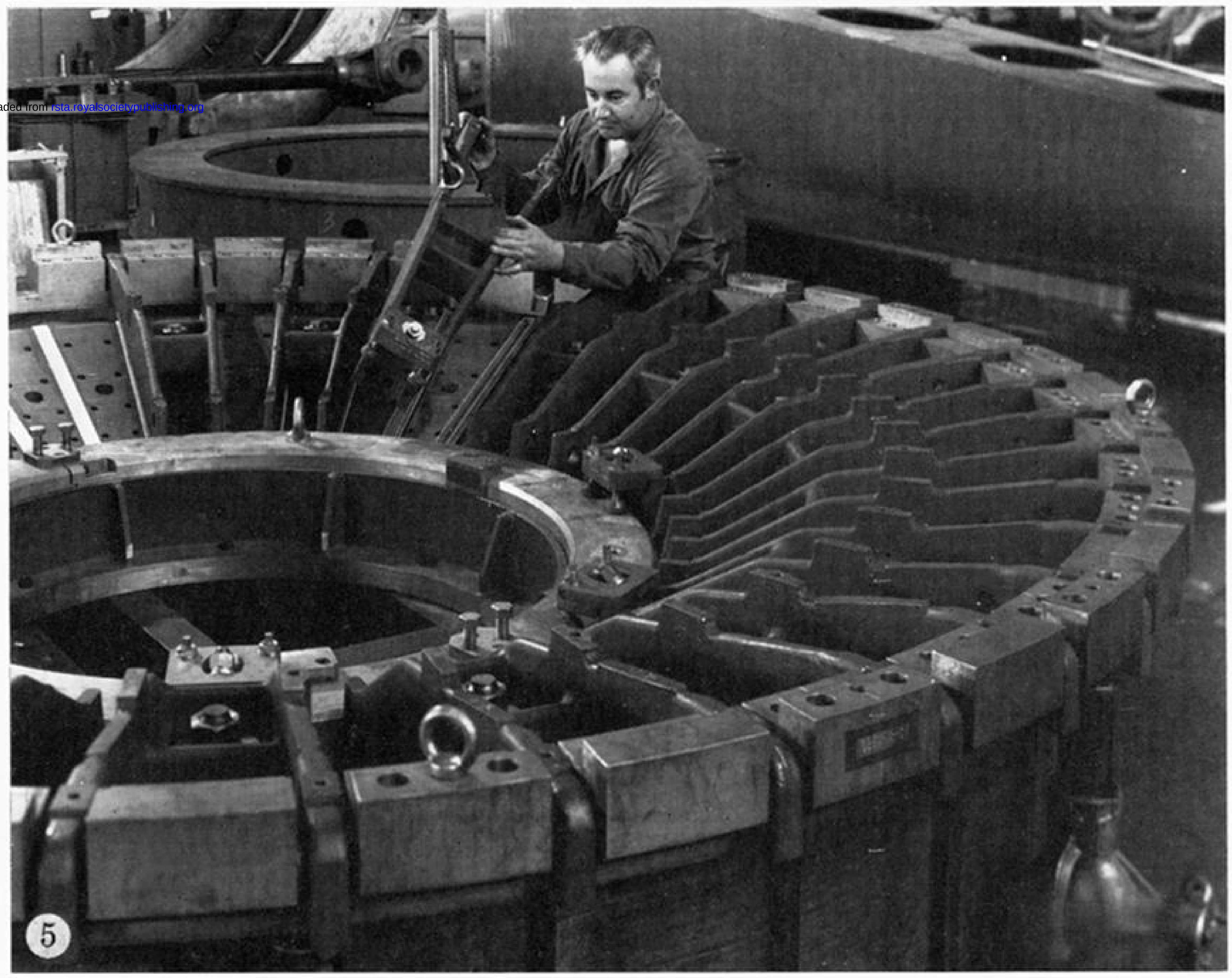
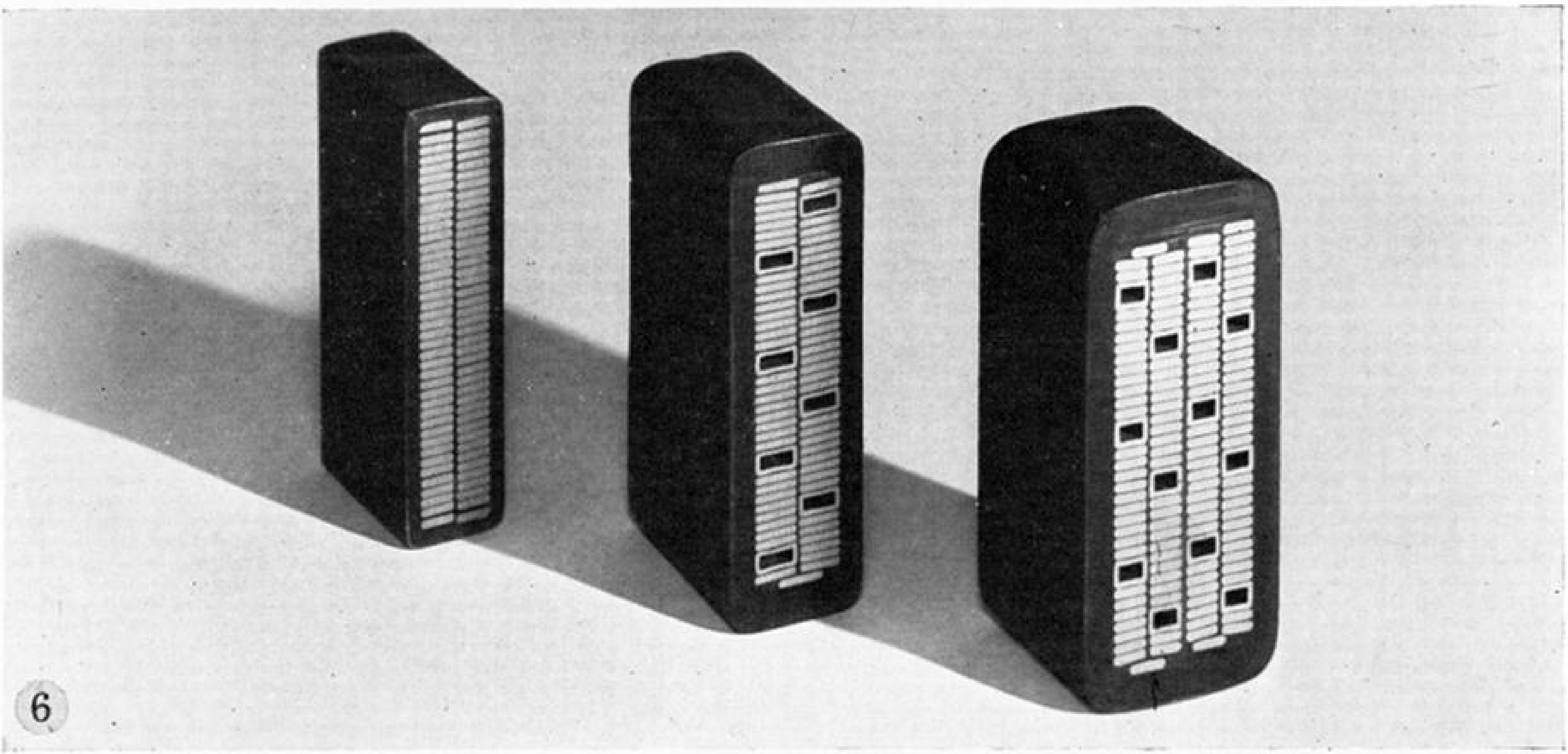


FIGURE 2. Multi-block rotor for 4-pole generators 1333 MVA/1100 MW consisting of one centre-body piece, two end-body pieces and a central shrink shaft with two shaft ends.

FIGURE 5. Conical core end section of resin-bonded stator laminations.



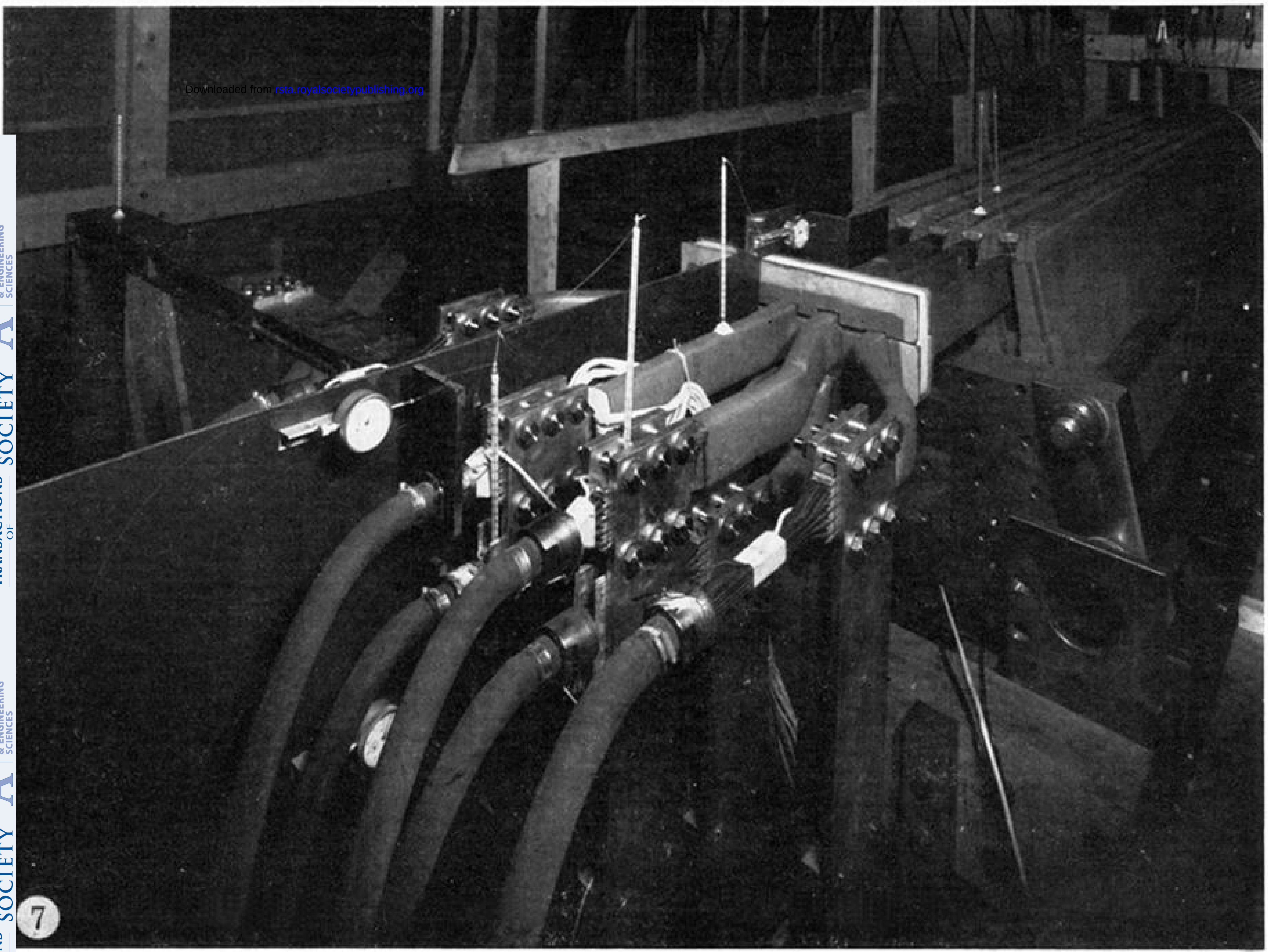


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FIGURE 6. Roebelbars for indirect gas cooling and direct water cooling.

FIGURE 7. Full-scale model for testing of stator bars for turbogenerators of over 1000 MW.

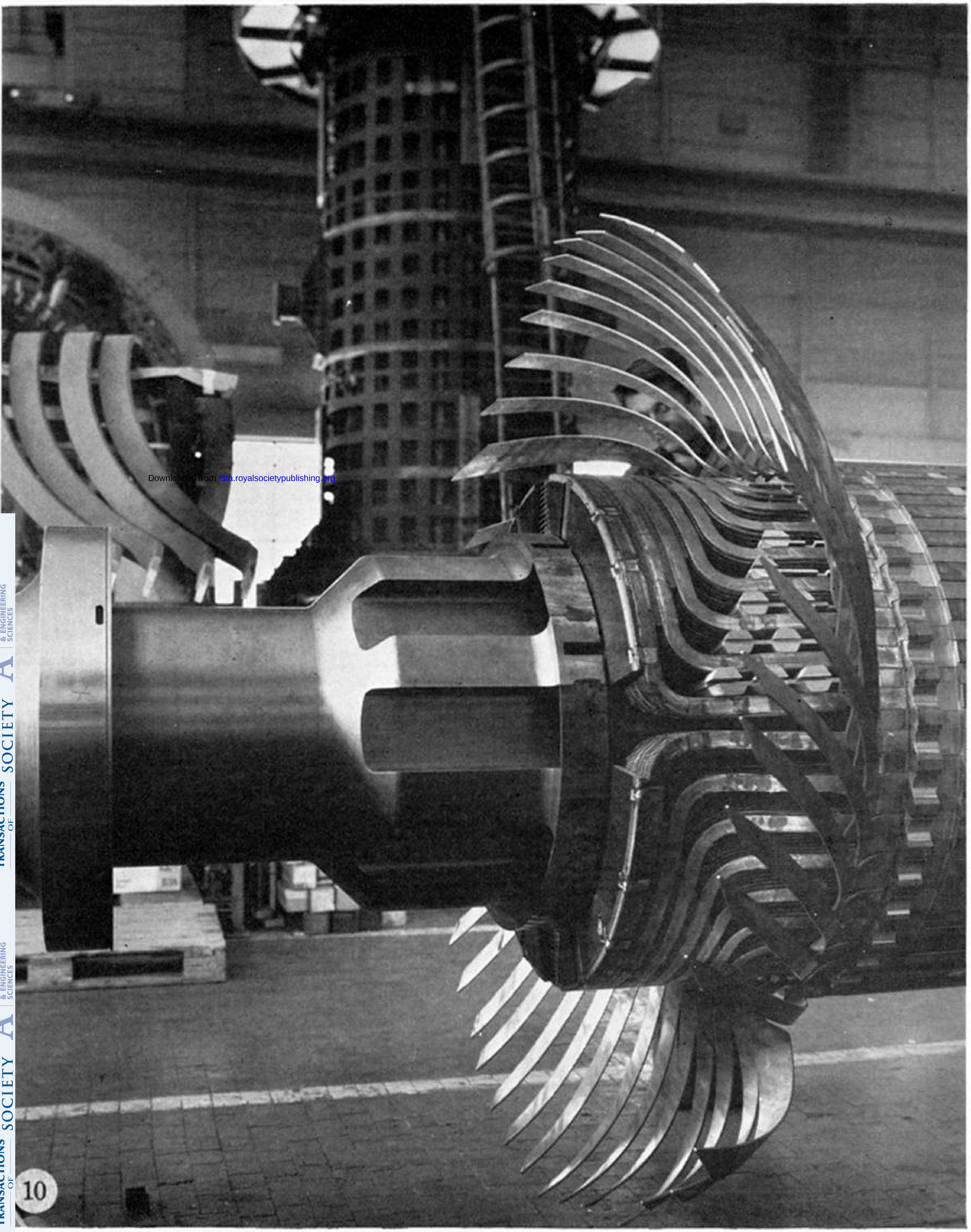
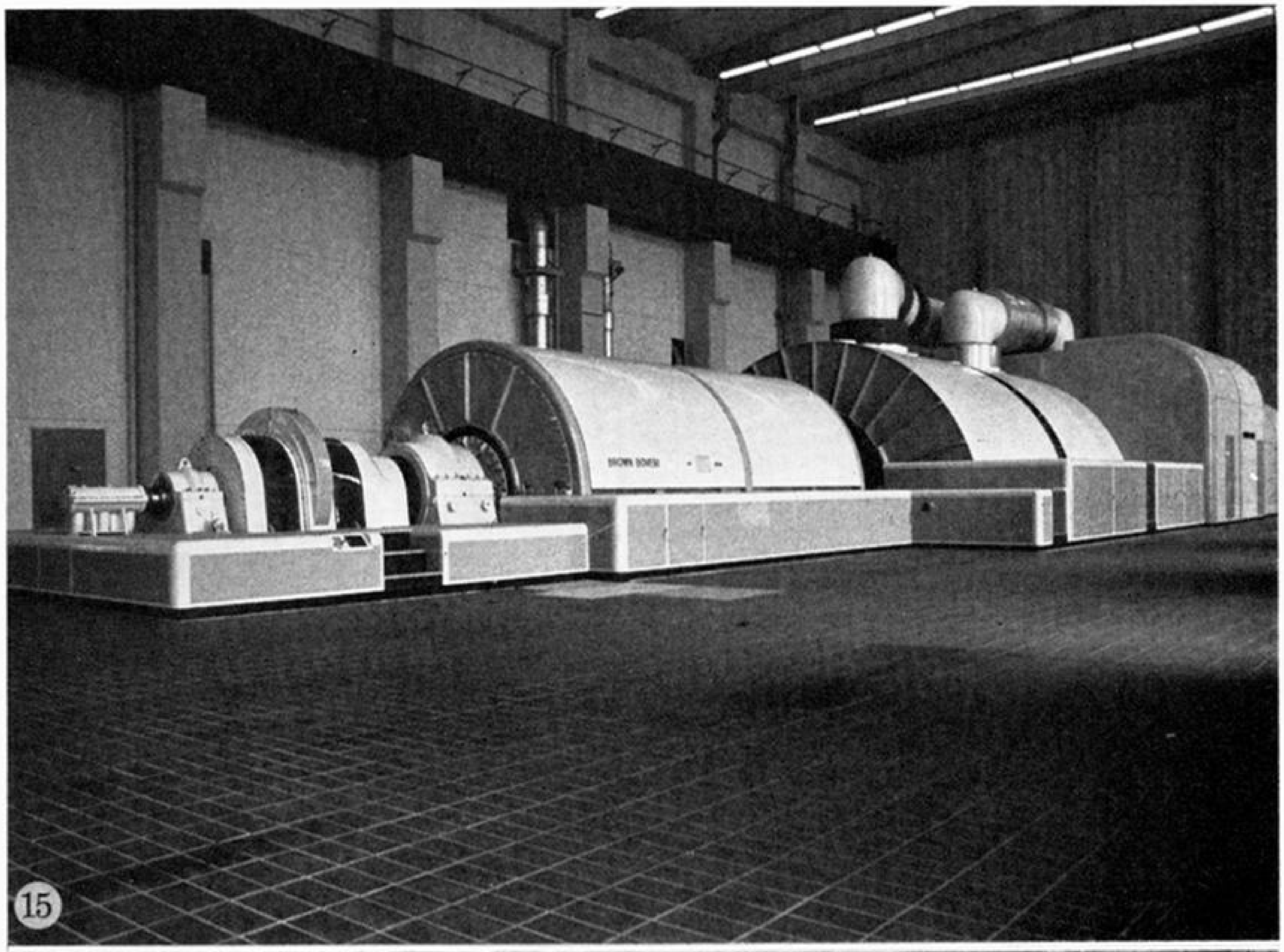


FIGURE 10. Damper winding for turbogenerators.



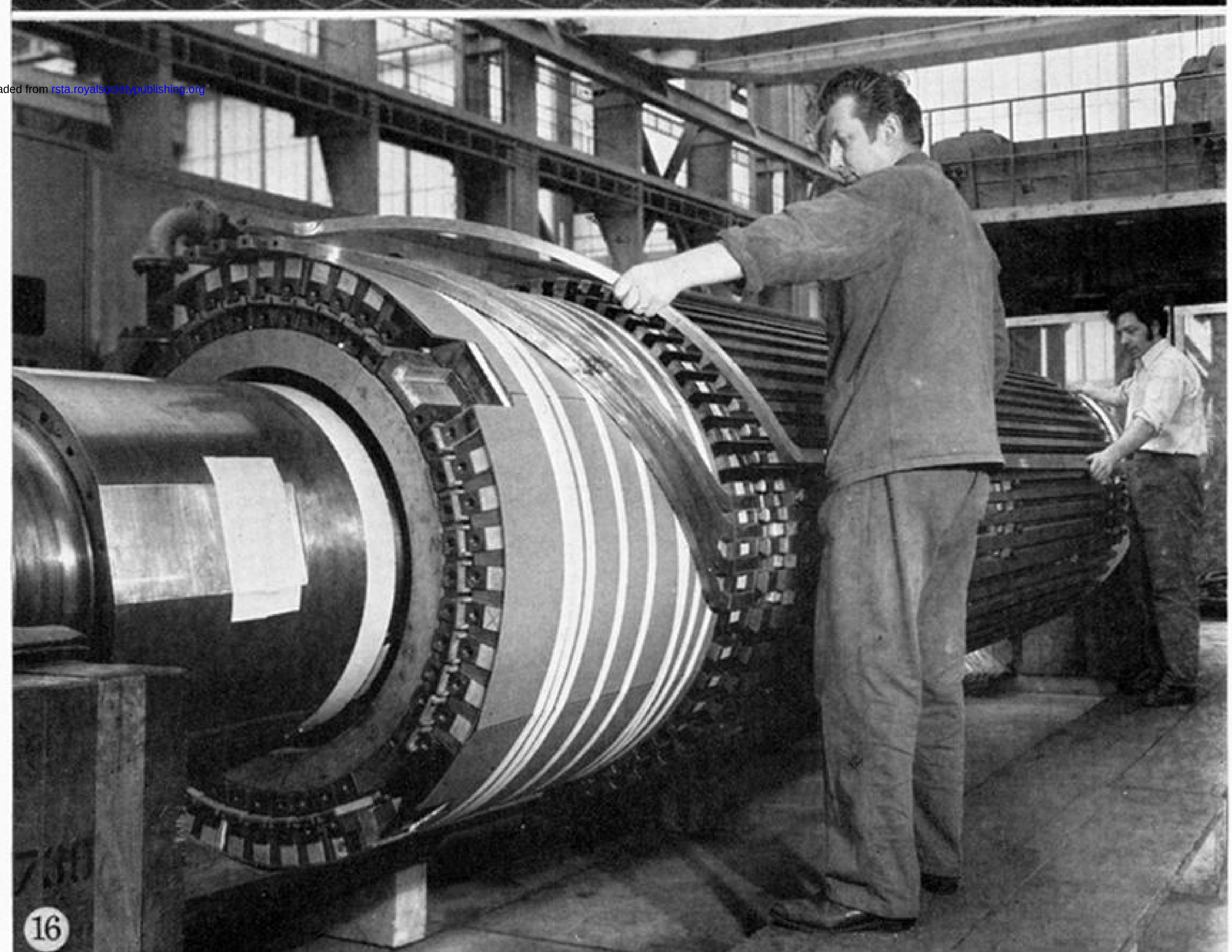


Figure 15. Turbine generator Skaerbaekvaerket with completely water cooled generator (330 MVA, 18 kV, 3000 rev/min).

Figure 16. Turbogenerator rotor with water cooled field and damper winding.

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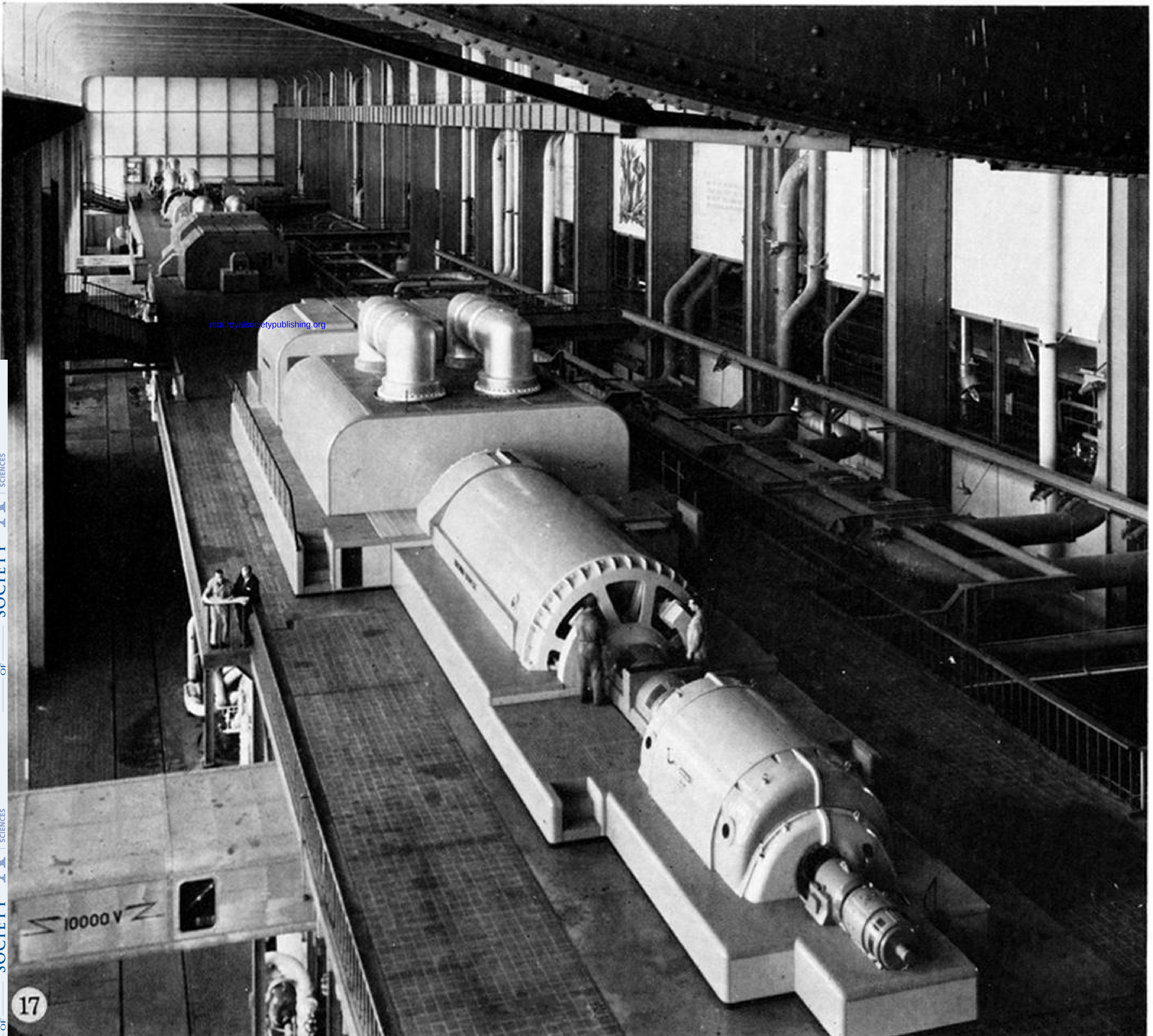

FIGURE 17. Turbine generator Amer V with oil cooled generator core and stator winding (254 MVA, 12 kV, 3000 rev/min).

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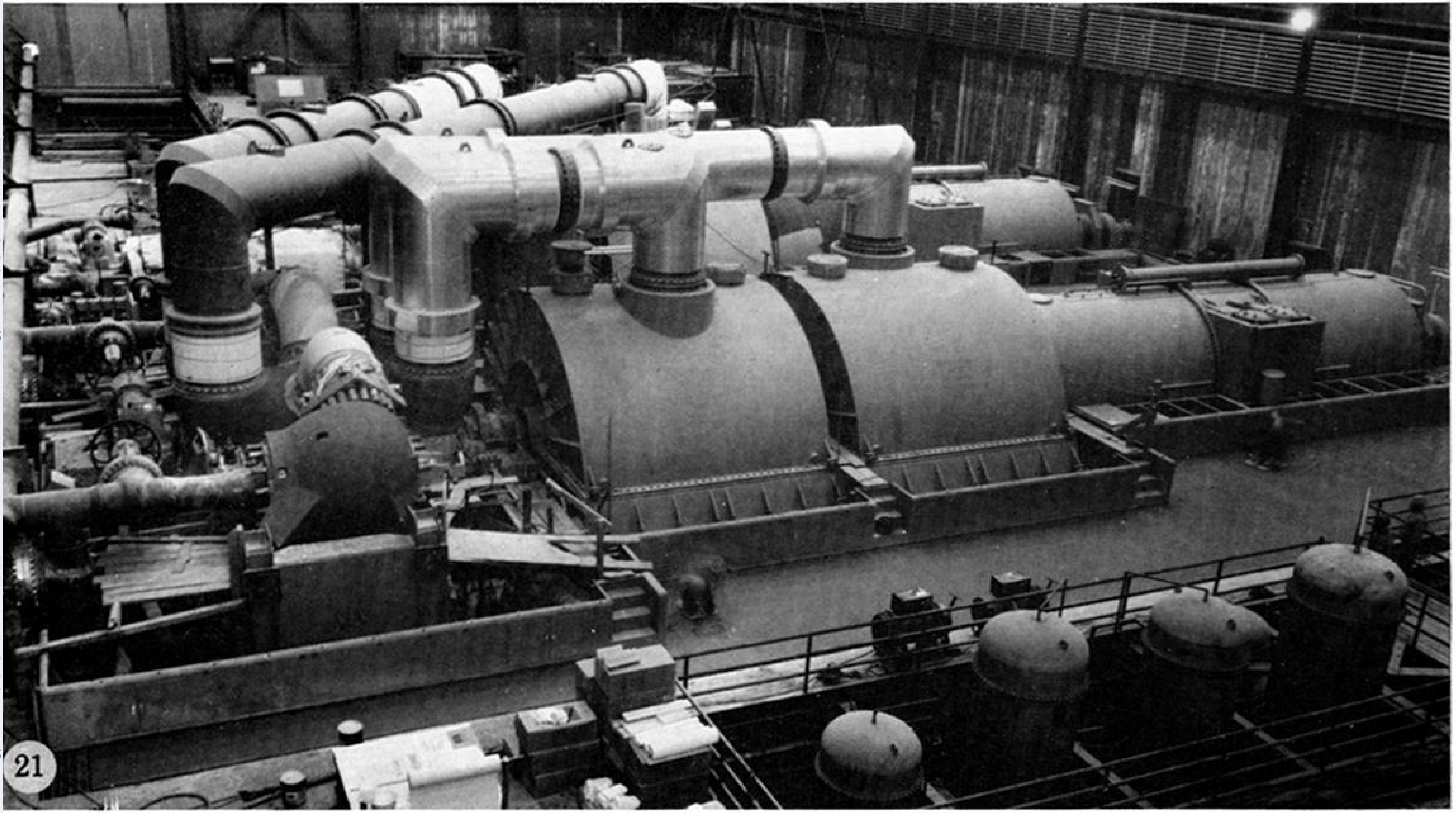

FIGURE 21. Cross-compound turbine generator Cumberland of TVA 1300 MW, 60 Hz.