Future Developments of Large Electric Generators

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I. MACHINES

Future developments of large electric generators

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[Plates 1 and 2]

Several observations can be made with respect to the continual development of large electric generators:

1. The tendency toward always increasing ratings, and especially toward increasing the rating for a given physical size.
2. The thermal problems of cooling and the mechanical limits of various stresses (for example, stresses in electrical windings, in shafts, and in rotor parts subjected to centrifugal force), overspeed on loss of load, critical speeds, and torsional oscillations.
3. The electrical questions of insulation, appropriate voltage rating, reactances, and excitation requirements.
4. Features related to the system requirements: reactances, rotary inertias, reactive power capability, rated and operating power factor, and unbalanced loading.
5. The type of steam generator as it may influence a tendency to use 4-pole generators, and the environmental considerations (i.e. thermal discharges) which may influence the prime-mover inertia.
6. Considerations of machine protection in view of the increased importance of large generating units and of the possibly different winding arrangements and heavy loadings.

The history of large electric generators may seem to indicate that we have always been near the frontier of knowledge and experience, and it has required some courage to predict with confidence a continued growth in rating. In spite of this, new concepts, research, development, and design studies have so far continued to open up a path to permit further increases in ratings, and it appears that this process can still be depended on for some time in the future.

Power system growth

Electric power systems continue to grow. In the U.S.A. they have doubled in total capacity about every 10 years for several decades and show every sign of continuing at almost the same rate for at least two more decades. Various predictions have been made as to the behaviour after 1990. Most of them predict further growth, but at a decreasing rate. Our personal prediction for the U.S.A. is that growth will not end until about 2030, with a load (and thus generation) of over 20 times the present value.

We cannot presume to speak with any authority about growth in the U.K., but cannot help but feel that the recent somewhat reduced growth rate may be a temporary phenomenon. Certainly, in the world as a whole there will be considerable further growth.

This increasing size of power systems obviously permits us to consider correspondingly increasing sizes of generating units. (On the presumption that the interconnecting transmission system strength also grows correspondingly, so that the system can continue to be considered as a whole from the viewpoint of reliability and economy.) Moreover, not only are we *permitted* to consider larger units but also we are *forced* to consider them by the pressures of economy of scale, of siting, and complexity of system operation.

As a general rule, one might expect the optimum size of generating unit to be a certain percentage of the size of the power system on which it is operating. Thus, since total power system capacity is about doubling every 10 years, we might expect unit sizes also to double every 10 years, even if no additional interconnexions are made (so that the geographical areas considered do not change). Since in the U.S.A., interties have been made, we should expect unit sizes to grow somewhat more rapidly. In fact, they have.

Figure 1 (Harrington & Jenkins 1970) shows curves of the ratings of the largest 2-pole (3600 rev/min) and 4-pole (1800 rev/min) steam turbine driven generators manufactured by the General Electric Company since 1937, plotted against year of shipment up to 1973. It is

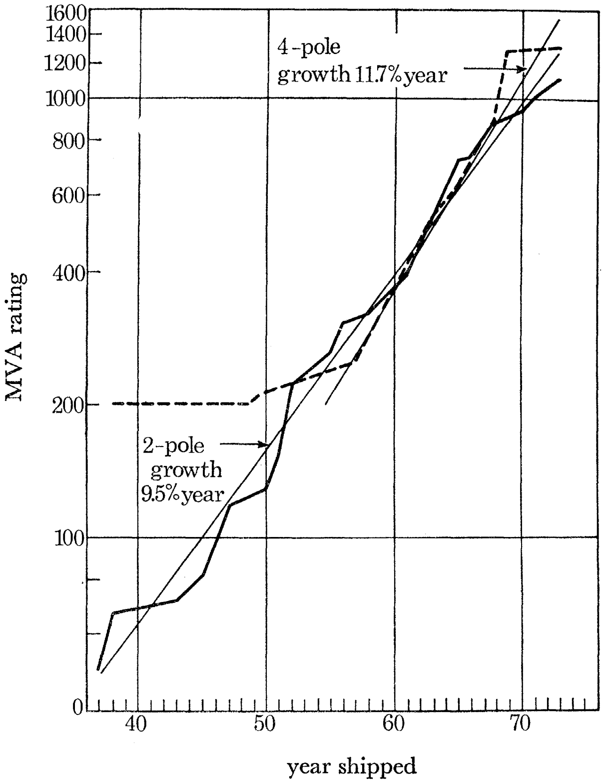

FIGURE 1. Largest turbine-generators as a function of year shipped.

seen that 2-pole generators have about doubled in size every 7.6 years for more than 30 years. On the other hand, the largest 4-pole generators, after remaining constant for several years, have had a very large growth rate recently (as occasioned by the advent of nuclear power), doubling in size every 6.2 years for the last 15 years.

However, these sizes are still very far from approaching what would be attained if we viewed all of the interconnected systems of the U.S.A. as a whole.

At the present time there is in the U.S.A. a large synchronized network (made up of many interconnected companies) having a total generating capacity of about 300000 MW. Thus even a generating unit of 6000 MW would be only about 2 % of this total network generating capacity, while the largest presently available units (of about 1500 MW) are less than $\frac{1}{2}$ %. It is evident that the appropriate generator size is controlled by other factors in addition to the total network size. Among these are the state of the technology of both generation and transmission.

LARGER GENERATORS

There are many challenges facing both the generator and system designer in the continual effort to build and apply larger and larger generators.

From the generator design point of view one of the most striking features of steam turbine driven generators, which we shall be discussing for the most part, is the high rotor speed (3600 or 1800 rev/min for 60 Hz systems and 3000 or 1500 rev/min for 50 Hz systems) required for good coordination with the turbine. On account of the centrifugal forces developed, these high speeds put a limit on the permissible rotor diameter, and thus indirectly on the physical size of the machine. Thus one must increase rating without a corresponding increase in size. Of course, even without such a physical limitation, there is an economic pressure to conserve materials, and thus costs, by increasing the power per unit volume of active material. Finally, there are size constraints imposed by shipping limitations. The results of this increased power density are many, but particularly: higher current densities and thus greater winding forces, and greater losses and thus more heat generated per unit volume. In addition, the necessarily larger physical size presents major materials and mechanical challenges.

From the power system design point of view, the increased power density tends to increase the generator reactances, and to decrease the generator rotary inertia. Both of these trends tend to have an adverse effect on stability. (It is of interest to note also that the present concern with thermal discharges to water may cause a greater use of cooling towers, which has the incidental effect of reducing the turbine inertia.) Further, with the relatively smaller volume and mass of material per unit power, the thermal transient performance becomes more critical. Finally, the effort to keep down the steady-state (synchronous) reactance (or keep up the short-circuit ratio) tends to increase somewhat the field excitation power requirements.

We shall discuss the ways in which these challenges have been met in somewhat more detail below.

WINDING FORCES

Stator winding forces are proportional to the square of the current. In a typical large generator, the force on a single pair of bars in a stator slot may reach 120 kN (12 tons; Harrington & Jenkins 1970), and for a 60 Hz generator this force is experienced by the bar over 10 million times per day. Bar forces may be held down as much as feasible by a combination of increasing generator length and stator slots (Holly & Willyoung 1970*a*). But these in turn increase voltage, which may require more space for insulation. The optimum strategy has been found to result in bar forces increasing at about the first power of rating (Harrington & Jenkins 1970).

Special winding arrangements to hold down forces have been considered. These include: the use of multiple circuits (which has already been extensively applied); and a '6-phase' connexion, with two separate 3-phase windings differing in phase by 30°, the voltage being converted to 3-phase by appropriate transformer connexions (which has been proposed (Holly & Willyoung 1970*a*)).

Aside from designing to keep down forces, there has been an enormous improvement in the strength of the winding supports. Every effort is made to assure that the bars are held securely, including the use of 'ripple springs' in the slots, as shown in figure 2, plate 1, and of total encapsulation of the end windings in a penetrating epoxy binder.

Along with the increased winding forces during normal operation, there is a corresponding increase in the short-circuit forces. However, the short-circuit currents have not increased quite in direct proportion to the rated currents, not only because of the inherently higher machine impedances, but also because of the unit arrangement in which each generator has its individual step-up transformer, to which it is connected by isolated-phase buswork that practically eliminates the possibility of a terminal short-circuit.

Cooling

If any one thing were to be singled out as making possible the very large generator ratings of recent years it might be the improved and more effective methods of cooling, by direct contact of the cooling fluid with the stator and rotor conductors. This has removed the insulation as an element in the heat flow path. So effective has this been that not only have the much larger ratings been made possible, but also the conductors are actually cooler than before. In case of the water-cooled stator conductors the temperature difference between copper and water is practically negligible. The consequent reduction in thermal stress adds margin for the required mechanical stresses and thus leads to the possibility of further advances. In the case of the rotor it has so far seemed more desirable to utilize gas cooling. The gap pick up rotor design, in which the coolant enters the rotor at several points, has effectively eliminated the rotor length limitations of the previous end-fed systems (see figure 3) and should suffice for even larger ratings. In this case in particular, we are speaking of our own company's designs. Some other manufacturers feel that liquid-cooled rotors may be desirable very shortly.

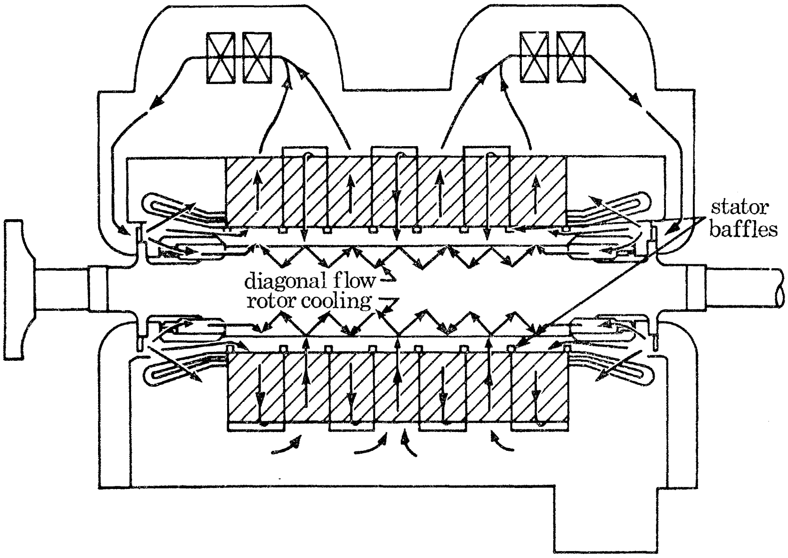

FIGURE 3. Hydrogen flow patterns in a large generator showing diagonal flow path through rotor conductors.

System performance

The effect of the probably higher reactances and lower inertias of future generators on system performance, particularly stability margins, has been studied in some depth (Concordia & Brown 1971). If we consider, for example, future generators of perhaps twice the size of the present largest planned machines, the parameters may change as shown in tables 1 and 2 for 2- and 4-pole machines respectively.

Table 1. Parameters for a 2-pole unit

	present	future
H	2.5	1.75
X'_d	0.22	0.35
s.c.r.	0.58	0.45
X_t	0.11	0.15
X_d (= 1/s.c.r.)	1.72	2.22

Table 2. Parameters for a 4-pole unit

	present	future
H	4.0	2.5
X'_d	0.35	0.50
s.c.r.	0.58	0.45
X_t	0.11	0.15
X_d (= 1/s.c.r.)	1.72	2.22

Table 3. Appropriate network voltage as a function of generator power rating

network voltage/kV	generator unit size/MW
230	200
345	500
500	1000
800	2500
1300	7000

The situation is aggravated by the fact that a power system with larger generators requires a higher voltage transmission network, very approximately as shown in table 3, and the reactance of the step-up transformer also increases with high-side voltage (and thus indirectly with generator rating), as shown in figure 4. This figure shows both a normal range and the smallest reactance, of about one-half minimum, which is available at a premium price. From only the standpoint of stability, we might expect that one would want the lowest possible value, or at least the minimum normal value. However, other factors, for example, size, shipment,

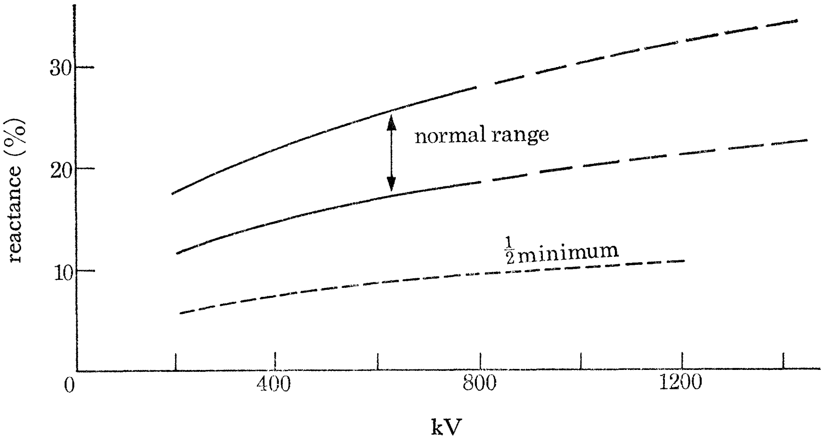

Figure 4. Transformer reactance as a function of high-side voltage.

fault duty, are often limiting. Thus many utilities are presently using transformers having reactances well above the normal minimum. In these cases it may be possible in the future to have reactances smaller than those of present practice, even at the highest voltages contemplated.

We have tried to evaluate the relative stability in the simplest possible way, as shown for example in figure 5. This figure shows the relative degree of stability of the very simple system of the diagram, expressed in terms of the critical clearing time, or the maximum duration of a 3-phase fault at the high-voltage terminals for which the generator is barely stable. Critical clearing time is plotted as a function of system reactance for two values of generator inertia.

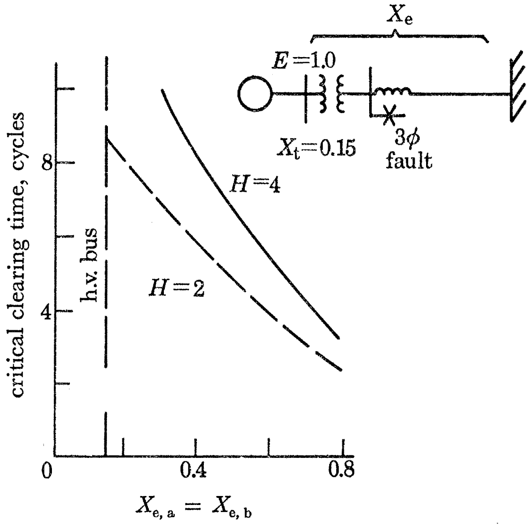

FIGURE 5. Critical clearing time as a function of system reactance – for system and high-side 3-phase fault as illustrated – effect of rotor inertia H: s.c.r. = 0.58; $X'_d = 0.45$. Excitation system response = 3; p.f. = 0.9 at rated kVA; subscript b and a mean before and after fault respectively.

This and other similar curves have shown that, as a very rough rule-of-thumb, for a given system reactance the critical clearing time varies at about half the rate of the three principal parameters. We have expressed this mathematically as an index of stability.

$$T_c \propto \sqrt{\left(\frac{H}{(X'_d+X_t)\,(X_d+X_t)}\right)},$$

where T_c is the critical clearing time, H the inertia constant, X'_d the transient reactance, X_d the synchronous reactance ($\simeq$ 1/s.c.r. where s.c.r. is the short circuit ratio) and X_t the transformer reactance.

Applying this index to the four machines described in tables 1 and 2, we find that the relative indices are:

	present	future	future/present
2-pole	2.03	1.21	0.60
4-pole	2.18	1.27	0.58

Then, even if, for example, the critical clearing time for the present generator were as low as 7 cycles, it would still be about 4 cycles for the assumed future generator, and thus still greater than the 3-cycle clearing time presently available.

However, it may be more meaningful for our present purpose to find out from curves such as figure 5 how much we must strengthen the transmission network to preserve the same margin of stability. For example, if the inertia is decreased from 4 to 2, we should have to decrease the effective system reactance as viewed from the generator terminals by about 20 %, from 60 to 40 %, to preserve a critical clearing time of 6 cycles.

Torsional oscillations

There are many ways of strengthening a network, but we shall mention only one, the use of series capacitor compensation, in order to illustrate the interaction between transmission and generation. At the same time, high response excitation systems with special stabilizers utilizing a shaft-speed signal have sometimes been used to improve stability. It turns out that both of these apparently unrelated devices may under certain conditions interact with the torsional natural frequencies of the turbine-generator rotor. This rotor consists in general of from three to six elements, a generator, two to four turbines, and possibly an exciter, as illustrated in figure 6, plate 1.

In an uncompensated power system there is the possibility of the direct currents temporarily induced by faults developing slip-frequency transient torques of rated system frequency (60 Hz). Thus it is more or less obvious that a torsional natural frequency of 60 Hz should be avoided. But if there is series capacitor compensation there is evidently the possibility of induced natural-frequency currents (rather than direct currents), having a frequency in the range of 20 to 40 Hz, which will develop slip-frequency torques in the range 40 to 20 Hz if they are balanced 3-phase currents, or in both the ranges 40 to 20 Hz and 80 to 100 Hz if they are not. Since the exact value of frequency to be expected depends on varying network conditions, number of lines and amount of series compensation in service, it becomes difficult to design around it. Moreover, under certain rather severe conditions, the compensated line may even spontaneously self-excite at the electrical system natural frequency. If this should happen to produce pulsating torques near a rotor torsional natural frequency, excessive and possibly damaging shaft stresses may result. This problem is under serious study at the moment.

The excitation system stabilizer problem is somewhat similar, but depends also on the fact that as generating units become larger and larger their mechanical natural frequencies, both their critical speeds and their torsional frequencies, tend to decrease. The stabilizer may be designed to respond to unit speed deviations, which have been conceived to occur mostly at rather low frequencies, in the range 0.2 to 2 Hz, as determined by the interaction of the electrical synchronizing torque and the total rotor inertia. However, if the rotor torsional natural frequencies become low, one has to be concerned with the response of the stabilizer to those frequencies also, where 'rotor speed' is no longer a simple concept but may be different for each element.

Voltage

Generator designers have always wished for the freedom to select the terminal voltage that results in the optimum generator design. With the generator–transformer unit system this becomes possible, but there remain questions of the standardization of voltage for auxiliaries fed from the generator terminals, when the over-all economy of the station is considered. So far ways have been found, utilizing innovations in terminal arrangements and winding connexions, to give suitable voltage levels.

Emergency capability

The capacity of a generator to respond to abnormal system conditions is also affected by uprating. Two aspects deserve particular mention.

One is the possible overloading of both armature and field due to the changed pattern of power flow that may occur following the loss of a major transmission line or generator. The capability of supplying large emergency reactive-power demands is a limitation even today, and is moreover one that is not always fully recognized. That is, even today, a large generator can only operate at ceiling excitation for a few seconds, and then the excitation voltage must be reduced to avoid damage. Moreover, the significant emergency reactive power requirements of the system are those lasting for perhaps 15 min, or the time required for an operator or automatic control to do something about the system condition. These requirements can best be met by taking them into proper account as one factor in the selection of generator rating. For example, with a well-planned reactive-power supply distributed throughout the system, not only is the normal reactive power demanded of the generator minimal, but also the severity of the disturbance and the magnitude of the consequent overloading is reduced. But, in spite of this, it has generally been found to be desirable to build-in reactive capacity by specifying a generator with a rated power factor of 90 % or even 85 % even though the normal operation power factor may be nearly 100 %.

The other example of abnormal operating conditions is a circuit unbalance, usually resulting from a fault, which may induce negative phase sequence currents in the generator rotor. The thermal capability of the generator rotor to withstand such currents is expressed in terms of $i_2^2 t$ (or the time integral of the current squared). While the higher power density has the effect of increasing the severity of the duty, there are mitigating factors. On the one hand, the higher per-unit reactance of future generators, together with the expected faster switching times, will tend to decrease the required $i_2^2 t$ duty, and on the other hand the requirements as embodied in present standards have been shown by recent studies (Brown 1973) to be generally much higher than is really demanded by the system even today, and consequently work is in process to reduce the standard requirements.

FUTURE TRENDS

We have discussed very briefly many of the factors which might be regarded as limiting the growth of generator unit ratings. But it has appeared that, at least so far, in every case ways have been found to push back these limits so as to permit a continual increase in rating, and even in physical size. What about the future?

In the first place it must be made clear that we have not yet reached the limit of unit rating with present technology, probable design improvements and innovations, probable improved material properties, and well-understood and already available methods of strengthening the transmission network. Indeed some of our colleagues have recently published (Jefferies *et al.* 1973) certain of the results of design studies of two 2000 MVA generators, one 2-pole and one 4-pole, for comparison with designs they had made of two similar generators having superconductive field windings. Further, they have concluded that: 'Present generator cooling technology, stator winding short-circuit and vibration control, and improved materials can be developed to provide conventional generators in the ratings predicted for the 1980's'.

This conclusion puts the question of radically new concepts of generation in its proper

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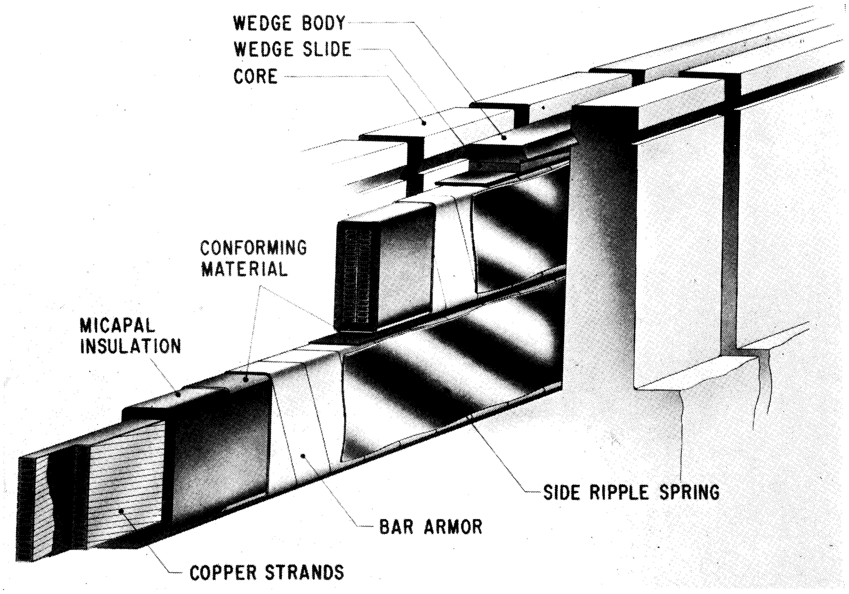

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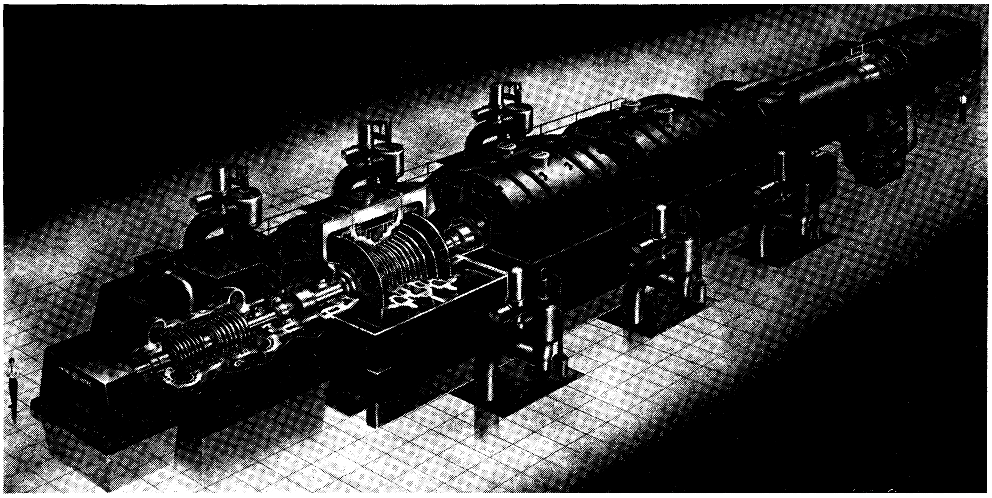

Figure 2. Lateral and radial wedging of armature bars.

Figure 6. Turbine generator unit showing rotor elements.

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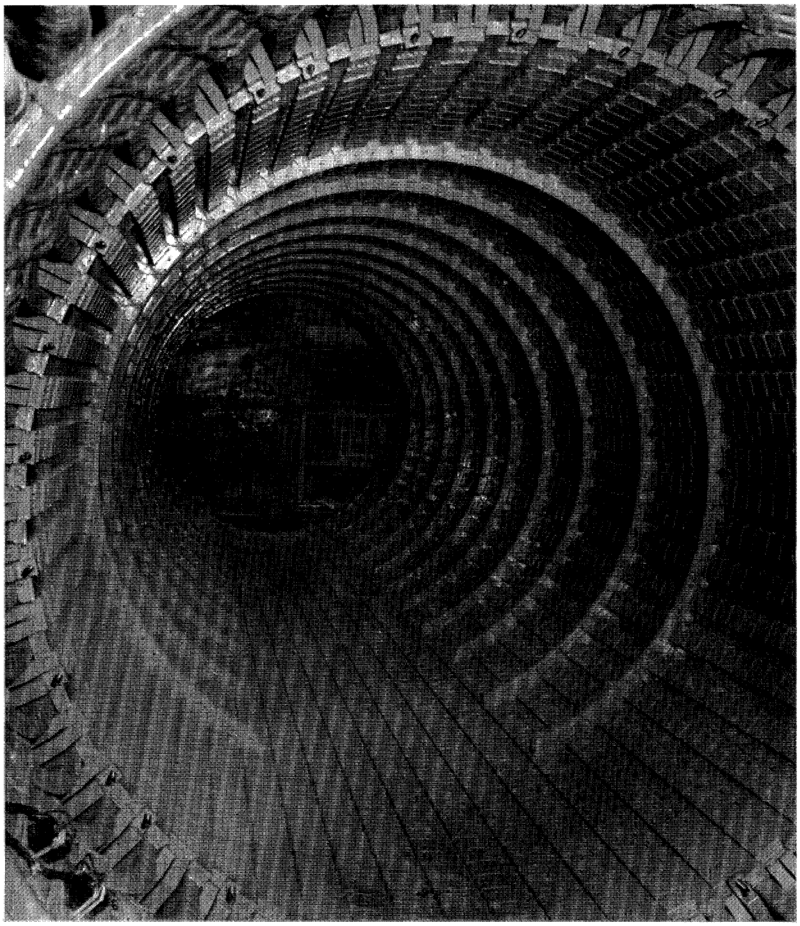

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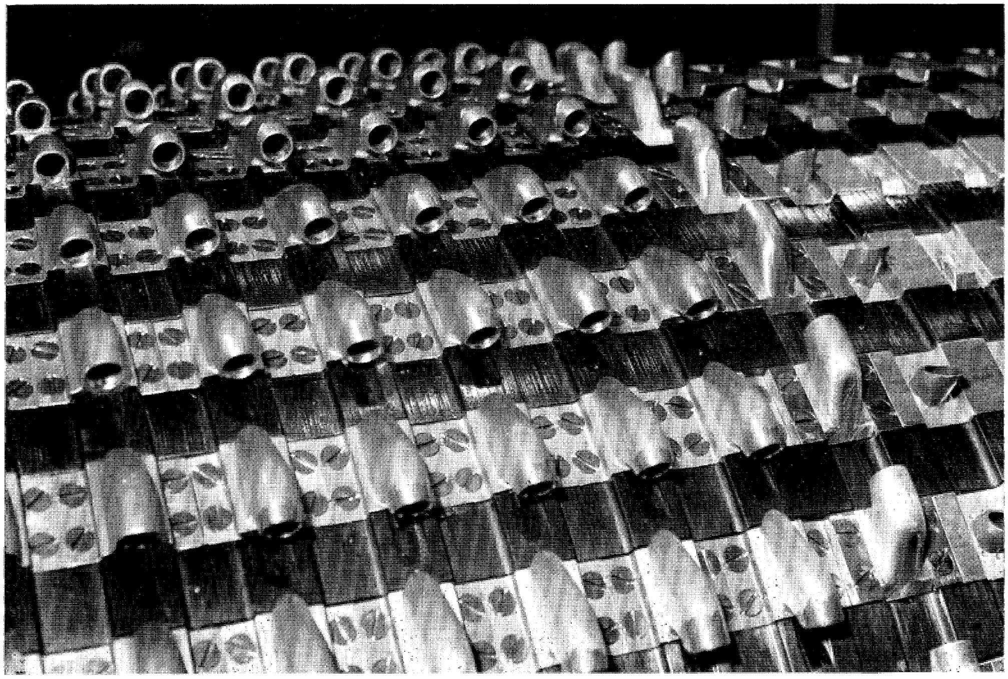

Figure 7. Generator stator core with segregating baffles.

Figure 8. Gap pick-up rotor surface with projecting scoops.

perspective. It is not a question of needing a radically new concept to design generators of perhaps twice the size of those presently available. Instead, and at least for the next 10 years, any new concept will have to stand on its own feet and compete in first cost, performance, economy of operation, and especially in reliability and availability with what we are now calling the 'conventional' design.

The last two factors, reliability and availability, are in a practical sense overriding considerations. Any decrease from the present high levels would not be tolerated by the electric utility industry. It would lead not only to the necessity for increased reserves, and thus increased capital costs, to preserve the same degree of system reliability, but also to increased outage time and thus increased operating costs, including the cost of replacement energy. This naturally leads to an appropriately cautious attitude on the part of the designer, and to the necessity for thorough testing of any new concept before it is incorporated in a design, and even to a reservation of final judgement until the new idea has been proven in actual utility service. Moreover, particularly with the advent of utility pooling, an order for a unit of advanced design may be followed by a dozen more before the first unit is even shipped, so that a very large commitment is made before any operating experience is available.

Turbine considerations

Progress in increasing generator unit size has, of course, to be coordinated with progress in increasing turbine unit size, and even boiler size. During the past many years they have kept fairly well in step, perhaps first one then the other being slightly ahead in technology. Not too many years ago the generator appeared to be the limiting component, but particularly with the introduction of direct conductor cooling of both rotor and stator windings the possibilities of generator advance became so great that at least for the moment the generator designer can be relatively comfortable with the assurance that he is not the bottleneck. It will have been noted from figure 6, that the generator is a relatively small component of the total turbine generator exciter unit.

Although it is not within the scope of this paper to discuss the turbine and boiler, we must remark that at the present time the task of increasing turbine unit rating appears to be somewhat more difficult than in the case of generators. There are many potential problems, such as handling the larger steam flows and ensuring rotor stability with possibly still lower critical speeds (and torsional natural frequencies).

Superconductive generation

Even though we may believe that reasonably predictable extensions of present technology may suffice up to double the present ratings, serious consideration has been given to alternatives. One of these is the superconductive field winding. As in the case of many new ideas, closer inspection has revealed both benefits and disadvantages (Jefferies *et al.* 1973). On the plus side are: reduced size and weights (to about one-third), higher efficiency (by about 0.4 %), somewhat improved stability, among others. Possibly on the minus side, or at least presenting serious design challenges, are: relatively very high short-circuit forces on the required electro-magnetic rotor shield (which does not have the inherent strength of a solid iron rotor), much higher stator conductor forces due to the absence of stator teeth (which are absent because of the much higher flux densities used), more severe overspeed control requirements because of the smaller inertia, and again some others. The relative cost, and especially the relative reliability and availability, must be determined by further research and development. It has been calculated (Jefferies *et al.* 1973) that an increase of about 1 day per year of forced outage would completely wipe out the savings produced by the 0.4 % increase in efficiency mentioned above.

In view of these considerations it appears that although it is certainly desirable to pursue the development of a large superconductive generator such a generator will not be required for at least the next 20 years.

Liquid-cooled rotor

The liquid-cooled rotor may be closer, and may be the logical next step when required, but even here there remain possibilities, as pointed out in a recent CIGRE paper (Holly & Willyoung 1970*b*), for further improvement in gas cooling and for extensions to considerably larger ratings, before it may become necessary to resort to liquid cooling. Liquid cooling, of course, is not a new idea, but has been under consideration for many years. Again it is a question of a balance of costs and reliability, rather than of technical feasibility. Potential problems that have been, and are, under investigation include corrosion, erosion, and high required pressures. Of all liquids studied, water appears to be the most suitable, indeed the only practically feasible, liquid.

On the other hand, the effectiveness and efficiency of gas cooling has been greatly increased by several design modifications. For instance, the use of stator baffle rings to segregate the inlet and outlet gas flow, as shown in figure 7, plate 2, has prevented recirculation, and it has been demonstrated that substantial increases in flow could be obtained by using scoops that project from the rotor surface, as illustrated in figure 8, plate 2.

HYDROGENERATORS

This paper has been concerned primarily with steam turbine driven generators, but for completeness a word should be said about hydraulic turbine driven generators. The required ratings of hydrogenerators have not been so large as for steam generators, but only within the past few years there has been a rather large increase in the maximum ratings available, up to very roughly 500 MW. It appears that such ratings are entirely suitable for the largest hydro power developments presently contemplated, so there is no great incentive for even larger ratings at this time.

Of course, the physical size of hydrogenerators is relatively much larger than that of steam-generators, because of the very much smaller speed, of only about 100 rev/min. For this reason, shipping limitations of a complete generator rotor have long since been exceeded, and much more assembling is done on site.

We shall not pass judgement on the relative difficulty of designing and constructing hydro and steam generators. However, one interesting point is that in the past hydro generators have been designed to stand a very great overspeed on sudden loss of load, corresponding to failure of all controls, while the steam generator has depended upon a correct functioning of at least the backup controls to limit overspeed. In order to design economically some of the more recent largest hydrogenerators, it has been found advisable to deviate from the former practice, and to count on limiting the overspeed.

From the system point of view, the hydrogenerator has somewhat different parameters, higher transient reactance and lower over-all inertia (because of the extremely small turbine inertia), but lower synchronous reactance. It will be recalled that the first two changes are detrimental, the third favourable, to power system stability.

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

CONCLUDING REMARKS

It will be evident from what has been said that the limitations, problems, or challenges of generator design may be expressed as:

thermal, involving the removal of heat, the possible reduction of losses, the required pumping power;

mechanical, involving the forces on, and bracing of the windings;

mechanical, involving the rotor dynamics, both laterally (critical speeds and rotor stability) and torsionally (interaction with the system);

electrical, involving the insulation, choice of voltage, and winding arrangements, excitation requirements; and

system, involving the desired generator mechanical and electrical parameters.

All of these have been shown to be very much interrelated, and it is perhaps artificial to classify them in this way.

There has been and continues to be a great pressure to increase ratings at a fairly rapid pace, and it is a tribute to the generator design engineer that, while forced to work always near the forefront of knowledge and experience, he has been able to meet the stringent requirements of the electric utility industry for high reliability and availability at a reasonable cost. However, it should be noted that very recently there has been some slowing down of this rapid rate of growth, which may indicate that growth might have been somewhat too rapid during the past few decades.

It should be evident that we are not reporting here only upon our own work. We are indebted for much of the information presented to many others, and in particular to the work of Mr C. H. Holley, Manager of Engineering for large steam turbine driven generators, General Electric Company, and his associates.

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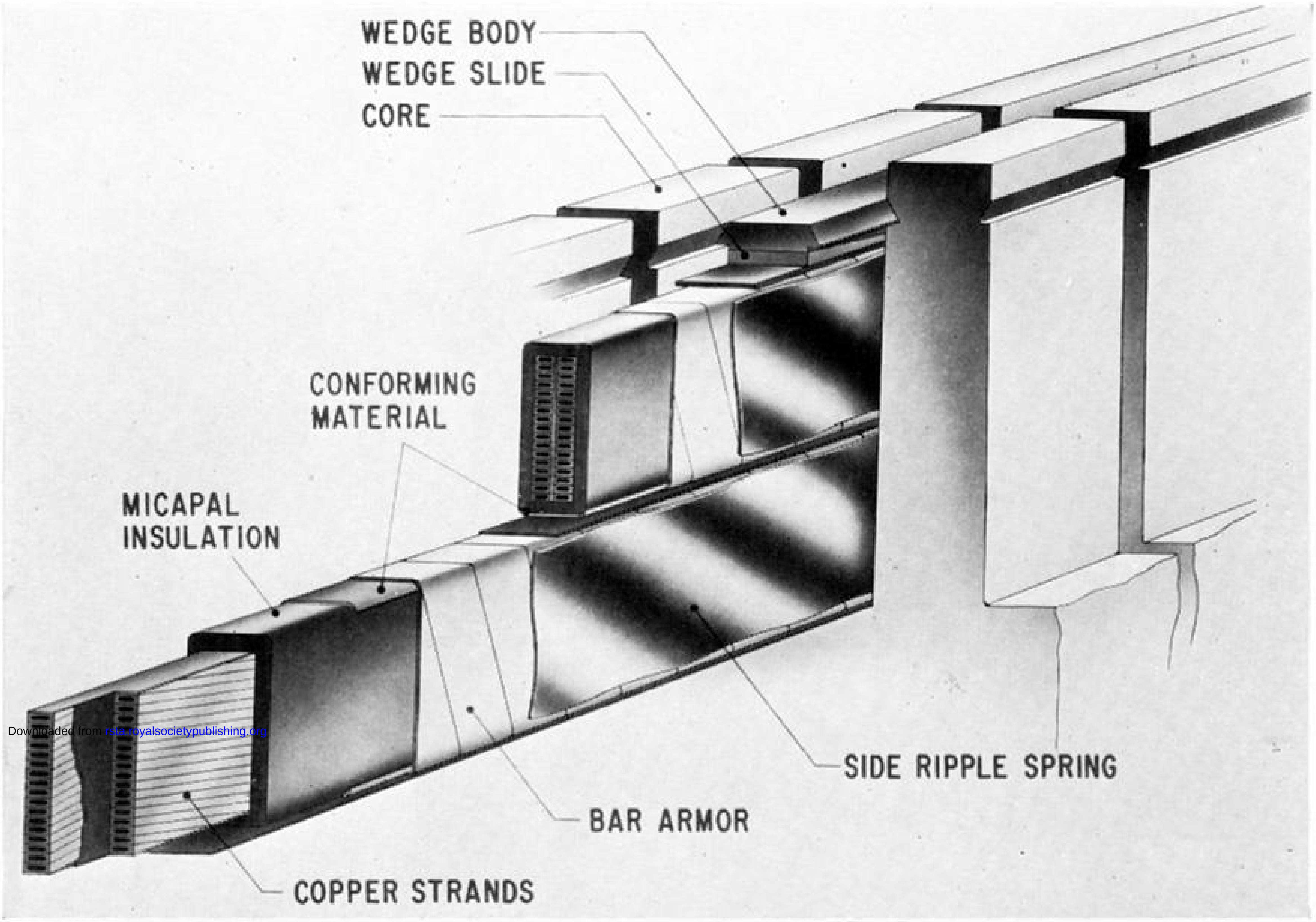

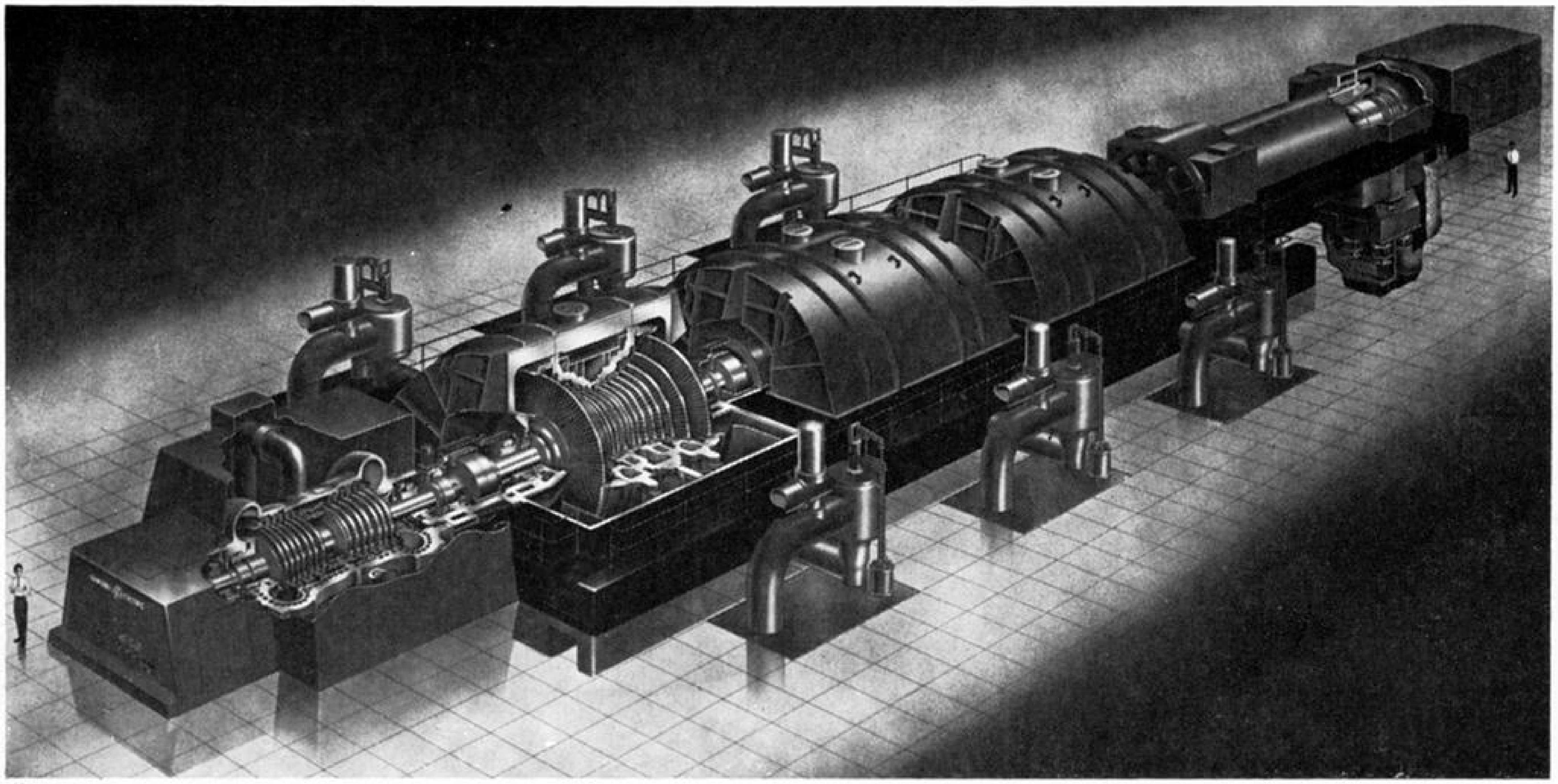

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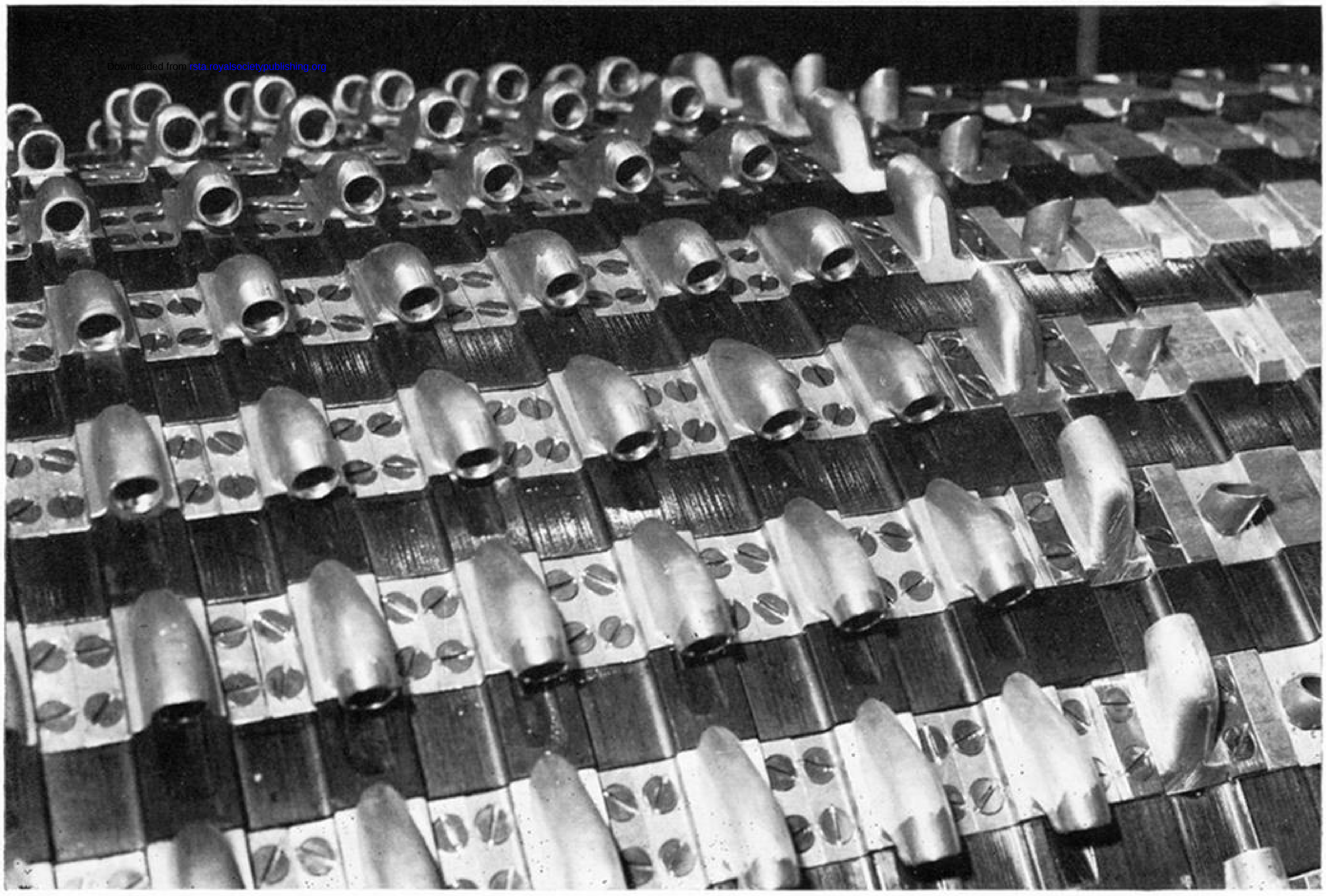

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