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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Homopolar machines

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[Plate 7]

The genesis of homopolar machines is to be found in Faraday's classical work on electromagnetic induction, and the first hint of their major problem, that of current collection, is contained in the account of the famous disk experiment which is given in his diary. Work within the last two years has provided a practical solution to this century-old problem and, together with a realization that ohmic losses in a steel rotor can be compensated by reduced excitation losses, has permitted the construction of an all-steel homopolar machine with a capability in excess of 100 kW.

The use of an all-steel construction enables the magnetic flux to be guided in such a way that many stages can be linked with the flux from a given number of turns and the power-rating greatly increased. The relatively short thermal paths within the machine permit these high-power densities without excessive temperature rises. Conceptual designs have been produced capable of powers of tens of megawatts, which employ magnetic flux densities that are familiar to the electrical machine engineer.

Michael Faraday first demonstrated the generation of a steady electromotive force in a moving conductor in 1831 by spinning a copper disk in an axial magnetic field. Since then, engineers have returned to this experiment many times in an endeavour to exploit it in a practical machine.

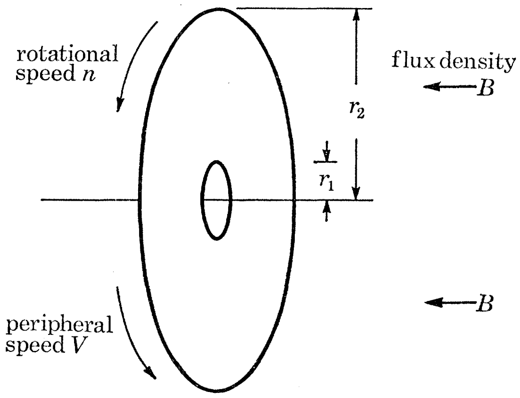

Figure 1. E.m.f. generated in disk.

$$\begin{aligned} \text{E.m.f.} &= B\pi(r_2^2-r_1^2)\,n \\ &= (\text{flux intercepted})\times n \\ V_{\max} &= \surd(\text{max stress/density})\times\text{constant.} \end{aligned}$$

The potential difference developed between the inner and outer radii of a spinning disk is given by the first equation shown on figure 1. The voltage is proportional to the flux density, the difference in the squares of the radii of the disk and the rotational speed, alternatively the potential difference is equal to the total flux intercepted by the disk multiplied by the rotational speed.

The upper limit to the voltage will be governed by the maximum flux density and the limiting peripheral speed of the disk. Assuming that the magnetic circuit will be achieved in a conventional steel, then the flux density can be in the region of 2.0 T and the peripheral velocity will be limited by the ultimate tensile strength of the material. The relationship for maximum velocity is also shown in figure 1, the velocity being equal to the square root of the ultimate tensile strength divided by the density of the material, multiplied by a constant depending upon the geometry of the system. Assuming the disk to be made of a low carbon steel then the peripheral velocity will be limited to 150 m/s, and if conventional copper is used a somewhat lower limit at 100 m/s. At a rotational speed of 3000 rev/min this represents, for steel, an upper limit of radius approaching 0.5 m and a disk of this radius is capable of generating about 72 V.

The current from such a machine will be limited by the ability to: (*a*) collect the current at the high current densities and surface speeds involved; (*b*) remove heat which is generated by the ohmic and other losses within the machine and maintain temperatures acceptable to the materials of construction; (*c*) provide sufficient torque to the rotor disk.

If these criteria can be met it may reasonably be expected that a machine could be developed that would generate low voltages and very large direct currents using conventional materials in fairly simple constructional forms.

The incentive to work on this class of machine in the second half of the twentieth century has arisen from a number of potential applications. The first of these is the growing large-scale use of electrolytic processes ranging from the direct production of chemicals to the manufacture of thin copper foil used in the printed circuit industry. As the processes become more sophisticated there is a requirement to supply individual cells to obtain the maximum control of the process. There could be advantage in other applications if the capital cost of the equipment were low enough to compete with the single large transformer rectifier and the relatively expensive associated busbars and switches. Under this general heading may be included the electrolytic recovery of metals from scrap.

The second major area of application is in the form of a combined motor and generator to replace the conventional Ward Leonard system. In a number of applications the precise control that can be obtained from this system is unequalled, although it is now progressively being achieved by solid state equipments feeding conventional d.c. machines. For a homopolar equipment to succeed in this market again capital cost is all important. In certain applications, such as marine propulsion, the power to mass ratio of the combined motor generator system is the important parameter and this may require designs that are optimized on slightly different bases.

A third area is in the liquid metal fast breeder reactor which is being developed throughout the world. There is a need to circulate the liquid metal, and although it has been recognized that electromagnetic pumps provide a very reliable means of achieving this, their low efficiency and high capital cost has so far prohibited their use other than in experimental systems. Conventional mechanical pumps are, therefore, more often employed. A homopolar generator can be used to drive a d.c. conduction pump to give an overall efficiency of better than 50 %.

At the time the work described below was started, computers were being developed which required currents in the region of 10 to 20000 A at their normal supply voltage of 5 V d.c. The homopolar machine would have three advantages in this application: (i) the very low inherent ripple voltage, (ii) the very low internal impedance and hence the good regulation which is required in this application, and (iii) complete isolation from the mains supply transients.

Our first major attack was on the problem of current collection since it was clear that conventional brushes would be difficult to operate at the peripheral speeds of interest and that their voltage drop and frictional losses would impose an immediate limit of about 75 % on the efficiency of such a generator. From our previous work on liquid metal pumping systems we were familiar with the magneto-hydrodynamics and chemical problems associated with liquid metal sliprings. At the speeds of interest the flow will be highly turbulent and the hydrodynamic power loss of a simple slipring will be proportional to the surface velocity to the power 2.9, the density to the power 0.9 and the kinematic viscosity to the power 0.1. From this relation it is clear that liquid metals of low density will minimize these hydrodynamic losses. The choices facing us ranged from sodium and sodium alloys with densities of around 1, up to mercury with a density of 13.6. At the density of mercury the hydrodynamic losses would almost certainly be unacceptable; sodium with its melting point of 98 °C would pose severe operational difficulties and the sodium potassium alloys with melting points below room temperature have been known to create problems when used in reactor experiments in various parts of the world. We closely examined the evidence of the instability of sodium potassium alloys and although systems to employ them could be effectively developed they might always suffer a certain adverse reaction, particularly as we were aiming for machines that could be used in a wide range of potential markets. We therefore focused our attention on alloys with densities approximately half way between sodium and mercury and ultimately chose the alloy of indium and gallium which has a melting point of 15.7 °C.

We also recognized, from our earlier work, that the presence of a magnetic field could modify the turbulent nature of the flow due to an interaction between the electrical and mechanical eddies in the fluid. At low magnetic fields of appropriate orientation some suppression of turbulence can be achieved whereas at high fields the losses markedly increase. For example, if the axial magnetic fluxes through the disk are allowed to penetrate the slipring region then the magneto hydrodynamic losses in the liquid metal are quite unacceptable. By careful design of the slipring area we have been able to obtain conditions where the magnetic fields help, rather than aggravate, the loss problem.

The next problem was the long-term stability of gallium indium. We had assumed from the start of the work that, while we could possibly totally seal a generator and its drive, this would not be possible for a homopolar motor, although we believed that the rate of ingress of oxygen could be limited. Indium and gallium both oxidize readily and in the liquid metal slipring, where the metal is often in the form of tiny droplets, this oxidation process is very rapid. If, for example, a simple slipring is run in an atmosphere of air the entire slipring will turn into a black powder within an hour or so and cease to be effective. Analyses carried out on powder produced in this way have shown that it consists of tiny droplets of liquid metal encapsulated in the oxides and hydroxides of gallium and indium.

We have looked closely at ways of reclaiming the liquid metal and ultimately devised the arrangement which is shown in figure 2. The liquid metal is circulated in the machine under its own centrifugal forces and is then passed into an electrolyte where the oxides and hydroxides go into solution and where the metal components may be recovered at the liquid metal cathode by the application of a d.c. voltage to the cell. We have operated systems like this for many hundreds of hours without observing any deterioration in the liquid metal characteristics. This major breakthrough in our research programme led to more meaningful experiments on liquid metal sliprings and our final configuration, with the appropriate application of the magnetic fields, showed a velocity dependence which had been reduced from the theoretical 2.9 to something much closer to a square law relation.

The immediate temptation was to construct a machine using a copper disk. More detailed calculations revealed that the excitation losses required to create the field in the low

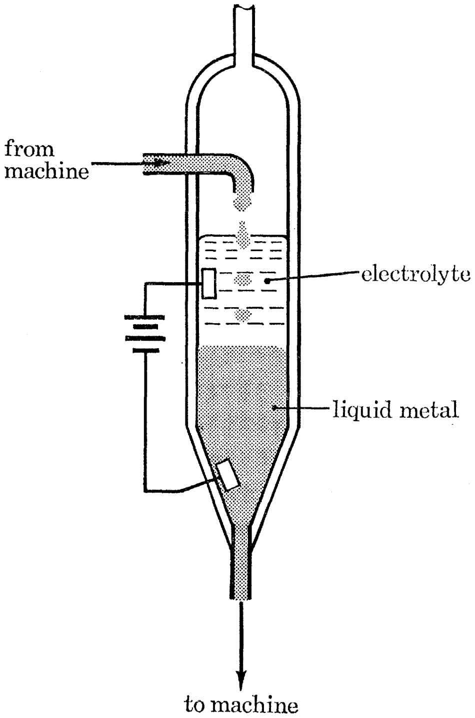

Figure 2. Electrolytic cell for reclaiming the liquid metal from the reaction products.

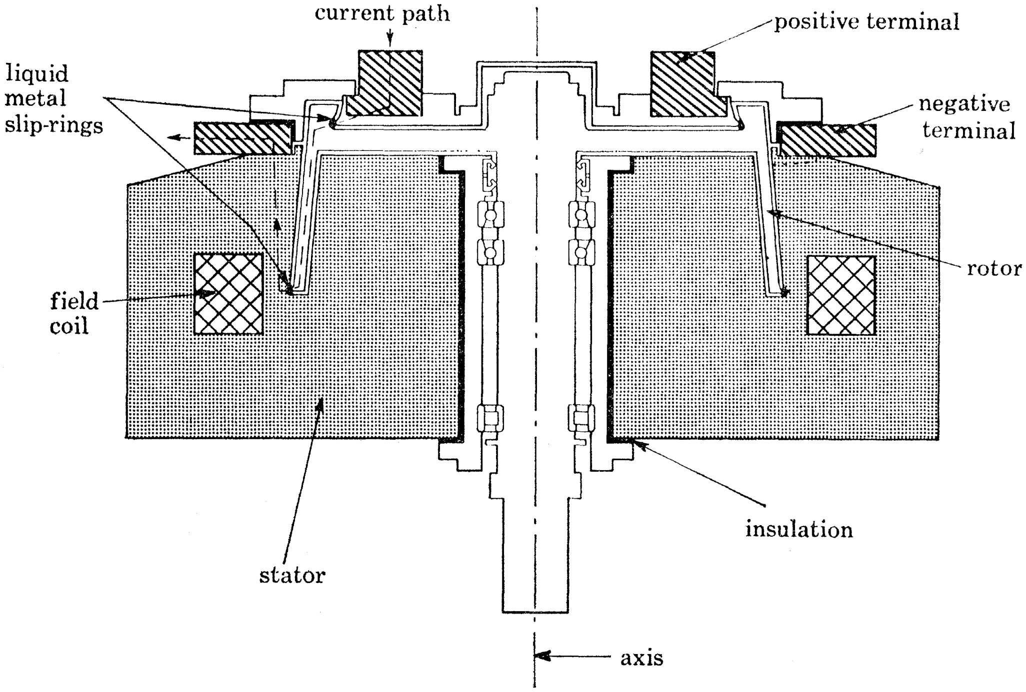

Figure 3. Section of single-stage iron-cored machine.

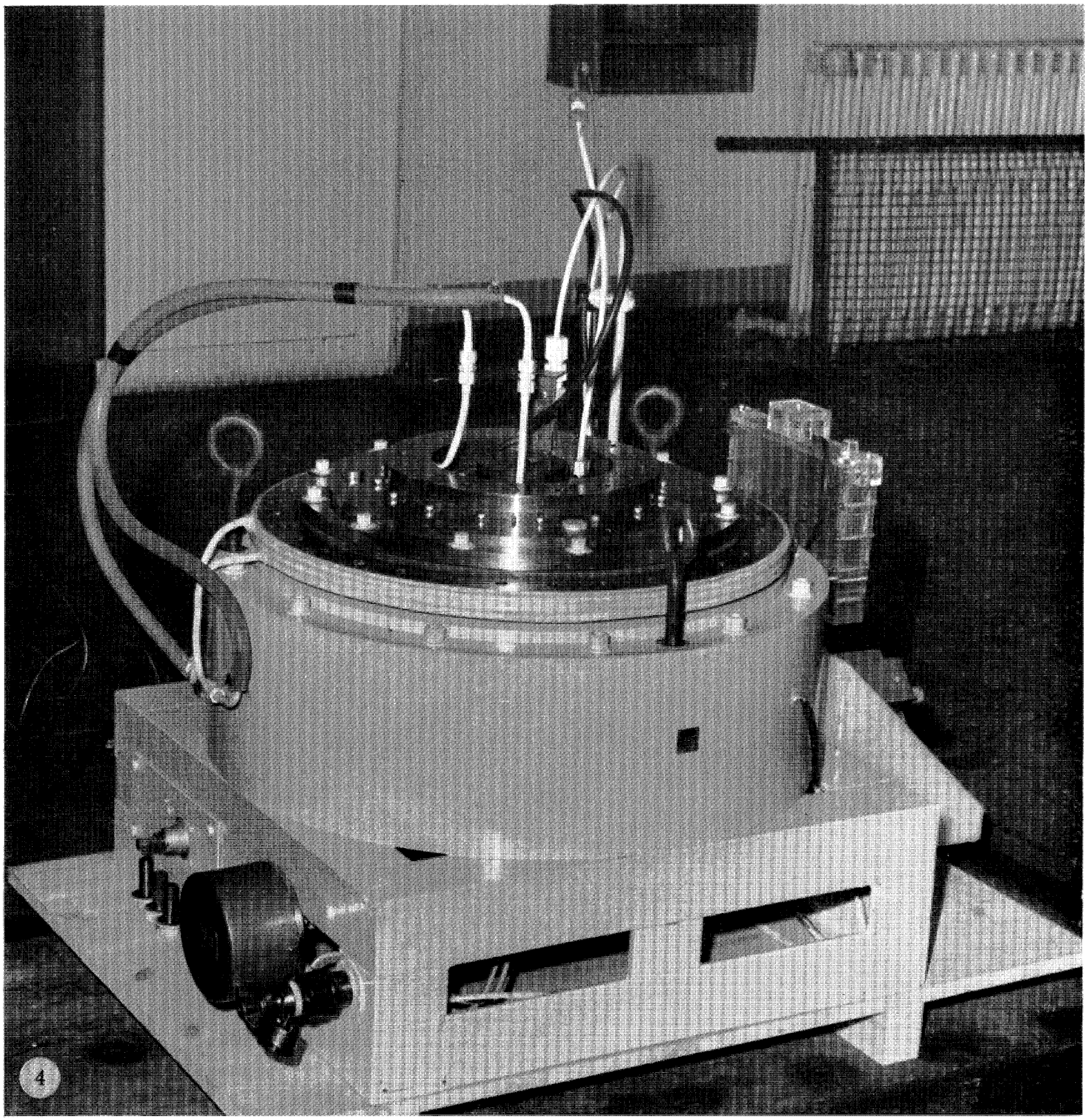

FIGURE 4. General view of generator.

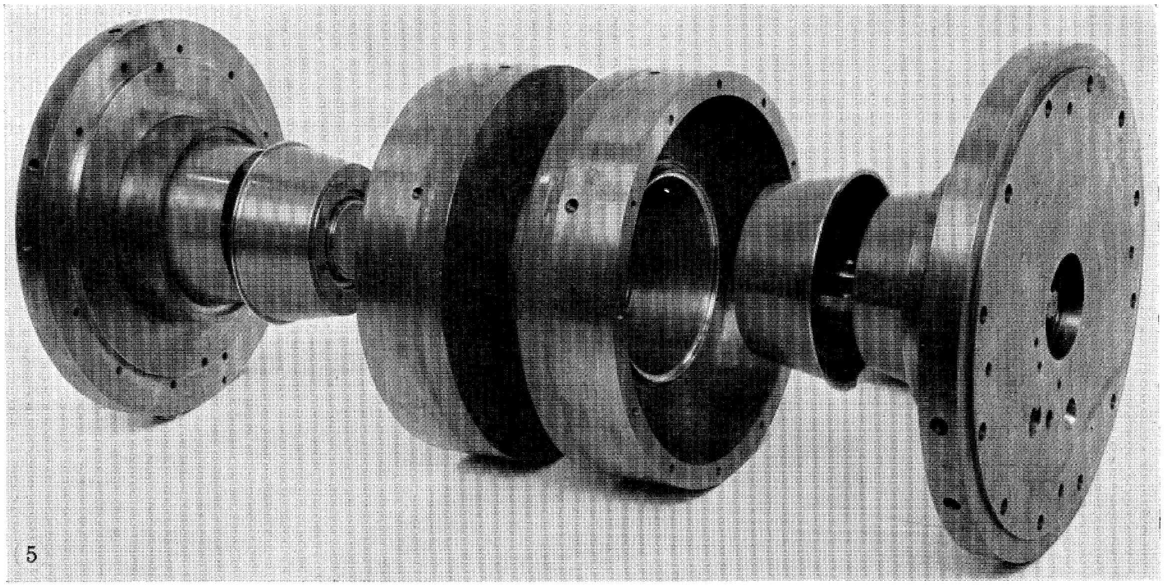

FIGURE 5. Exploded view of a torque converter.

permeability gap presented by the copper disk could be effectively traded against the increased ohmic losses with a steel rotor of high permeability. There is some slight loss in overall efficiency with this system, but steel also has the great merit of being unreactive in liquid metal systems at moderate temperatures, and in several years of work we have had no evidence of harmful erosive or corrosive processes taking place. There were some initial problems in producing true, as distinct from oxide, wetting between the liquid metal and the steel but by the application of suitable electrochemistry the problem was also successfully overcome. A disk design has the advantage that centrifugal forces can be used to circulate the liquid metal but has the disadvantage of large current concentrations towards the centre of the disk with correspondingly high ohmic losses. The compromise was to use a tapered cone as the rotor and a design which we are currently using is shown in outline in figure 3. It consists of a bucket-shaped rotor contained within a low carbon steel yoke with simple metal sliprings on the inner and outer ends of the conical section. The return current flows in the yoke to this terminal ring, and the close proximity of the opposing currents is important in reducing the cross-excitation in the steel rotor. Torque reaction is between the rotor and the stator, and no special provision is necessary to hold the field coil in position. Excitation for the machine is provided by a simple helical coil, also shown in figure 3. Liquid metal circulation is more than adequately provided by the centrifugal forces in the machine.

Figure 4, plate 7, shows a photograph of this machine which we have now been running, at intervals, for some 18 months. It produces 7 V at 3000 rev/min for a rotor diameter of 0.36 m, and we have drawn currents up to 23000 A. The overall diameter is 60 cm and its height some 30 cm. The overall efficiency of this generator is 92.5%. The liquid metal recovery cell is mounted on the outside of the machine and its transparent plastic case can be seen on the right-hand side of the photograph. It is quite possible to modify the form of the cell to enable it to be included as a more integral part of the machine block. This machine has been transported several hundred kilometres by road and has achieved its design performance without any major attention when required. We believe that we have by no means exploited the limit of this technology in these single stage machines and that powers of up to $\frac{1}{2}$ MW can be achieved at 3000 rev/min.

By mounting two rotors back to back with a common yoke, as shown in figure 5, plate 7, we have achieved a self-contained generator–motor situation for use as an electric torque converter. The photograph shows the two bucket-shaped rotors and the steel yoke. The wetted areas of the liquid metal sliprings can also be seen. The current generated in one rotor is fed to the other via a common slipring and returns through the yoke. Separate field coils are mounted in each half of the yoke to provide the necessary control of speed and torque.

The next step in the evolution of these machines is to return to the disk geometry and to mount a number of rotor and stator disks in parallel on a common shaft to increase both the voltage and the power density. Figure 6 shows an outline drawing of such a machine with a number of disks excited from a common field. As the machine increases in length the flux density in the centre of the machine diminishes, even though the rotor and stator are of carbon steel. In many applications it is essential to cancel the external magnetic field and this can be achieved by supplementary coils mounted on the axis of the machine. These coils not only achieve cancellation of the external field but also markedly improve the uniformity of flux within the rotor stack. Dr K. J. R. Wilkinson, who has been closely associated with this work, will be publishing an account of these multi disk machines.

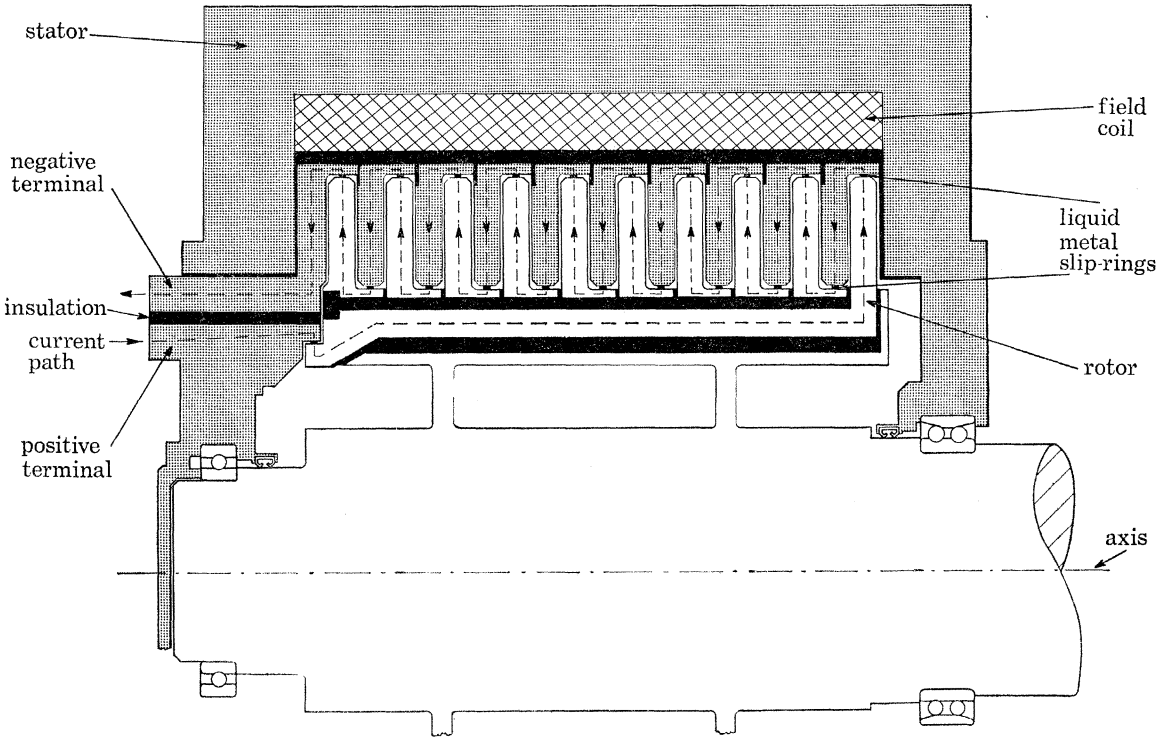

FIGURE 6. Section of multi-stage machine.

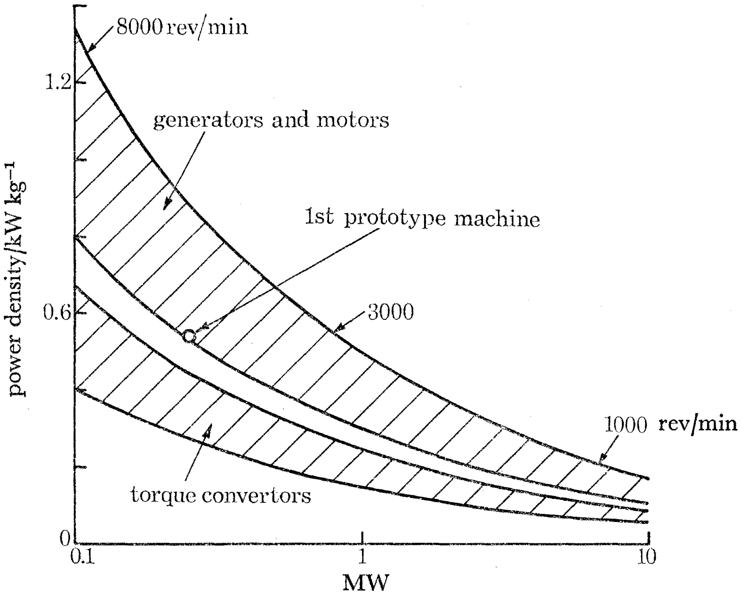

FIGURE 7. Single-stage iron-cored homopolar machines. Projected data.

Figures 7 and 8 are an attempt to summarize the present position. Figure 7 shows the variation of power to mass ratio as a function of power for single-stage homopolar machines. Because the main limitation of these machies is in the peripheral velocity at the slipring surface the power a machine can develop increases as the rotational speed falls and the curve shows that 10 MW would be possible at a rotational speed of 800 rev/min. An experimental point for our first machine is also shown.

Figure 8 extends these data to multistage machines and further illustrates the marked dependence on speed. For example, we have designed a generator at 3000 rev/min which produces 2$\frac{1}{2}$ kW/kg and is probably the highest power density achieved in any homopolar machine so far conceived. The motor which this was intended to drive at 200 rev/min could not be optimized to give the same power density and it only achieved a modest $\frac{1}{2}$kW/kg. Also shown on this diagram are some points for conventional mechanical transmission as used in marine propulsion and one or two values derived by us from published information (McCann & Mole 1972) for superconducting machines. The output speed for these machines was 250 rev/min. It would appear that when the associated cryogenics are taken into account the power to mass ratio of a superconducting machine is no better than that for an iron cored version.

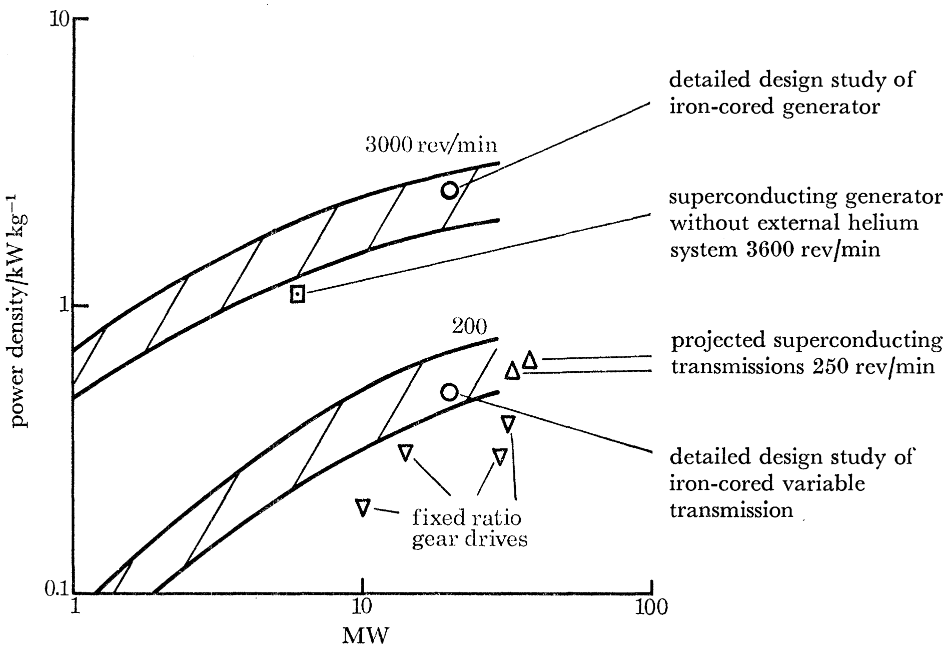

Figure 8. Multi-stage iron-cored homopolar machines. Projected data.

During the course of this work we have not neglected the important question of costs. Our initial estimates would suggest that prices for iron-cored homopolar generator sets with drive having a capacity of 20 to 40 kA at 6 to 7 V will fall at the bottom end of the range for comparable industrial rectifier units.

In summary we have reached the point in our work where we now believe that we have solved the major technical problems of the homopolar machine and that in a number of applications it will be competitive with existing equipments. We are now proceeding to establish that reliability will be sufficient for these purposes and early indications after 1000 h of operation under varying load conditions are encouraging.

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McCann II, E. F. & Mole, C. J. 1972 Superconducting electric propulsion systems for advanced ship concepts, AIAA/SNAME/USN Advanced Marine Vehicles Meeting, Annapolis, Maryland, 17–19 July 1972, paper no. 72-590.

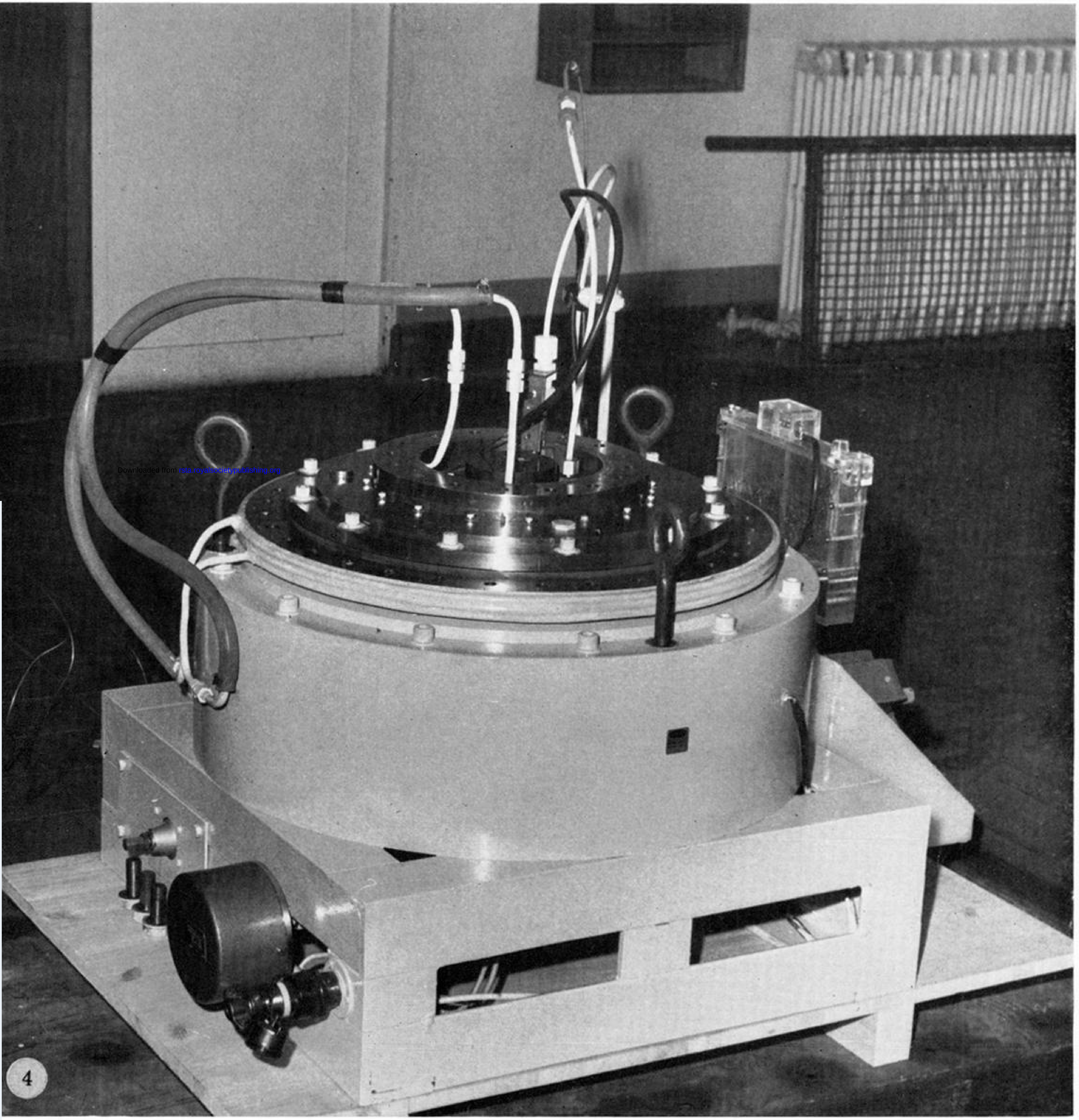

FIGURE 4. General view of generator.

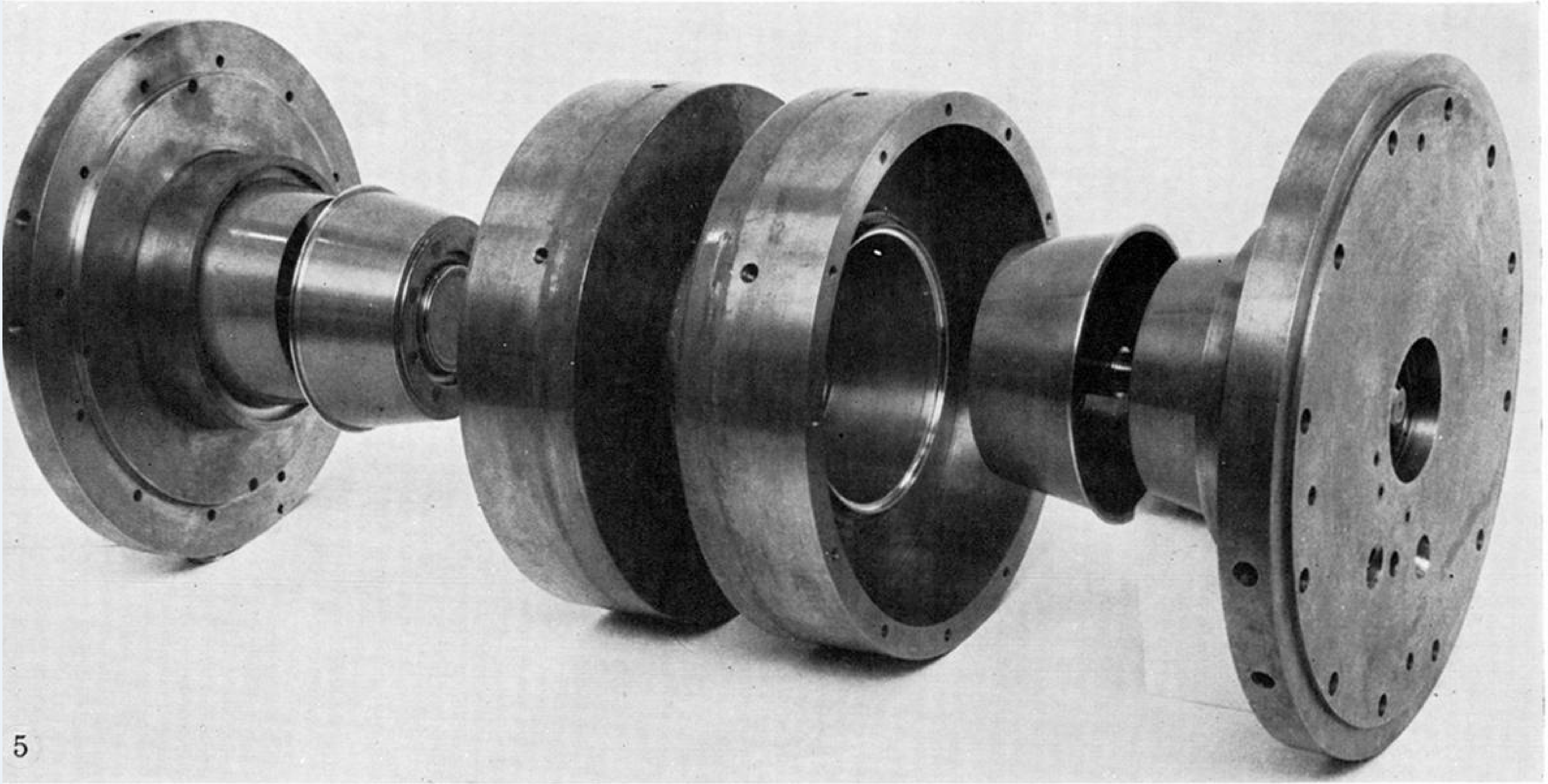

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FIGURE 5. Exploded view of a torque converter.