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The Behaviour of Various Electrodes and Insulators in an Experimental M.H.D. Generator

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XIV. The behaviour of various electrodes and insulators in an experimental m.h.d. generator

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[Plate 24]

The special features of an m.h.d. generator in which there is an electrically produced temperature modulation of the gas stream are discussed.

Methods and equipment for producing a striated plasma are described together with the first experimental apparatus (*MHD* 5) used to study such flows. A critical examination of the materials employed in the first series of experiments lead to the conclusion that hot electrodes were most suitable and indicated other aspects which would need further study. The limitations of the *MHD* 5 duct lead to the design of *MHD* 6 and the gas conditions, geometric dimensions, duct rigidity, thermal expansion problems, material compatibility and heat transfer of this equipment are discussed in some detail.

1. Introduction

Open cycle m.h.d. energy conversion makes direct use of the combustion gases from fossil fuels. In the most common direct current m.h.d. generator the gases are simultaneously the vehicle for the energy to be converted and the medium which interacts with the magnetic field. The two functions are closely interdependent. The high electrical conductivity required of the gases for the second function imposes a lower limit of 2500 °K on the useful temperature range, although the enthalpy of the gas is still high at this temperature.

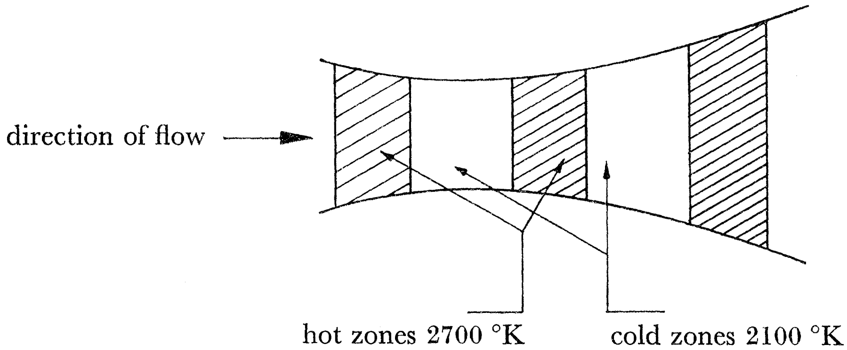

Figure 1. Diagrammatic plan of a temperature modulated gas stream working on the inhomogeneous gas stream principle.

The concept of inhomogeneous striated flow described by Thring (1962) and Ricateau & Zettwoog (1963) separates the two functions by employing a fluid flow formed by a continuous succession of hot and cooler zones (figure 1).

The hot conductive zones undergo most of the interaction with the magnetic field and expand nearly isothermally since ohmic heating in them is high. The cooler zones are practically non-conducting and, by almost isentropic expansion, transfer their energy into kinetic energy through the hot zones and thus to electrical energy.

The arrangement approaches that of a turbo alternator set in which the gas driving the turbine transfers its energy via the turbine blades to the copper conductors rotating in the alternator's magnetic field. The hot zones are the 'blades' driven by the less hot zones.

Theoretical study of the cycle shows the system to have several advantages over steady flow generators. The specific power is increased for a given efficiency and so the size of generators can be reduced. The generator can use gases with a lower mean temperature so that the fuel can be burned in air with no or only slight oxygen enrichment. The lower mean temperatures lead to lower heat losses to the walls so that efficient generators can be made in sizes smaller than the 1000 MW input size usually reckoned to be needed to make the straightforward m.h.d. generator efficient.

The C.E.A.–I.F.P. group at Rueil has an experimental programme to produce such temperature modulated flows and study their stability (Lemaire 1963).

There are several methods of producing striated flow: the temperature may be modulated either electrically (Devime, Lecroart & Zettwoog 1964) by pulsated combustion or altering the stoichiometry of the burning gas (Karr 1964): or the seed flow may be modulated.

This paper describes experiments using an electrically temperature-modulated flow with special emphasis on materials used for building the generator.

2. Electrical modulation

2·1. *Method*

Modulation is achieved in the experiments in two stages as shown schematically in figure 2. In the first stage a voltage is applied intermittently from a 1000 c/s alternator feeding through a solid state rectifier. The modulation wavelength depends only on the gas velocity, whereas the relative proportions of hot and less hot zone depend on the

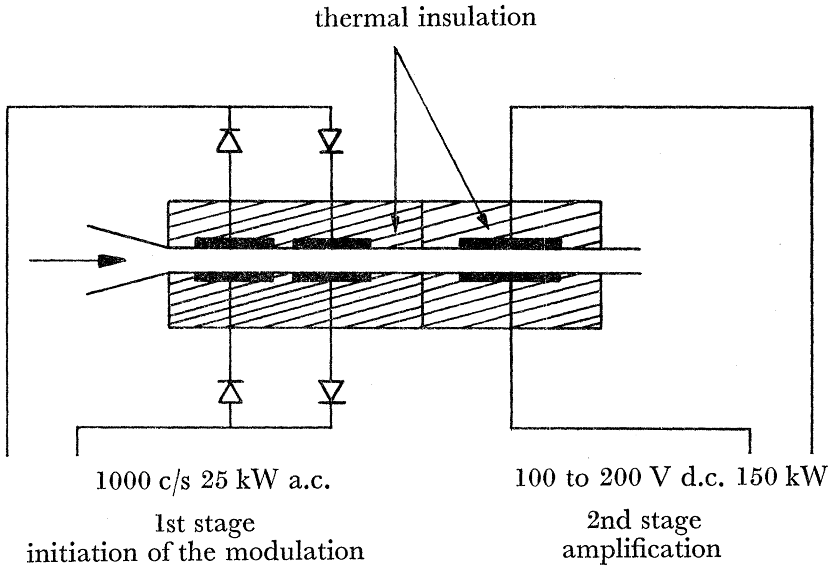

Figure 2. Diagram of the two-stage electrical modulation system.

electrode length and duration of the applied electric field. The modulation is amplified in the second stage by passing the gases between electrodes supplied by a 115 kW d.c. dynamo. The hotter zones become hotter since their electrical resistance is lower and they absorb relatively more energy from the d.c. supply than the less hot zones.

2·2. *The apparatus*

The specification of the *MHD* 5 experiment was: frequency 0·5 to 1 kc/s; input to combustion chamber 150 kW: kerosene–air + 0·8 mole % potassium; duct size 2 cm × 4 cm; velocity 310 m/s; hot zones 2700 °K, 10 cm long; cold zones 2100 °K, 20 cm long.

A study of modulation stability in a 2 × 6 cm duct was made. A magnetic field of 1·7 T over a length of 90 cm was used. The modulation is destroyed by several factors, of which the most important are turbulent diffusion and Rayleigh–Taylor instabilities. The latter effect is accentuated by a non-uniform magnetic field.

The modulator consists of four pairs of electrodes in series along the duct: the first two immediately after the combustion chamber constitute the premodulation stage and the remaining two the amplifier. Cooling is by air which is subsequently used for combustion. The limited electrical power available restricted the thermal inputs that could be used.

2·3. *Materials*

Selection of materials was guided by several considerations. A high wall temperature (1900 °K) was required to reduce heat losses so that a fairly high plasma temperature could be maintained along the generator, whose length was about 2 m. Furthermore, voltage drops through the boundary layers were to be kept low (since the duct was small (2 × 4 cm) and the induced e.m.f. only about 20 V). This consideration, too, called for a high wall temperature.

The method adopted consisted of insulating the duct by packing the space between the wall plates and the containing stainless steel cylinder with magnesia powder. The containing shell was double and it was air cooled (see figure 3, plate 24).

The insulating walls were in the first place made of adequately pure sintered magnesia and, before improvements were implemented, the electrodes were of graphite. Graphite appeared at first sight to be the only possible hot electrode material, and in fact had been used for runs of several minutes in an earlier generator.

Unfortunately the graphite burnt very rapidly and in the present experiments never lasted more than 10 to 12 min.

Thermal equilibrium was never reached so that ordinary difficulties of studying the conversion process were compounded by uncertainties about time-dependent effects and particularly about physical and chemical changes in the duct structure materials.

New difficulties arose later when means were found to run for 30 min. However, it was possible to cine-photograph cathode spots on the graphite electrodes, the spot intensity being modulated by varying the supply power. Filming was done by removing one of the two insulating walls.

Wall and electrode material improvements were made simultaneously.

In view of the high temperatures at which it was intended to run the insulating walls the use of calcium or strontium zirconate was considered, these materials being both

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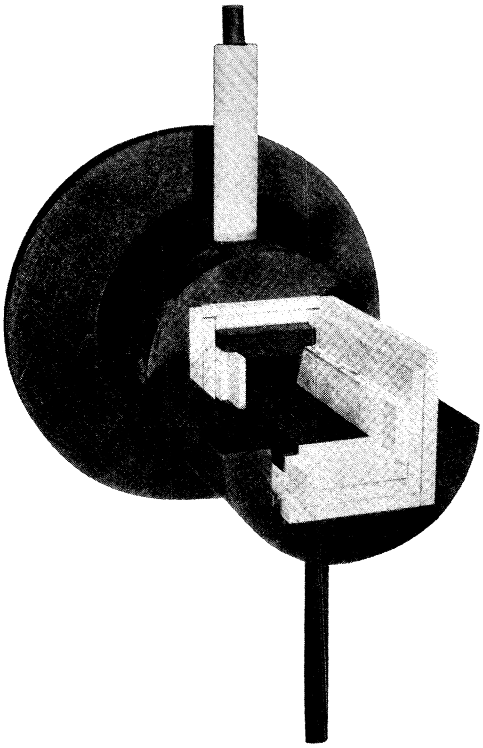

FIGURE 3

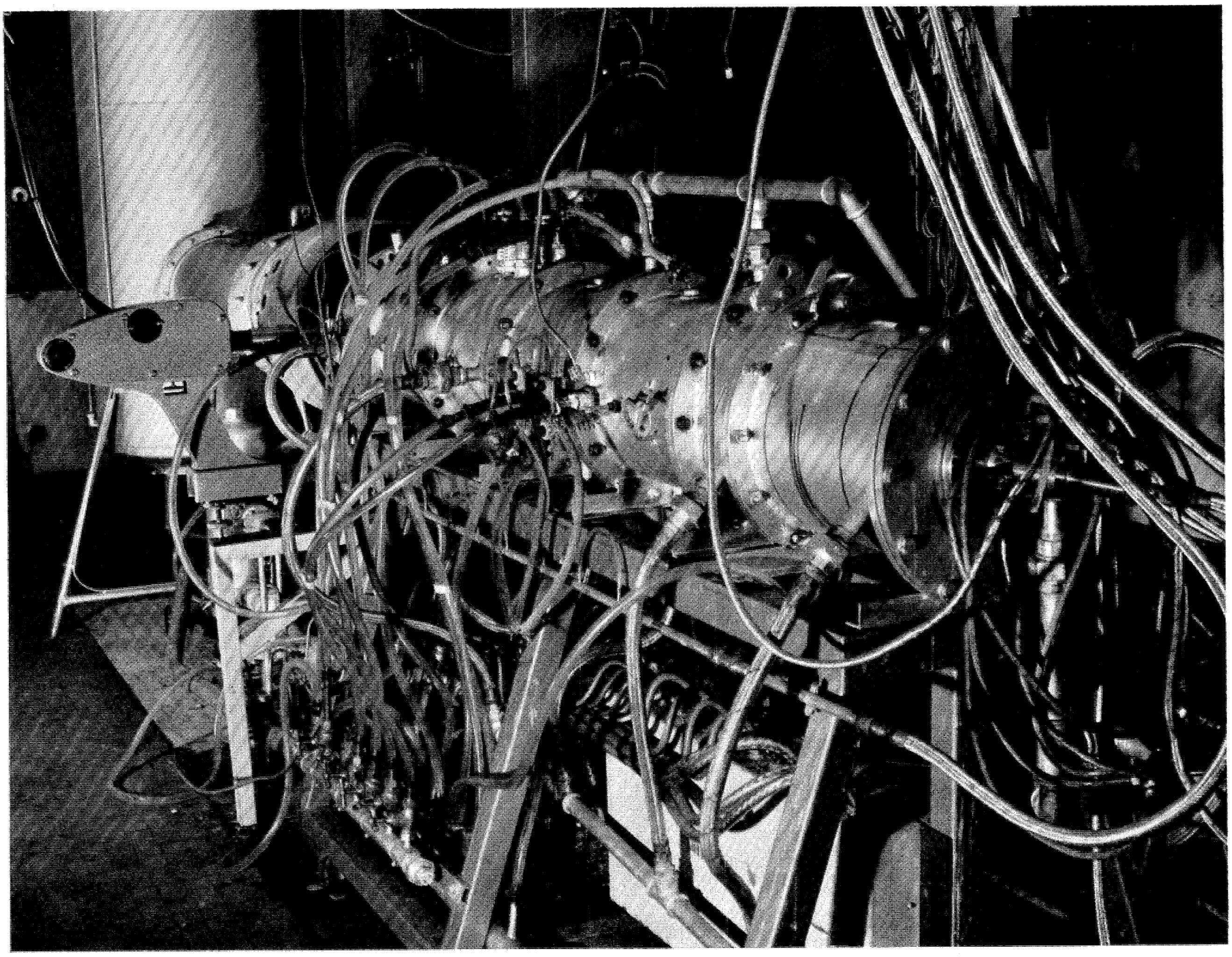

FIGURE 6

(*Facing p.* 498)

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highly refractory and amongst the best of electrical insulators with, in addition, a low vapour pressure (magnesia evaporates very rapidly above 1900 °K). Furthermore, zirconia, which was being considered for an electrode, is at high temperatures chemically compatible with zirconates but not with magnesia.

The zirconates were not well known materials and the help of the University was enlisted to study them. Perfectly stoichiometric $SrZrO_3$ is highly stable and the second best known electrical insulator; single crystal MgO is the best. But no refractory material is sufficiently insulating above 1900 °K and it is idle to suppose that an m.h.d. generator insulating wall could work above this temperature.

Some progress has been made with electrodes too. After the first disappointing experiments, both carbides and borides of zirconium and titanium, and a compound of 90% ZrB_2 and 10% $MoSi_2$ were tried. The carbides and borides were not much better than graphite, lasting 15 to 20 min compared with 10 to 12 min for graphite, and moreover formed disastrous eutectics with the magnesia walls. The compound became coated with silica, which although protecting the electrode, prevented all gas/electrode electrical contact.

An oxide with good high temperature conductivity was sought next and calcia- or yttria-stabilized zirconia was selected (50 mho/m above 1600 °K).

These materials are good thermal insulators and their use led to high gas face temperatures and so to a reduced electrode voltage drop. Not only was the electrical resistance of the gas layer reduced but it appeared that there was considerable thermionic emission from the surface since arc spots were observed to have disappeared. Electrode life was increased to 5 or 6 h at current densities of 1 to 2 A/cm^2.

A major problem lay in the poor electrical conductivity of the zirconia at low temperatures where it made contact with the metal support. Several designs were conceived to overcome this difficulty of which three were especially good.

The first design consisted of a layer of zirconia 2 to 3 mm thick supported on a finned base of graphite. This arrangement could carry 1 to 2 A/cm^2 but would last only 30 min as no means could be found to prevent the graphite oxidizing.

In the second design several graded layers of mixtures of chromia and zirconia were sintered together to give pure zirconia at the high temperature face and pure chromia on the back face.

Chromia is a good electrical conductor up to 900 °K and could be mounted directly by brazing onto metal.

Current densities of 1 to 2 A/cm^2 were reached with this electrode too and the electrode lasted about an hour without being destroyed by arcing or stray currents but did suffer from electrolysis of the zirconia in the manner described by Anthony & Yerouchalmi (1965).

A similar type of electrode was tested in a larger 7×10 cm duct using electrodes which lasted 6 h before electrolytic effects set in and destroyed the cathode.

The third method used a high temperature non-oxidizing refractory metal in contact directly with the zirconia (Wang & Yerouchalmi 1965). The arrangement is shown in figure 4 and consists of plates of zirconia 2 to 3 mm thick brazed to each other by 30 to 50 μm of a platinum/rhodium alloy, so that the metal contacts the zirconia in a hot region. The back of the structure is also coated with the alloy.

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Tests lasted about 1 h in the *MHD* 5 duct and invariably ended with arc formation in the electrode structure (see figure 6, plate 24). The plates were still well stuck together and there was no other gross damage apart from slight cracking due to thermal shock and arc burns. However, it was found that there had been partial evaporation of the metal and it is clear that without very careful temperature control of the hot face, and indeed throughout the electrodes, it would be impossible to ensure that they could withstand the high temperatures for long periods.

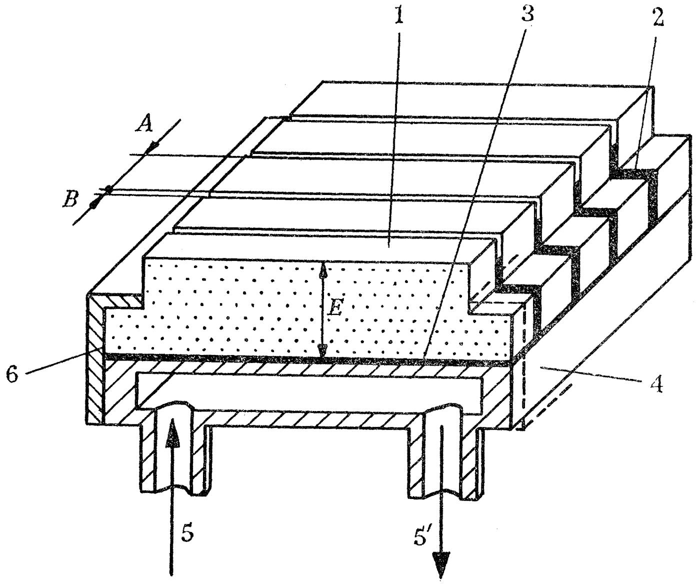

FIGURE 4. Electrode arrangement. 1, Ceramic plate; 2, thickness of Pt/Rh; 3, bonding metal between 1, 2 and 4; 4, cooled metal holder; 5, 5′ water and current supply; 6, mechanical clamping.

2·4. *Interpretation of measurements*

Many experiments were performed. The difficulties encountered with erosion of the duct and changing electrode and wall conditions prevented very clear and definite conclusions. However, modulation of the gas temperature was found to be highly efficient and reproducible but limited to a temperature differential of only 350 °C which corresponds to a conductivity ratio of 1 to 8 (typically one experiment gave a cold zone temperature of 2100 °K and a hot zone temperature of 2460 °K).

The modulation was limited by the smallness of the nozzle in which effects of wall roughness and inhomogeneous electrode emission (which led to arc formation) were comparatively large.

Amplification of the modulation was observed, though not reproducibly, and only with graphite, whose wear is regular and which does not give rise to uneven electron emission. The short life of graphite electrodes of only 10 min did not give enough time to examine sustained amplification.

To extend the test duration electrodes of 90 % ZrB_2 + 10 % $MoSi_2$ were used but these gave increased arcing in the modulation stage. The arcing was in fact uncorrelated with the power supply. This could be explained by the formation on about 15 % of the surface of rough patches which gave intense local electron emission.

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In the amplifier stage it was possible to apply the voltage across the longer dimension (4 cm) of the duct cross-section and to obtain temperatures of 2600 °K but without selective heating. Turbulence and ohmic heating of the boundary layer, which moves more slowly than the mainstream, were possibly responsible for this indiscriminate heating.

To summarize, synchronous electrical modulation is highly efficient but was limited in our experiments by alternator power. Amplification is not reproducible and frequently marred by uncontrolled effects of the gradual degradation of the duct materials. More pronounced marking of the hotter zones is required. Despite the difficulties further study of modulation at 1000 c/s in a magnetic field is planned. The difficulties discussed above have led to a modified design of duct.

3. A new approach

This paper has been concerned with wall and electrode materials for a system having an electrically modulated temperature. In parallel there have also been experiments in which the gas temperature is varied by injecting alternately different fuels which have given temperature differences between zones of 350 °K at frequencies between 100 and 900 c/s (see figure 7).

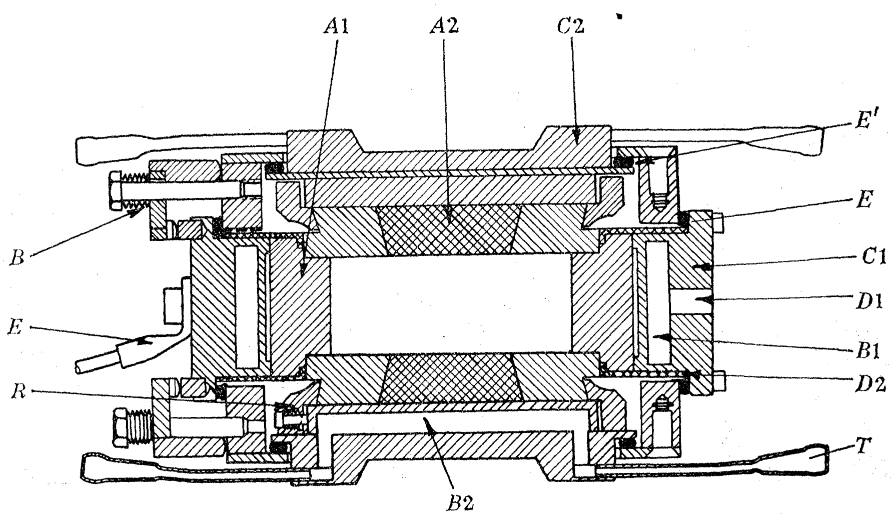

Figure 5. Duct design showing compensated clamping arrangements for the electrodes.

	1. electrode	2. insultant
A	conductive ceramic	insulating ceramic
B	water flow cavity	water flow cavity
C	copper holder	
D	water supply	water supply
E	current supply	
B	compensated clamping of electrodes	
R		compensated clamping of insulant
E	sealing by flexible ring seal	
E′		flexible seal and compensation for expansion
T	lateral clamping of electrodes	

To examine zone stability, whether the zones are created electrically or by different fuels, a new generator (*MHD* 6) has been designed. It is larger (4×10 cm cross-section) than *MHD* 5 and the gases move through it more slowly (100 m/s). The larger section will reduce the relative importance of electrode voltage drops. The length is as before, 90 cm and limited by the electromagnet available.

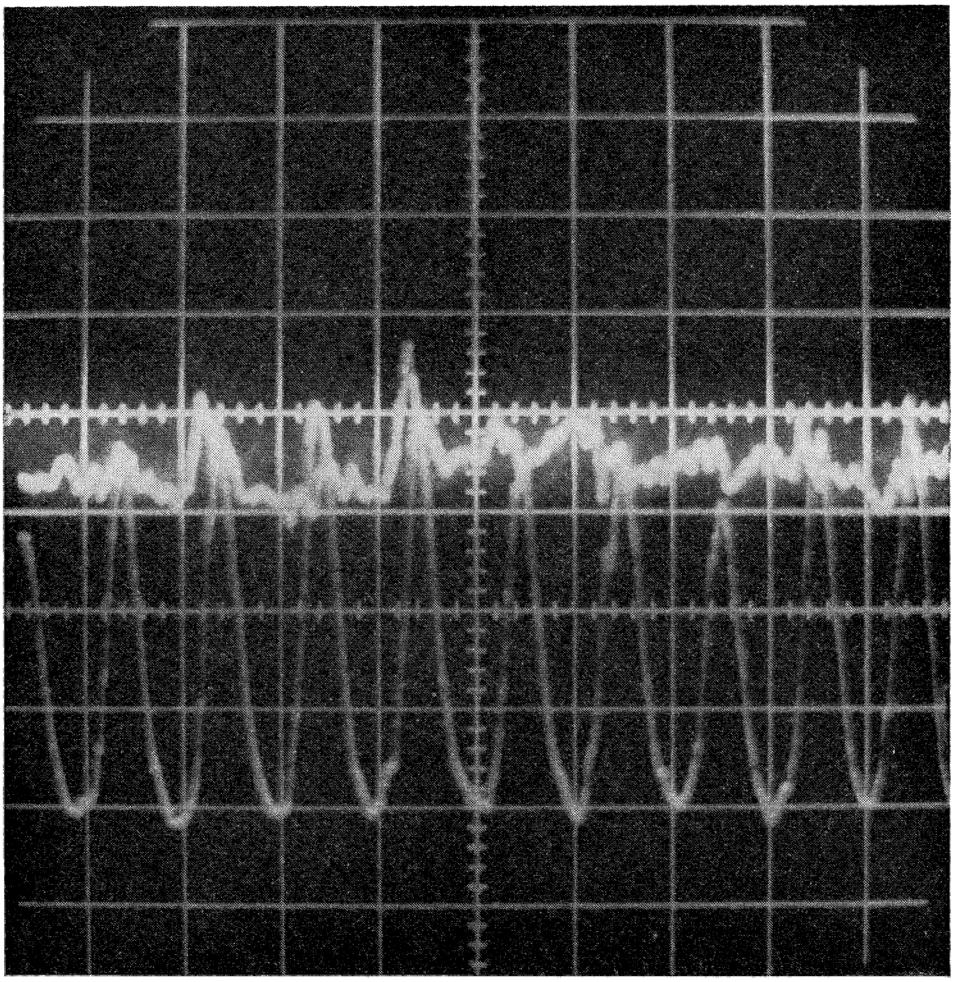

FIGURE 7. Modulation of temperature. Frequency, 1000 Hz; temperature of hot zones, 2460 °K, of cold zones 2100 °K; ratio of conductivities $\sigma_{\text{hot}}/\sigma_{\text{cold}}$, 8·7.

3·1. *Materials*

The success of the new generator will depend paramountly on the electrodes and wall structures. The highest allowable temperature of the gas face is 1900 °K at which all materials become conducting. Below about 1600 °K the liquid seed will deposit and migrate through the ceramic materials. The materials must not react chemically either with each other or with the seed. The structure must be rigid: thermal expansion will be accommodated by a flexible clamping arrangement (see figure 5).

But the key factor, to which all others must be adapted, is the control of the surface temperature by correct design. The thickness of ceramic is determined by the choice of front and back surface temperatures, by the heat flux from the hot gas stream, and by the effective thermal conductivity of the ceramic (Wang & Yerouchalmi 1965).

For *MHD* 6, with a front face temperature of 1900 °K, a back water cooled face of 350 °K and a heat flux of 7 W/cm^2, the zirconia electrodes of the kind shown in figure 5 are 25 mm thick and the insulating walls of strontium zirconate (with 20% porosity) are 20 mm thick. Both electrode and insulator ceramics are clamped on copper water boxes as separate units for mounting together to form the duct (figure 5). The whole is held together with a resilient support structure to accommodate thermal expansion.

4. Conclusions

Experience with the *MHD* 5 generator has highlighted the importance of materials in generator construction and it is hoped that to some extent the difficulties have been overcome in the design of duct *MHD* 6. One major problem remains: to find or devise ceramic conductors whose conduction mechanism is electronic rather than ionic so that electrolytic effects will be eliminated. Some work in this important direction is reported by Anthony & Yerouchalmi in the following paper.

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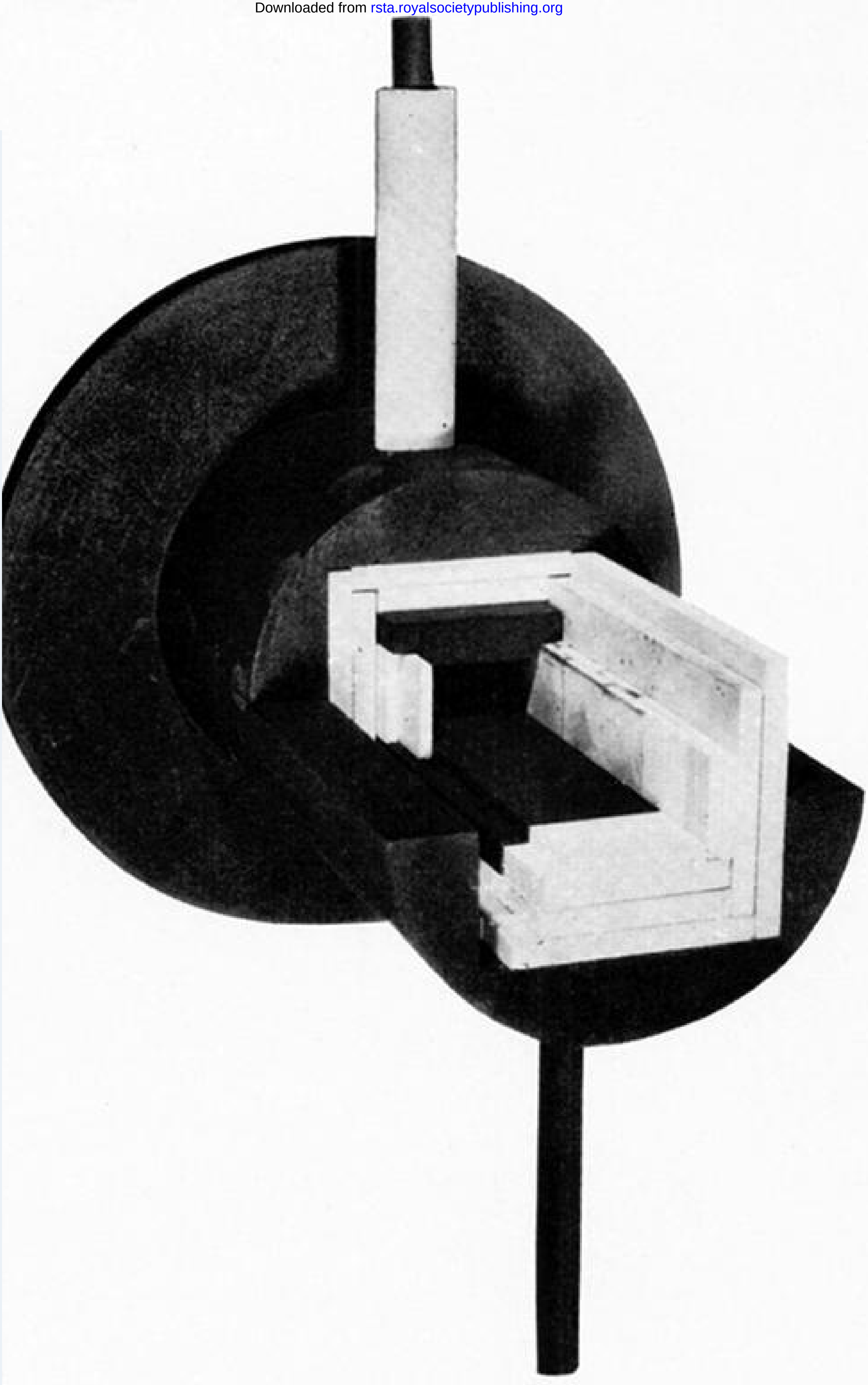

FIGURE 3

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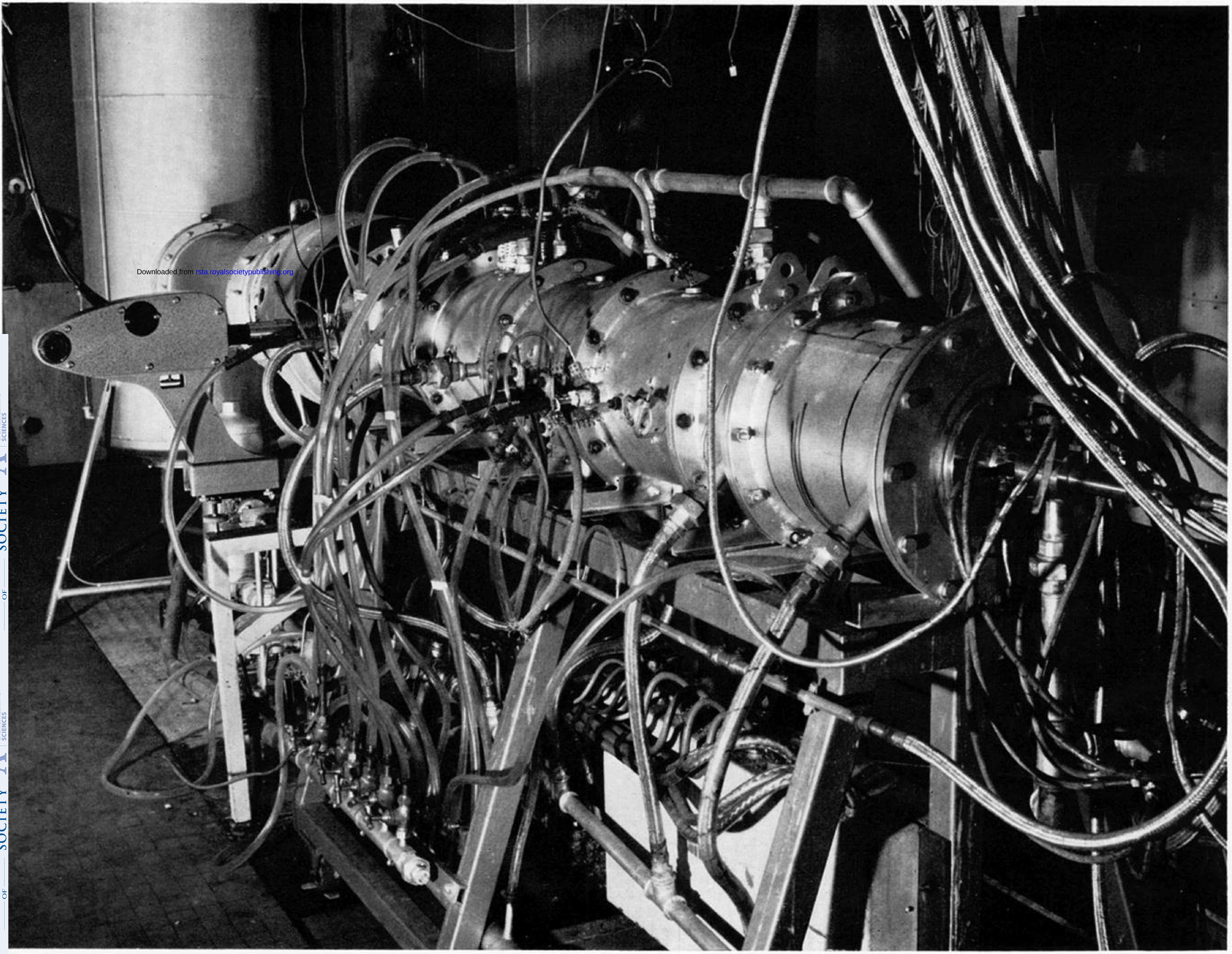
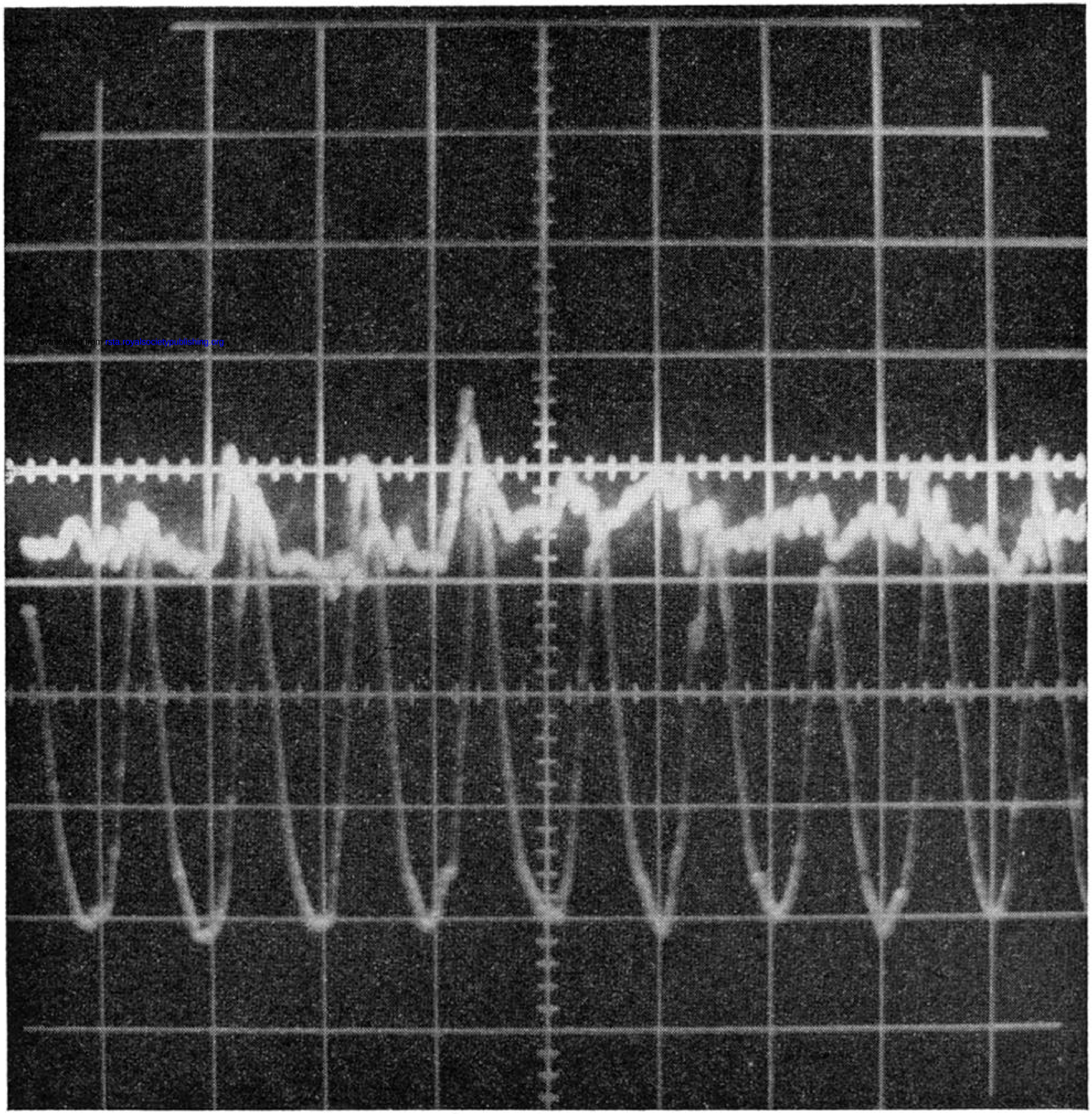


Figure 6



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