First Results of the Electricite de France 8 MW M.H.D. Experimental Rig at Centre de Recherches et d'Essais des Renardieres [and Discussion]

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V. First results of the Électricité de France 8 MW m.h.d. experimental rig at Centre de Recherches et d'Essais des Renardieres

By J. Pericart* and A. de Montardy†

[Plates 21 and 22]

During its first year of service the m.h.d. experimental rig at Renardieres has been used for various studies on the performance of different sized m.h.d. generators and of the technology of electrodes and insulating walls. However, these experiments are not yet finished, and this report aims only at describing the present state of the most interesting studies and at comparing the results with those published by other research teams.

The paper briefly describes the characteristics of the experimental plant and the conditions under which m.h.d. experiments have been carried out.

Changes in the electrical and physical conditions of ionized gases during their passage through the test section have been studied, as a knowledge of these conditions is necessary for the correct interpretation of conditions in full size m.h.d. generators.

Studies on m.h.d. generator materials have included insulating walls, 'hot' electrodes and 'cold' electrodes. However, only the studies on 'cold' electrodes are reported in detail as they are the most advanced to date; the studies on 'hot' electrodes have not progressed far, and for insulating walls, the use of cold 'peg walls' developed by Avco has been adopted.

Finally some results of studies on generator operation are discussed.

1. Characteristics and scope of the experimental rig

1·1. *General*

The Renardieres m.h.d. generator experimental rig has been described in detail in a recent paper (Pericart 1965) and it is therefore only necessary to summarize its main characteristics.

The rig is used mainly for tests on open cycle m.h.d. generation on a scale intermediate between the laboratory and operational power plant; it is designed for semi-permanent operation (8 consecutive hours).

8000 kW of thermal power is obtained by combustion of light oil in oxygen-enriched air (1 vol. of nitrogen for 2 vol. of oxygen). A solution of potassium hydroxide in methyl alcohol is used to introduce the ionizing seed.

The test section is 1·30 m long and has a constant internal cross-section of 7 × 13 cm. Input velocity of the gases is 600 m/s, with a static temperature of about 2900 °K and a static pressure of 1·9 bar (abs.). The steady state magnetic field, in normal operating conditions, is 2·6 to 2·8 T (with a maximum of 3·1 T).

The electromagnet and test section are cooled by de-ionized water circulating in closed loops.‡ Test section cooling circuits are equipped with meters for measuring and recording the flow rate and temperature of the water at the input and output of the elements so that accurate heat transfer measurements are possible.

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‡ The de-ionized water cooling system was not in service at the time of the first description of the plant given by Pericart (1965).

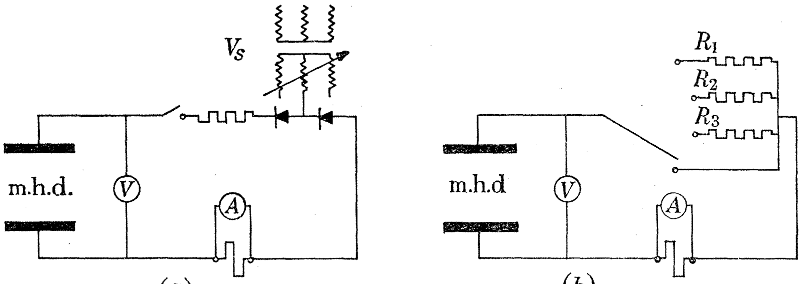
1·2. *M.h.d. test procedure*

1·2·1. *Electrical equipment*

From the electrical viewpoint, the test section is completely insulated from earth. On the upstream side, the burner is insulated with an insulating ring and the different input pipes are designed so as to avoid any earthing.

The order of magnitude of the insulation level obtained in practice is about 2000 Ω upstream and about 300 Ω for the downstream sections.

The m.h.d. duct is tested either without a magnetic field (as a load) or with a magnetic field (as a generator).



(*a*) (*b*)

FIGURE 1. Electrical circuits for m.h.d. tests. (*a*) Circuit diagram of the 'load' tests. (*b*) Circuit diagram of the 'generator' tests.

Figure 1 (*a*) shows the electrical system of the 'load' tests. The m.h.d. duct is supplied by a direct voltage from a silicon rectifier and the voltage can be varied continuously, from 50 to 500 V. This enables the applied voltage to be plotted as a function of the total current. This kind of test is only suitable for ducts with one pair of output terminals.

The electrical system used for the 'generator' tests is given in figure 1 (*b*). The m.h.d. generator is loaded by a resistor (three values plus short-circuit and open-circuit operation are possible) and, as in the previous case, the V–I characteristics can be plotted.

M.h.d. ducts have sometimes to be tested as loads but in the presence of a magnetic field; here, too, the circuit in figure 1 (*a*) is used; the extra e.m.f. supplied through the rectifier is added to the generator e.m.f. Such tests are necessary in order to assess m.h.d. generators under current density conditions similar to those of future full size generators (i.e. several A/cm^2). In general these densities cannot be reached on the experimental rig with the induced e.m.f. alone; this is because of the voltage drop at each of the gas–electrode contacts when the electrodes are cold. These voltage drops, which can reach 100 to 250 V, will be discussed later (cf. §3·6); they are large compared to the internal induced e.m.f. which is about 230 V for a 2·7 T magnetic field and a gas velocity of 650 m/s. Obviously the very poor voltage efficiency is a scale effect and in a power plant producing several kilovolts, the electrode effects, which would not change much, would represent only a small fraction of the generated e.m.f.

Remote control by means of relays and contactors allows the switching of resistances and the selection of one or other of the circuits described.

During the m.h.d. tests, voltages and currents are recorded on continuous chart recorders; in addition, direct reading meters and oscilloscopes record fast phenomena, transients, etc.

1·2·2. *Duct structure*

The duct section is always 7 cm (in the horizontal magnetic field direction) by 13 cm (in the vertical electric field direction). The maximum length is 1·30 m, but as equipping the entire length with generating elements is very costly normally only part of the duct is used. Most of the experiments are carried out on a very short m.h.d. generator (only 10 cm long) which is insulated upstream and downstream by sections of insulating walls either of the peg wall type, or of another type formed by a thin layer of alumina sprayed on a cooled metal block; the entire 'active' section and the two 'guard' elements form together a unit 30 cm long.

This unit can be situated at various distances from the burner by interposing 50 cm long elements of constant cross-section. These elements are simply formed of water cooled metal cased ducts.

Longer m.h.d. generators have also been constructed; a Faraday type generator with copper continuous electrodes (effective length 0·9 m) and a Hall type generator with copper rings (effective length 1·15 m). These generators together with the test results are described in §4.

2. CHANGES IN THE PHYSICAL PROPERTIES OF THE GAS ALONG THE DUCT

Under the test conditions only a small amount of heat is converted into electricity. It has been possible to attain 100 kW for a 1·30 m long m.h.d. generator with hot electrodes, but this represents only about 1 % of the initial enthalpy of the gas. Generally less than 0·1 % of the enthalpy is converted. Heat losses are considerable, for example heat transfer through the walls amounts to more than 20 % of the initial enthalpy when using cold walls.

Thus it is possible, with given combustion characteristics (pressure, fuel/oxygen ratio, N_2/O_2 ratio) to determine the changes in the physical characteristics of the gas along the duct independently of the m.h.d. phenomena if account is taken of duct shape, wall friction, and heat transfer. Such a study has been made for the following operating conditions: thermal input power 8000 kW, $N_2/O_2 = 0{\cdot}5$, stoichiometric combustion, seeding rate, 0·5 % and with the most frequently tested duct arrangement, i.e. that of figure 2 (m.h.d. unit in middle position). Pressure at various points along the flow, as well as the heat transfer rate, were determined experimentally. Combustion temperature was calculated from thermo-chemical data and, in addition, the temperature was measured at the test section output.

By means of these results and with the Mollier diagram of the combustion gas* determined on an IBM 7094 computer, we were able to calculate changes in all the physical properties (pressure, temperature, enthalpy, velocity) and of the electrical conductivity of the gas along the duct. The results are shown in the curves of figures 2 and 3. The curves near the m.h.d. generator outlet show that the flow probably becomes supersonic at the entrance to the diffuser and then undergoes a recompression shock wave.

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* This diagram was calculated using a simplified assumed function to describe the properties of the seed material because of lack of data on the high temperature thermodynamic constants of potassium and its compounds; this is a small correction.

As the m.h.d. electrodes are modified, the heat transfer is also modified and the rate of change in the physical properties is altered; however, since the m.h.d. section is short (10 cm), these variations are small and the above results remain very closely valid.

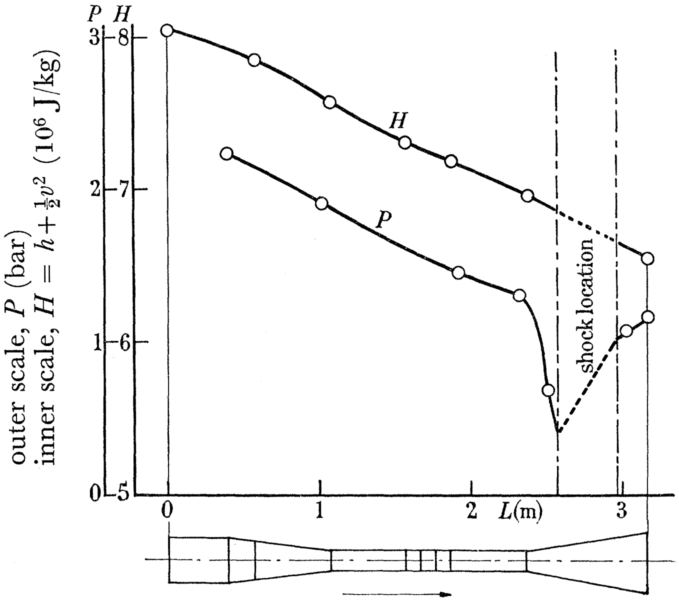

Figure 2. Change in specific enthalpy and static pressure along the duct length (from experimental results).

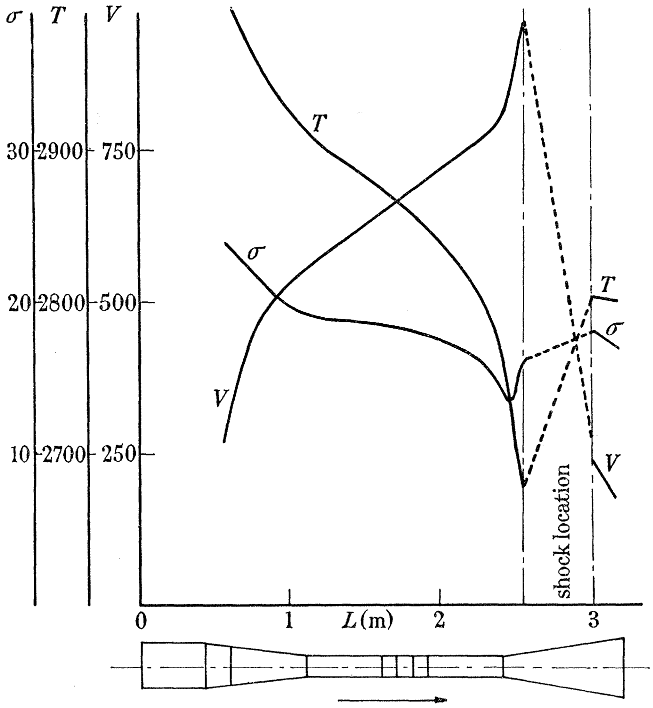

Figure 3. Change in gas temperature T, velocity V, conductivity σ, along the duct length (calculated values from experimental pressure and heat exchange data).

3. An examination of cold electrodes

3·1. *Problems*

From the outset, the use of cooled metal electrodes in an m.h.d. generator, appeared desirable, in spite of high heat transfer, because of the simpler design and of the reasonable resistance (when cold or at low temperatures) of metals such as copper and iron to the corrosive elements (potassium, sulphur) present in the m.h.d. duct.

However, such electrodes give rise to problems concerned with the type of electron emission at the solid/gas interface. The gas boundary layer, on contact with the metal is too cold for electrical conductivity, and small electric discharges may occur to transfer the current between the metal and the hot bulk of the gas. This phenomenon is liable to produce a significant voltage drop on each electrode, and considerable erosion of the metal.

It is not certain that these discharges possess the usual properties of electric arcs, as they occur in very different conditions from ordinary arcs (high velocity ionized gas, cold boundary layer able to conserve a certain remanent ionization, etc.). However, these questions can be answered only by experiment.

3·2. *Factors to be considered*

Electrode performance is influenced by many variables:

nature of the ionized medium,
pressure and temperature profile in the gas,
structure of the boundary layers,
nature of the electrodes,
temperature of the electrodes,
magnetic field intensity,
electric field intensity,
scale of test.

The nature of the ionized medium, its temperature and its pressure determine the gas conductivity and can thus affect the slope of the characteristics of the voltage variation at the generator terminals as a function of the current. The gas composition depends on the ratios fuel–combustion, nitrogen/oxygen, and on the seed flow rate. Furthermore, the temperature and the degree of ionization vary as a function of the velocity and pressure, i.e. for a given generator shape at mass flow rate. Therefore, all the parameters defining the ionized medium are practically interdependent. On the other hand, the gas velocity can affect current transfer between the electrode and the plasma. The velocity along with the geometrical shape determines the structure of the boundary layer. This latter is very difficult to investigate in the case of small m.h.d. generators like our own and it is obvious that this seriously affects the results obtained.

The nature of the electrodes and their temperature are two important variables which affect electron emission. The temperature range obviously depends on the properties of the electrode materials employed (for example, up to 400 °C for copper, and up to 1000 °C for steel). Corrosion resistance decreases as the temperature increases, which is an obstacle to the use of high temperatures, even if this is advantageous from the electrical point of view.

The magnetic field can affect the electronic emissivity (Bekiarian, Graziotti & de Montardy 1964), and in particular can, by the Hall effect, concentrate the current lines at the edge of the electrodes.

The electrical field in the boundary layer can be much higher than in the rest of the gas and can directly influence the electronic emissivity at the cathode; in our case the electrical field changes are over a layer which is much thinner than the previously considered aerodynamic layer.

Finally the degree of turbulence and the formation of the boundary layers vary according to the scale of the test, and the transfer of the test results to an industrial scale will demand very careful extrapolation.

Furthermore, it should not be overlooked that the phenomena are different for the cathode and the anode and can be affected differently by the various factors considered, and as far as possible it is advisable to study the performance of the two electrodes separately.

3·3. *Experimental difficulties*

As previously discussed many of the factors affecting electrode performance are interdependent and cannot be studied separately, which complicates the interpretation of the test results. This difficulty is increased by the instability and turbulence typical of m.h.d. tests which always cause a certain scatter in the measurement results; even the measurements of certain factors normally accurately measurable such as temperature and pressure, are not entirely accurately determinable in the conditions imposed by m.h.d. tests. Finally, the experiments are relatively long and expensive when carried out on a large scale, which considerably restricts the number of tests that can be carried out in a given period of time. All these practical reasons add to the difficulty of such experiments.

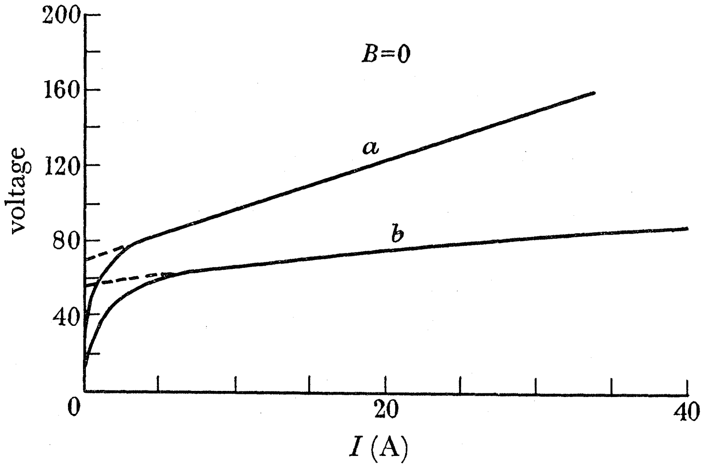

FIGURE 4. General shape of the V–I characteristic as obtained (a) by the C.E.G.B., (b) by Arnold Air Force Station.

The appearance of the V–I characteristics obtained (figure 4) was similar to that of the first category of tests, but the magnitudes were different. The electrode voltage drop was about 60 V for high currents. Half hour tests produced practically no erosion; such results seem to exclude the presence of arc phenomena, at least as a major mechanism for the current transmission. The authors themselves have proposed physical explanations for the phenomena. According to Dicks (1964) the current passes by means of an electron emission produced by a high electrical field in a very thin layer close to the electrodes.

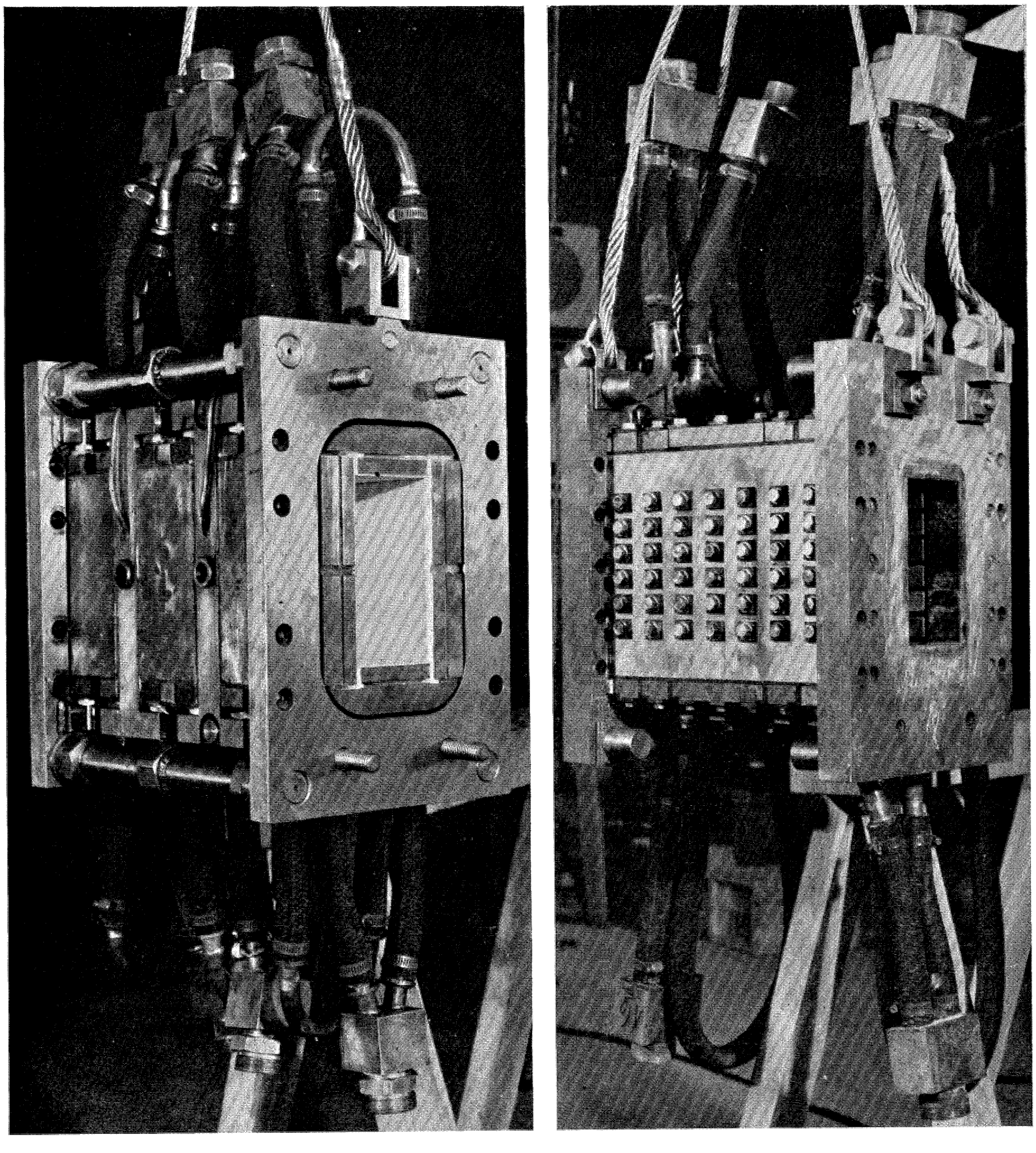

FIGURE 5. Photograph of the ducts with a 10 cm long m.h.d. section between two 10 cm long insulating sections. (*Left*) Side walls sprayed with alumina. (*Right*) Peg wall type side walls.

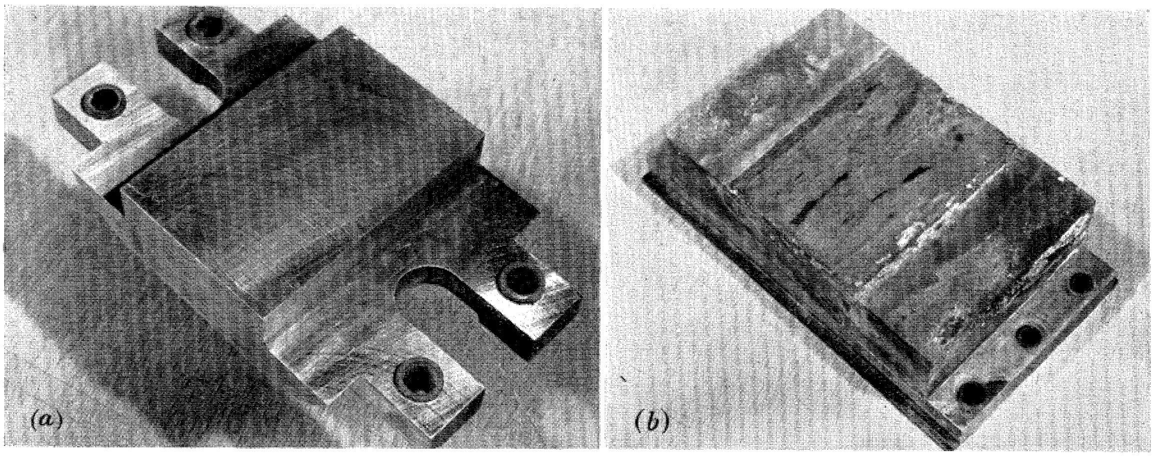

FIGURE 6. Photograph of the individual electrodes shown *in situ* in figure 5. (*a*) Electrode used with alumina side walls. (*b*) Electrode used with peg walls.

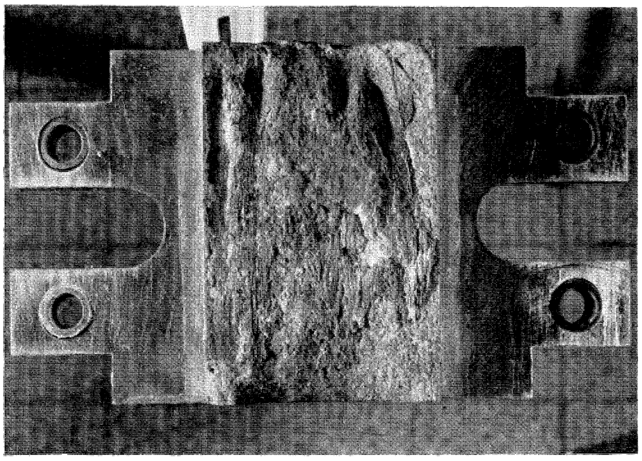

FIGURE 13. Photograph of an NS 30 electrode after a 1 h 20 min test showing the extent of erosion.

In addition to these two sets of results, we would mention the studies of Armstrong, George & Messerle (1965) made in an argon flow with externally cooled graphite electrodes and with adjustable temperature by means of electrical heating. These studies aim at showing the influence of the temperature of the electrodes on the cathode and anode voltage drops.

3·5. *Results of element tests*

3·5·1. *Description of test units*

All the results described in the following paragraphs have been obtained with a short m.h.d. generator section (10 cm long) which consisted of two electrodes and two insulating walls, set between two insulating guard sections as described in paragraph 1·2·2. The position of the m.h.d. unit in the test duct was as shown in figure 2 (m.h.d. unit in middle position).

The photographs given in figure 5, plate 21, show the two kinds of test units employed; in (*a*) the insulating walls are cooled metal side walls coated with alumina (using the technique of the Compagnie Generale d'Électricité); in (*b*) the same walls are formed by cooled copper pegs ('peg walls', Avco type). The water flows in the cooling chamber at several metres a second, and there is no boiling. Figure 6 (*a*) and (*b*), plate 22, show the electrodes separated from each of these units.

3·5·2. *Insulation between electrodes*

The insulation level obtained with the different types of wall has to be measured during the tests under normal operating conditions but this changes during a test. The following figures were obtained for over-all leak resistances: for alumina insulating walls: from 50 to 100 Ω; for copper peg insulating walls: about 40 Ω with seeding.

The leak currents due to insulation defects are, within a first approximation, proportional to the voltage between electrodes, and are non-existent in short-circuit tests.* In 'generator' operation these currents have to be added to the measured current in order to determine the total current passing through the ionized gas; on the other hand, they have to be subtracted under load operation.

3·5·3. *Influence of end effects*

The lengths of the insulating guard sections upstream and downstream of the m.h.d. section were calculated so as to avoid any perturbation of the m.h.d. generator by the metal pieces making up the rest of the duct. A calculation to be published shortly in the *Revue Generale de l'Électricité*, shows that an axial length of insulation of about the same distance as that between electrodes was adequate. The length of 10 cm adopted for the guard sections was confirmed in this way.

Under such conditions, the end effects can be estimated from the results published by Schultz-Grunow & Denzel (1964), which are valid for a continuous electrode m.h.d. generator of finite length, set between guard sections of infinite length, with a uniform and

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* Strictly speaking, the short circuit current can be affected by insulation defects when, because of such defects, an insulating wall acts as an emitting or collecting electrode. However, in general, insulation defects affect the open circuit voltage far more than the short circuit current.

infinitely extended applied magnetic field. This theory, however, assumes uniform conductivity throughout the gas.

If R_0 denotes the electric resistance of the plasma in the absence of end effects and of magnetic field ($R_0 = L/\sigma S$, if L is the interelectrode gap, S the electrode surface area and σ the scalar conductivity of the ionized gas) the actual resistance to be taken into account is obtained by multiplying R_0 by a coefficient k, whose value as a function of the Hall parameter μB, is shown as the curve in figure 7. The end effect reduces the generator internal resistance as it allows the current lines to expand outwards, whereas the Hall effect, due to the magnetic field, counteracts this reduction.

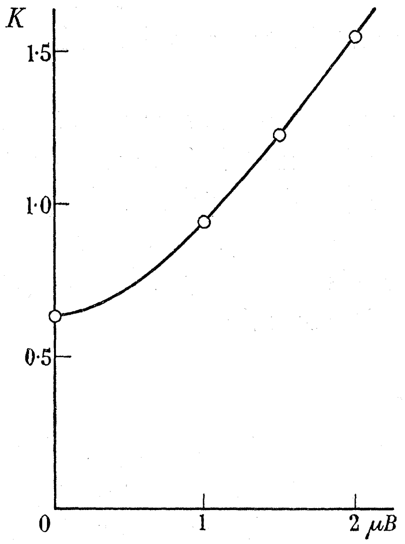

FIGURE 7. Plot of the coefficient $K = R/R_0$ as a function of the Hall parameter (μB).

3·6. *Tests and results*

3·6·1. *V–I reference characteristic*

As a reference test we shall examine a study carried out under the following conditions:

electrode material: copper, surface 7×10 cm per electrode;
surface temperature: 150 °C;
insulating walls: copper pegs;
combustion conditions: thermal power $P = 7{\cdot}5$ MW;
stoichiometric conditions: $N_2/O_2 = 0{\cdot}5$, seeding 0·5 % potassium;
magnetic field: 2·64 T;
gas temperature, velocity and pressure: according to the curves given in figures 3 and 4, about 2800 °K, 660 m/s, 1·5 bar (abs.).

Figure 8 gives the load characteristic obtained; the voltage (ordinate) is that at the electrode terminals; curve *a* shows the current previously delivered externally (measured value) and curve *b*, the current actually collected by the electrodes with the leakage through the insulating walls being taken into account. The part of the curve $V > 0$ corresponds to 'generator' operation and $V < 0$ to 'load' operation. The average current density varies from 0 to about 1 A/cm² since the electrode surface is 70 cm². The apparent electrode voltage drop is obtained, for a given operating point A, by taking a tangent AT

to the characteristic and by measuring segment TA_0, A_0 corresponding to the generator e.m.f. In the test conditions $E = BVL = 2{\cdot}7 \times 0{\cdot}13 \times 660 \simeq 230$ V. The electrode drop (anode plus cathode) is about 200 V for $I > 20$A. This figure is much higher than that obtained by other authors under almost similar conditions.

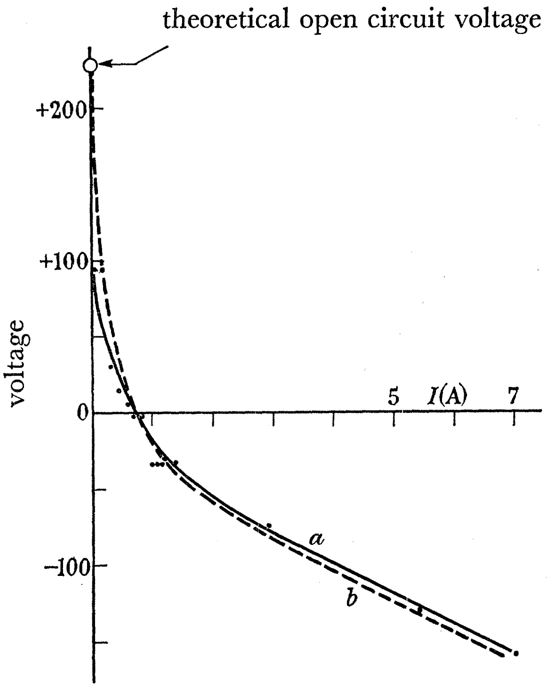

FIGURE 8. V–I characteristic obtained with a pair of copper electrodes 7 × 10 cm, under the following reference conditions: electrode temperature, 150 °C; distance between electrodes, 13 cm; side walls, peg wall type; thermal power, 8 MW; nitrogen/oxygen ratio, 0·5; stoichiometric conditions; seeding rate, 0·5 %; velocity, 660 m/s; static pressure, 1·5 bar; magnetic field, $B = 2{\cdot}64$ T. Curve (*a*) measured current, (*b*) current corrected for leakage currents. ●, Experimental points.

3·6·2. *Influence of the electrode material*

Copper, NS 22 S stainless steel and copper–nickel alloy (Monel) electrodes have been compared at similar operating temperatures and under the same conditions as those described for the above reference tests. In view of the usual scatter in the measurement points, the average characteristics do not appear to differ greatly from those shown in figure 8. Therefore it would appear that all cold electrodes have about the same performance at low temperatures.

3·6·3. *Influence of the temperature of the electrodes*

This effect has been studied for steel and Monel electrodes. The temperature of the inner surface of the electrode (i.e. gas side) is measured by thermocouples and the measurement is checked by an approximate heat transfer measurement which allows for calculation of the temperature difference between the water cooling chamber and the surface.

Figure 9 shows the results obtained with NS 22 S stainless steel electrodes, formed by 1 mm thick sheets, brazed on a cooled copper block (C.G.E. fabrication). The surface temperature is about 500 °K. Figure 9 also shows a curve relating to Monel massive electrodes operating at about 1200 °K. The electrical characteristics obtained with the latter is definitely better than that obtained with the others as the apparent voltage drop for 70 amp. is reduced to about 130 V. Thus the influence of the temperature on the voltage drop seems to be negligible below 1000 °K and therefore much improvement cannot be obtained with copper electrodes by raising the surface temperature.

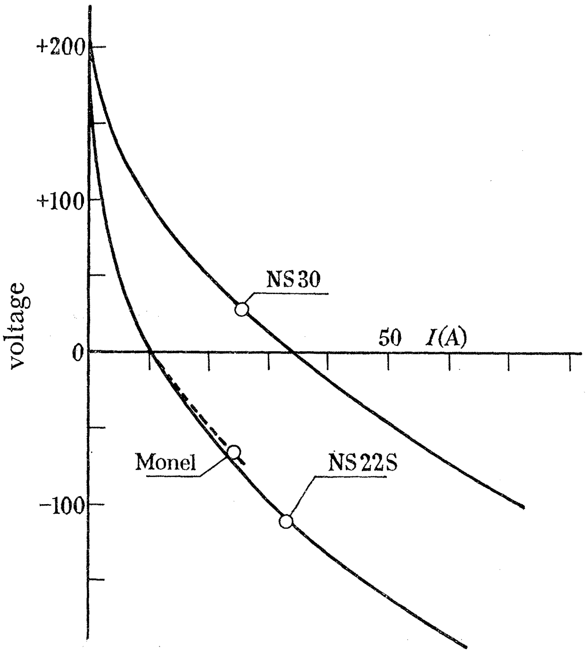

Figure 9. V–I characteristics obtained with various electrode materials operating at different temperatures. The other operating conditions are the same as those in figure 8. The curves have been corrected to take into account leakage currents. Stainless steel—grade NS 22 S; temperature, 500 °K. Monel; temperature, 875 °K. Stainless steel—grade NS 30; temperature, 1300 °K.

3·6·4. *Influence of the magnetic field intensity*

The curves in figure 10 are plotted for copper electrodes in the reference test condition, but with magnetic fields varying between 0 and 2·64T. The curves have been corrected to take into account the leakage currents.

The various curves are approximately parallel in their straight portions and, as the slopes represent the plasma resistance, the influence of the magnetic field on the electrode voltage drop is considerable, as can be seen in figure 11 which is obtained from the preceding one by plotting the tangents to the operating points. For example, it can be seen that for $B = 0$, the voltage drop for $I = 70$ A does not exceed 130 V, i.e. almost half the value for $B = 2{\cdot}64$T.

3·6·5. *Influence of the fuel/oxygen ratio*

This effect is demonstrated by the curves shown in figure 12, for fuel/oxygen ratios varying from 1:02 to 1:15; the results show no great variations and are difficult to interpret.

3·6·6. *Long duration tests*

Long duration tests are in progress. During these tests the maximum magnetic field is applied, and the current is adjusted to 70 A. A 1 h run with NS 30 electrodes (surface temperature 1200 °K) gave the following results: the downstream edge of the cathode (figure 13, plate 22) was badly eroded, the upstream end of the anode was also eroded, but less so than the cathode.

As a check, another run showed that, without current, the cathode's edges remained sharp.

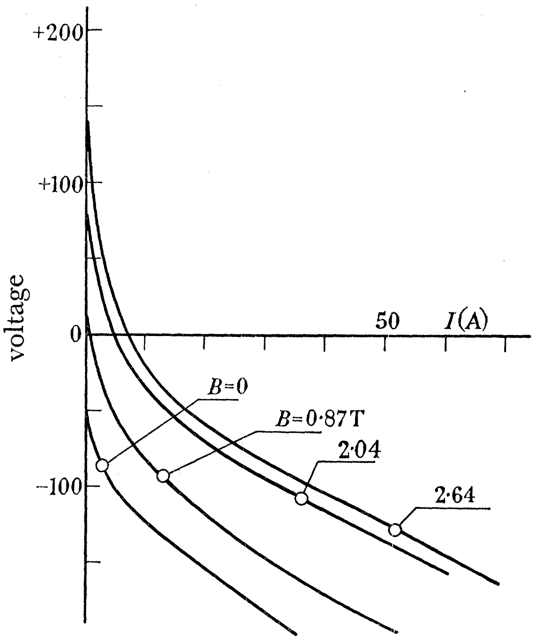

FIGURE 10. V–I characteristics using copper electrodes and various magnetic field intensities. The other operating conditions are the same as those in figure 8. The curves have been corrected to take into account leakage currents.

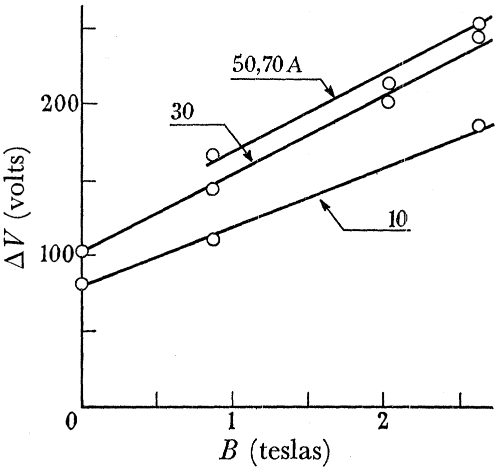

FIGURE 11. Plot of the apparent voltage drop as a function of the magnetic field for specific load currents. The other operating conditions are the same as those in figure 8.

3·7. *Discussion of the results and comparison with previous studies*

3·7·1. *Scatter of results*

The scatter in the voltage drop results was small after the leakage current corrections had been made. However, the scatter was extensive for the short circuit current values (i.e. intersections of the curves with the axis $V = 0$). A series of tests with copper or stainless steel electrodes have produced, under apparently identical conditions, variations of almost 30% of this current (i.e. 5 A above and below an average value of about 15 A). To date this scatter remains unexplained; the uncertainties in gas condition, the magnetic field, etc., do not account for such extensive scatter. However, it is not of great importance as this short circuit value appears to be typical of the experimental rig and industrial operation would require much larger currents for which the scatter would be smaller.

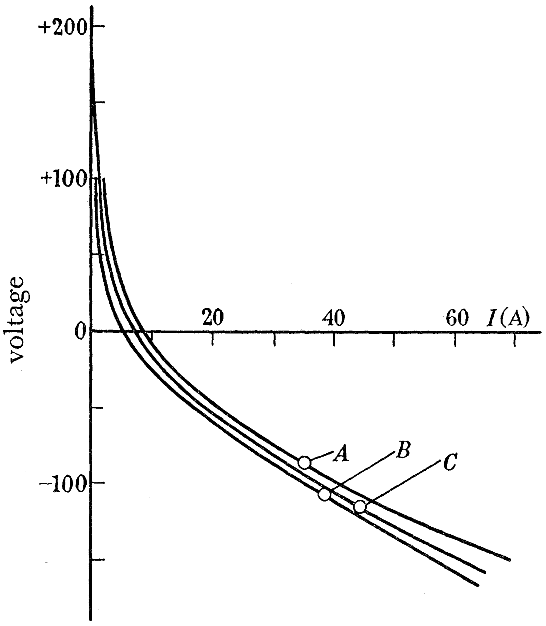

FIGURE 12. V–I characteristics for different values of fuel/oxygen ratio. The other operating conditions are the same as those in figure 8. The curves have been corrected to take into account leakage currents.

curve	fuel/oxygen ratio	mass flow rate
A	1·15	0·97
B	1·02	1·02
C	1·05	1·02

3 7·2. *Discussion: comparison with the results obtained by other authors*

The above series of tests emphasize several main points:

the order of magnitude of the apparent voltage drop at the electrodes: 220 V under a magnetic field of 2·7 T;

the considerable influence of the magnetic field on this voltage drop (varying, for example, from 130 to 220 V when the field varies from 0 to 2·7 T);

the slight influence of the temperature of the electrodes in the 300 to 1000 °K range on the considered phenomena.

The results published by other research teams working under comparable physical conditions (C.E.G.B., Avco, Stanford Institute) cite voltage drops of 70 to 100 V without magnetic fields and do not give any results obtained with a magnetic field. These are very different from our own figures for $B = 0$. This difference could be due to the much larger surface area of our electrodes which, no doubt, lead to considerable variations between the average current densities and the actual densities in the emitting zones. If we take, for example, the curves shown in figure 11, it can be seen that for $B = 0$, the apparent voltage drop is only 100 V for $I = 30$ A and 80 V for $I = 10$ A. It is possible that the actual current of several A/cm^2, similar to those obtained by the other authors, is already being attained locally.

The influence of the magnetic field is a factor which acts most unfavourably on cold electrodes. It could be that the increased current concentration is accompanied by a serious reduction in emitting zones on the surface.

The relatively small influence of the temperature below 1000 °K was to be expected in view of the fact that the thermal electron emission from the metal is very low in this temperature range.

Finally, erosion seems more serious than that cited by the other teams; this suggests that the mechanism of the current flowing through the cold layers is approaching that of an electric arc.

3·7·3. *Future direction of cold electrode experiments*

The present series of experiments is far from complete, and several aspects still need to be examined:

the influence on the *V–I* characteristics of the velocity of the gas, of its pressure and of the potassium seeding ratio; such studies are difficult to carry out on the experimental rig because of the great interdependence of these variables during combustion changes;

the influence of the electrode surface—this is an important question—a study of the geometrical conditions is necessary to identify the factors which reduce the local concentration of the current; success in this direction could be an essential condition for the success of the cold electrode technique;

a separate study of the anode and cathode effects; it appears that to date only one report has been published on this subject, that of Armstrong *et al.* (1965);

the performance of narrow segmented electrodes and of the electrodes of the normal or *oblique ring* Hall effect generators; these configurations, the only ones with a future, should be the normal design for analytical studies on cold electrodes.

No physical explanation of the phenomena affecting cold electrode performance can be offered at the moment. Tests, in which the conditions of the current flow through the gas could be visualized, would be useful. The 8 MW experimental rig is not adapted for these kinds of studies which would be easier to carry out on a low powered free flame.

4. Study of long ducts incorporating cold electrodes

The following studies were carried out immediately after the experimental rig was put into service, and before the analytical investigations described above. Relatively rudimentary equipment built in 1964 was used; nevertheless, the results obtained may be helpful for the design of more elaborate generators.

4·1. *EC* 1 *continuous electrode generator*

4·1·1. *Description*

The electrodes of the EC 1 generator are made of two copper blocks 90·7 cm long and 7 cm wide (gas side). Each of these blocks is cooled with an axial water flow. The insulating walls are made of a set of spaced copper tubes, parallel to the axis and embedded in alumina cement. These tube bundles are mounted, by means of insulating clamps, on external supporting copper plates. The cooling is achieved by water circulating in the tubes.

4·1·2. *Tests*

The m.h.d. generator is assembled in the test section by direct connexion to the accelerating duct in front and to the output diffuser at the back.

Full load test has been carried out under the following conditions:

combustion: normal rated conditions;
gas velocity: 650 m/s (average);
magnetic field: 2·7 T.

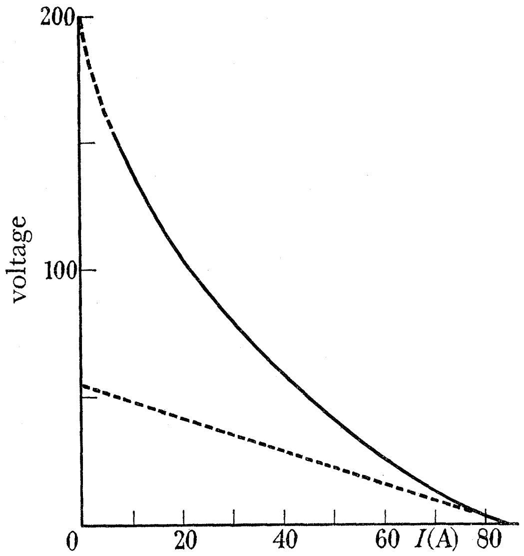

Figure 14. *V–I* characteristic of the EC 1 generator.

The *V–I* characteristic is given in figure 14. It is strongly curved; the open circuit voltage is 200 V, therefore very near the calculated e.m.f. (230 V); the short circuit current is 70 to 90 A. The short circuit apparent current density is only about 0·1 A/cm^2, which is very low, but the current is probably very localized and peak densities may be much higher. No obvious erosion was observed after 1 h of short circuit operation.

The plasma internal resistance has been calculated, taking the Hall effect into account, by assuming a uniform current distribution and neglecting the end effects. If we assume that this resistance represents the slope of the V–I characteristic, the calculated and measured values can be compared as follows:

R calculated for $B = 0$: 0·12;
for $B = 2{\cdot}7\,\mathrm{T}$: 0·23;
R measured from the curve on figure 14, for $V = 0$: 0·65.

The apparent voltage drop at the electrodes, during short circuit operation, is about 180 V. This value is approximately the same as that for the short sections mentioned in §3, for equal apparent current densities.

The heat transfer has been measured separately for each electrode and each insulating wall and corresponds to rates of 1·5 to 1·6 MW/m^2 at the electrodes, and 0·7 MW/m^2 at the insulating walls. The electrode surface temperature, calculated from these values, is about 300 °C.

4·2. *Hall effect generator* (H1)

4·2·1. *Description*

The H1 duct is a rectangular channel of 1·50 m length and 7 × 13 cm internal cross section, formed by a stack of rings alternately conducting and insulating. The conducting rings, 1 cm thick, are made of copper; the insulating rings, 5 mm thick, are made of 'cuiranite', an amianthus-neoprene synthetic material. In order to avoid contact with the hot gas, the cuiranite rings are receded below the level of the copper inside the channel, and the gaps thus formed are filled with Secar refractory cement.

The whole system is cooled by means of twenty water channels parallel to the axis and formed by the alinement of holes bored in each of the copper and cuiranite plates. The circuit is made watertight by the use of a plastic glue during assembly and by tight clamping. To make it easier for erection the duct is formed of nine sections each of which consists of eleven rings. Water is fed in at each end.

Electrical leads for the output are connected to the upstream end flange and to a rim placed 1·20 m downstream from the latter (figure 15). That part of the duct between this point and the downstream end, i.e. 60 cm, is not used for electrical generation, but serves only to improve the electrical insulation of the system with respect to earth.

4·2·2. *Tests*

(*a*) *V–I characteristic.* This curve was determined under identical conditions to those of the EC1 continuous electrode generator (magnetic field 2·7 T). However, at the time of this test, the electrical insulation of the burner was not completed, and the exercise was carried out by electrically short-circuiting the burner to earth, the system being insulated upstream.

The V–I characteristic is clearly linear, the open circuit voltage being 300 to 330 V and the short-circuit current 13 to 15 A. The apparent internal resistance is 20 to 25 Ω and the maximum electrical power is slightly above 1 kW.

(*b*) *Transverse currents.* The existence of transverse currents is an important feature of Hall generators. The currents in the copper rings have been measured in open circuit and in short circuit conditions, by cutting selected rings along the transverse axis parallel to the magnetic field and by inserting shunted ammeters (figure 15).

The results are as follows:

current (A)	open circuit	short circuit
ring *A*	1·5	1·0
ring *B*	3·75	3·0
ring *C*	2·75	2·5

(*c*) *Insulating resistances.* Generator insulating defects can exist: between successive plates of the duct; between the downstream electrical terminal and earth.

The insulation between two successive conducting plates measured under normal operating conditions (without a magnetic field) is about 5 Ω; this represents a 300 Ω resistance branched between the two electrical output terminals. Leakage currents flow through the cooling water (which is not de-ionized) and through the ionized gas as it enters the exhaust duct.

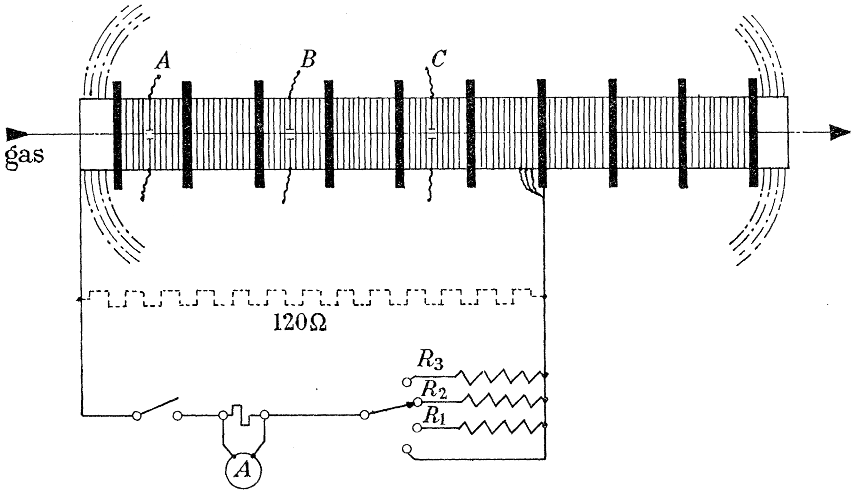

FIGURE 15. Details of the electrical circuit connected to the H 1 generator. The dotted line resistor represents leakage currents. Transverse currents are measured in sections *A*, *B*, *C*.

A variable leak current (average value not exceeding 1·5 A) is observed, equivalent to a resistance of at least 200 Ω, branched between the two generator terminals. Therefore, the over-all insulation level is represented by two resistances, 200 and 300 Ω respectively, i.e. 120 Ω resistance between the terminals.

(*d*) *Long duration tests.* In view of the low densities of the currents obtained the erosion cannot be estimated accurately.

4·2·3. *Analytical study*

The operating equations of a Hall effect generator are:

$$J_x = \frac{\sigma_0}{1+\beta^2}[E_x+\beta UB], \quad J_y = \frac{\sigma_0}{1+\beta^2}[\beta E_x - UB],$$

J_x and J_y being the components of the current density in the gas along the generator axis and along the transverse axis perpendicular to the magnetic field. E_x is the component of the electrical field along the axis, U the gas velocity, B the magnetic induction, σ_0 the scalar electrical conductivity of the ionized gas. β is the Hall effect parameter defined by $\tan \beta = \mu_e B$, product of the electrical mobility μ_e and the magnetic induction.

These equations apply to a uniform flow at velocity U and imply that the transverse electrical field, along the y axis, has dropped to zero through the conducting rings. However, because of the voltage drop due to current emission by the cold electrodes, this does not occur and, if this electrode voltage drop in the transverse direction is called ΔV, UB must be replaced by $(UBh-\Delta V)/h$, h being the height of the generator perpendicular to the magnetic field (i.e. 13 cm).

The quantity $UBh-\Delta V$ can be called 'useful transverse voltage'. ΔV is unknown. It can be assumed that it may be given, as a function of the transverse current density J_y, by a relationship similar to those obtained for the copper electrode tests (§3, figure 8).

A density J_y varying from 0·1 to 0·5 A/cm^2 can be estimated from the measurements of the transverse currents (4·2·2) and the surface of the transverse parts of the rings operating as electrodes.

For such a density, a ΔV drop of 170 to 200 V is possible, i.e. average $\Delta V = 185$ V.

With the above equations it is possible to calculate the open circuit useful voltage, the short circuit current, and the open circuit and short circuit transverse currents.

It is assumed that $\beta = 1$, $B = 2{\cdot}7$ T, $U = 650$ m/s, $\sigma = 10$ S/m.

The calculations are made on the hypothesis of perfect insulation in the duct but include a 120 Ω resistance between the electrical terminals, to represent the over-all insulation faults. The results are as follows:

	perfect insulation	real insulation
open circuit voltage	400 V	358 V
short circuit current	28·3 A	28·3 A
apparent internal resistance	14·1 Ω	12·6 Ω
open circuit transverse current	6·54 A	6·20 A
short circuit transverse current	3·27 A	3·27 A

Obviously the short circuit values are the same in both cases.

It can be observed that the open circuit voltage agrees with the test figures, but that the short circuit currents are overestimated. The same remark applies to the comparison of the experimental and theoretical EC1 generator results. A possible explanation is that of overestimation of the gas temperature.

5. Conclusions

This report is a review of the present state of our studies on m.h.d. None of the studies are complete and, therefore, we can only summarize the main results obtained to date and indicate the lines of future experiments.

From our studies on cold electrodes, it would appear that, for operating temperatures between 0 and 500 °C we can expect much greater voltage drops in the presence of magnetic fields than in the absence of magnetic fields. While the actual values obtained depend on the design of the electrode increases in voltage drop of 50 % can occur with a magnetic field of 3 T. This drop might be even greater with higher magnetic fields such as those obtained with a superconducting magnet in an industrial plant.

Another more serious disadvantage of cold electrodes is their erosion resistance. Even if the actual current densities can be greatly reduced by improved distribution, it is doubtful if this improvement will be sufficient to allow 100 to 1000 h operation, for example.

In the immediate future, experiments on cold electrodes must concentrate on designs capable of considerably reducing local current densities, for example, by fine segmentation and then, if possible, by other methods. Understanding the physical causes of the observed effects would be helpful to such work, but, we have not as yet, reached this position.

Furthermore, our studies on experimental rigs for obtaining information for the operation of large generators need to be restarted with more sophisticated equipment than we have used hitherto.

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VI. Discussion

M. W. Thring (Queen Mary College, University of London)

In the simple d.c. Faraday type m.h.d. generator the rate of external power generation per unit volume of magnetic field is equal to

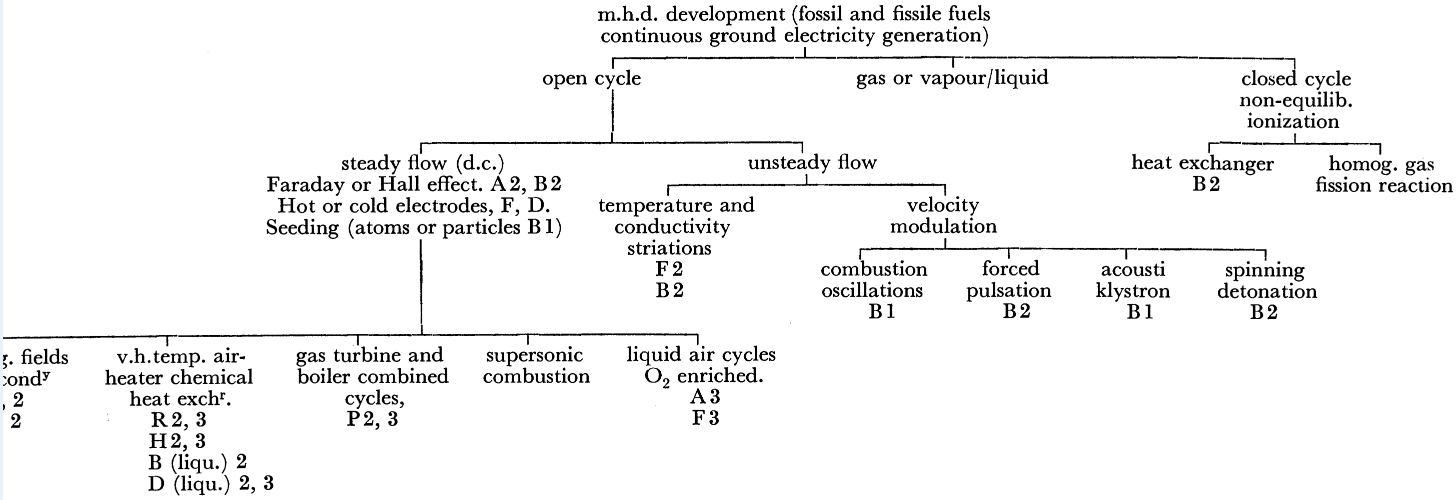
$$\frac{10^{-16}}{(1+\alpha)^2}\,\sigma u^2 B^2\ \mathrm{W/cm^3},$$

where σ is the gas electrical conductivity (mho/cm), α the ratio of external circuit resistance to gas circuit resistance, u the gas velocity (cm/s), and B the magnetic field (G).

Thus for example with $B = 1000$ G, $u = 30\,000$ cm/s, $\sigma = 1$ mho/cm and $\alpha = 1$ (condition for maximum external power), the external energy release rate is 0·02 W/cm^3 of magnetic field volume. Thus it is necessary to use a field strength of at least 10 kG when one can obtain 2 kW/l. of magnetic field volume with a gas conductivity $\sigma = 1$ mho/cm. Even with seeding by potassium this gas conductivity requires an equilibrium gas temperature in the magnetic field of the order of 2500 °K. However, to obtain a gas velocity corresponding to a Mach number greater than one requires an adiabatic temperature drop in the nozzle of many hundreds of degrees Kelvin. This means that the combustion temperature of the gas upstream of the nozzle must be well over 3000 °K. To obtain this type of combustion temperature with any normal commercial fuel such as fuel oil requires either a preheat of the combustion air after compression to a temperature greater than 1000 °C or the use of pure oxygen for combustion.

Table 1 is a diagrammatic family tree of the work going on in all parts of the world in the attempt to solve this basic problem of obtaining a high gas conductivity and a high gas velocity simultaneously. There are essentially three main types of system: (1) the open

TABLE 1



rance, D = Germany, H = Hungary, A = U.S.A., B = Britain, R = Russia, P = Poland.
f Development (experiments or design calculations): 1, Fundamental applied research. Do the separate parts have reasonable rate coefficients? (Scale, watts.) pilot plant. Can the proposed cycle work? (Scale, kilowatts.) 3, Large pilot plant. What will be the capital and running costs of a full size plant? (Scale, tts.) 4, Full size. Industrial production. (Scale, hundreds of megawatts.)

cycle in which the heat is released essentially in the working fluid which then passes through the nozzle and magnetic field; (2) a new system being studied in which the working fluid (heated gas) is used to accelerate a liquid to reasonable velocity but the electrical conductivity is essentially that of the liquid. Finally we have the closed cycle (3) in which either the working fluid is heated externally through the walls of a heat exchanger or the working fluid is itself the reactant in a nuclear fission reactor of a homogeneous gaseous type. The former of these suffers from the difficulty of requiring a heat exchanger operating at an even higher temperature than that required for the air preheater in the open cycle type. The homogeneous gaseous fission reactor completely surrounded by boiler heating surface and going critical and rising to a very high temperature indeed before its expansion to low pressure through the nozzle provides a very exciting cycle for the future with a possibility of an over-all thermal efficiency of 70 or 80% and with no materials at any point hotter than those corresponding to the boiler tubes of a high pressure boiler. However, this is very much in the future and no country appears to be working on it as yet.

The remainder of the work is all concentrated on the open cycle which may in turn be divided into steady flow systems which basically produce d.c. and the unsteady flow systems where there is either a time variation at a given point in the magnetic field of gas temperature and electric conductivity or of velocity. Work on the unsteady flow which is shown in table 1 as being carried out in this country and France is devoted to small pilot plant experiments since these more sophisticated ideas are still in an early stage of development. However, if one of them does prove successful on the small pilot plant scale it will undoubtedly prove a much more economic alternative than any of the d.c. systems because it is essentially based on separating the two functions of (1) the working fluid which could go through an ideal cycle from the thermodynamic point of view, and (2) the electrically conducting fluid, the sole function of which is to provide low internal resistance for the electric output.

All the large pilot plant work, that is, work on systems to give outputs of the order of a few megawatts, is being done on fairly conventional modifications of the classical steady flow d.c. system. Most countries are interested in the possibility of obtaining field strengths up to 100 kG by means of currents circulating in closed loop superconductors. On the large scale the problem of having temperatures close to absolute zero in a pair of rings between which gases at very high temperatures flow is no longer a major problem.

If one can produce a heat exchanger which takes the combustion gases immediately after they have lost their velocity in a magnetic field and pass them through a very high temperature heat exchanger to preheat the combustion air to temperatures of the order of 2000 °C one can obtain a direct generation efficiency in the m.h.d. cycle of over 50%. In Russia this idea is being extended to the possibility of the use of some of the waste heat carrying out an endothermic reaction in the fuel which thus increases its calorific value and provided one does not have to introduce much non-calorific material to react with it (e.g. steam) it will also increase the maximum flame temperature substantially. The design of a suitable heat exchanger which will probably have to be of the regenerator type, that is with the heat passing into and out of the same surface when two fluids are alternated at the surface, is being extensively studied in a number of countries. Some particularly interesting work has been reported from Hungary by one of the first two people to work on m.h.d., Dr Halasz who was present at the Symposium. The system combining the waste heat utilization for air preheat, steam production and operation of a gas turbine to carry out the air compression is being studied extensively in Poland and can probably lead to a more efficient utilization of the heat at each stage of temperature drop. The supersonic combustion idea is concerned with the preheat of the combustion air after compression, then expansion to a high Mach number followed by further preheat back to the same temperature and then combustion. This is a device for passing more enthalpy into the gases in spite of the wall temperature limitation. The liquid air cycles are concerned with combining the air compression with liquefaction so that combustion can take place with oxygen enriched air produced as part of the main cycle.

The small pilot plant work at Queen Mary College and Sheffield University Fuel Department is all in the field of the open cycle unsteady flow system concerned with temperature striations and velocity modulation.

I. Fells (University of Newcastle upon Tyne)

One point which arises from the preceding papers is the difference of approach between workers in the open cycle and closed cycle fields. Materials problems are inevitable in m.h.d. experiments, but whereas open cycle workers are prepared to accept temperatures of about 2600 °C, the temperature necessary for thermal ionization of seed material in combustion products, workers in the closed cycle field, where temperature limitations are more stringent, have concentrated on non-equilibrium ionization of the working fluid in order to lower the operating temperature. I should like to suggest that the possibilities of non-equilibrium ionization in open cycle systems have not yet been fully explored, magnetically induced non-equilibrium ionization is by no means the only possibility. Mr Freck's paper (p. 471 below) points to some interesting possibilities and several proposals made a few years ago have not yet been investigated experimentally. The high temperature problems for open cycle systems have clearly been solved for short running times. I should like to ask Dr Brogan and Dr Wright how near we are to duct lives of 10 kh or more? Would a reduction in running temperature of a few hundred degrees, perhaps achieved by non-equilibrium ionization, materially improve the running life of ducts? The successful operation of an m.h.d. generator does not, of course, mean an m.h.d. power station will necessarily be a success. I should like to ask Dr Wright where he sees the rate controlling step in the conception of an m.h.d. 'topping' station, is it in the development of the high temperature chemical engineering necessary for seed recovery, in corrosion of the water tube boiler, in heat exchanger design, in magnet construction or in electrode life?

Turning to Dr Lindley's papers on closed cycle systems, it is interesting to see operating temperatures of 1800 °C being quoted as realistic and also the suggestion that even lower operating temperatures will be possible. It would, of course, be a mistake to lower the operating temperature too far as one would then find oneself in competition with the gas turbine. The upper working temperatures on gas turbines may also be raised by using new high temperature materials the production of which has been stimulated by m.h.d. research.

One disturbing point in Dr Lindley's paper is the decrease of electrical conductivity with increase in pressure in helium–caesium systems. For thermal ionization conductivity varies as $P^{-\frac{1}{2}}$ and for non-equilibrium ionization conductivity varies as P^{-4}. The particle suspension system described in Mr Waldie's paper in which conductivity varies only as $P^{-0\cdot13}$ could be a more attractive system for high temperature, and, consequently, high pressure reactors.

It is interesting to see the idea of a closed cycle fossil fuel fired system being examined again. The heat exchanger presents problems, of course, and helium may well prove to be lost too easily through ceramic walls at 1800 °C, a particle suspension in argon might well be less susceptible to loss by pore diffusion and is also a better heat transfer medium.

The possibilities of reducing temperature and, consequently, simplifying some of the associated engineering problems, make a new assessment of the methods for promoting non-equilibrium ionization in open cycle as well as closed cycle systems worth while. But it is essential that proposals should be examined experimentally as well as theoretically.

Dr C. Szendy (Eroterv, Hungary)

It is a generally held view—also accepted by Dr J. K. Wright in his introductory lecture—that m.h.d. generators are most satisfactorily utilized when employed as topping units. This is based on the theory that the heat of the high temperature working fluid discharged from the generator duct is still available for power production and therefore has to be used in a conventional power station. However, this reduces the efficiency of the m.h.d. cycle quite considerably, and it may in fact scarcely exceed 50 %. At the same time investment costs are increased and the resulting combined cycle is rather complicated and difficult to regulate.

The topping unit solution is not a theoretical necessity, however, as a considerable part of the heat of the working fluid at a temperature of 2000 to 2400 °K can be transferred, by means of a heat exchanger, to the combustion air for the m.h.d. unit. This would raise the temperature of the air to just below that of the working fluid. By this means about 65 % of the thermal energy of the fuel may be converted in the working duct into electric power.

Many design and layout difficulties would of course have to be overcome for such a heat exchanger. Only exchangers of the regenerative type would be suitable and must be capable of operating under the following conditions:

(1) The ceramic charge should withstand the operating temperature of 2000 to 2400 °K required for practical application.

(2) Pressure loss due to the flow across the regenerative unit should be small compared with the operating pressure drop.

(3) Regular operation of the regenerative unit should not be adversely affected by the fact that the specific weight of air to be heated is generally ten times as high as that of the working fluid discharged from the generator duct. The heating and cooling periods should be of equal duration.

(4) Security of operation should be assured by the use of very reliable opening and closing valves.

In addition to those enumerated a lot of other difficulties are likely to be encountered. However, they are all theoretically and practically resolvable problems and many are being successfully tackled by research workers.

There is one other aspect of m.h.d. operation that needs consideration. Any generator duct designed according to a given system will be capable of yielding a definite output. The behaviour of the working fluid in the duct is very sensitive to output variations, especially in the case of Hall generators or those provided with series connected electrodes. It would be worthwhile therefore adopting an arrangement for the generator which would reduce the dependence on output variations. This would necessitate suitable adjustment of the magnetic flux and working fluid characteristics.

I think that it is timely today to draw attention to these problems and to suggest that it would be profitable to devote more research towards their solution.

P. J. Nowacki (Swierk, Warsaw, Poland)

I should like to make a few remarks concerning the very interesting paper, presented by Dr Wright (p. 347 above), especially on the provision of long lived m.h.d. ducts and electrodes. The design discussed has been described by J. Maycock, D. T. Swift-Hook, J. K. Wright & P. Ramsden in *Nature, Lond.* 1962 **196**, 260, and also in paper 72 of the *2nd Int. Symp. on m.h.d. elect. power gen., Paris*, July 1964. The proposed design contains water-cooled tubes bent into rectangles and inclined at a certain angle to the duct axis, according to a proposal by de Montardy.

I should like to mention, that this construction is valid only for one load condition and depends on the Hall parameter β and, therefore, demands generally a stabilized magnetic induction B as well as a constant electron-mobility μ. One of the crucial problems to the successful utilization of high power d.c.–m.h.d. ducts is the extraction of d.c. power and therefore, it might be advisable to concentrate the future research on the Hall type generator, which gives an output at a relatively high d.c. voltage and requires, in its basic form, only one load resistance.

There is also a second field of utilization for m.h.d.—electric power generation; for certain purposes there are requirements for high power pulses in short bursts, e.g. for geological research, etc. In this case it might be advisable to utilize explosion driven m.h.d. generators.

H. R. Hoy (The British Coal Utilization Research Association) [Plate 23]

Some of the problems of using coal to produce high temperature gases for m.h.d. power generating systems are being investigated at the British Coal Utilization Research Association. The programme of research and the necessary augmentation of the Association's finances were approved by the National Coal Board at the end of August 1964.

The immediate objective is to provide data for designing a combustor suitable for an experimental power generating system with a thermal input of 60 MW. The proposed unit would consume about 9 tons of coal an hour.

The tentative specification involves burning coal in air at a temperature of 1200 °C and a pressure of 5 atm; a gas temperature approaching 2400 °C is thought to be acceptable.

The basic problem is to keep heat losses down to a low level. The heat losses (including the heat required to vaporize the seed) must not exceed 11 % of the coal heat input if this temperature is to be attained.

The main areas of uncertainty in the combustion of coal from this point of view are:

First, the combustion intensity that can be achieved. This is directly related to the time needed to burn the coal particles. There are no reliable data on the burning times of coal particles at the temperatures and pressures applicable to m.h.d. systems. Combustion chamber design principles also differ in some important ways from those of conventional p.f. combustion systems.

Secondly, there is uncertainty as to the heat transfer rates to the combustion chamber walls: the walls must be liquid cooled. We think that the refractory constituents of the coal ash will provide an insulating layer on the walls but the extent to which this will occur has to be proved. The effective flame emissivity is also in doubt.

Thirdly, there is uncertainty as to the heat that will be lost in vaporizing the ash. The extent of vaporization will depend amongst other factors on the temperature-time history to which the ash is subjected in the combustion system; this is related to the design of the combustion chamber.

To resolve these and other uncertainties both laboratory-scale and pilot-scale investigations are in progress at the Association's Leatherhead research station.

The equipment

For the pilot scale investigations a test rig (see figure 1 and figure 2, plate 23) suitable for combustors burning up to 1 ton/h of coal sized from normal p.f. down to 100% smaller than 30 μm, in air enriched with oxygen and preheated to temperatures up to about 1400 °C, has been constructed.

On this scale of operation heat losses are too high for the required gas temperature to be attained at the specified air temperature without either enrichment of the air with oxygen, or fine grinding of the coal. The need for oxygen enrichment or fine grinding would decrease with increase in plant size and probably would be entirely eliminated in a large commercial-scale plant.

The oxygen-enriched air for the experimental combustor is at present heated by burning oil in it; oxygen is added to compensate for that used in the process. The combustion chamber for the direct-fired airheater is also to be used to fire a pebble-bed airheater; by combining these two systems the combustor can be operated intermittently with non-vitiated air or continuously with vitiated air. It is considered that the latter is adequate for providing a preliminary assessment of design features.

Fluidized systems have been developed for feeding coal and seed.

The present combustion chamber is approximately 12 in. in diameter and 36 in. long; larger chambers could be contained within the pressure casings.

The walls of the combustion chamber and the measuring section that follows it are formed of a number of sections of water-cooled pipe coils. Measurement of flow and temperature at the outlet of each section provides data on heat transfer.

The temperature of the gases at the outlet of the combustion chamber is measured using sodium line reversal. The equipment that has been developed is semi-automatic and is remotely operated. Corrections to light transmission losses due to the optical system and due to the presence of particles in the flame are made by measurements of lamp intensity with and without the optical system and with and without the flame.

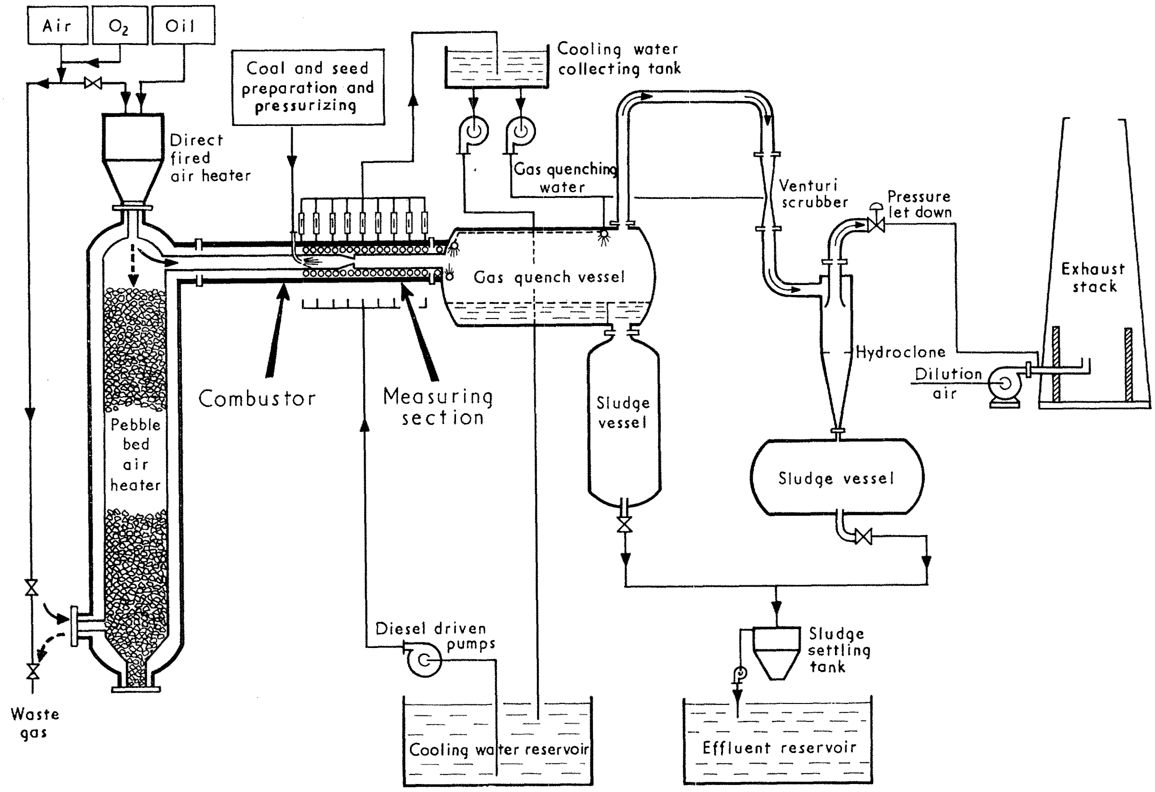


FIGURE 1. M.h.d. power generation: layout of test plant for high intensity coal-fired combustor.

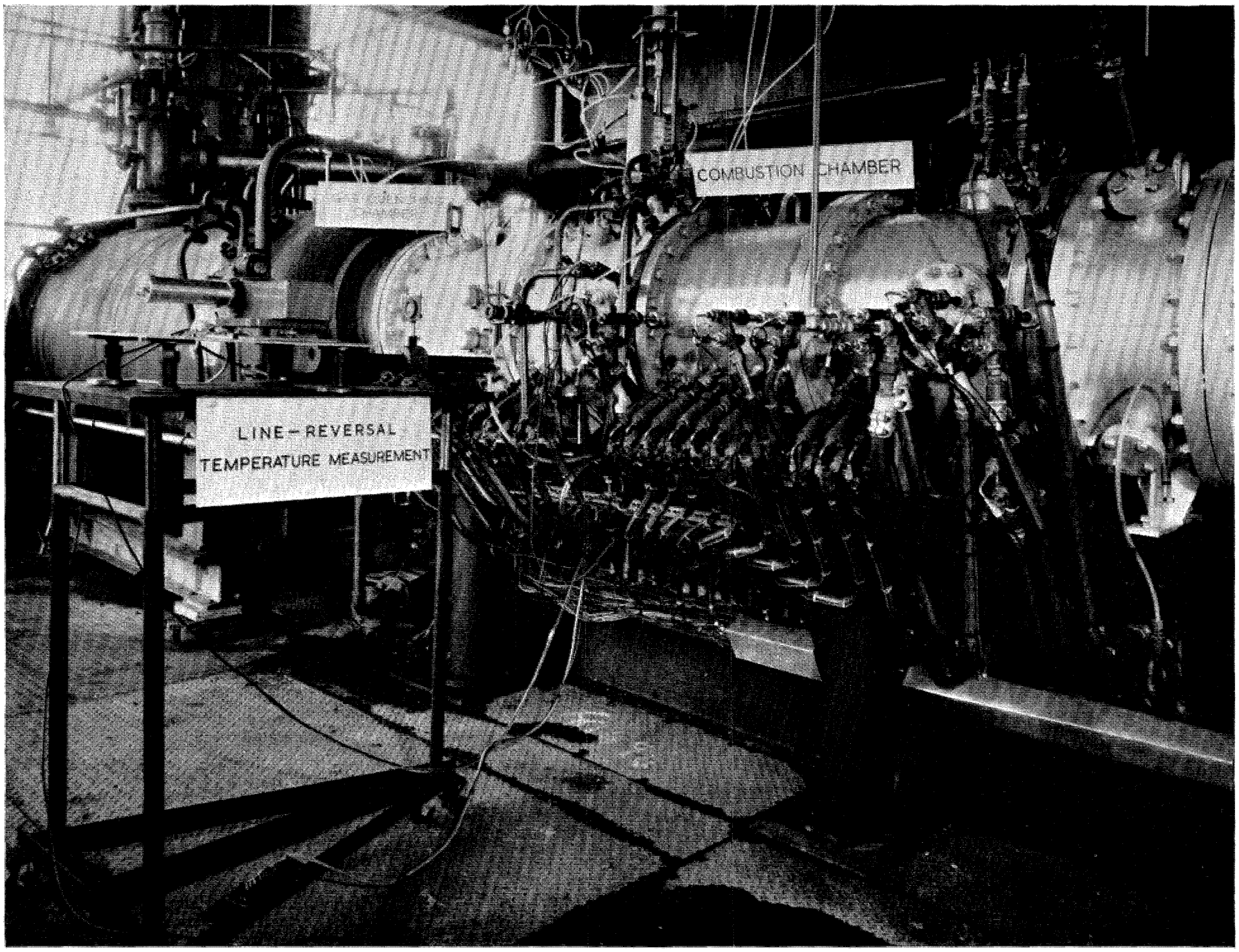


FIGURE 2. General view of the pilot-scale combustor, measuring section, and gas quenching chamber. Equipment for measuring temperature by line-reversal method, sited across the combustion chamber outlet. Above is a retractable gas sampling probe.

The combustion gases are sampled continuously at the outlet of the combustion chamber through a special design of probe. Water is injected into the gas sample stream at the tip of the probe and a rodding device passes through the aperture every few seconds to keep it clear. The gases are also sampled at the outlet of the measuring section. Equipment for sampling the solids and mineral matter carried in the gas stream and for measuring gas conductivity is to be installed.

The gases leaving the measuring section are quenched in water and the solid matter is finally removed from the gases in the venturi scrubber and hydroclone that follow the quench vessel. The pressure in the system is controlled by a valve at the outlet of the hydroclone. This has the advantage over using choked nozzles in that burning rate and pressure can be varied separately.

Combustion chamber design

After considering the relative merits of alternative combustion systems it was decided to study the possibility of achieving a high combustion intensity (at least $5{\cdot}0 \times 10^6$ Btu ft.$^{-3}$ h^{-1}) and low heat losses in a simple design of plug flow combustion chamber.

The main factor influencing the combustion intensity and efficiency achieved under comparable conditions of excess air, oxygen concentration and fuel size, is the way in which the coal is dispersed across the cross-section of the chamber. Rapid and uniform dispersion are essential and the main variables in achieving this are the shape at the inlet to the chamber and the design of the equipment for projecting the particles of fuel across the airstream. The latter is not simple to achieve because the quantity of air (cold) used to convey and disperse the coal must be small, otherwise there is a significant drop in the temperature of the combustion gases. If only 1 % of the air is fed cold the temperature is reduced by 6 °C.

Ignition is simplified by using combustion air at a temperature of 1200 °C, but using air at this temperature complicates the design of nozzles and devices for dispersing the coal in the airstream and increases their size.

Experimental work

The first test run on coal was carried out at the end of July this year, despite major components being delivered many months behind schedule. Unfortunately, however, the effect of dishonoured delivery dates could not be entirely overcome and it was not until October that it was possible to install the equipment in the measuring system needed for measuring gas temperatures and for sampling the gases.

Eleven short runs have been carried out so far—all at 5 atm pressure and using oxygen-enriched air preheated to 1200 °C. The film of slag on the combustion chamber walls has not yet reached equilibrium, consequently the performance data obtained are liable to be revised.

The present indications are, however, that the combustion efficiency is normally better than 96 %; the combustion intensity for almost all of the tests has been in excess of 3×10^6 Btu ft.$^{-3}$ h^{-1} and on one occasion 4×10^6 was exceeded.

Obscuration by slag of the ends of the sight tubes for the line reversal system for measuring temperature is currently a problem and has limited the amount of data obtained. The apertures at the ends of the tubes are swept by nitrogen, but this is not sufficient to keep them clear for long.

At the low combustion intensity of 3×10^6 Btu ft.$^{-3}$ h^{-1} temperatures at the outlet around 2300 °C have been measured; direct-fired airheating involves a penalty of 90 °C and allowing for this, the temperature achieved was close to the value expected for the particular operating conditions.

It is hoped that by the end of 1965 sufficient information will have been obtained on the design of devices for obtaining good dispersion of coal particles for us to proceed with the extensive experimental work needed to provide information for scaling up to the 60 MW plant.

Basic work to support the pilot scale studies is being carried out on the burning times of closely sized char particles at temperatures in the range 2000 to 2400 °C, and on the physical and chemical behaviour of coal minerals when heated to such temperatures.

R. C. Jeffrey and R. C. Pole (Babcock and Wilcox Ltd, Renfrew)

Present designs of commercial, open cycle m.h.d. generators are based on the combustion of pulverized coal or heavy residual fuel oil. In either case, the assumption is at present that the combustion products must achieve a temperature of around 3000 °K and a pressure of up to 10 atm. Little is known about either the mechanisms of combustion or the thermodynamic and transport properties of the combustion products under these conditions.

To achieve the high temperature required, the combustion air must be preheated to about 1450 °C, the alternative being oxygen enrichment which would be too expensive. In systems using oil, this high air preheat may possibly lead to extensive cracking of the oil before combustion. Any such carbon formation would extend the time necessary for combustion, whereas the high air preheat will tend to reduce it. The combined effect may, or may not, produce a combustion time about equal to that for existing high intensity residual oil combustion chambers, namely about 60 ms.

Another factor which may affect the combustion process is the seed which has to be introduced into the gases to make them sufficiently electrically conducting before they enter the m.h.d. generator itself. This seed will probably be K_2SO_4 (for economic reasons) and will have to be added in a quantity equal to a quarter of the weight of the fuel. The seed could be sprayed directly into the combustion chamber in a molten state, carried in by the air stream in the form of vapour or droplets or mixed with the fuel as a slurry or emulsion; the method chosen may also affect the combustion process.

A combustion chamber is being built by us to investigate some of these problems. This chamber, which will burn residual fuel oil, is 5 ft. 0 in. long and $13\frac{1}{4}$ in. in diameter. The air preheat is supplied from a diesel oil fired, pebble bed regenerator with a half cycle time of about 20 min.

Operated continuously, the thermal input to the rig will be 18 MW. In designing the combustion chamber it was assumed that the combustion gases would contain large quantities of carbon, thus giving a flame emissivity of near unity. This produces a very large flow of radiant heat to the walls of the chamber. These will therefore be protected by extensive water cooling and by a layer of flame sprayed zirconia. Initially the seed will be introduced with the fuel in the form of a slurry.

Measurements will be made of gas temperature (using the sodium D-line reversal method), residence time necessary for complete combustion, heat fluxes and gas electrical conductivity at exit from the combustion chamber.

T. R. Brogan

Dr Fells asked me a question on channel endurance. I definitely believe that m.h.d. duct lives in excess of 10 kh are to be expected. Water cooled circular Hall Channels of the type discussed in my paper have already been tested in power generator situations for several hundred hours with negligible change in performance in our Long Duration Test Facility. These tests could have been extended greatly, given sufficient incentive, since an equilibrium situation had been established.

On the subject of running temperature, I presume that it is the gas temperature that Dr Fells is referring to. It should be noted that electric field strength in the channel, and not heat transfer, is the chief problem in duct design. I doubt that reduction in gas temperature would lead to improvement in duct life; instead, the opposite is to be expected. Achievement of non-equilibrium ionization in combustion gases appears to be fundamentally impossible by virtue of the close coupling between electron temperature and the vibrational energy of the gas molecules. Since this is the case, reduction in gas temperature must lead to reduction in electrical conductivity so that, for equivalent power density, the magnetic field must be increased. This always leads to an increase in electric field strength in the channel, with consequent increased danger at breakdown.

With regard to m.h.d. power stations, I could quote some of our own work but that is not necessary since many studies have concluded that m.h.d. offers a route to high efficiency and reduced power cost. We believe that a large percentage of the fossil fuelled plants being built, say in the late 1970's, will be m.h.d. plants.

J. K. Wright

Dr Fells has asked me two questions, one about electrode performance and running temperature, and the other about the critical factors in the design of a complete power station. Dr Brogan, to whom the first question was also addressed, has replied fully on the subject of electrodes and non-equilibrium ionization. I have little of substance to add to what Dr Brogan has already said other than to draw attention to the paper by Mr D. Freck later in this symposium where the whole subject of non-equilibrium ionization in combustion is thoroughly discussed.

In the other question about the power station as a whole, Dr Fells has raised an exceedingly important issue. In pure science one has the utmost admiration for a man who, after years of discouragement, makes a significant advance on a narrow front. If one discounts the 'scientific fall-out' that results from a project, applied scientific research covering a broad technological front is only successful if each of the links in the chain is in itself successful. Moreover, applied science must be carried out against an economic background which may be changing with time, and hence, for the work to be successful, must be completed within a given time scale. The stature of an applied scientist will be measured not only by his persistence in overcoming difficulties, but also in his ability to recognize at an early stage, which of those projects are likely to be capable of being carried through to a practical, economically successful conclusion. It is unfortunate that this sort of judgement does not always seem to be employed with m.h.d. studies.

In the Central Electricity Generating Board we identified some years ago that the open cycle fossil fuel generator was the type most likely to give a real economic return provided it was developed fairly quickly. Even so there are a number of obstacles to be overcome but the rewards of success are sufficient to warrant the risking of the money and scientific manpower involved in mounting a sufficiently large programme to meet the time scale. Dr Fells has correctly identified many of the critical areas—these are duct life, duct flow stability and control, seed recovery, air heater development, boiler tube corrosion and the development of a superconducting magnet. These are still areas of active development work, and are being studied in parallel. There is no one item that is critical in controlling the rate of progress of the project as a whole, but the project is planned in such a way that it is hoped that any insuperable difficulties that may arise will be identified as soon as possible.

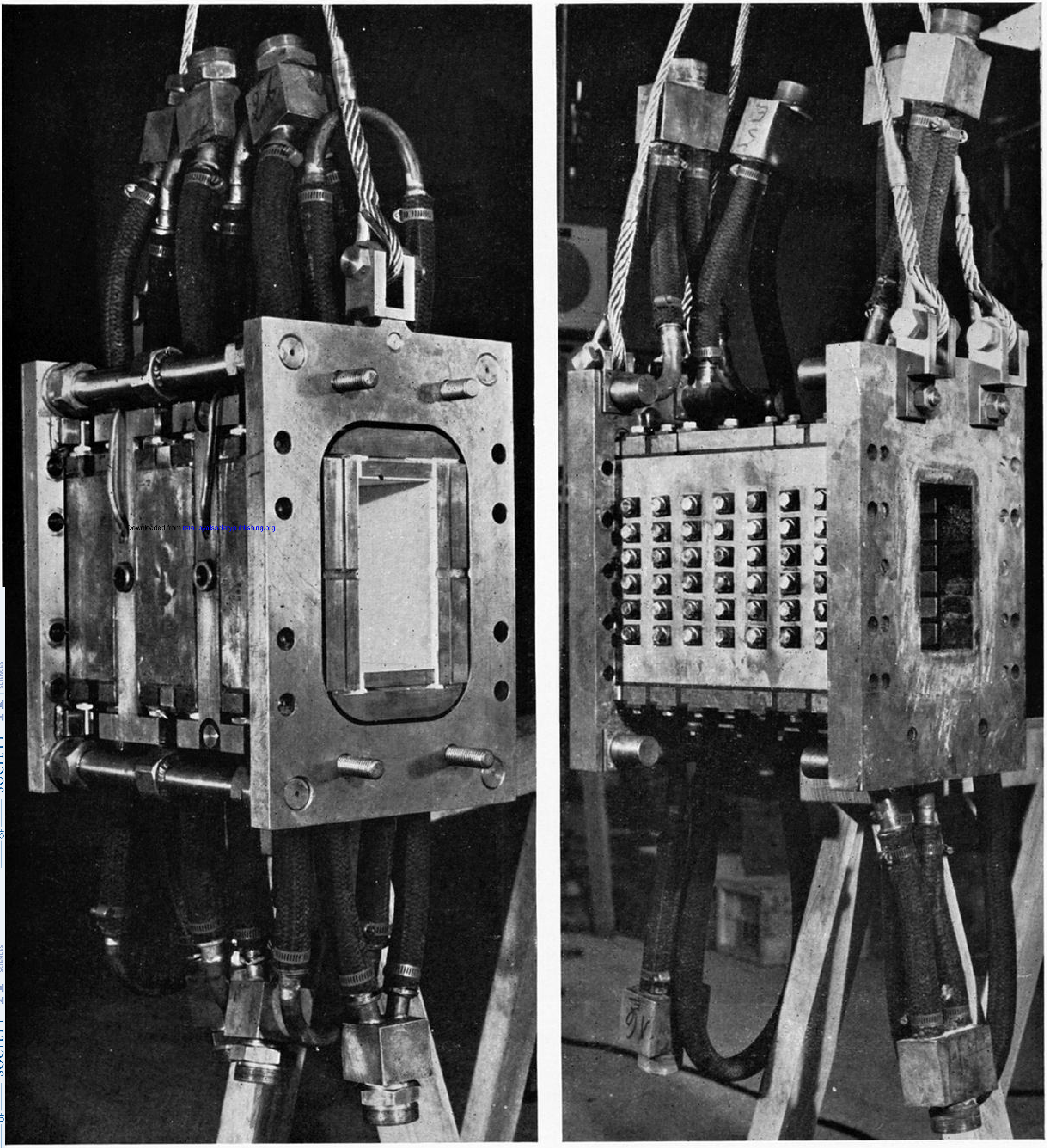


FIGURE 5. Photograph of the ducts with a 10 cm long m.h.d. section between two 10 cm long insulating sections. (*Left*) Side walls sprayed with alumina. (*Right*) Peg wall type side walls.

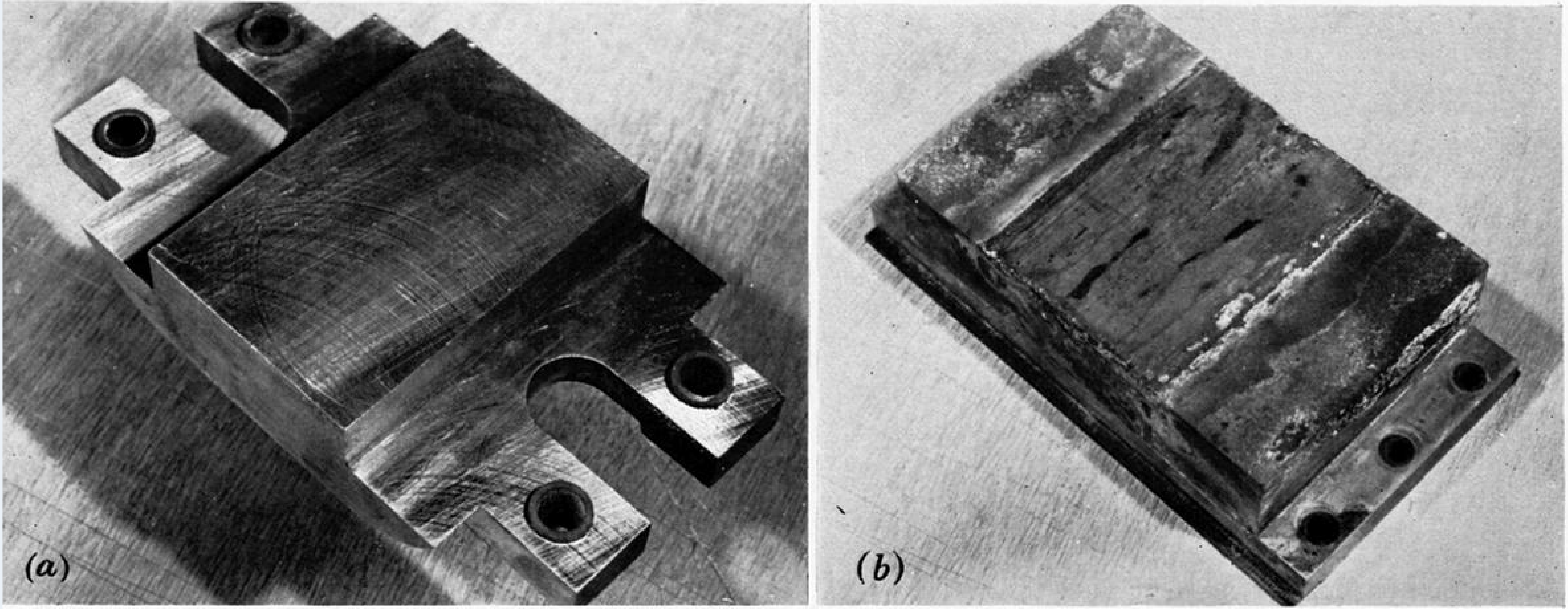
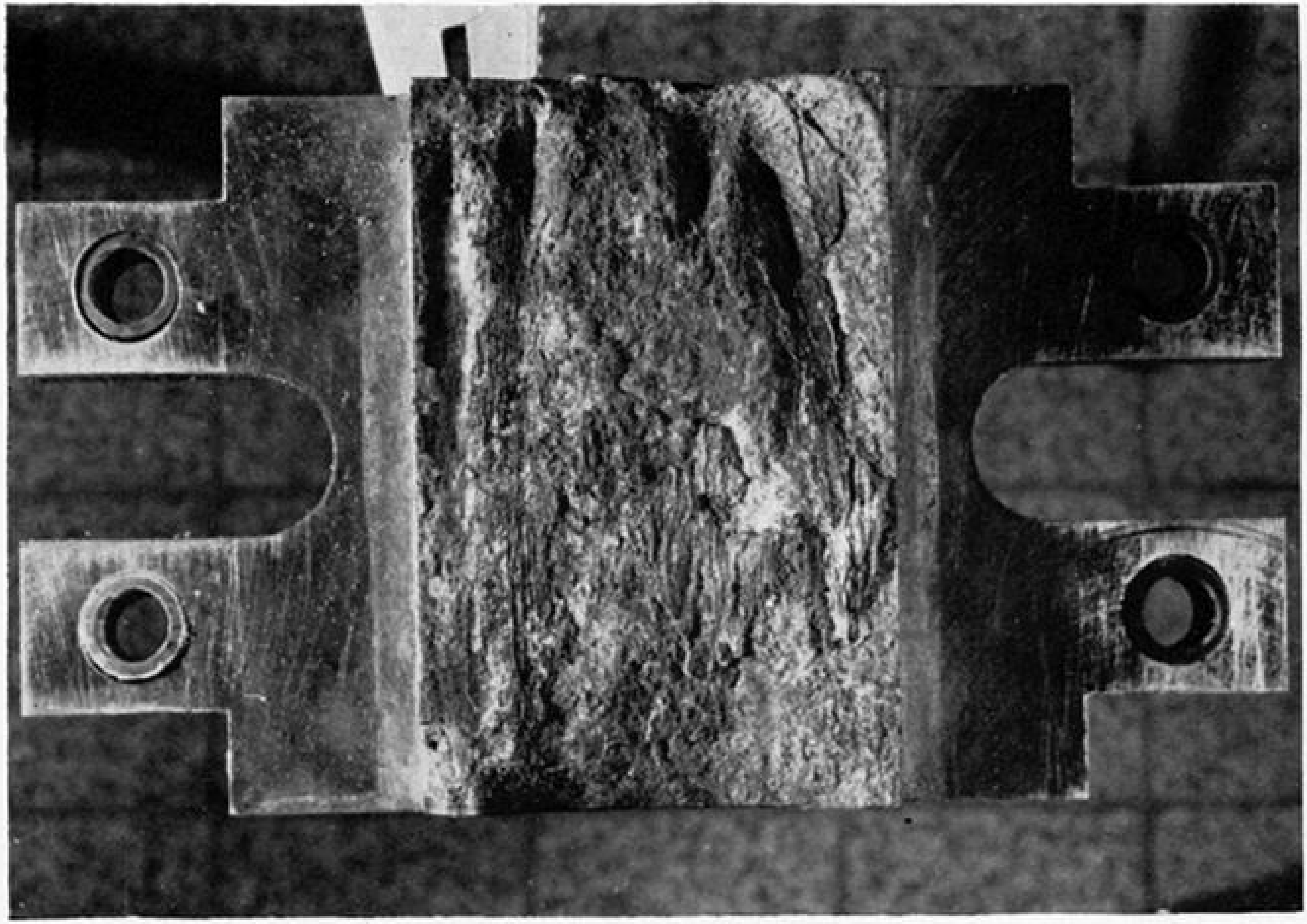
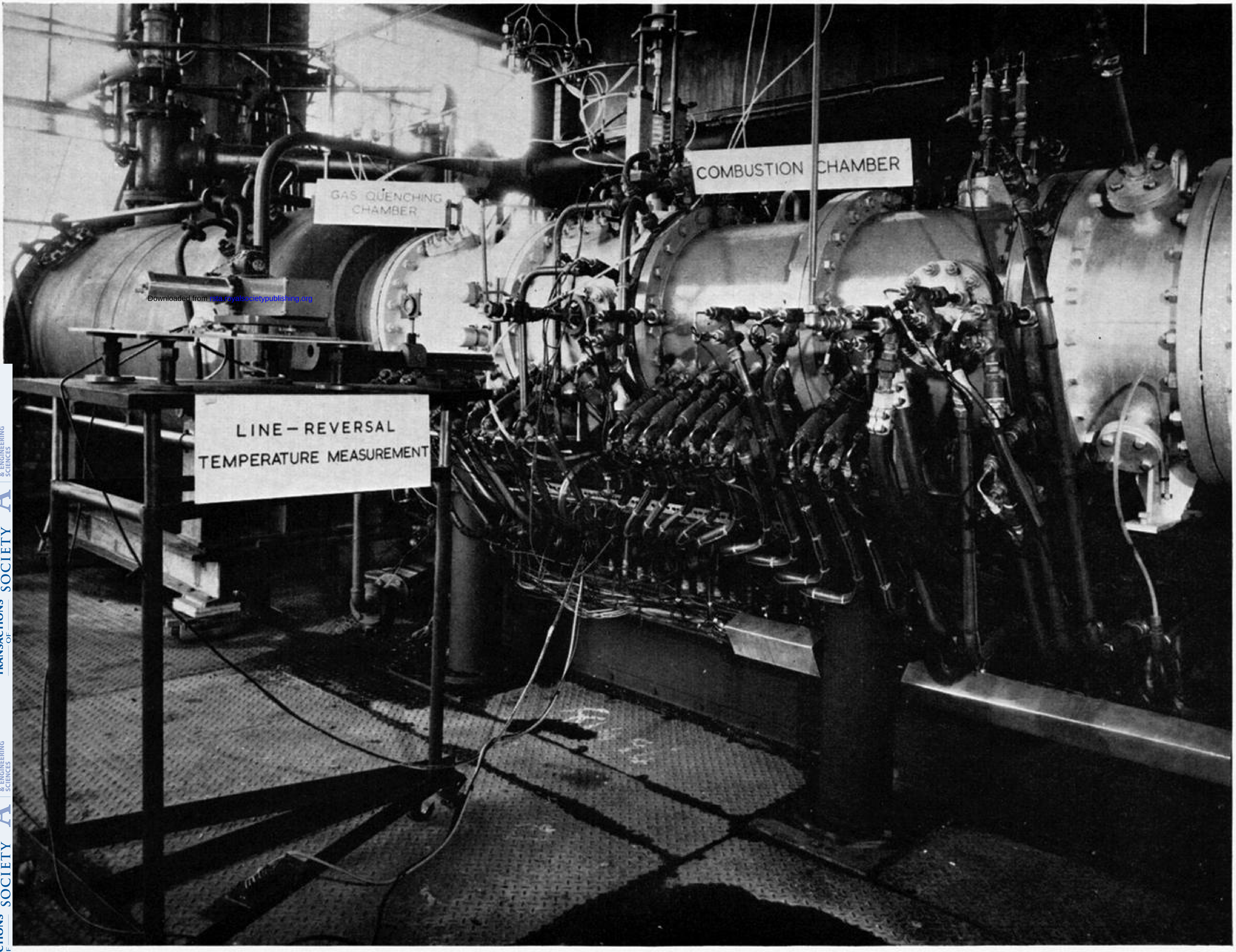


FIGURE 6. Photograph of the individual electrodes shown *in situ* in figure 5. (*a*) Electrode used with alumina side walls. (*b*) Electrode used with peg walls.



IGURE 13. Photograph of an NS 30 electrode after a 1 h 20 min test showing the extent of erosion.



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