The Prospects for Closed Cycle M.P.D. Power Generation

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III. The prospects for closed cycle m.p.d power generation

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[Plate 20]

The basic features of closed cycle m.p.d. systems are described, introducing the three main combination cycles (direct nuclear, indirect nuclear, indirect fired) which could be adopted for commercial power stations.

Because of the high temperatures and attendant problems associated with thermal ionization of the working gas plasma, emphasis is placed upon achieving non-equilibrium ionization. This phenomenon is generally applicable only in closed cycle systems employing certain gases as the working fluid: the basic theory and required operating parameters of several techniques for inducing non-equilibrium ionization are reviewed.

Matching a heat source, whether based on combustion or nuclear energy, to the m.p.d. stage imposes a number of restrictions. Nuclear reactors to provide temperatures suitable for m.p.d. systems (perhaps up to 1800 °C) have yet to be developed, but design criteria can be formulated. Cycle studies to specify operating parameters (including temperature, pressure, associated steam cycle, etc.) are presented. The technical feasibility of an indirect fired heat exchanger is considered. Over-all system performance, development time scale and incentives are also examined.

In the United Kingdom, experimental research and development towards closed cycle m.p.d. power generation is mainly in progress at International Research and Development Co. Ltd and at A.E.R.E., Harwell. Details of the programmes are given and achievements in terms of experimental data are presented.

Finally, the prospects for closed cycle m.p.d. power generation are reviewed.

1. INTRODUCTION

The closed cycle m.p.d.-steam plant concept (Lindley 1962*a*; Dunn & Wright 1963; Lindley 1964*a*, *b*; Dunn, Lindley & Wright 1964) appears to offer many attractive technical features for large-scale commercial power stations. These include:

(1) The working fluid may be selected on the basis of heat transfer and fluid flow parameters in over-all circuit performance, optimization of plasma conditions in the m.p.d. generator, and on grounds of chemical compatibility with the circuit constructional materials; retention in the circuit of working gas and seeding constituent means that even expensive materials may be acceptable.

(2) The possibility of non-equilibrium ionization in certain working gas plasmas allows the top temperature in the cycle to be chosen for thermodynamic reasons and not from a requirement for thermal ionization.

(3) Several possible versions of the closed cycle system (figures 1 (*a*), (*b*), (*c*)) will permit utilization of available sources of energy (coal, oil and gas or nuclear fission) if the required top temperature proves sufficiently low.

The implications of these statements will be considered in some detail and the status of experimental research reviewed to evaluate the prospects for closed cycle m.p.d. power generation.

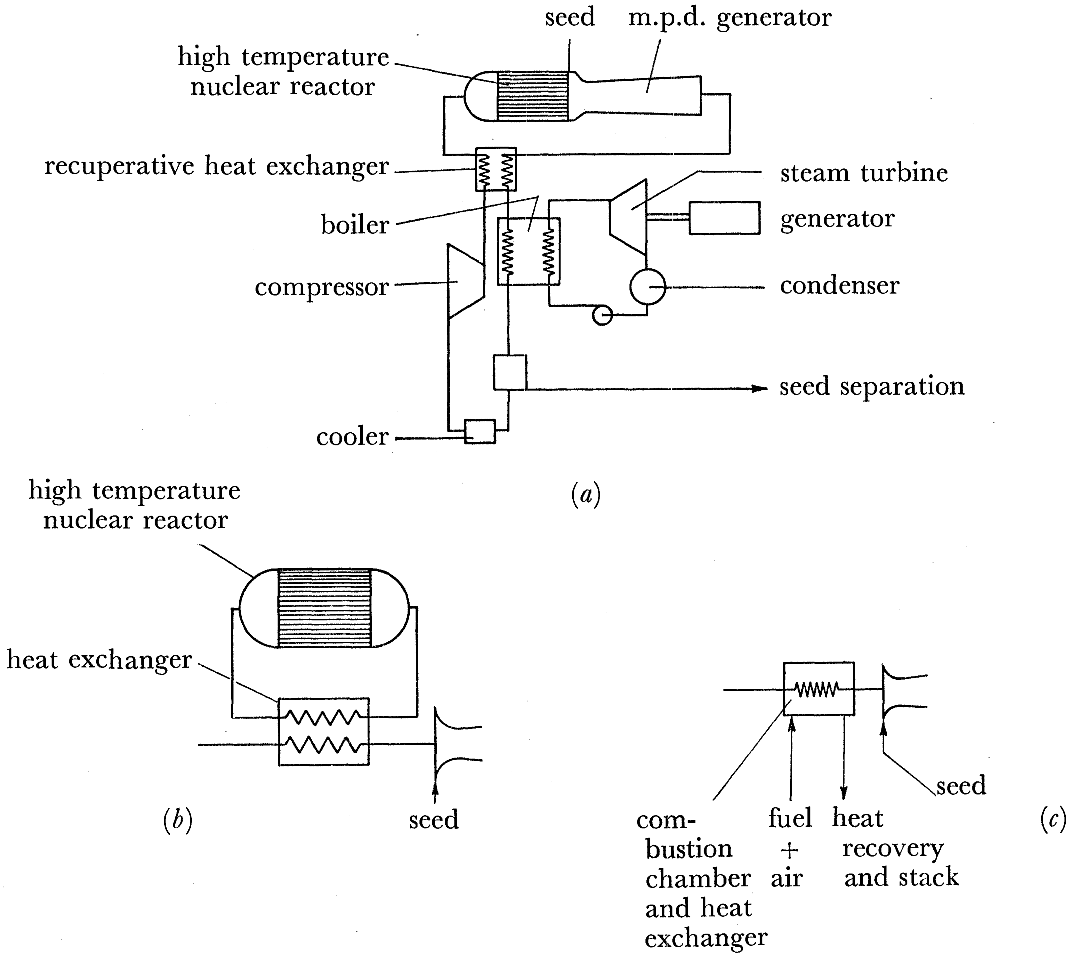


FIGURE 1. Versions of closed cycle m.p.d. steam plant: (*a*) direct nuclear; (*b*) indirect nuclear; (*c*) indirect fired.

2. NON-EQUILIBRIUM IONIZATION

2·1. *Methods for non-equilibrium ionization*

In a plasma which is in thermodynamic equilibrium the electron concentration may be determined from the equation given by Saha & Saha (1934). Examination of this equation shows that for a given element, high temperatures and low pressures are required for high electrical conductivity. These temperature and pressure requirements are not consistent with those generally considered feasible for operation with a nuclear reactor or other form of heat source; consequently, there is considerable emphasis at present on establishing the feasibility of non-equilibrium ionization in inert gas-alkali metal plasmas at moderate temperatures (say, from 1200 to 2000 °K) and pressures from one to a few atmospheres absolute. In such non-equilibrium plasmas the electrical conductivity is almost independent of the thermodynamic state of the uncharged particles which constitute the main proportion of the plasma.

Karlovitz & Halasz (1936, 1962) investigated several modes of extrathermal ionization in their natural gas fuelled combustion generator. Most attention was given to ionization by high voltage electron beams but glow discharges, direct current arcs and radio-frequency electromagnetic radiation were also employed. All these attempts were unsuccessful, mainly because of dissociative recombination which rapidly removed the electrons created by the ionization process.

Sternglass, Tsu, Griffiths & Wright (1965) have compared theoretically non-equilibrium ionization for nuclear-m.p.d. systems using electron beams, β rays from fission products and direct current arcs. Of these methods, electron beams appear the most promising in view of the relatively high efficiency with which beams can be generated, the feasibility of continuous application, ease of adjustment of the energy spectrum and lack of contamination caused by their use. Fission product ionization is less efficient and may lead to some radiation hazard. Recently Shair & Sherman (1965) have reported experimental results using electron beam pre-ionization in an argon–caesium plasma. The electron beam (40 keV, 50 mA) entered the plasma through cooled aluminium foil windows. Significant non-equilibrium ionization was produced, with electrical conductivities an order of magnitude greater than for thermal equilibrium.

An interesting ionization technique proposed by Maitland (1962) is to utilize photo-ionization produced by a high energy light beam. This suggestion has been examined by Voshall & Emmerich (1964) and by Balfour & Harris (1964). The latter authors conclude that the process is not likely to be very efficient unless high magnetic fields can be employed.

Braun, Nygaard & Witalis (1964) have suggested that the addition of suitable elements to the coolant gas of a nuclear reactor may result in the production of electrons through energetically favourable nuclear reactions. An experimental investigation of such a process, using helium 3 in helium 4, is now in progress.

A further method of obtaining non-equilibrium electrical conductivities, suggested independently by Lindley (1960) and Eschenroeder & Daiber (1960), depends on maintaining frozen flow conditions through the rapid expansion of an ionized gas. Such effects are well known in hypersonic flow and combustion conditions and their relevance to m.p.d. has been examined by Eschenroeder (1962) for air, and by McNab (1964*a*) for inert gas–alkali metal mixtures.

In most of the methods of non-equilibrium ionization outlined there are basic disadvantages: in the indirect use of electrical energy, the conversion efficiency of the ionizing means is less than unity and may be very small; re-application of the ionizing means to the plasma in transit through the generating region may be impracticable and the non-equilibrium state will decay rapidly.

Kerrebrock (1961), Hurwitz, Sutton & Tamor (1962), and others, have proposed magnetically induced ionization. In essence the phenomenon which is employed is as observed in conventional gas discharges where the presence of an electric field acts to raise the electron temperature above the gas temperature. In an m.p.d. generator the electric field is that existing internally in the plasma and produced by the magnetic field-plasma flow interaction; thus the Joule heating effect which is always present when a current is drawn can be turned to advantage.

2.2. *Theory for magnetically induced ionization*

In the simple theory developed initially by Kerrebrock (1961) the degree of Joule heating of the electrons in the internal electric field of the generator is equated to the energy loss of the electrons in elastic collisions with the gas atoms. This procedure leads to the following expression for the electron temperature in a segmented-electrode generator (following Hurwitz *et al.* 1962):

$$T_e/T_a = 1+\tfrac{1}{3}\gamma\beta M^2\delta^{-1}(1-K)^2, \tag{1}$$

where T_e is the electron temperature, T_a the atom temperature, γ the ratio of specific heats, β the Hall coefficient, M the Mach number, K the generator loading factor and δ the inelastic collision factor. The following assumptions are made:

(*a*) The inelastic energy loss in collisions of electrons with gas atoms is small. (Inelastic collisions are accounted for by use of the factor δ, which is close to unity for pure monatomic gases and increases to 10^2 or 10^3 for molecular gases.)

(*b*) The time for randomization of electron energies is taken to be very short compared with that for electron-atom energy exchange: the electrons rapidly spread their energy amongst themselves and an electron temperature may be defined.

(*c*) The electron energy distribution is Maxwellian, any deviation being included in the δ factor.

In evaluating the plasma electrical conductivity, electron-atom ionizing collisions are assumed dominant under typical m.p.d. generator conditions, and the Saha equation based on electron temperature is used to calculate the electron concentration. BenDaniel & Tamor (1962) conclude that, provided the seed atom concentration is greater than 3×10^{15} cm^3, the Saha equation should be valid under most experimental conditions. Supporting experimental evidence has been obtained by Sheindlin, Batenin & Asinovsky (1964) and by Zukoski, Cool & Gibson (1964); indirect evidence is obtainable from electrical conductivity measurements.

From equation (1) certain conclusions may be drawn regarding the operating conditions for magnetically induced ionization. For example, molecular impurities in the plasma should be minimized in view of the inherently high value of δ. The maximum permissible impurity content of any species can easily be calculated if the δ value is known for that species. High Mach numbers and Hall coefficients are required to achieve a high electron temperature.

At first sight there seems no reason why a generator should not operate with as large a Hall number as possible, provided ion slip is not significant. At high values of the Hall coefficient the generator would be designed to operate in the Hall or axial mode, rather than the Faraday or transverse mode. However, Rosa (1962) has shown that in a non-uniform gas the electron temperature elevation can be severely reduced compared with that expected in a uniform gas. For typical conditions the effects produced by the non-uniformities are most significant for Hall parameters between 10 and 100 (exactly the range for a Hall generator).

In small laboratory experiments effects occur which require modification of the theory, one important factor being related to the assumption that all collisions are either elastic or ionizing. In practice inelastic exciting collisions occur with energy loss from the electron gas. If the excited atom is not further excited to the point of ionization, de-excitation either by radiative or collisional processes will occur. De-excitation by superelastic electron collisions (a relatively minor factor, in any case) will not affect the net electron energy balance, but merely return energy to the electron gas. The main energy loss is likely to be through radiative de-excitation in which, if the plasma is optically thin, the emitted photon escapes from the plasma. The probability of this escape may be computed from the expressions given by Holstein (1951), as shown by Lutz (1965). Combining the simple expression for the degree of electron heating (equation (1)), the Saha equation and the probability of photon escape should therefore give agreement with experiment, provided the original assumptions are correct.

Kerrebrock (1965*a*) has recently proposed that a particular type of conductivity non-uniformity may be responsible for the apparent lack of success recently encountered with segmented-electrode generators. Over the surfaces of the electrical insulator separating the electrode segments the current normal to the insulator surface must be zero; it can be shown that at these insulator surfaces the electron temperature elevation will, for large Hall parameters, be much greater than that in the body of the plasma. Rosa (1962) showed that this leads to a reduction in the Hall voltage and electron temperature elevation. Hurwitz, Kilb & Sutton (1961), and others, have also discussed the influence of high Hall parameters on the current distribution in an m.p.d. generator. It is found that severely non-uniform current distributions can exist, particularly near the leading and trailing edges of segmented electrodes. These effects will contribute to performance degeneration of segmented-electrode generators through preferential electron temperature elevation near the electrodes, although inadequately explaining observed experimental results.

Electrode voltage drops may have a significant effect on the performance of generators. Few measurements of these drops are available; at current densities of about 1 A/cm^2 Kerrebrock (1961) found voltage drops of about 10 V, with lower drops at lower current densities.

If magnetically induced ionization is to be of practical value in an m.p.d. generator electron temperature elevation and consequent ionization of seed are attained within a distance short compared with the generator length. Relaxation times for the electron temperature elevation have been obtained by Wright (1963) and Kerrebrock (1965*b*), and for the electron concentration by Smith (1965) and McNab (to be published). With low electron temperature elevation the ionization process is limiting while at high electron temperatures the rate of rise of the electron temperature is limiting. These conclusions are supported by the work of Zukoski *et al.* (1964). For small laboratory experiments the relaxation lengths may be large enough to inhibit electron temperature elevation; this may even be true in large-scale experiments under certain conditions. Hurwitz *et al.* (1961), Dzung (1963), and others, have shown that electrical leakage occurs when a conducting fluid enters and leaves a magnetic field region.

The stability of a plasma in which magnetically induced ionization occurs may be questioned, and several proposed mechanisms by which the plasma may become unstable have been examined theoretically by a number of authors, the most general conclusion being that the plasma may indeed become unstable under certain operating conditions. To date there is insufficient evidence to conclusively support one or other of these theories, or indeed to indicate that instabilities are a severe practical problem, although Klepeis & Rosa (1965) have observed considerable fluctuations in the output of a Hall generator.

Experiments thus far performed in an attempt to establish the viability of magnetically induced ionization have been based on static gas experiments where transient effects are studied, and flowing gas experiments using either applied electric or applied magnetic fields.

2·3. *Non-equilibrium ionization in static plasmas*

A tantalum conductivity cell was constructed at A.E.R.E. to enable the thermally induced electrical conductivity of a variety of gas mixtures to be measured. Extremely high values of electrical conductivity (greater than 100 mho/m) were found in argon with a small potassium content at gas temperatures as low as 1000 °C (Ralph 1963 *a*, *b*). As these data were being analysed other information became available, notably from Kerrebrock (1961) who obtained similar effects in a seeded jet and gave an explanation based on elevated electron temperature. At about the same time, theoretical papers were published by Wright & Swift-Hook (1962) and by Hurwitz *et al.* (1962) in which the application of this effect to a practical m.p.d. generator was examined. The experimental work at A.E.R.E. has continued and the conditions necessary for transition from the thermal ionization mode to the non-equilibrium mode investigated experimentally and theoretically (Sakuntala 1964, 1965).

A spectroscopic study of the discharge indicated no ionization of the inert gases and electrostatic probes showed that the potential distribution in the plasma consisted of a relatively large cathode fall followed by a region of constant gradient extending to the anode. In the large duct dimension of a full-scale m.p.d. generator the electrical conductivity of the positive column will be the important parameter.

The following conclusions have been drawn from the experimental work (Ellington 1965 *a*, *b*, *c*):

Caesium-seeded argon has the highest electrical conductivity, although with potassium seeding the levels are almost as high.

Positive column fields of 3 V/cm resulted in an electrical conductivity of 200 mho/m in caesium–argon at gas temperatures of about 1000 °C.

In general the inert gas tends to control the positive column field (and hence the conductivity of the discharge) and the seed material determines the cathode emission, fall and transition point.

Figures 2 to 4, with tables 1 and 2, provide a summary of results. Current work includes the study of recombination, improved pulse techniques for measurements and consideration of the effect of different electrode materials.

2·4. *Experiments with applied electric fields*

The flowing gas experiments performed by Robben (1962), Kerrebrock (1961), Kerrebrock & Hoffman (1964), and Zukoski *et al.* (1964) with applied *electric* fields show fair agreement between theory and experiment. The most significant departure from theory

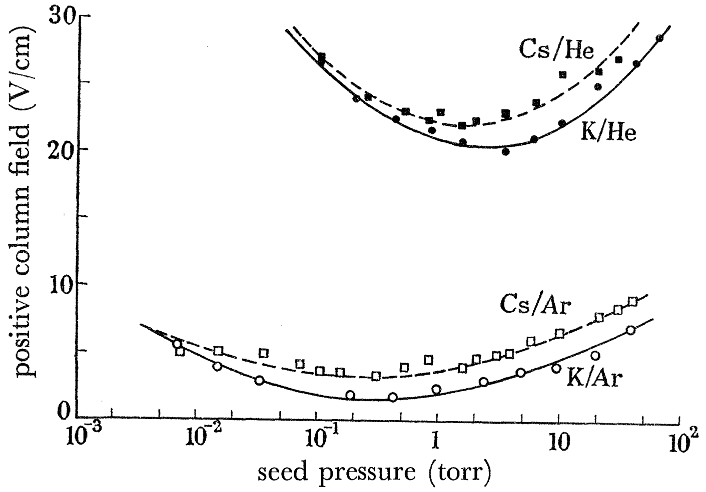


FIGURE 2. Positive column field as a function of seed pressure. Experimental conditions: gas pressure = 1 atm; gas temperature = 950 °C; total current = ½A, cathode: ½ in. diam. stainless steel; anode: 1¼ in. diam. stainless steel.

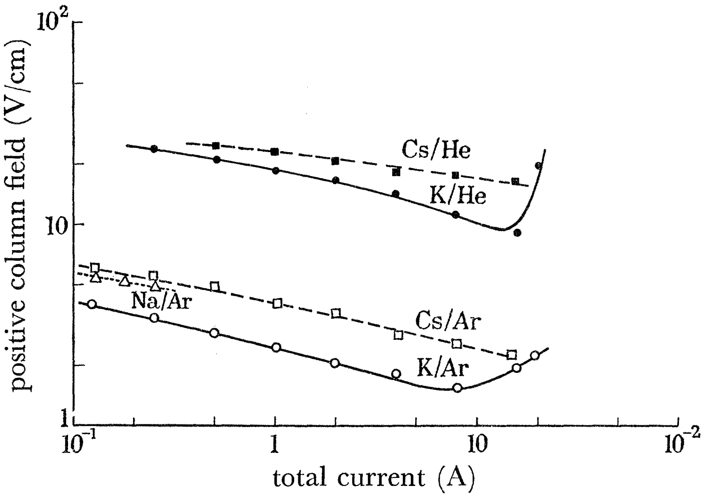


FIGURE 3. Positive column field as a function of total discharge current. Experimental conditions: gas pressure = 1 atm; seed pressure = 3·5 torr; gas temperature = 950 °C; cathode: ½ in. diam. stainless steel; anode: 1¼ in. diam. stainless steel.

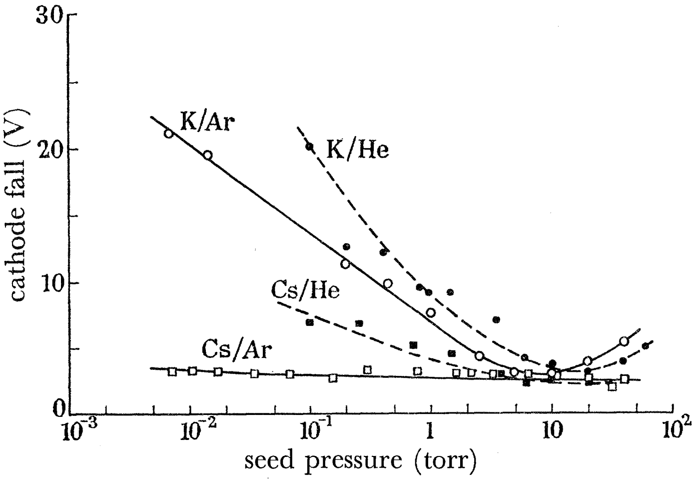


FIGURE 4. Cathode fall as a function of seed pressure. Experimental conditions: gas pressure ± 1 atm; gas temperature = 950 °C; total current = ½A; cathode: ½ in. diam. stainless steel; anode: 1¼ in. diam. stainless steel.

occurs at low current densities where conductivities greater than predicted are found. As pointed out by Kerrebrock (1961) these deviations from theory occur at the point where simple theory indicates that the electron energy distribution will begin to deviate from Maxwellian. The current densities at which this effect occurs are not large enough to be of practical significance in a generator. The transient studies conducted by BenDaniel & Bishop (1963) in low temperature helium–caesium plasmas also indicate that electrical conductivities much greater than those predicted from equilibrium theory can be obtained.

TABLES 1 AND 2. DATA OBTAINED IN DISCHARGE STUDIES IN SEEDED INERT GASES

TABLE 1

mixture	highest current possible at 3·5 torr seed pressure and 950 °C (A)	lowest temperature at which $\frac{1}{4}$A could be supported at 3·5 torr seed pressure (°C)	lowest seed pressure at which $\frac{1}{4}$A could be supported at 950 °C (torr)
Na–A	$\frac{1}{4}$	850	0·6
K–A	20	600	7×10^{-3}
Cs–A	above 25	500	below 7×10^{-3}
K–He	20	700	10^{-1}
Cs–He	above 25	above 600	below 10^{-1}

TABLE 2

mixture	cathode fall (V)	positive column field (V/cm)	positive column current density (A/cm^2)	positive column conductivity (mho/cm)	breakdown voltage (V/cm)
Na–A	2·2	5·0	1·7	0·33	90
K–A	4·5	3·5	5·0	1·3	31
Cs–A	1·1	5·3	12·5	2·3	30
K–He	4·0	24·0	8·0	0·3	170
Cs–He	1·9	26·0	24·0	1·0	140

2·5. *Experiments with applied magnetic fields*

Robben (1962), using arc-heated argon and potassium in a segmented-electrode generator, obtained a single experimental point, perhaps the first indication that magnetically induced ionization could be produced. Zauderer's experiments (1964) in a xenon shock tube, while giving electrical conductivities less than for thermal equilibrium, also indicated that magnetically induced ionization was occurring: the conditions of the experiments were, however, considerably removed from those of practical interest. Talaat & Bienert (1964) measured electrical conductivities some three orders of magnitude greater than for thermal equilibrium in a helium–caesium plasma flowing through a segmented-electrode generator at gas temperatures of about 1000 °K; the current densities were very much lower than required in practice. The measured non-equilibrium conductivities were higher than predicted by theory; as stated earlier the theory becomes questionable at very low current densities.

The experiments of Klepeis & Rosa (1965) in a segmented-electrode geometry at high Hall coefficients (about 15) showed that only slight increases in electrical conductivity occurred, probably due to preferential electron heating over the insulator surfaces.

Similarly, only a small Hall voltage and slight electron heating were observed by Croitoru, Bekiarian, Graziotti & Pithan (1964) using arc-heated argon and potassium (Hall coefficient about 20). Following these unsuccessful attempts with segmented-electrode generators a disc geometry was adopted by Klepeis & Rosa (1965); magnetically induced ionization was observed although the measured conductivities did not reach the theoretically predicted level and some instabilities occurred which proved impossible to control. Kerrebrock (1965*a*) suggested that inlet relaxation may be responsible for the disagreement with theory.

Brederlow, Eustis & Riedmüller (1964) measured electrical conductivities in arc-heated argon–potassium plasmas at gas temperatures between 1500 and 2000 °K. A magnetic field of 1 T caused the electrical conductivity to drop by 50 % from the value measured in zero field.

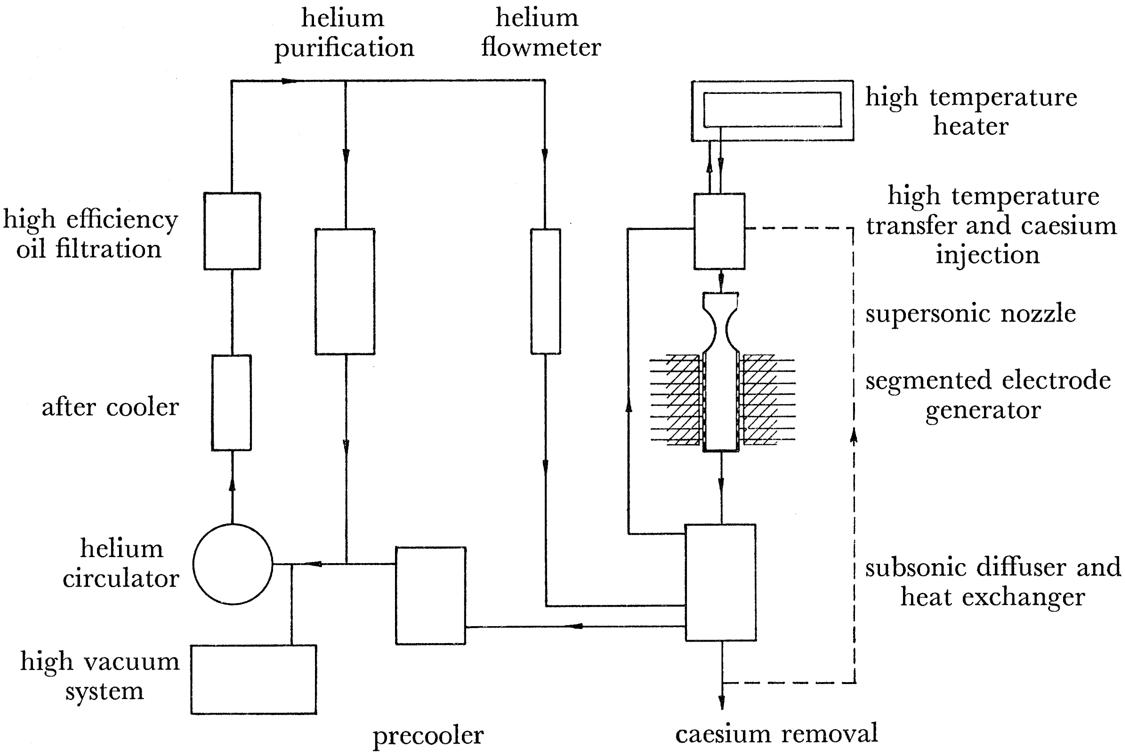


FIGURE 5. Components of I.R.D. closed cycle m.p.d. loop.

Initial experiments with the I.R.D. helium–caesium closed m.h.d. loop were reported at the International Symposium on M.h.d. Electrical Power Generation (Paris, July 1964) Lindley, Brown & McNab (1964); later experiments have been briefly discussed (McNab 1964*b*, 1965; McNab & Brown 1965). The basic components of the I.R.D. loop are shown diagrammatically in figure 5; the loop simulates a high temperature closed cycle nuclear m.p.d. system, with the nuclear reactor replaced by a high temperature electrical heater. Detailed descriptions of the engineering developments connected with the loop have already been reported (Lindley 1962*a*, *b*; Lindley *et al.* 1964).

Electrical conductivity measurements are made by switching a series of load resistors on to the electrode pairs and measuring the voltage drop across these resistors. Linear voltage–current characteristics indicate thermal equilibrium conductivities (which may be obtained from the slope of the characteristics); concave characteristics are indicative of magnetically induced non-equilibrium ionization. For most of the experiments carried out on 14 July 1964 (McNab 1964*b*) linear voltage–current curves were observed, although the electrical conductivities derived from these curves were considerably higher than for thermal equilibrium ionization at the measured static gas temperatures (figure 6). Measurements of open circuit voltages in the generator channel showed a decrease down the channel, contrary to the expected behaviour for subsonic flow; this is illustrated in figure 7. The open circuit voltages measured were considerably less than expected from simple generator theory ($V_{\text{o.c.}} = BUd$) and exhibited a saturation effect as the magnetic field strength was increased (figure 8).

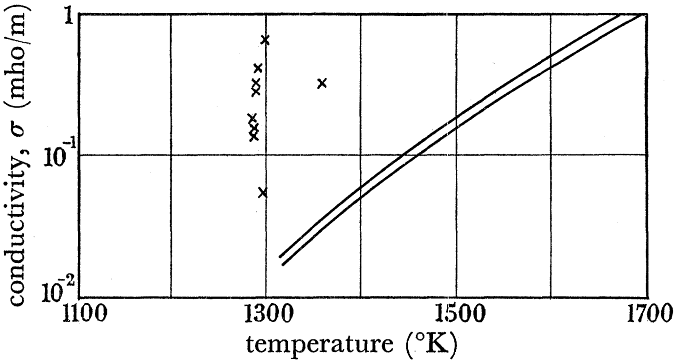


FIGURE 6. Theoretical (—) and measured (×) plasma electrical conductivities (14 July 1964).

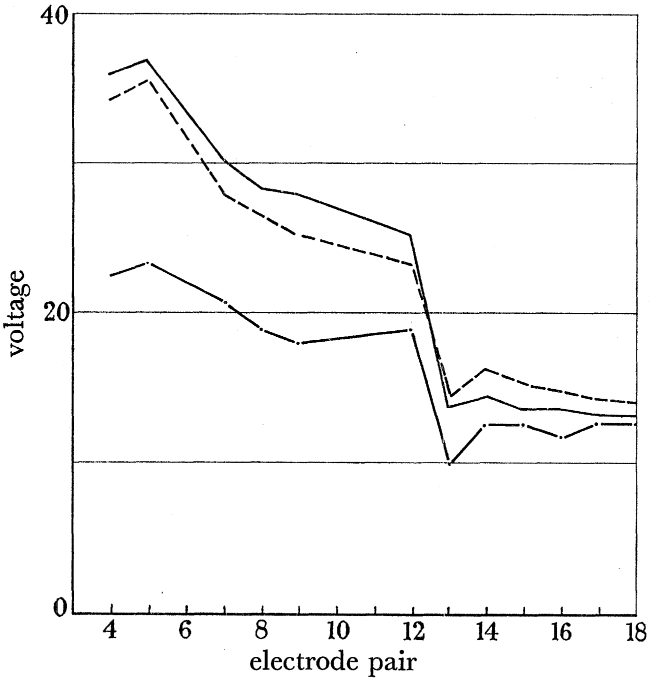


FIGURE 7. Open circuit voltage along m.p.d. generator duct length (14 July 1964).

A series of experiments were performed (7 September 1964) at different gas temperatures: the highest temperatures were 200 °C higher than those of earlier runs but at these temperatures considerable interelectrode leakage of current occurred so that the results

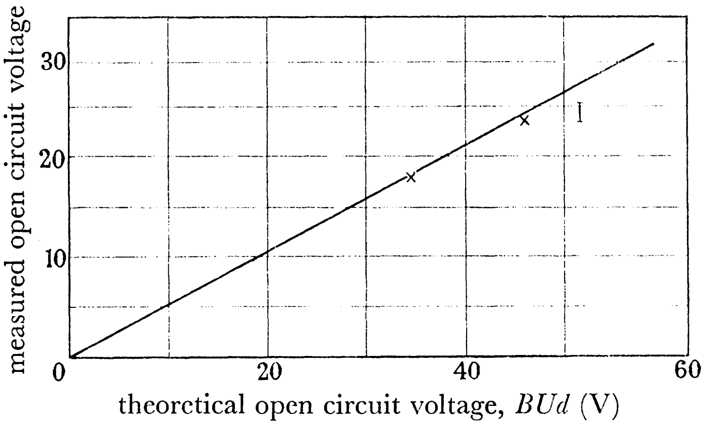


FIGURE 8. Open circuit voltage compared with theoretical value (14 July 1964).

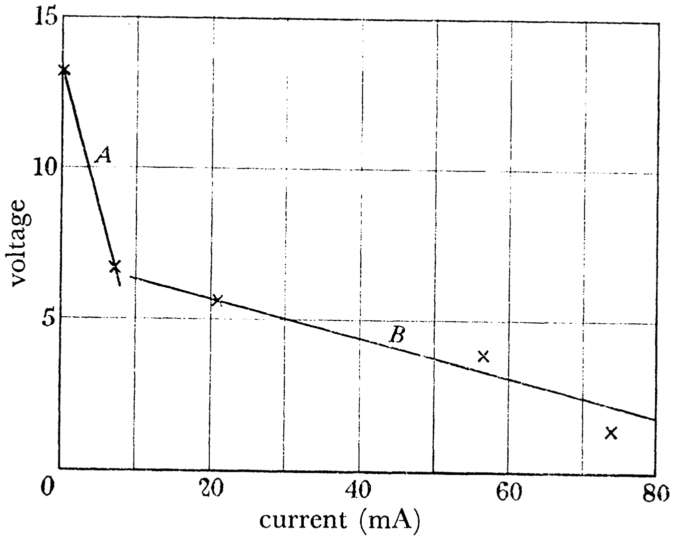


FIGURE 9. Voltage–current characteristic (7 September 1964).
From A, $\sigma = 0{\cdot}5$ mho/m; from B, $\sigma = 8{\cdot}0$ mho/m.

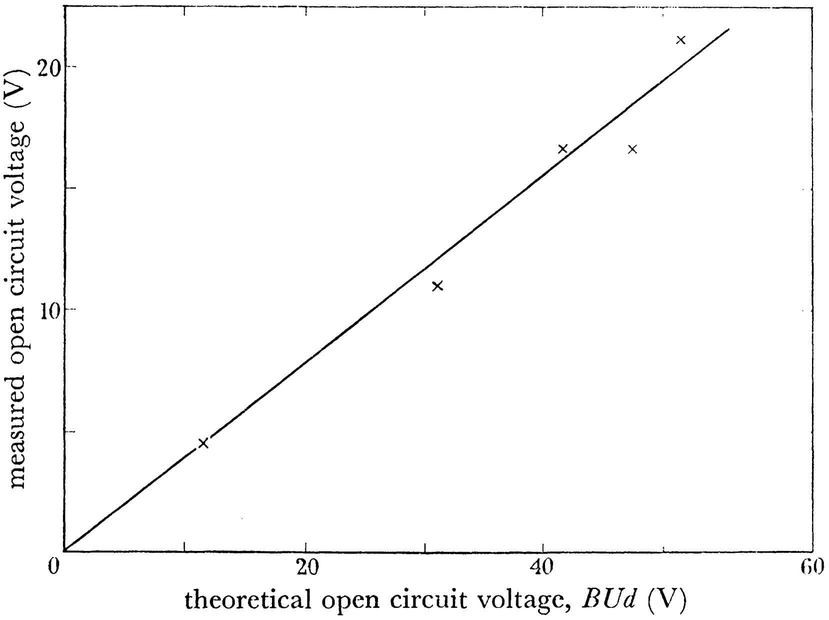


FIGURE 10. Open circuit voltage compared with theoretical value (7 September 1964).

were not reliable. Some twenty caesium-seeded runs were performed in all (McNab 1965). For most of these runs linear voltage–current curves were observed and the electrical conductivities derived from these curves were in fair agreement with theory for thermal equilibrium ionization: no non-equilibrium ionization was observed. In a number of cases non-linear voltage–current curves were observed, as shown in figure 9 (where the electrical conductivity increases to 8 mho/m); however, the recording instruments are least sensitive at low voltages so that these results are not certain. As in the previous experiments the measured open circuit voltages were considerably less than the theoretical values, although there was no saturation effect as the magnetic field strength was increased. Figure 10 shows that the observed open circuit voltage was about 0·4 *BUd* at magnetic field strengths between 0·2 and 1·0 T (the highest field available with the present magnet).

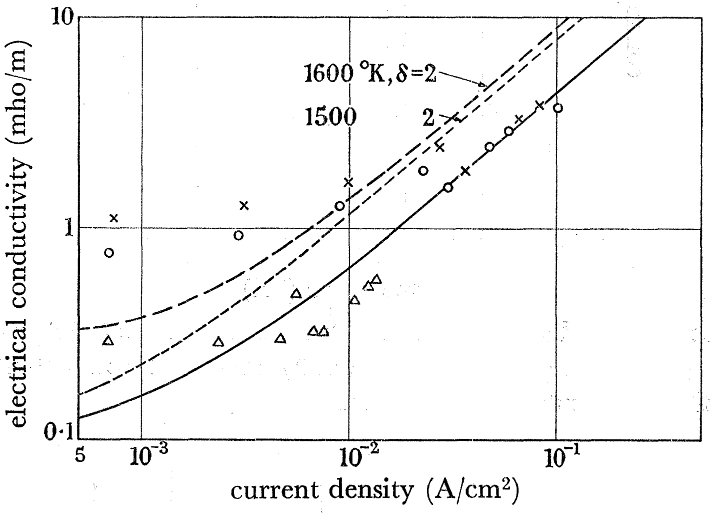


FIGURE 11. Experimental and theoretical variation with current density of plasma electrical conductivity (31 March 1965). △, run 2A (0·1 at. %); ○, run 3A (0·15 at. %); ×, run 4 (0·15 at. %). —, Kerrebrock theory for He. T_e = 1500 °K, p = 0·9 atm (a); x = 0·15 at. % Cs; δ = 8.

Two main difficulties made the results difficult to interpret and rather uncertain: efficient caesium recovery had not been achieved so that the seed injection period was limited to a very short time, during which the seed content varied rapidly; and at the highest temperatures of operation, highly conducting material layers were formed on the inner channel surfaces which partially shorted out the electrical output from the plasma. Improvements were made by modifying the caesium injection circuit to give smoother injection and through using alumina channels in place of the boron nitride. Following these modifications the loop was again operated (31 March 1965) (McNab & Brown 1965), with a single electrode pair in the alumina generator channel. The theoretical (allowing for protrusion of the electrodes into the gas stream) open circuit voltage was obtained and electrical conductivity measurements indicated in several cases that considerable magnetically induced non-equilibrium ionization was occurring. The derived electrical conductivities are shown in figure 11 compared with the simple theory of Kerrebrock (1961).

Seven electrode pairs were then operated in a new alumina generator channel (27 and 29 April 1965). Most of the voltage–current curves were linear and the derived electrical conductivities agreed with the theory for thermal equilibrium ionization (figure 12). The measured open circuit voltages had values of about 0·5BUd (figure 13). The magnetic field strength was varied between 0·23 and 1·05 T but the electrical conductivity decreased with increasing field rather than the reverse as expected from Kerrebrock's theory (figure 14). For the majority of these runs the seeding fraction was kept constant at between 0·1 and 0·2 at. %. However, during one run the seeding fraction was increased to more than 1·0 at. %. The electrical conductivity measured during this run was very much

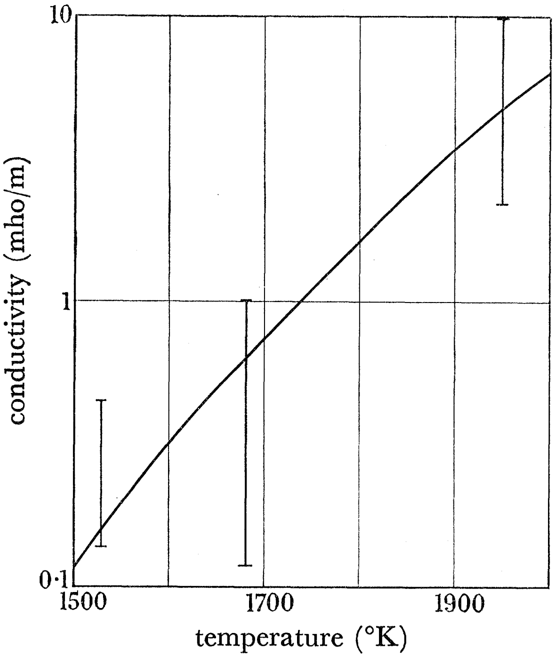


FIGURE 12. Plasma electrical conductivity as a function of temperature (29 April 1965). x = 0·15 at. %; p = 0·9 atm (a). I, ranges of experimentally measured conductivity. ——, Electrical conductivity for thermal equilibrium ionization.

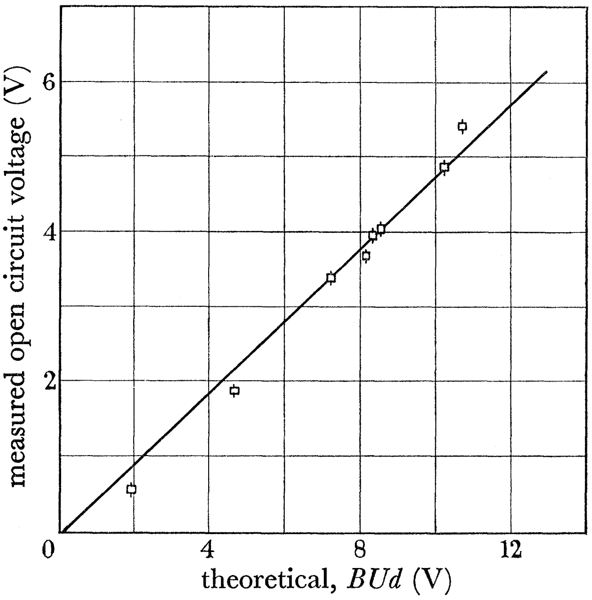


FIGURE 13. Open circuit voltage compared with theoretical value (29 April 1965).

higher and the variation agreed with the simple theory (whereby the electrical conductivity should vary approximately with the square root of the seeding fraction). The generated voltage–current curve for this run is shown in figure 15. At the highest seeding fraction the curve became slightly concave at high current densities, indicating some magnetically induced non-equilibrium ionization: the electrical conductivity at the highest point is 58 mho/m.

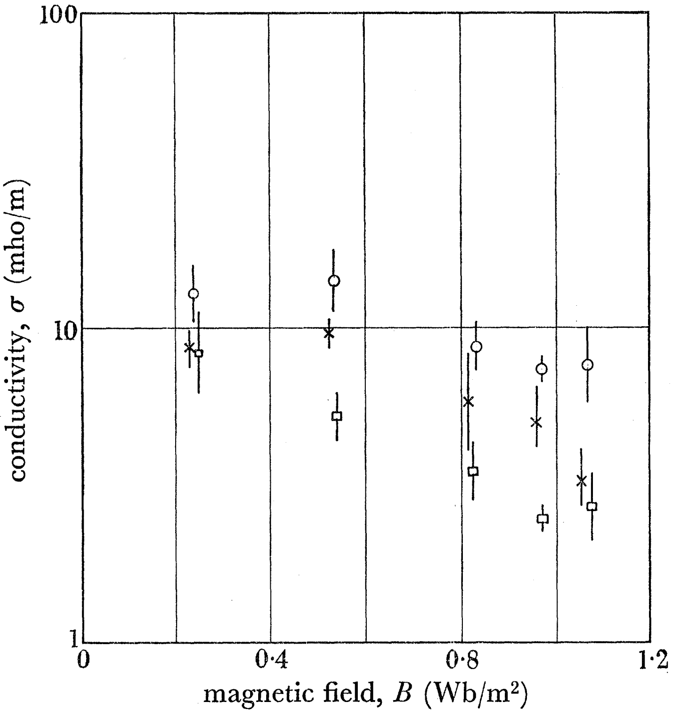


FIGURE 14. Plasma electrical conductivity as a function of magnetic field (29 April 1965).

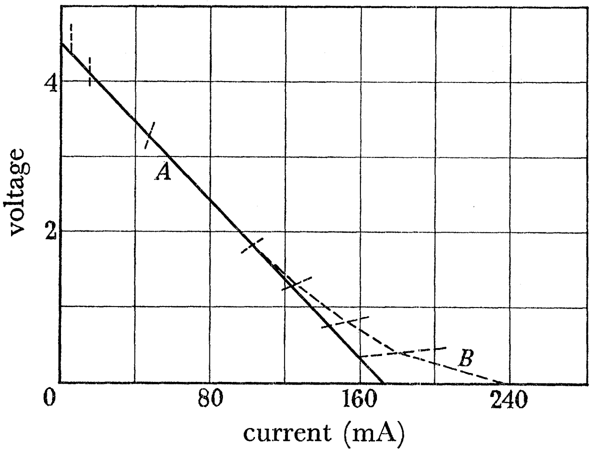
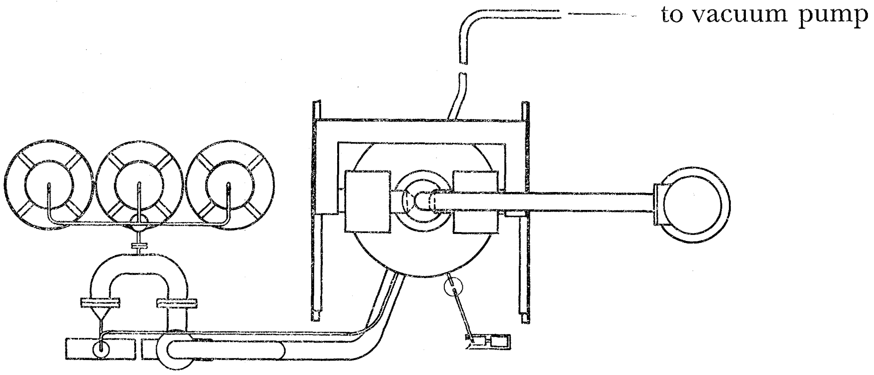


FIGURE 15. Voltage–current characteristic (29 April 1965). From A, σ = 16·5 mho/m; from B, σ = 58 mho/m.

To complement the experiments on static plasmas at A.E.R.E. a rig (figure 16 and figure 17, plate 20) has been designed to enable the elevation of electron temperature to be studied in the self-induced field of an actual m.p.d. generator. Argon from high pressure cylinders is heated to 1400 °K in passage through an alumina pebble bed storage heater.

The gas is then seeded with 1 at. % potassium vapour, accelerated to Mach 0·8 and passed through a generating section situated between the poles of an electromagnet capable of fields up to 1·8 T. The mass flow is 200 g/s, corresponding to a thermal rating of 300 kW. The m.p.d. generator duct size is $3\ \text{cm}\times 1\frac{1}{2}\ \text{cm}\times 20\ \text{cm}$ with sixty pairs of electrodes; the open circuit voltage is 23 V. The rig is now complete and the first seeded runs made at argon temperatures of about 1100 °C.



Plan view.

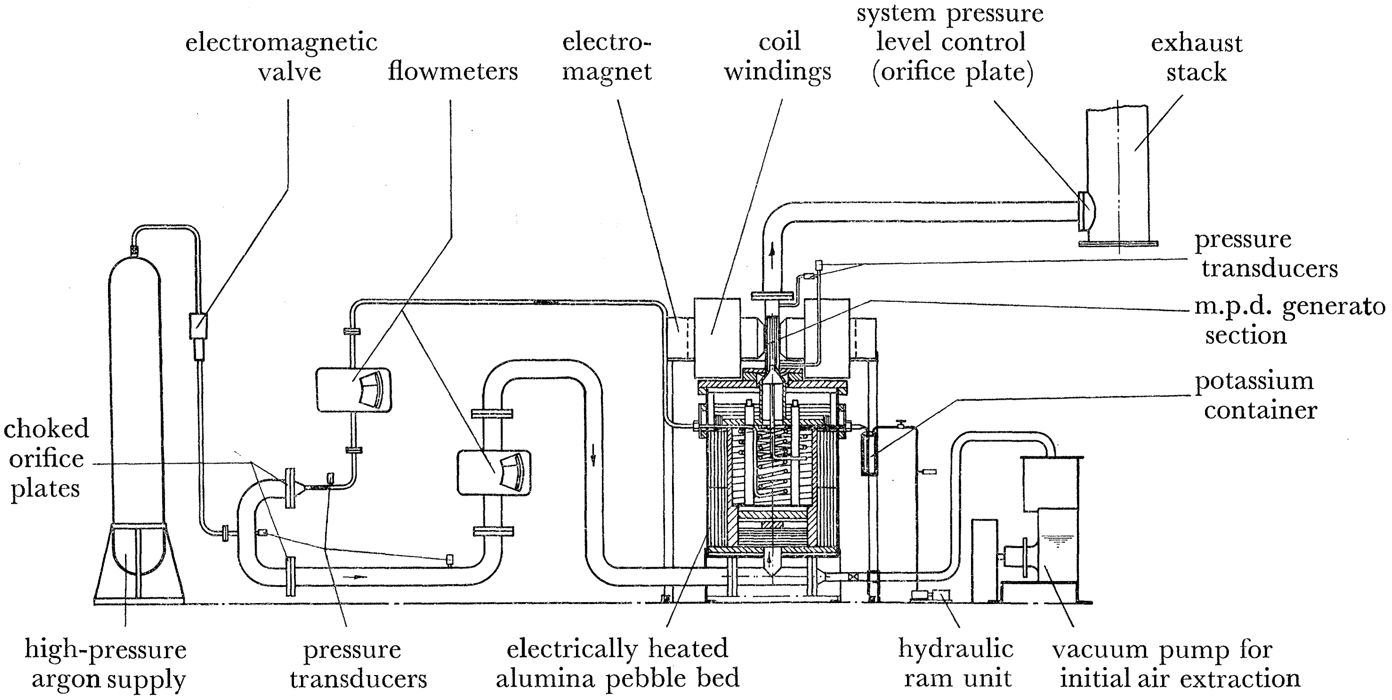


FIGURE 16. Expanded view of rig.

From the experiments discussed above there is now little doubt that electron temperature elevation *can* exist under the plasma conditions required for practical power-producing m.p.d. generators. When applied magnetic fields are employed the electron temperature elevation is much less than that predicted by the theory for applied electric field measurements. The factors affecting this discrepancy are not fully understood although electrode segmentation and the value of the Hall coefficient play an important part. Although the

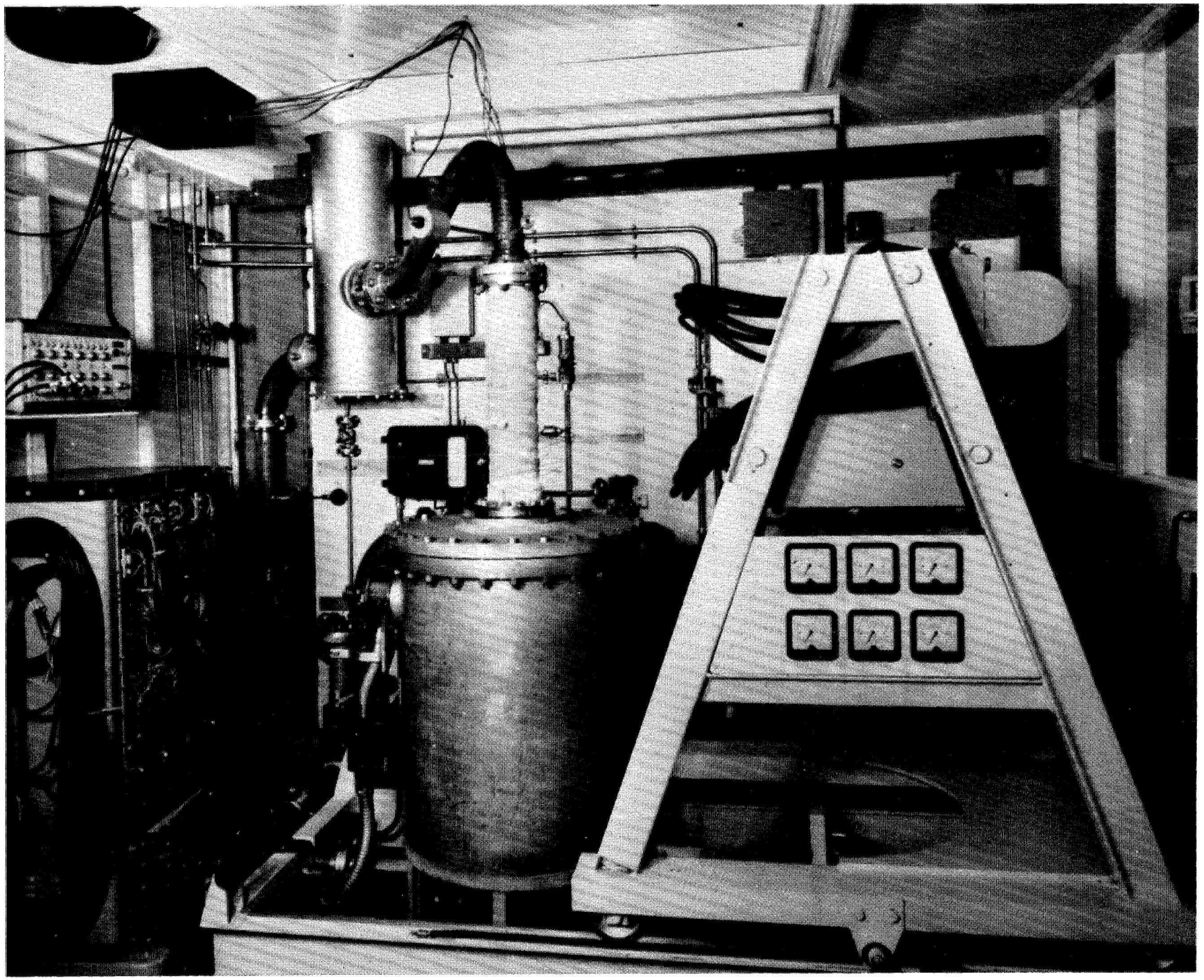


FIGURE 17. A.E.R.E. blow-down argon–potassium m.p.d. rig.

theory developed by Kerrebrock (1961) agrees with the trends observed in some experiments, much more experimental evidence is required before the theory can be considered proven.

3. M.P.D. SYSTEM STUDIES

3·1. *Nuclear reactor development*

For m.p.d. plant to become technically attractive it must be demonstrated that a suitable heat source can be constructed for the required levels of temperature. On thermodynamic grounds, if the addition of an m.p.d. stage is to be economically viable, the top temperature must be at least in the 1200 to 1500 °C range, eventually approaching 2000 °C with continuing development of the heat source. There is little doubt that nuclear fission reactors will form the basis of an ever-increasing proportion of new power plant installed in the United Kingdom. Consequently, the closed cycle m.p.d. system should receive attention in view of the long-term prospects for adoption of nuclear power on a very large scale in Britain. Since the British power reactor development programme has been based on gas-cooled systems it is logical that this general class of reactors should be further developed for higher temperatures and thermodynamic efficiencies. The U.K.A.E.A. reactor programme, although not specifically directed towards m.p.d. power generation, is broad enough for much of the existing research and development programme on materials and other aspects to be applicable; extension, where this appears to be necessary, can readily be accomplished.

TABLE 3. GRAPHITE-MODERATED GAS-COOLED REACTORS

reactor	t (MW)	coolant	coolant outlet temp. temp. (°C)	coolant pressure (Lb./in^2(a))	start-up date
Calder A and B	360	CO_2	330	100	1956/58
AGR (Windscale)	100	CO_2	575	285	1962
EGCR	85	He	566	315	1963
Dragon	20	He	750	280	1964
HTGR (Peach Bottom)	115	He	750	350	1965
AVR (Julich)	9	He	850	150	1966
UHTREX	3	He	1300	500	1964
Nerva NRX-A3	1100	H_2	2000	620	1964

Table 3 gives some typical values of coolant temperatures showing the general temperature enhancement over the past decade. The most likely reactor for use with a closed cycle m.p.d. generator is a helium-cooled dispersed fuel graphite-moderated system. Although the required increase in temperature from current designs to the level dictated by m.p.d. generation is substantial the general development of the AGR programme, initially for improved steam conditions and later for possible use with a gas turbine, will provide data on both technical and economic problems associated with operation at high temperature. Extension of the OECD Dragon project will also provide relevant experience. In this programme carbide nuclear fuels in the form of dispersed coated particles have been operated in the 1800 to 1900 °C region. The fuel element in the Dragon experimental reactor is thermally inefficient, its design having been dictated mainly on safety considerations. However, by adopting a configuration which provides only a very short heat conduction path to the heat transfer surface the coolant outlet temperature can much more nearly approach the maximum fuel temperature.

With available information it is difficult to give a realistic time-scale for the development of a high-temperature reactor but it is unlikely, with an acceptable rate of investment, that a suitable design could be developed and built before 1980. In a complete nuclear m.p.d. plant capital costs additional to those of a conventional system are likely to be incurred in respect of: high temperature ducting from the reactor to the generator; m.p.d. generator duct; superconducting magnet and associated cryogenic equipment; inverter to convert the d.c. output of the m.p.d. generator to a.c.; seed injector, extractor and circulator; fission gas clean-up plant; and high-pressure ratio compressor. In addition, the capital cost of the reactor may be considerably more than in current practice if a reduced coolant pressure (*q.v.*), and hence reduced core rating, proves necessary; alternatively, the cost of a heat exchanger might be included if the indirect nuclear cycle (figure 1(*b*)) proves attractive. Against these factors must be set an increase in over-all efficiency from about 45% which will be achieved in conventional plant to 55% or higher in m.p.d. plant. The increase in efficiency represents a very substantial improvement over conventional plant, but much more work is necessary before such a system can be demonstrated to be economically viable.

3·2. *Fired heat exchanger*

The indirect fired system offers an alternative to the nuclear system (figure 1(*c*)). Temperatures approaching 2000 °C can be achieved in burning fossil fuels with atmospheric air so that, if the closed cycle m.p.d. generator can be shown to work at moderate temperatures, the air preheat and/or oxygen enrichment essential for the direct open cycle generator becomes unnecessary. The requirement would then be for a heat exchanger operating with maximum material temperatures in the region of 1400 to 1800 °C. This unit could be of a balanced pressure design with the closed cycle working fluid at a few atmospheres pressure on one side of the heat exchange surfaces and combustion gases at approximately the same pressure on the other side. The surfaces in contact with combustion gases would probably be of a ceramic material with an impermeable barrier to the closed cycle fluid. Although such a heat exchanger presents many technical problems these are undoubtedly less severe than in some forms of air preheater for an open cycle system.

3·3. *M.p.d. generator specific power output*

To achieve an acceptable capital cost and size of the m.p.d. generator the specific power should be greater than about 10 MW/m^3. Calculations have been carried out at A.E.R.E. for both argon and helium as the working fluid and with either potassium or caesium as the seed material (Rice 1965). Total head temperatures at nozzle inlet of 1600 and 1875 °K have been assumed with isentropic expansion at a range of Mach numbers. Specific powers are shown as a function of seeding ratio in figures 18 to 20.

It is observed that for argon–potassium there exists an optimum seed ratio of about 7×10^{-5} to 10^{-4}, under non-equilibrium conditions. With argon–caesium the specific power is less than with potassium; for example, at $T = 1600$ °K, $p = 20$ atm (a), $B = 8\,T$ and $M = 0\cdot8$ the specific power is reduced from 50 to 34 MW/m^3. The optimum seed ratio remains at 7×10^{-5}. From figure 20, for helium–potassium, it is seen that the specific power is considerably less than for argon as the working fluid (with certain assumptions about the collision cross-section), and that the optimum seeding ratio varies considerably along the generator duct. This is a result of ion slip and introduces a performance limitation. The low value of the optimum seed ratio compared with that for thermal ionization should be noted; this results from the dependence of electron temperature on the seed ratio and is supported experimentally by Ellington (1965*a*, *b*, *c*).

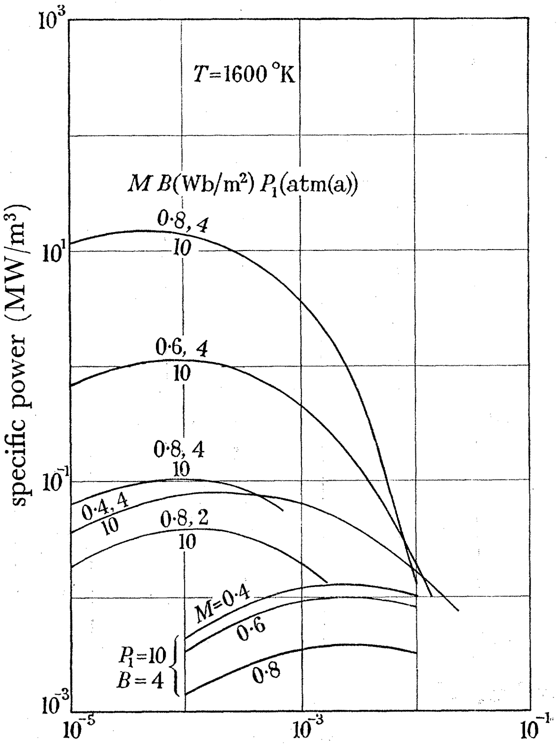


FIGURE 18

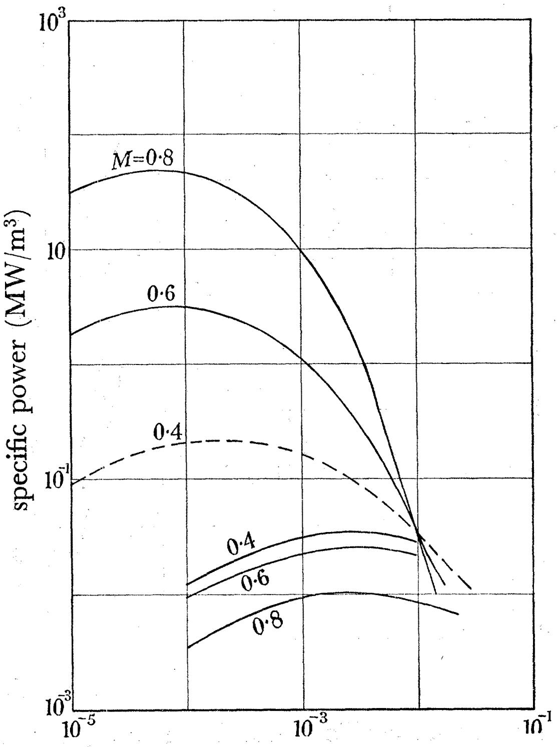


FIGURE 19

FIGURE 18. Specific power of m.p.d. generator as a function of seed ratio (argon–potassium). The bottom three curves refer to thermal equilibrium ionization.

FIGURE 19. Specific power of m.p.d. generator as a function of seed ratio (argon–potassium). The bottom three curves refer to thermal equilibrium ionization. $B = 8$ Wb/m²; $T_1 = 1600$ °K; $P_1 = 20$ atm (a).

If a nuclear direct cycle is employed, selection of operating pressure level presents a problem: the reactor should operate at as high a pressure (typically 10 to 40 atm (a)) as is technically and economically feasible to give good heat transfer for a permissible pressure loss and pumping power, whereas the m.p.d. generator benefits in plasma electrical conductivity by operation at low pressures (1 atm (a) or less). For thermal ionization, at a given seed ratio, the plasma electrical conductivity, σ, varies approximately as $p^{-\frac{1}{2}}$ over the temperature range of interest (< 2500 °K); with magnetically induced ionization, over appropriate ranges of parameters, σ varies very approximately at p^{-4}.

In optimizing specific power the usual procedure is to maximize σu^2 (u is the plasma flow velocity) assuming thermal ionization conditions; subsonic Mach numbers (about 0·5 for helium–caesium) result. With magnetically induced ionization the ratio of electron to gas temperature (which governs the non-equilibrium electrical conductivity) is controlled by the Hall number, $\beta \propto B/p$. The restriction on flow velocity, imposed by thermal ionization at low static temperatures and high Mach numbers, no longer applies and there is the possibility of operating supersonically at high specific power. In this case the expansion pressure ratio in the accelerating nozzle will be high, so that the reactor operates at a

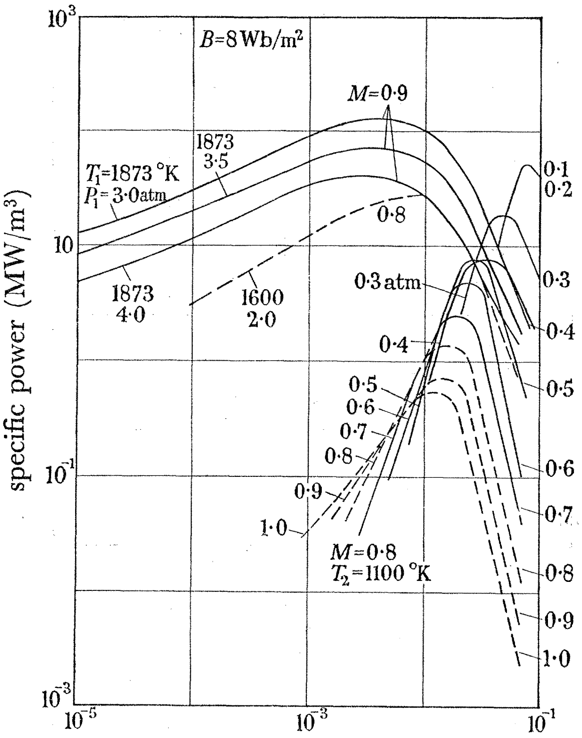


FIGURE 20. Specific power for m.p.d. generator as a function of seed ratio (helium–potassium).

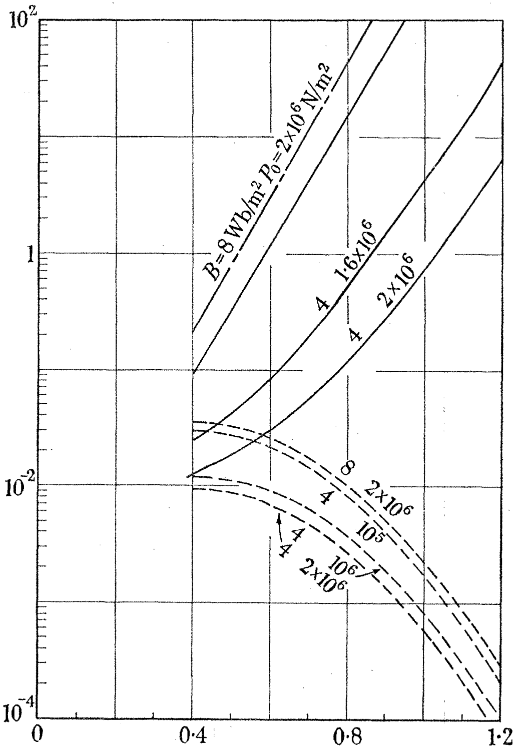


FIGURE 21. Specific power as a function of Mach number for optimized seed fraction (argon–potassium).

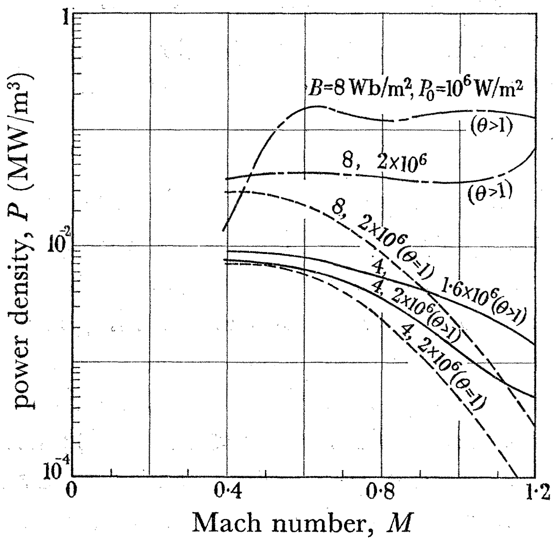


FIGURE 22. Specific power as a function of Mach number for fixed seed fraction (argon–potassium). - - -, Thermal (i.e. $\theta = 1$); $K = 0{\cdot}8$; $T_0 = 1600$ °K; $I = 0{\cdot}01$.

much higher pressure level than the m.p.d. duct; minimum diffuser loss and a high diffuser efficiency are essential.

The variation of specific power with Mach number for optimized seed fraction of potassium in argon at a total heat temperature of 1600 °K is shown in figure 21. Consideration of results at a seed fraction other than the optimum is indicated by comparison of figures 21 and 22 which is for a seed fraction of 0·01. Figures 23 and 24 indicate the

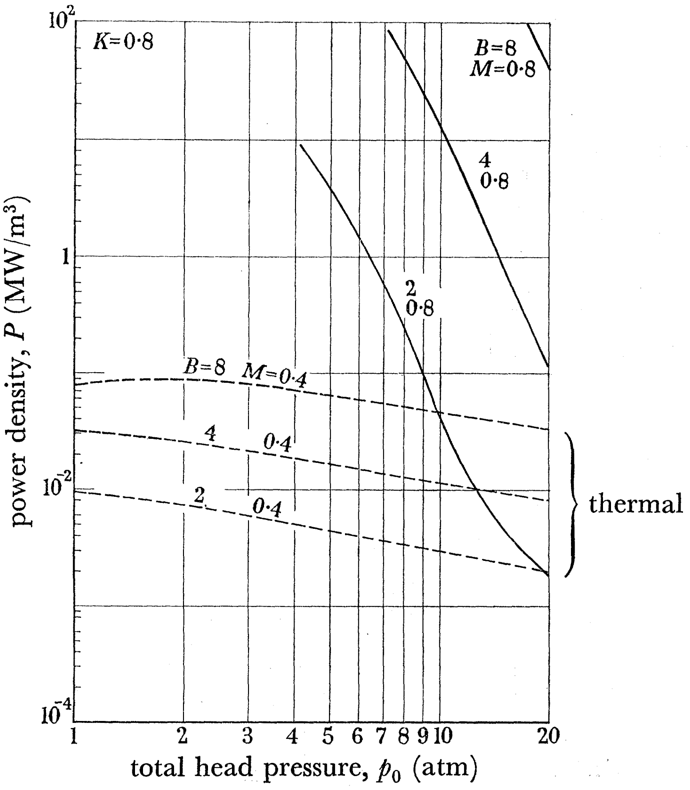


FIGURE 23

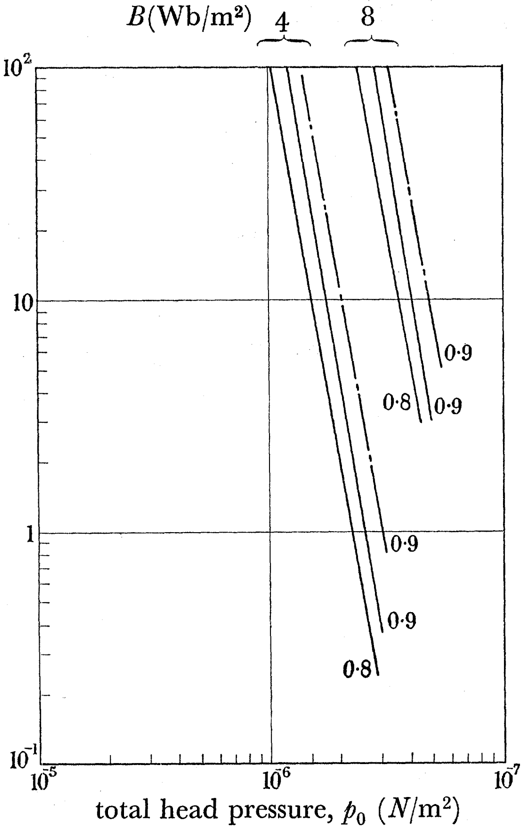


FIGURE 24

FIGURE 23. Specific power as a function of pressure (argon–potassium; optimized seed fraction, $M \leqslant 0{\cdot}8$; $T_0 = 1600$ °K), - - -, thermal.

FIGURE 24. Specific power as a function of pressure (argon–potassium; optimized seed fraction; $T_0 = 1873$ °K (—) and 2000 °K (- - -)).

TABLE 4.

temperature (total head) T (°K)	magnetic field, (T)	Mach number, M	pressure (total head) p (atm (a))	specific power (MW/m^3)
		m.p.d. generator inlet conditions		
1600	4	0·8	10	15
1873	4	0·9	20	5
1873	8	0·9	49	4
1873	8	0·9	40	12
1873	8	0·9	32	53
		m.p.d. generator exit conditions		
1100	4	0·8	4	17
1100	8	0·9	10	28

variation of specific power with total head pressure for argon–potassium with optimized seed fraction and total head temperatures of 1600, 1800 and 2000 °K. Comparison with thermal ionization conditions indicates the order of increase with non-equilibrium ionization, until at some high pressure the levels converge. The importance of attaining high magnetic fields is apparent since high specific powers are then feasible at even high reactor operating pressures. Some data for argon–potassium and a range of inlet pressure are given in table 4; the seeding ratio is 7×10^{-5} throughout.

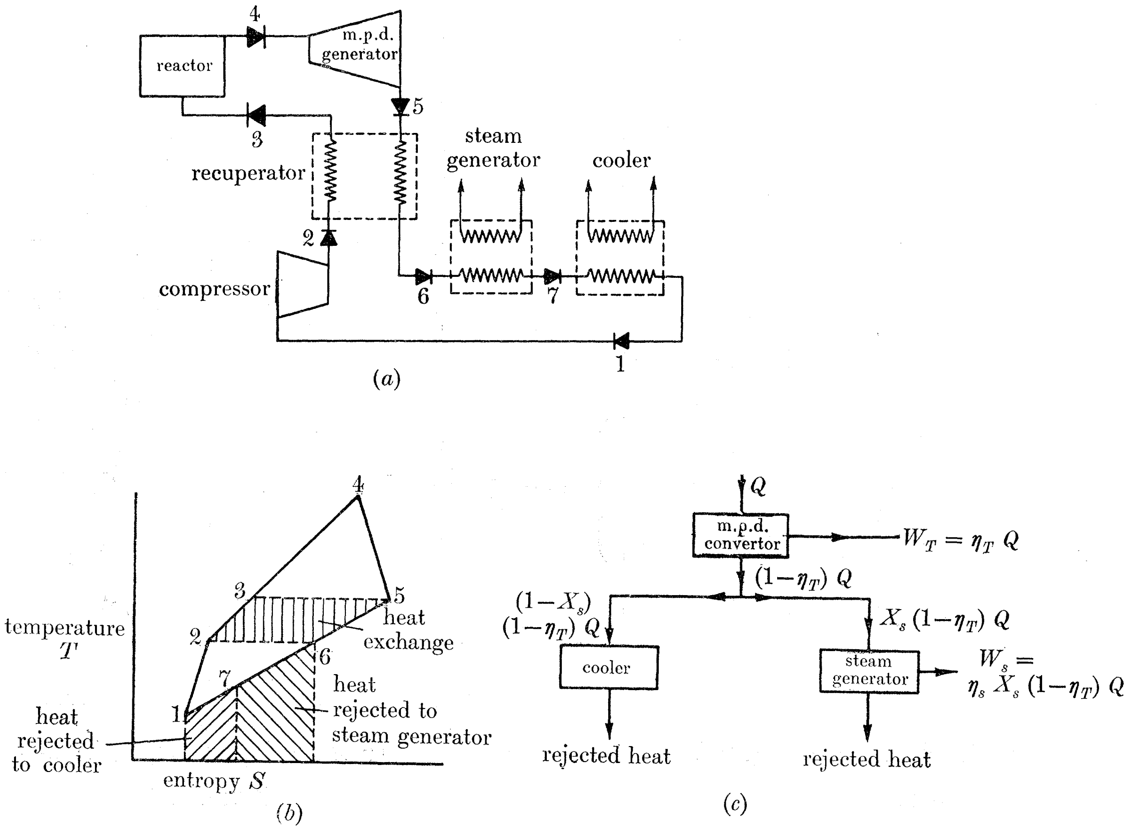


FIGURE 25. Brayton m.p.d. cycle with recuperator and steam operator: (*a*) plant components; (*b*) temperature-entropy diagram; (*c*) heat balance.

$$\text{Cycle efficiency} = \eta_T = \frac{\text{net work done}}{\text{heat supplied}} = \frac{(T_4 - T_s) - (T_2 - T_1)}{T_4 - T_3},$$

or

$$\eta_T = \frac{\eta_G T_4 (1 - 1/Z) - T_{1/\eta_c}(Z - 1)}{T_4[1 - R + R\eta_G(1 - 1/Z)] - T_1[1 + (Z-1)/\eta_c](1 - R)},$$

where R = recuperator thermal ratio $= \dfrac{T_3 - T_2}{T_5 - T_2} = \dfrac{T_5 - T_6}{T_5 - T_2}$;

$Z = (\gamma - 1)/\gamma$, where γ = pressure ratio;

η_G = m.p.d. generator isentropic efficiency;

η_c = compressor isentropic efficiency;

X_s = fraction of heat rejected from m.h.d. convertor that goes into steam generation, i.e.

$$X_s = (T_6 - T_7)/(T_6 - T_1);$$

η_T = m.p.d. convertor efficiency (including recuperator);

η_s = steam plant efficiency.

3·4. *Over-all cycle performance*

In studies of thermodynamic performance by Parsons & Rice (1965) and Rice (1965) of A.E.R.E., maximum temperatures in the cycle have been assumed to be limited by reactor considerations; two cases of 1300 and 1600 °C have been considered with a heat rejection temperature between 40 and 50 °C. Within this range the thermodynamic variables may be adjusted for optimum performance, a further restriction being set by the need to achieve acceptable specific power output in the m.p.d. generator.

A combined Brayton/Rankine cycle (figure 25) has been considered, incorporating a recuperator and feed heating on the steam side. The over-all efficiency can be expressed as

$$\eta = \frac{W_T+W_S}{Q} = \frac{\eta_T Q + X_s Q \eta_s (1-\eta_T)}{Q},$$

where W_T and W_s are respectively the useful work output of the m.p.d. generator and steam cycle, η_T and η_s are the corresponding efficiencies and Q is the heat input. The factor X_s (figure 25) takes account of the heat bypass through the recuperator.

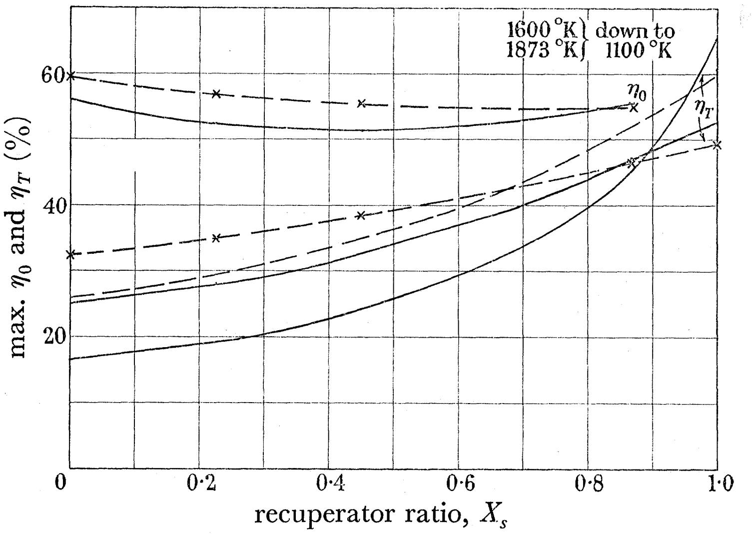


FIGURE 26. Over-all efficiency and m.p.d. generator efficiency as a function of recuperator ratio.

A counterflow single pressure steam raising unit with a pinch point difference in temperature of 20 to 30 °F is assumed. It may be noted that over-all cycle efficiency is insensitive to the recuperator ratio (figure 26) and that, although feed water heating improves the efficiency of the steam cycle, the required elevation of the exit gas temperature effects a reduction in the over-all cycle efficiency. With no recuperator the over-all plant efficiency (assuming superheat and double reheat) is 56% which should be compared with a plant incorporating seven feed heaters and a recuperator but without the m.p.d. stage which would give an over-all efficiency of 52%.

3·5. *Scale effect*

Scale effects have been considered by several workers (for example, by Lindley (1963)) with the general conclusion that m.p.d. generators always benefit by an increase in scale and may, indeed, offer the only means at present foreseeable for producing outputs of several thousand megawatts from a single unit (if this were needed). It has also been concluded, especially for fired systems with water-cooled combustion chamber and m.p.d. generator construction, that there is a minimum size (ranging from tens to hundreds of megawatts, output, depending upon the detailed assumptions) below which m.p.d. generators could not produce a net output.

However, it is becoming apparent that closed cycle m.p.d. systems could be technically feasible for much smaller sizes (perhaps in the few hundred kilowatt range of output) (McNab 1964*a*). This is because the low temperature and compatible working fluid allows critical sections of the system to be operated at or near the plasma temperature (thus reducing the heat loss) and because the specific power can be extremely high (thereby reducing friction losses). Systems work has already started in the United States.

Discussion and conclusions

It is apparent from the foregoing review that the closed cycle m.p.d. system offers many technical advantages over the direct fired open cycle m.p.d. generator. The various cycle concepts (direct and indirect nuclear, indirect fired and modifications of these) would allow both fissile and fossil fuels to be utilized as the energy source.

Especially important in closed cycle m.p.d. systems is the feasibility of non-equilibrium ionization so that the electrical conductivity in the m.p.d. generator is not set by thermal ionization at the gas temperature. A number of techniques for inducing extra-thermal ionization have been suggested, some of which have been tried experimentally; the most attractive appears to be based on elevation of the electron temperature in the magnetically induced electric field of the generator itself. It is possible that the maximum temperature in the cycle (at reactor outlet in a nuclear system) can be reduced to 1300–1600 °C (that is, to a level dictated on thermodynamic grounds) by employing this technique. There remains an incentive to further increase the temperature to 2000 °C or higher, depending ultimately on system economics.

Technically, it appears feasible to design and construct high temperature reactors to give the required gas coolant outlet temperatures. Such a reactor may be helium-cooled, graphite-moderated and employ dispersed carbide fuel elements. There is already operating experience at temperatures in the 1700 to 1800 °C range with this type of fuel in the O.E.C.D. Dragon reactor programme.

Of the indirect fired systems, it may be said that certain problems are much reduced in comparison with the direct open-cycle system. In particular, combustion of fossil fuels with atmospheric air is adequate to produce the required temperature, the combustion gases do not have to be seeded (thereby eliminating some materials problems and the need for seed recovery), and fouling is restricted to the combustion chamber and heat exchanger. The heat exchanger to transfer heat from combustion gases to closed cycle working fluid is technically formidable, but perhaps less so than an air heater to give the ideal preheat temperature in an open cycle system.

Small scale closed cycle m.p.d. generators (upwards of a few hundred kilowatt electrical output) may be technically feasible for certain specialized applications (either nuclear or indirect fired). It could be expected that the fired system would be capable of development in a relatively short time scale (4 to 7 years).

In considering the engineering development of large scale commercial closed cycle systems technical advances over the last 5 years (1960 to 1965) should be noted. Relatively little effort and expenditure has been devoted to closed cycle m.p.d. experiments but many aspects of the technology of a full scale system have been explored (the I.R.D. loop has operated for many hundreds of hours at gas temperatures up to 2200 °C) and some evidence for magnetically induced non-equilibrium ionization has been established in small generator channels. Similarly, nuclear reactor technology has advanced significantly and several experimental reactors, either operating or in course of construction, show that conditions in the range appropriate for m.p.d. power are potentially achievable. Given an increased level of support and effort there appears no obstacle to establishing full engineering capability to construct a nuclear m.p.d. system by about 1980, provided that the economic incentive can be proven.

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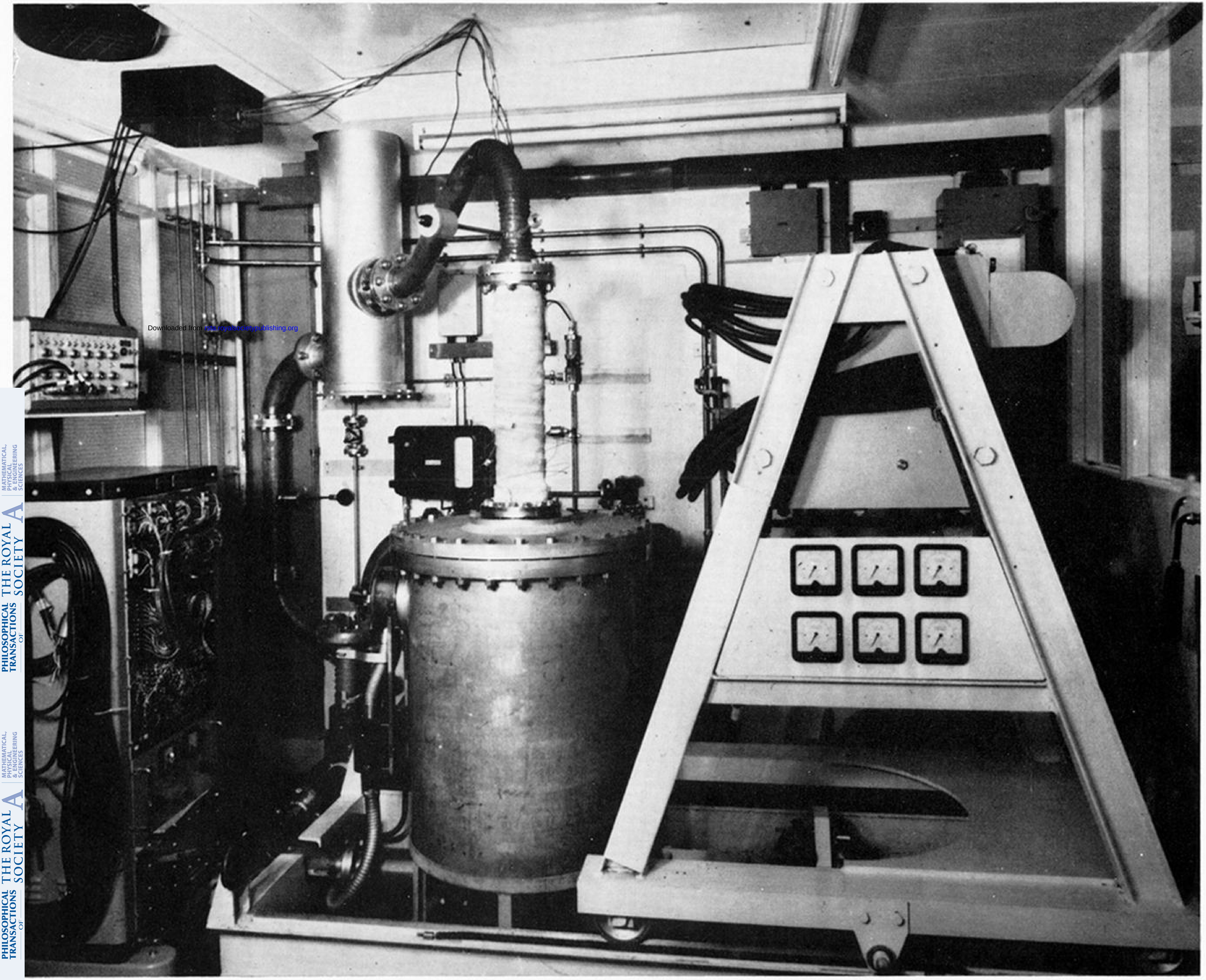

FIGURE 17. A.E.R.E. blow-down argon–potassium m.p.d. rig.