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Recent Progress in the Development of Combustion Fired M.H.D. Generators

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II. Recent progress in the development of combustion fired m.h.d. generators

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[Plates 18 and 19]

This paper reports on some recent progress in the development of the large combustion fired m.h.d. generator with particular emphasis on commercial central station application.

The segmented electrode Faraday configuration m.h.d. generator is highly efficient but has the disadvantage of delivering its output in a multiplicity of loads each of which floats at a different potential. For this reason our recent work in m.h.d. generator fluid mechanics and long duration channel development has been concentrated on examination of the high voltage two-terminal Hall configuration, and this work will be described.

The chemistry and economics of seeding must be carefully evaluated in order to assess the potential of m.h.d. and the paper will describe recent work which has demonstrated the feasibility of efficient low cost seed recovery employing vapour phase separation.

Superconducting field coils appear to be essential for commercial m.h.d. power generation and the 'stabilized' principle of constructing such coils will be described. Using this principle it is possible to operate a large coil on the *H–I* curve of a short sample of wire. This development reduces the construction of large superconducting coils to an engineering problem.

Introduction

The unique feature of the m.h.d. generator is its ability to utilize a very high temperature, high energy, heat source. This advantage derives from the fact that the m.h.d. process occurs in the volume. The m.h.d. channel may be cooled and can operate at temperatures well below that of the working fluid, so that, in principle, a working fluid at any temperature may be employed. Thus the attractiveness of the m.h.d. generator derives from the fact that the materials of construction of the m.h.d. channel need not be operated at or near the temperature of the working fluid.

With combustion gas working fluid, the basic advantage of the m.h.d. process extends to the heat source as well, since the combustion chamber may be cooled and thus operated at temperatures low compared to the flame temperature. It might be noted here that this advantage is shared with some other systems which have been proposed, notably those employing gaseous core nuclear reactors as the heat source (Rosa 1962). The large heat fluxes associated with m.h.d. generators of attractive size are easily produced by highly developed combustion technology. A further advantage derived from this latter point is that the ease with which large heat flux can be produced with combustion systems has made it possible to construct experimental combustion driven m.h.d. generators of interesting size with reasonable effort and expense.

It is for these reasons that the development of the combustion fired m.h.d. generator has proceeded faster than those systems employing other heat sources. The main objective of the development has been to overcome certain disadvantages with combustion gases in particular, such as chemical reactivity, low electrical conductivity necessitating high magnetic field, and the problems associated with seeding and corrosion in commercial systems. This paper is concerned with the review of recent events in this development.

Self-excited m.h.d. generator performance

The m.h.d. generator is ideally suited to the production of large amounts of power in a single unit. For certain situations requiring a large amount of power for a limited duration, the m.h.d. generator can fulfil the requirements with simple and inexpensive equipment. In this application a rocket engine is fed with combustibles which are stored in advance and the combustion products are ducted into the m.h.d. channel where power is extracted. The magnet may be either self-excited or separately excited. The exhaust products are discharged directly to the atmosphere. This method of power generation is suited for limited durations because of the relatively high cost fuel and oxidizer which is employed.

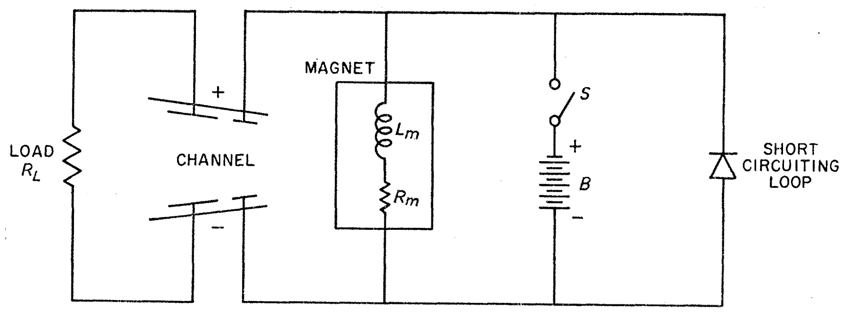

Figure 1. Electrical circuit of the self-excited m.h.d. power generator.

Beginning in early 1962, a programme was inaugurated to design, develop, and test a prototype self-excited, rocket-driven m.h.d. generator (Mattsson *et al.* 1965). An electrical schematic of the generator, which is called the mark V, is shown in figure 1. The m.h.d. channel is split into two parts. The output of the upstream portion is extracted on a single electrode pair and is used to drive the room temperature heat sink copper field coil for the generator. Downstream of the self-excitation section are fifty separate segmented electrode pairs, each connected to its own load. Water cooled insulating walls are employed (Novack & Brogan 1963).

Operation of the generator is as follows. Before ignition of the burner, the battery bank excites the magnet to a low value of magnetic field. At this point the burner is ignited, and the batteries and m.h.d. channel drive the field coil in parallel. As the field builds up the generator output voltage exceeds the open circuit voltage of the battery bank. The battery bank is then disconnected, and the field continues to build up to its design value. At the same time power is extracted in the load resistors. On shutdown the combustion is extinguished and the magnet discharges through the short circuiting loop.

A photograph of the completed mark V generator is shown in figure 2, plate 18. The combustion chamber burning a mixture of gaseous oxygen and hydrocarbon or alcohol is at the left. Potassium hydroxide seeding is employed. The 35 kG air core electromagnet constructed of uncooled copper conductor is contained by the steel beams and houses the m.h.d. channel. Magnet heating limits run time to approximately 3 min. The wires above the magnet carry the output power to the loads and the exhaust duct on the right conveys the spent combustion products to the atmosphere.

The observed net and gross power output of the mark V generator as a function of magnet current (current from upstream portion of channel) is shown in figure 3, for a flow 51 kg/s, 85% of the design value. The maximum net output is achieved at a magnet current of 15 kA. The maximum net output is 23·6 MW. The maximum gross output is 31·3 MW. Thus at maximum net output the field coil dissipation is 7·7 MW. The maximum net output is nearly 20% in excess of the design value of 20 MW while the field coil dissipation is less than half the design value, and this occurs at only 85% of the design flow. The reason that the actual performance exceeded the design performance is due to the fact that during operation of the generator it was found that the optimum operating point corresponds to a high supersonic Mach number near 2 in the power section of the channel. The design flow Mach number had been low supersonic, that is below 1·25. The increased flow speed as compared with the design value made it possible to offset the decreased conductivity due to lower temperature at higher speed, while simultaneously utilizing a lower value of magnetic field than the design value and a lower mass flow.

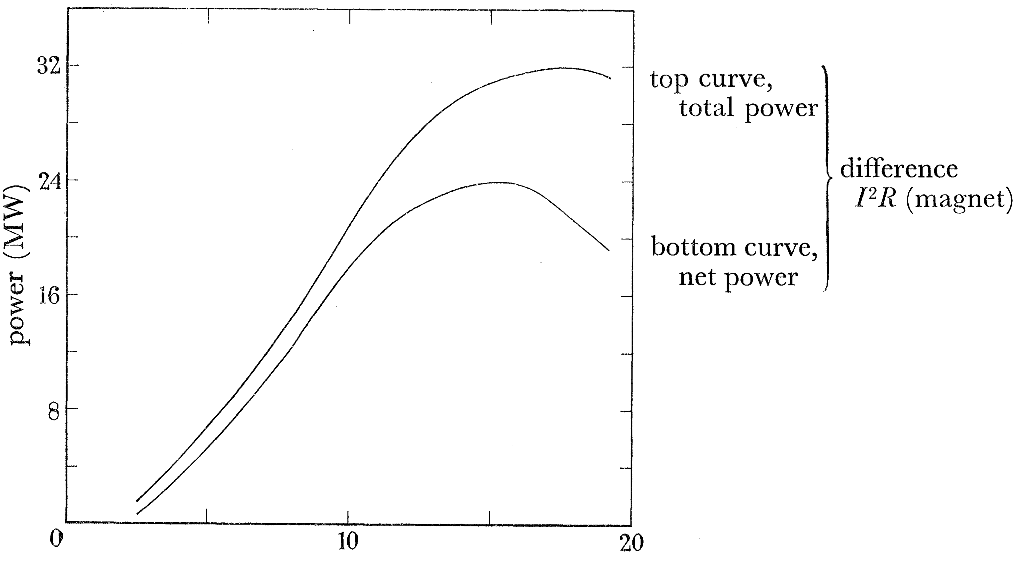

FIGURE 3. Net and gross power output of the mark V generator as a function of magnet current. (Test no. 56; m = 115 lb./s; η = 2% K feed.)

The performance of the mark V generator is a demonstration that such a generator can extract large amounts of energy from a rocket engine. It is also a demonstration that these generators can be designed for a specific load which, in the case of the mark V, was the field coil. Finally, the improved performance as compared with the design is an indication that progress is the development of m.h.d. generators is just beginning.

HALL CONFIGURATION M.H.D. GENERATORS

While the segmented electrode Faraday generator is the most efficient m.h.d. configuration and its operation is well understood (Louis, Lothrop & Brogan 1964) the multiplicity of outputs is practically an inconvenience, since it leads to a large number of load circuits all floating at a different potential. It should also be mentioned that the fact that there is both a transverse and a longitudinal electric field with the segmented electrode Faraday

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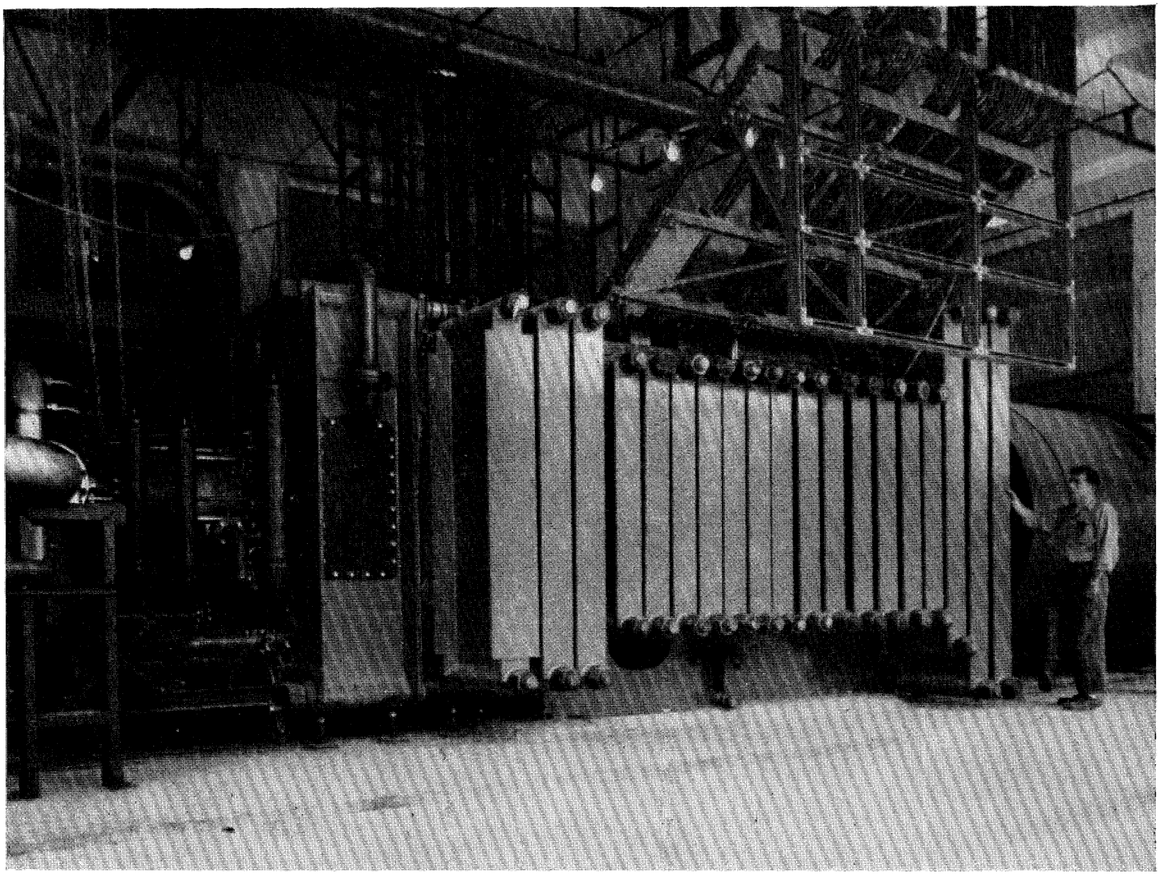

FIGURE 2. The 20 MW (net electrical) mark V rocket-driven self-excited m.h.d. power generator.

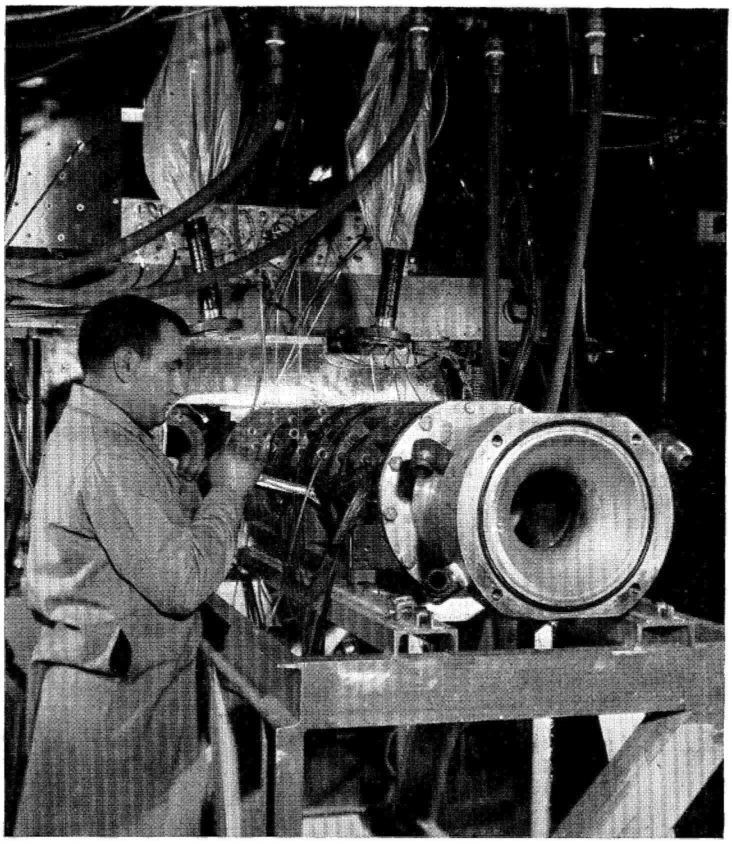

FIGURE 4. Circular Hall channel, Mach 2.1 nozzle and combustion chamber for mark II experimental m.h.d. generator.

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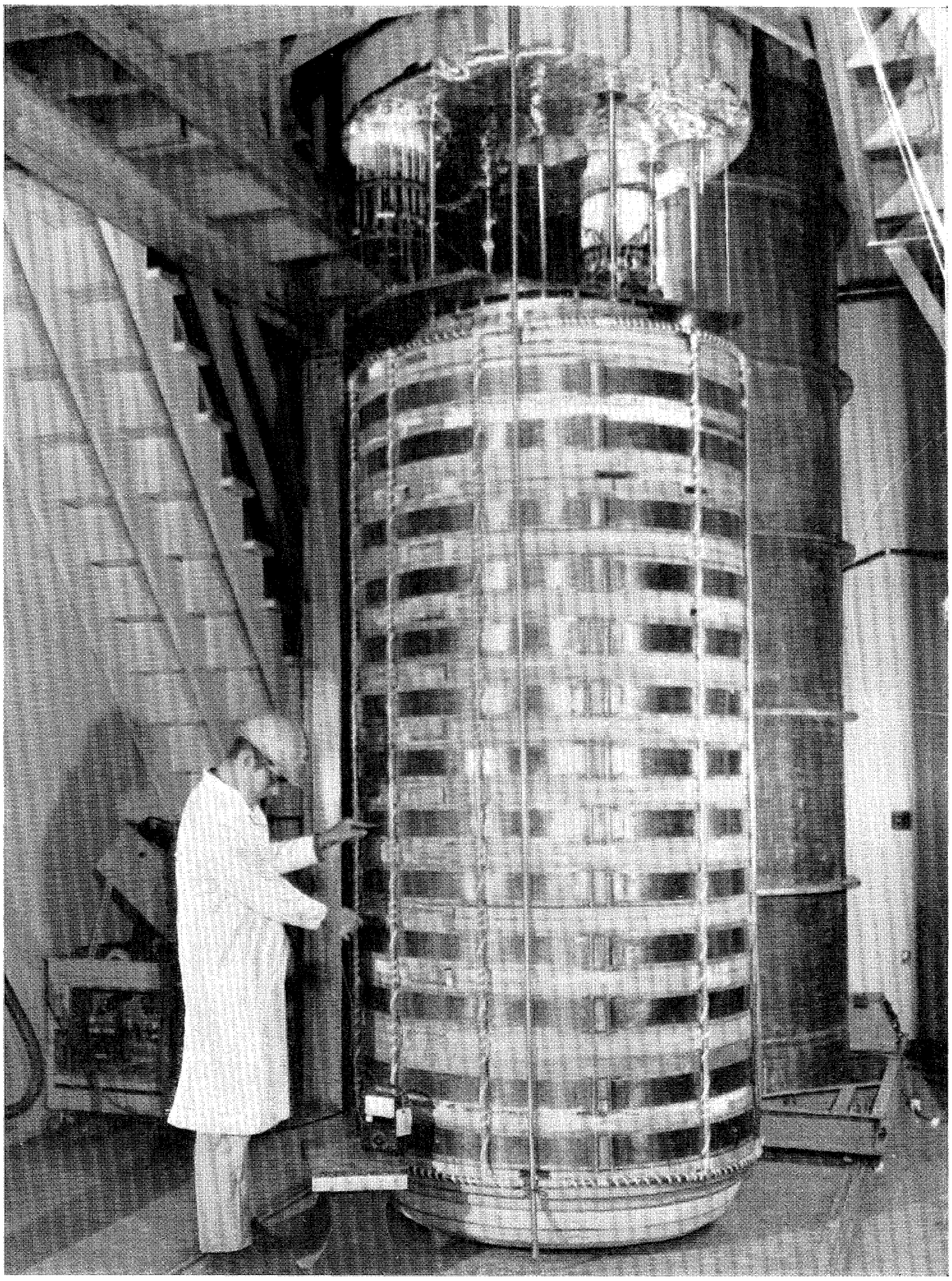

FIGURE 6. Completed 40 kG stabilized saddle-shaped superconducting field coil with bore of 12 in. diameter × 5 ft. long before installation in helium test Dewar chamber shown in background.

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generator leads to difficulties of a practical nature, since the channel must be built with insulating walls to withstand both of these potentials.

The inconvenience due to the multiplicity of outputs can be circumvented in a number of ways. First, a single transverse electrode may be used and the design adjusted to minimize the effects of Hall currents shorting. A second possibility for circumventing the great multiplicity of outputs is to employ the diagonal connexion of the m.h.d. generator. A third solution, and one which also leads to a very simple method of construction for the channel, is to utilize the Hall configuration. At high values of the Hall coefficient the ideal efficiency of this configuration approaches that of the Faraday generator, and in practice improved performance and compactness results from the higher field strength which can be utilized. For this reason our recent efforts in generator fluid mechanics and channel development have concentrated on the Hall generator.

Initial work on the fluid dynamics in the Hall configuration has been reported (Teno, Burkhart & Brogan 1965). For this work the rectangular channel employed for the investigations of the fluid mechanics of the segmented electrode configuration (Louis *et al.* 1964) was employed.

Since the transverse electric field in a Hall generator is zero, the channel need withstand only the Hall field. The channel may be of circular cross-section, and an attractive method of construction is to build the channel of rings stacked together with insulators between. A heat sink channel of this type is now undergoing test, and the channel together with burner and Mach 2.1 supersonic nozzle removed from the magnet is shown in figure 4, plate 18. An output of 930 kW has been observed with this channel and the observed phenomena can be explained with a simple analysis. A number of circular Hall channels have also been tested in our long duration test facility. Test duration in excess of 200 h for water cooled channels has been recorded during which time the expected value of Hall potential was developed and with the channel in excellent condition at the conclusion of the test.

Superconducting field coils for m.h.d. generators

The relatively low gas temperatures for commercial m.h.d. generator systems make it necessary that a superconducting field coil be employed for production of the magnetic field. For some time the development of such field coils was stymied by the unpredictable performance of the wire when wound into a coil. This phenomenon, known as coil effect, degradation, etc., made it impossible to predict the performance of the wire in the coil, and led to current carrying capacity much below that of a short sample at identical temperature and magnetic field. This difficulty has been eliminated by the development of the 'stabilized' principle of coil construction (Kantrowitz & Stekly 1965). With this principle the superconducting material is embedded in a matrix of a good normal conductor such as copper. If any phenomena causes a sudden appearance of a normal region in the coil the current transfers into the copper. The copper in turn is exposed to liquid helium which can carry off the heat that is generated. The coil is stable if the temperature rise in the copper is less than that which would drive the wire normal. If this is the case, the wire must return to the superconducting state.

The characteristics of a 5 in. diameter bore solenoid built to test the 'stabilized' principle and utilizing niobium–zirconium are shown in figure 5 (Kantrowitz & Stekly 1965). There is no voltage until 720 A has been reached. Above this value of current the voltage across the coil increases gradually. Then, when the current is reduced the voltage goes to zero at the same point that voltage first appears during increase of current. Thus the process of going normal is completely reversible. Moreover, the use of a 'stabilized' construction permits the wire to be operated at or very near the *H–I* curve for the short sample, thus leading to much improved economy in the utilization of high cost superconducting material. It is felt that the development of the 'stabilized' principle has reduced the problem of superconducting field coils to engineering.

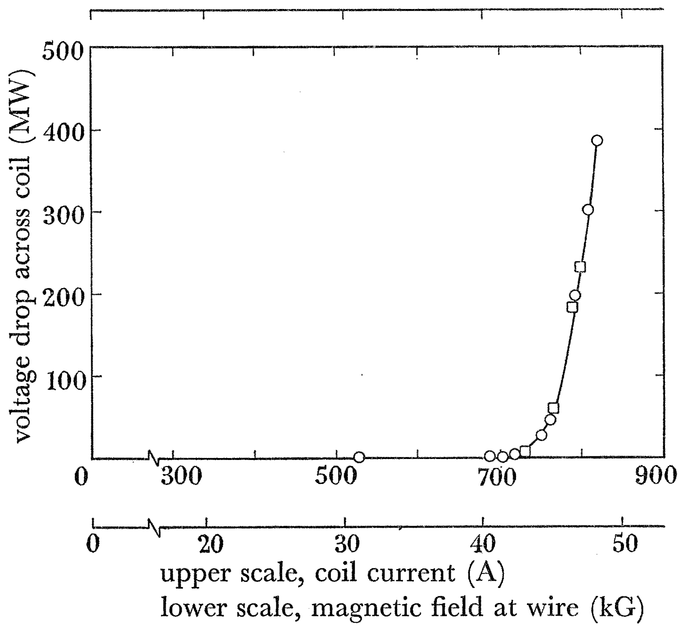
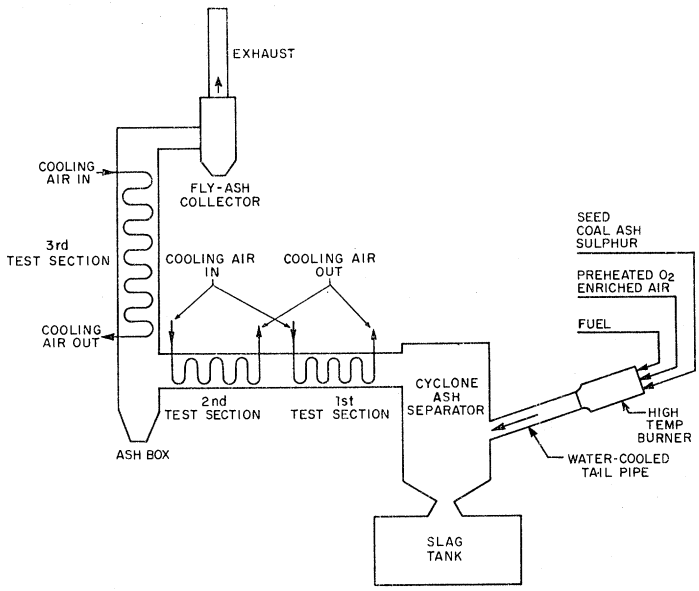


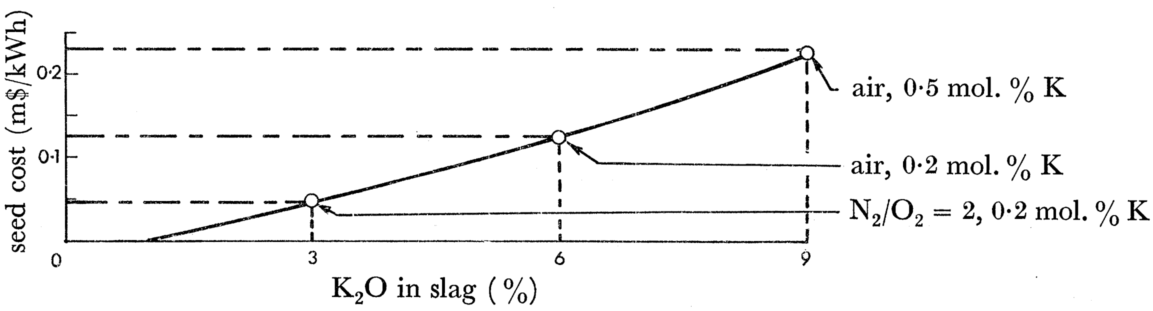
FIGURE 5. Voltage–current characteristics of 5 in. diameter stabilized superconducting solenoid using niobium–zirconium.

A stabilized saddle shaped superconducting field coil with a 12 in. diameter bore 5 ft. long for a field strength of 40 kG has been built and tested under the direction of Z. J. Stekly. It is a one third linear scale prototype of the field coil which would be appropriate for a 30 MW experimental m.h.d. power plant. The completed coil is shown in figure 6, plate 19, before installation in the helium test Dewar which is in the background. The coil has been successfully tested at the design field strength.

TECHNICAL AND ECONOMIC CONSIDERATIONS FOR SEEDING

It is necessary that the working fluid in a combustion m.h.d. generator be seeded, usually with a salt of potassium, in order that adequate conductivity be obtained. The seed concentration varies with the combustion temperature, pressure, and mode of operation of the generator. However, in general, if a very large portion of the seed flow through the generator is not recovered and recirculated, any improvement in efficiency through the use of the m.h.d. process will be more than offset by the cost of the seed. Further, owing to the fact that much of the difficulties with high temperature heat exchanger surface in modern boilers is attributed to the presence of alkali, the influence of seeding on the conventional heat exchanger surface downstream of the m.h.d. generators needs to be assessed.





Total seed cost (m$/kWh); cycle efficiency, 50 %; coal, 13 kB.t.u./lb.; ash content in coal, 10 %; K_2O content in coal, 1·5 %; slag separation efficiency, 80 %; cost of seed delivered (K_2SO_4), 4·8 c/lb. K_2O; precipitator system efficiency, 98 %.

FIGURE 7. Seed recovery and corrosion test apparatus, and cost of seeding derived from the test results.

A method of recovering the seed, along with the results of experiments conducted, is shown in figure 7 (Hals, Keefe & el Bindari 1964). The apparatus shown schematically in the upper portion simulates a commercial m.h.d. system. With addition of ash, seed and sulphur, the burner produces gas which approximates that appropriate to a coal fired m.h.d. system. The temperature drop and cooling rate of an m.h.d. generator are simulated in the water cooled tailpipe. The remainder of the apparatus represents the steam generator which would be downstream of the m.h.d. generator. The effluent from the m.h.d. generator enters a cyclone separator. Most of the seed is still in the vapour phase, while the slag is condensed along with a small portion of the seed which may be dissolved in it. The condensed slag is removed in the separator and discarded, and thus the dissolved seed is lost. The flue gases enriched in alkali pass through several test sections which both cool the gas and provide a means of testing the effect of the flue gases on various material surfaces. The data in the lower portion of figure 7 indicate the results of the recovery measurements. The air oxidizer plus 0·2 mol. % potassium is most appropriate for commercial systems, and the indicated seed cost of 0·12 m$/kWh is obtained from the measured potassium loss of 6 % in the slag. It is believed that higher air preheat temperatures than the value employed here (1200 °F) would lead to even lower seed costs owing to reduced seed solubility in ash at the higher m.h.d. generator discharge temperature which would result from increased preheat.

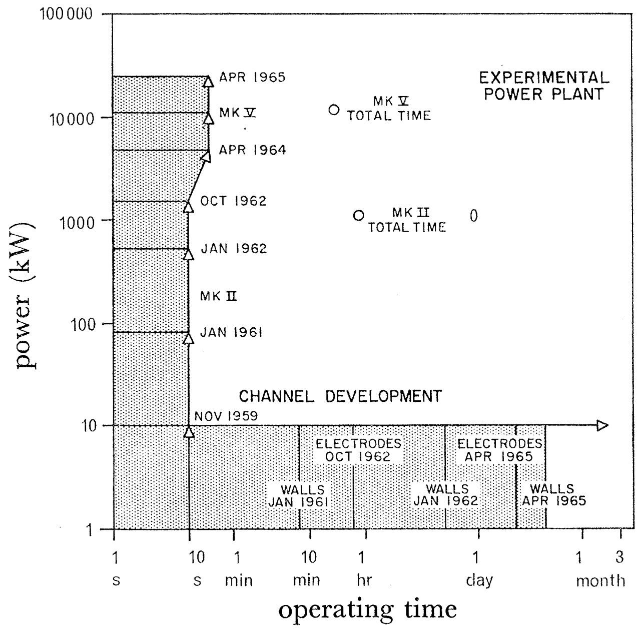


Figure 8. The current status of combustion-driven m.h.d. generator development.

Many hundreds of hours of test time were accumulated with the recovery and corrosion apparatus. No complex or pyrosulphate corrosion of the kind usually encountered was observed. However, with metal temperatures of 1530 °F and above, rapid corrosion was observed due to the potassium sulphate–sodium sulphate eutectic. Although this corrosion is drastic, it appears to be of little practical importance, since metal heat exchanger surface at operating temperatures like 1500 °F probably cannot be considered for economic reasons.

It is felt that this work has demonstrated that seed recovery is technically and economically feasible, and further that the use of seed will not lead to intolerable problems with heating surfaces downstream of the m.h.d. generator.

Conclusions

The present status of the m.h.d. generator development is shown in figure 8, which shows how the operating duration and power level of m.h.d. generators has progressed. Gross power outputs as high as 31 MW have been achieved, while at the same time operating durations of several hundred hours have been observed with smaller units. In addition, the development of practical superconducting coils and demonstration of the feasibility of seeding on a technical and economic basis add up to an encouraging picture

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for m.h.d. power generation. It is believed that the development has reached the point where the construction and operation of an experimental m.h.d. power plant, duplicating, at a level of about 30 MW, all of the features of a commercial m.h.d. power plant, is technically feasible and justified by the ultimate promise of the concept.

References (Brogan)

Hals, F., Keefe, L. & el Bindari, A. 1964 Studies of seed recovery and corrosion in coal fired m.h.d. power plants. *A.S.M.E. Pap.* 64-WA/ENERS.

Kantrowitz, A. R. & Stekly, Z. J. 1965 A new principle for the construction of stabilized super-conducting coils. *Appl. Phys. Lett.* **6**, 56–57.

Louis, J. F., Lothrop, J. & Brogan, T. R. 1964 Fluid dynamic studies with an m.h.d. generator. *Physics Fluids*, **7**, 362–374.

Mattsson, A. C. J., Ducharme, E. L., Govoni, E. M., Morrow, I. B. & Brogan, T. R. 1965 Performance of a self-excited m.h.d. generator. *Int. Conf. energetics*, 18–20 *Aug.* 1965, *Univ. Rochester.* See also *Mech. Eng.* **88**, p. 38, November 1966.

Novack, M. E. & Brogan, T. R. 1965 Water cooled insulating walls for m.h.d. generators. *A.S.M.E. Pap.* 63-WA-348; also: *Advanced En. Conv. J.* **5**, 95–102.

Rosa, R. J. 1962 The application of m.h.d. generators in nuclear rocket propulsion. *A.R.S. Jl* **32**, 1221–1230.

Teno, J., Burkhart, K. & Brogan, T. R. 1965 Studies with a large combustion driven hall m.h.d. generator. *Int. Conf. Energetics*, 18–20 *Aug.* 1965, *Univ. Rochester.*

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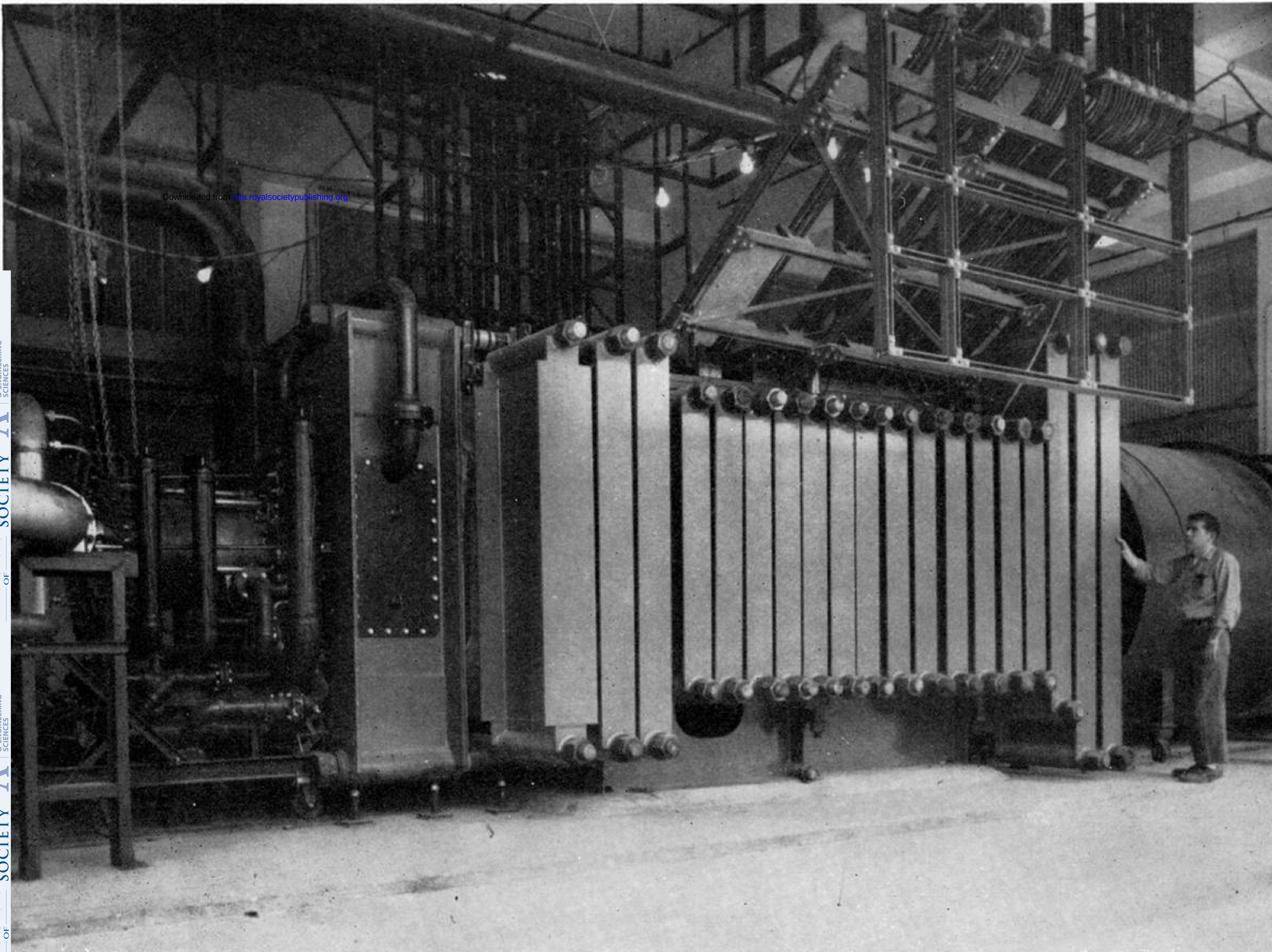

FIGURE 2. The 20 MW (net electrical) mark V rocket-driven self-excited m.h.d. power generator.

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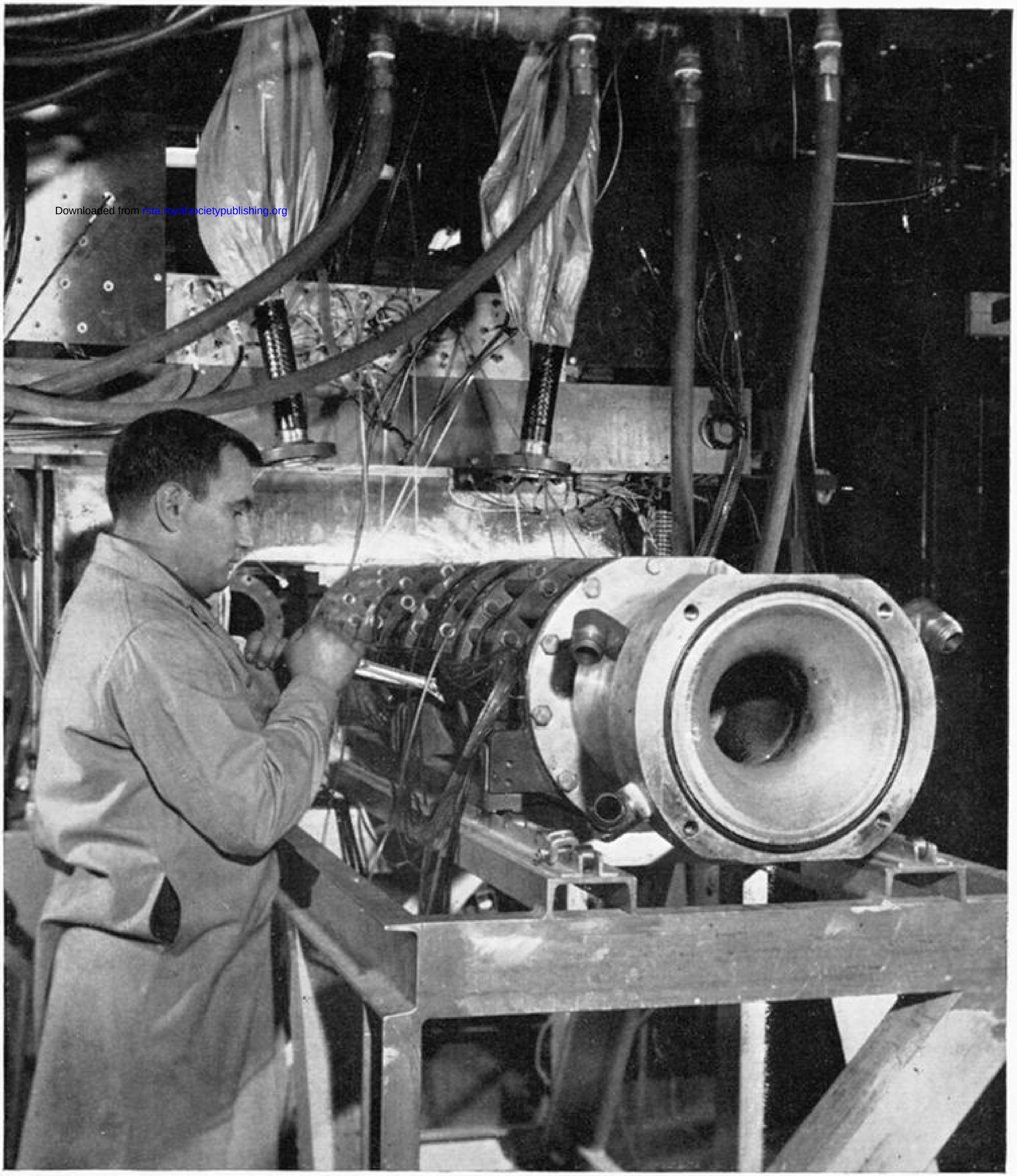

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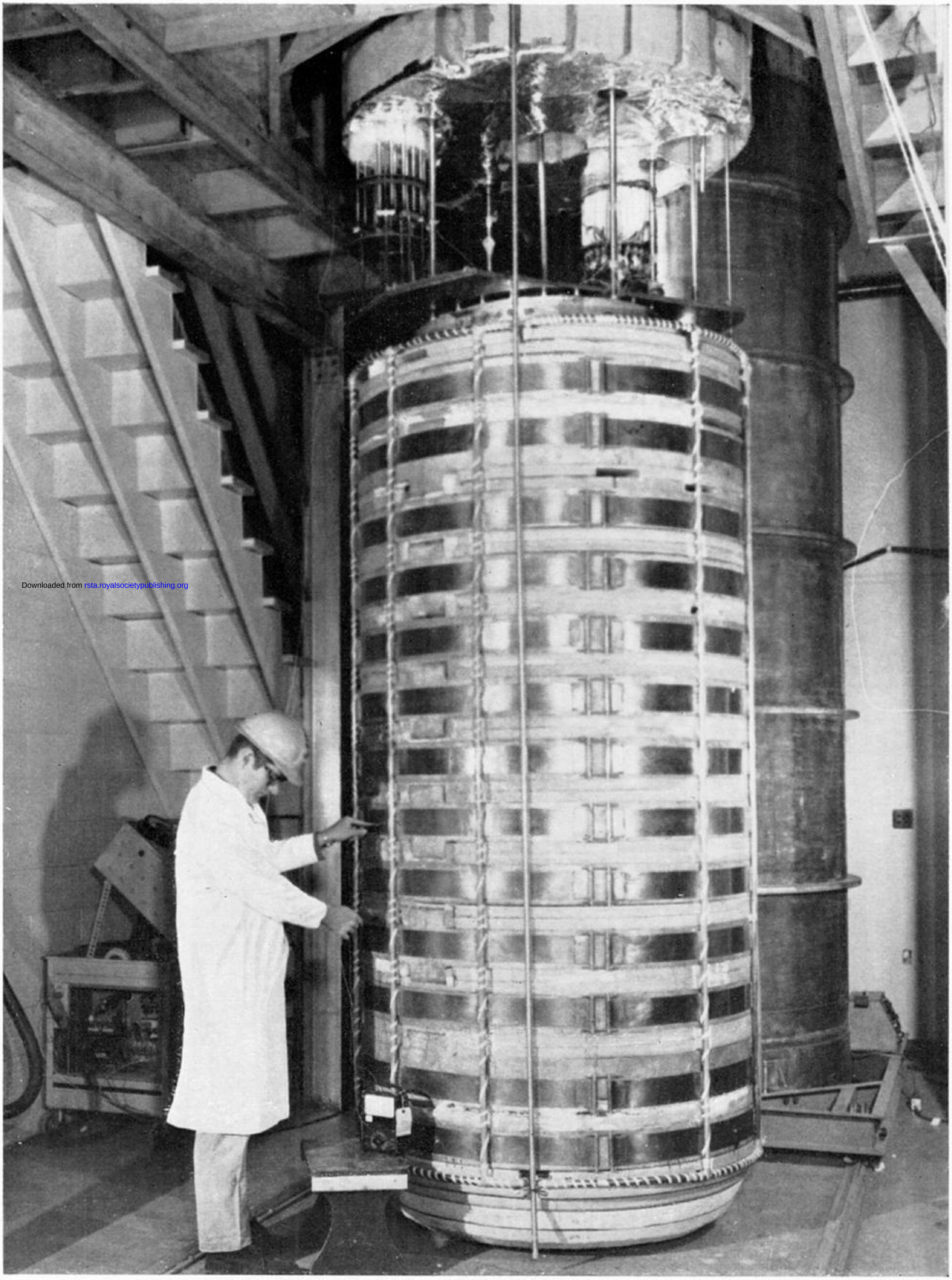

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