Air Heaters and Seed Recovery for M.H.D. Plant

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XVI. Air heaters and seed recovery for m.h.d. plant

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[Plates 26 and 27]

The only economic way of producing sufficiently high flame temperature for m.h.d. power generation using fossil fuels is to burn them with air preheated to at least 1200° C. The factors affecting the design of suitable air heaters for the high temperature stage of this process will be discussed and the features of three general types will be described. One of these is a completely novel concept in which a circulating stream of molten material is used to transfer heat between hot combustion products and air. Experiments which are being carried out to provide design data for these three types will be described and cover the pumping and atomization of high temperature fluids; the testing of suitable refractory materials; aerodynamic model studies; the development of refractory seals.

Seeding chemicals introduced to enhance gas conductivity pose special problems of corrosion and deposition in the air heaters and investigations into the interdependent processes of heat and mass transfer will be described. Since the seed cannot be allowed to escape from the system, studies of recovery processes will be referred to in the paper.

1. Introduction

In an open cycle m.h.d. system, that uses coal or oil fuel it is essential to preheat the combustion air to a temperature greater than 1200 °C if the required flame temperature of approximately 2500 °C is to be achieved without the use of additional oxygen. Such a flame temperature is necessary to achieve adequate gas conductivity throughout the generator.

The magnitude of this task is illustrated in the following table which compares the air heating requirements of a 2000 MW thermal input m.h.d. generating unit with those of current industrial practices.

Table 1. Comparison of duties of an m.h.d. air heater with current industrial practices

application	air flow (10^6 lb./h)	pressure difference between fluids (Lb./in.^{2})	final temp. (°C)
m.h.d. unit (2000 MW thermal input)	5·54	100 to 130	> 1200
modern boiler air heater (1350 MW thermal input)	2·73	0·5	260
open hearth furnace	0·6	0·3	1000 to 1200
glass melting tank	0·54	0·3	1250
hot blast stove	0·43	44·0	1000

Table 1 illustrates clearly that the combined requirements of high temperature, large mass throughput and high pressure differential has no industrial precedent. A reduction in preheat temperature could be obtained by using oxygen combustion or partial oxygen enrichment, but design studies have proved these methods to be economically unacceptable.

However, the most severe problem of all is created by seeding chemicals, such as potassium compounds, introduced to enhance the electrical conductivity of the gas. These not only deposit in the air heater tending to cause blockage but they are extremely corrosive at high temperature to almost all likely ceramic and metallic materials of construction. The seed chemicals are expensive and must be recovered and recycled. It is misleading to think of seed recovery as a separate function as the mass transfer processes involved are intimately dependent on the heat transfer taking place in the air heater and elsewhere. Thus, a large proportion of the seed will be deposited on heat transfer surfaces throughout the system as the gas cools. The remainder, which will be present as a smoke or fume, must be separated from the cool gas prior to discharge to the atmosphere.

2. Development of preferred types of air heaters

In a practical system the air will be heated in a multistage process, the low temperature stage of which will be a conventional recuperator and will be disposed in the normal way following the steam raising and superheater surfaces. In this paper, it is therefore not intended to refer further to these low temperature stages.

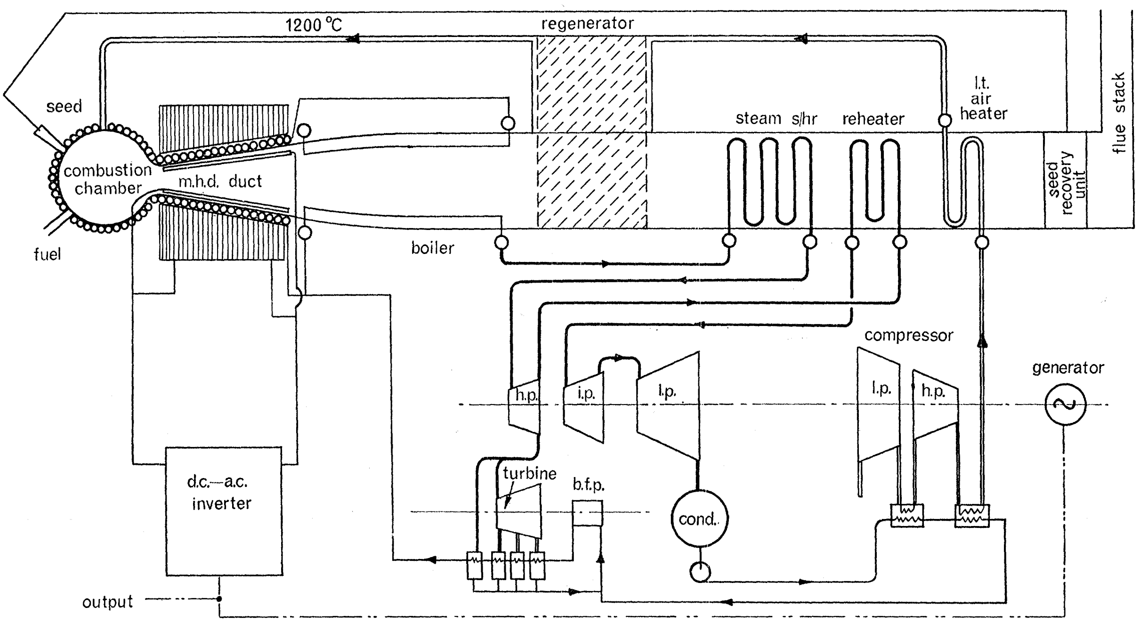


Figure 1. Typical cycle diagram of the m.h.d.–steam power plant with a directly fired air heater.

For the high temperature stages (i.e. from about 450 °C upwards) various forms of air heater have been considered and it is on the most promising of these forms that the paper will be concentrated. In the air heaters considered, all heating and containing surfaces must be made from ceramic materials due to the high temperatures and corrosive chemicals present and much depends on their successful development to withstand these conditions for long periods. Metallic recuperators have not been considered here as the special alloys make the cost too high, although continued developments in oxidation resistant metals may change this situation.

The required final air temperature can be obtained either by locating this stage of the heating unit in the exhaust gases downstream from the m.h.d. duct (i.e. direct heating) as illustrated diagrammatically in figure 1. Alternatively the high temperature heating can be carried out in a separately fired unit (i.e. indirect heating) as shown in figure 2. In this system gas and air pressures are equalized and, moreover, seed is excluded from the air heater, although it will then be present in greater concentrations in the remaining parts of the plant. It can be seen in the scheme illustrated that a gas turbine is used to recover the pressure energy of the hot burnt gas from the air heater, pressure on gas and air sides being equalized by the gas turbine compressor. The use of a separately fired system is slightly less efficient than the direct process as part of the thermal energy is utilized at a lower temperature than that of the m.h.d. duct. The plant also becomes more complicated and the metallic part of the air heater must operate at a higher temperature. However, it does reduce the problems associated with environmental conditions and may give rise to a less expensive unit.

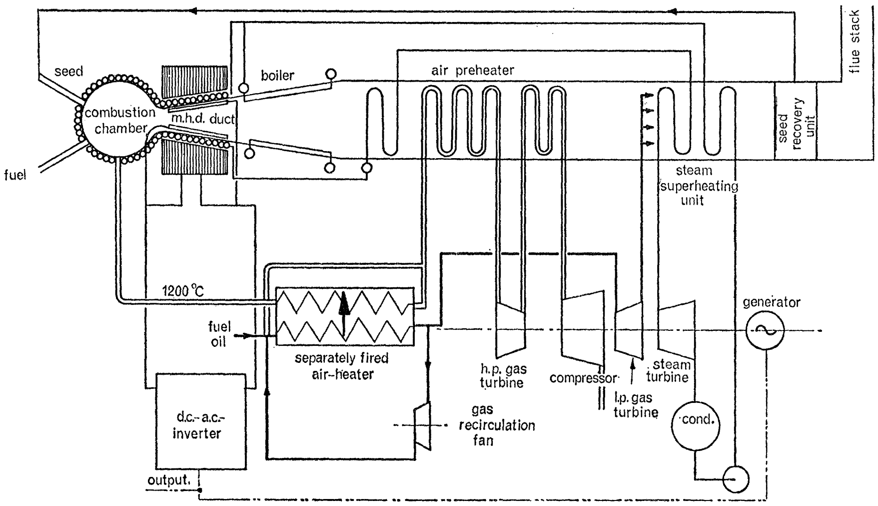


Figure 2. Typical cycle diagram of the m.h.d.–steam power plant with a separately fired air heater.

A survey of various air heaters has led to the selection of four general forms for further study as described below. It would be inappropriate in this paper to attempt to present a full engineering design of each of these types and, therefore, the authors have concentrated on highlighting the basic features of each, the problems to be overcome and the current research programmes. One type is given greater prominence than the other three because of its technical novelty, but not necessarily because it is considered to have the greatest prospect of success.

2·1. *Tubular ceramic recuperator* (*indirect continuous*)

This form of air heater is based on the established design concept of a conventional heat exchanger in which heat from the combustion products of liquid fuel is passed to the cooler air through a tubular wall. It would be necessary for this air heater to be separately fired for two main reasons. First, the available ceramic materials are porous and would not withstand the pressure differential between the fluids of a direct system (7 to 9 atm approximately). Secondly, none of the ceramic materials which resist corrosion by seed contaminated gases have yet been produced in tubes of significant dimensions.

A diagram of one possible design, shown in figure 3, having overall dimensions 100 ft. high and 12 ft. in diameter, has been based on a nominal working pressure on both gas and air sides of 8 atm, at the top tube plate and differential pressure of 5 Lb./in.^{2} at the lower tube plate. With this particular design it was concluded that for a 2000 MW (*T*) generating station, it would be necessary to have ten such vessels on load.

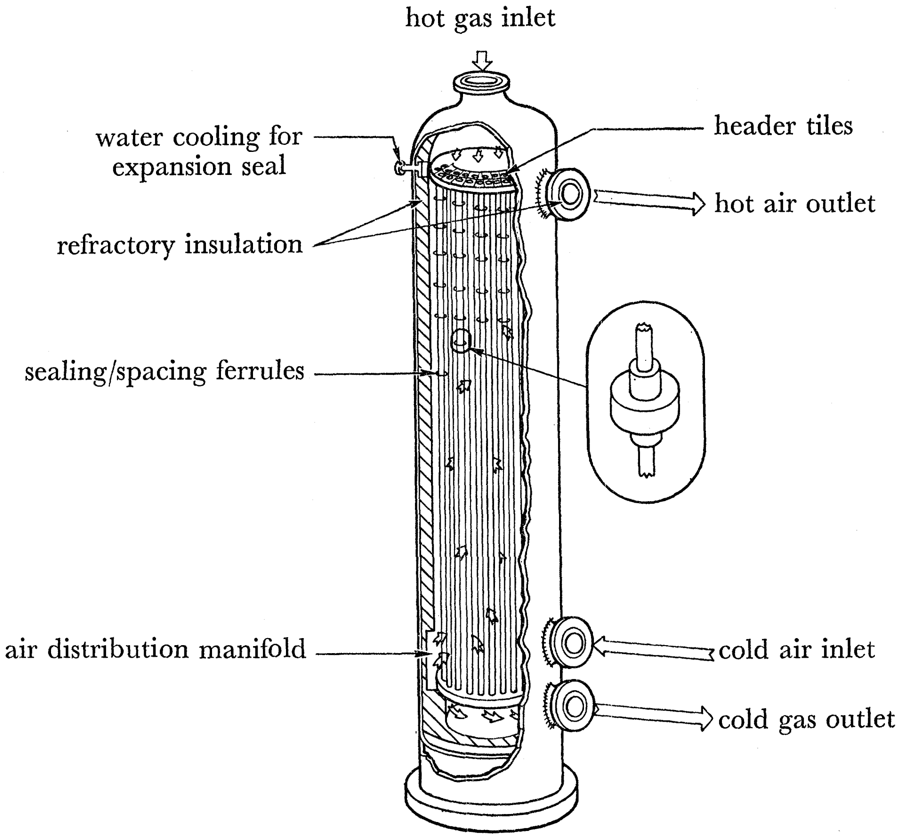


FIGURE 3. Schematic layout of a recuperative air heater.

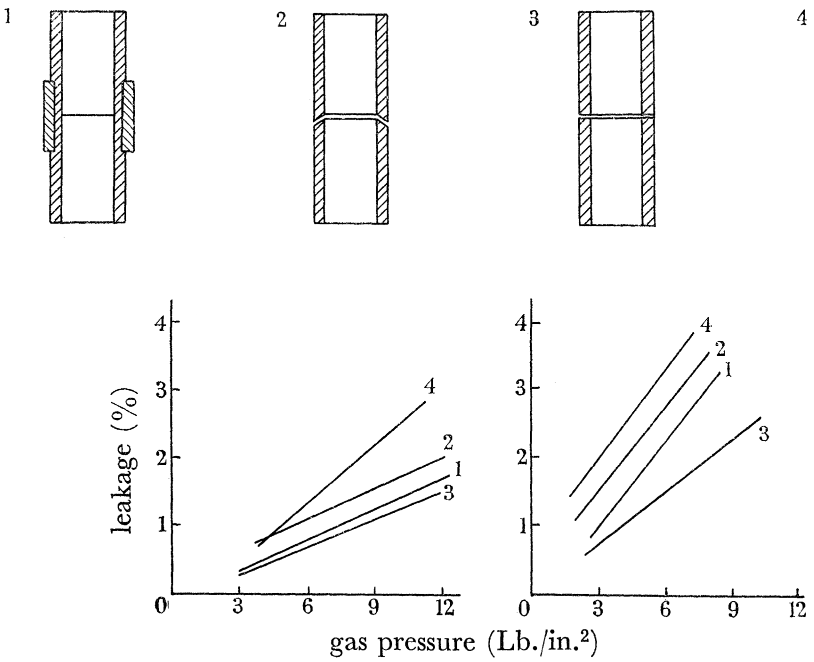
The principal problems which require solution are: (i) leakage through ceramic joints with and without jointing compounds; (ii) vibration of the mechanically weak matrix; (iii) corrosion and/or blockage of the ceramic matrix by oil ash.

Investigations are being carried out on all three of the above items but only studies relevant to the first two of these will be reported in this section.

Studies of leakage rates have so far covered four types of dry joints (i.e. without jointing compound) with a differential pressure range of 3 to 10 Lb./in.^{2} at ambient temperature, leakage measurements being made by a water displacement technique. Preliminary results obtained, together with the types of joints tested are shown in figure 4 and indicate that under these conditions three of the four joints give leakage rates considerably less than the accepted maximum permissible level of 5 %. In later tests fluid temperatures of the order of 700 to 800 °C will be used and leakage detected by trace gas technique.

The operating conditions of the design shown in figure 3 are based on air and gas inlet velocities of 100 to 120 ft./s respectively. These levels were considered to be of sufficient magnitude to justify first a design study of the possible vibrational problems likely to be encountered and secondly the initiation of a research programme based on this design study to provide a better understanding of these problems.

Previous experience in both conventional and nuclear steam generators has shown that the designer cannot afford to treat these problems lightly and further that their solution is unlikely to be simple. To reduce the possibility of subsequent trouble it is fundamentally desirable to ensure that the frequencies of the exciting impulses do not correspond with the acoustic or mechanical natural frequencies. It is, in fact, desirable to design for the predominant forcing frequencies to be lower than these natural frequencies, but this criterion may not permit an economic design. A vibration analysis has suggested that this situation is likely to be met with in the initial design proposed and as it may be very difficult to incorporate any design modification to raise the natural frequencies above the level of the forcing frequencies, alternative designs are being considered.



(*a*) at 11·25 ft.³/min (*b*) at 7 ft.³/min

FIGURE 4. Joint types for use with ceramic tubes.

To provide more reliable information, a research programme is now in hand with the following objectives:

(i) To determine the fatigue strength properties of tubes and tube connexions over the working range of temperatures using the rotating bending technique with the specimens in an environment of liquid fuel combustion products.

(ii) To determine by wind tunnel tests at atmospheric pressure the relation between the forcing frequencies and gas velocity for a tube bundle arrangement similar to that incorporated in the design shown in figure 3.

(iii) To determine by further model tests what transverse frequencies, if any, are likely to be set up in the air heater over its range of operating conditions.

(iv) To determine by tests on models of the design shown in figure 3 the aeroelastic stability of tubes situated in the vicinity of the air inlet and outlet ducts and also in the main bulk of the air heater.

2·2. *Rotary matrix regenerator* (*indirect continuous*)

An alternative design to the tubular ceramic air heater is the rotary ceramic honeycomb matrix regenerator, which is based on the established principle already widely used in conventional air heaters in modern power stations. This form of air heater must also be separately fired, again due to the reasons specified in §2·1 plus probable blockage of the small matrix passages.

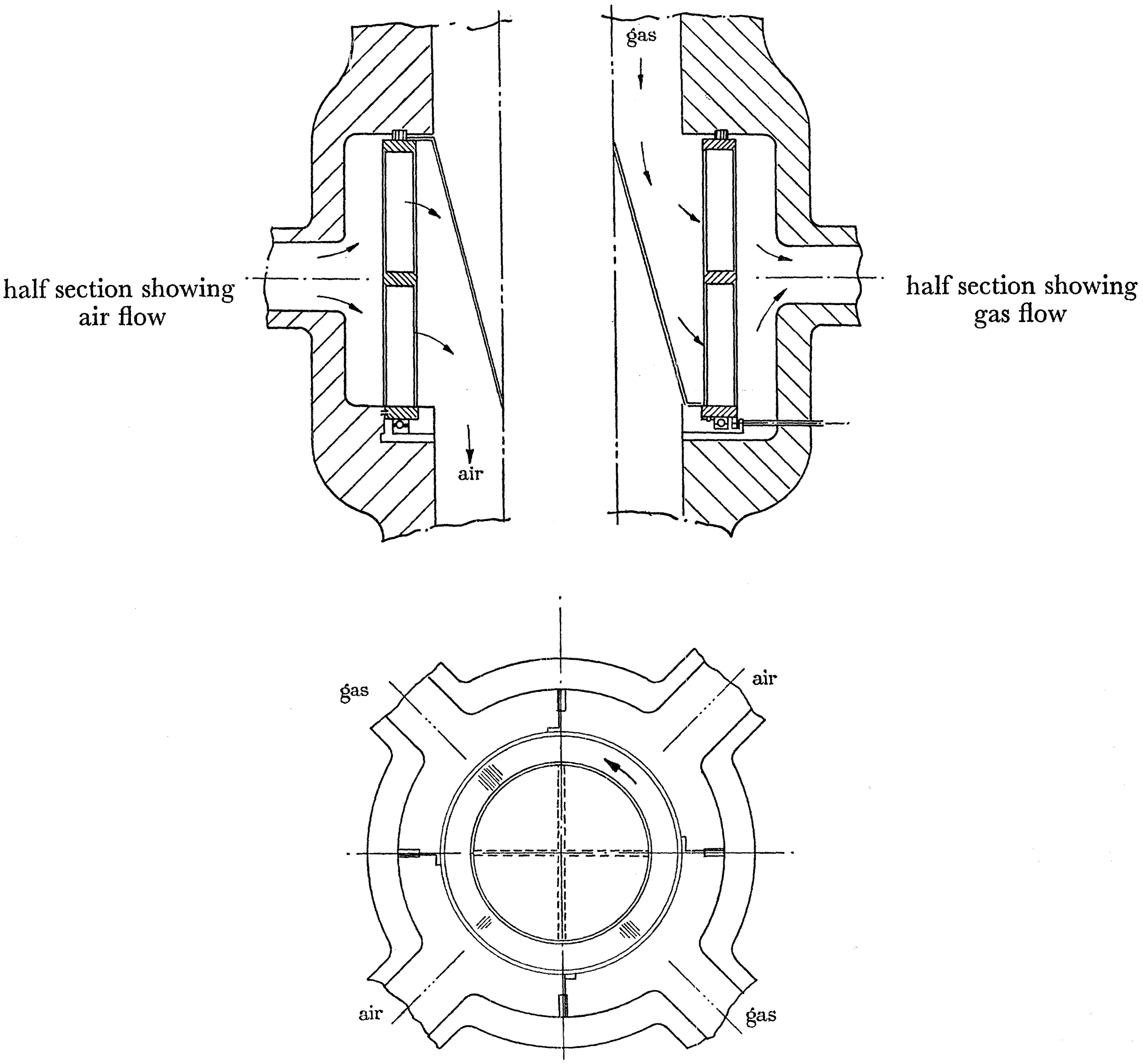


FIGURE 5. Drum type rotary ceramic air heater.

One possible design is shown in figure 5 and a typical matrix geometry is illustrated by the test disc shown in figure 6. A range of geometries is being considered with 1, $4\frac{1}{2}$, 10 and 20 corrugations per inch. This concept could provide an extremely compact design if the blockage can be restricted to an acceptable level. For instance, in a drum type design with matrix dimensions $4\frac{1}{2}$ corrugations per inch, the required duty can, theoretically, be obtained in one vessel of 22 ft. diameter, 22 ft. high. However, the blockage suffered by such small passages remains to be checked together with the resulting pressure drop.

As with the tubular ceramic unit, this design has been based on a balanced working pressure of 8 atm. If current investigations of deposition and corrosion prove encouraging then further investigations of the effectiveness of seals with rotating parts at elevated temperature and the containment of vibrations to permissible levels will be started. Some preliminary tests have been carried out to guide this work.

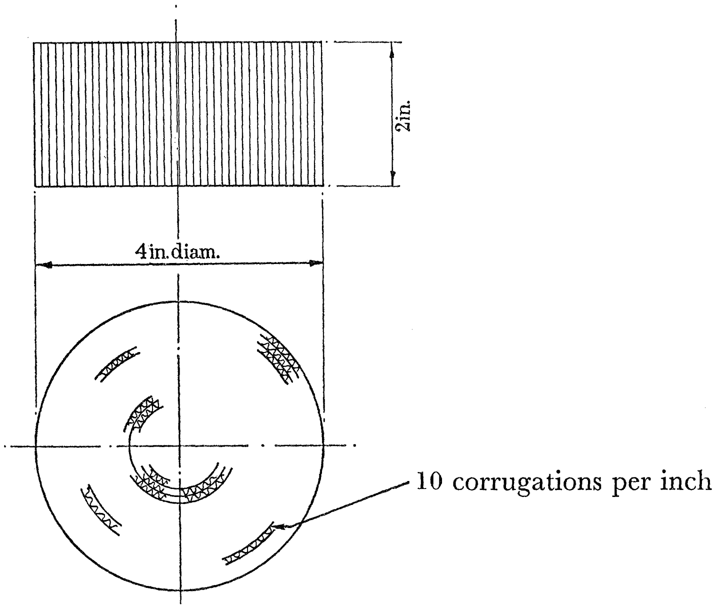


FIGURE 6. Typical test ceramic disk used for blockage experiments.

2·3. *Liquid slag regenerator (direct continuous)*

The third form of air heater is completely novel in concept and its development is fraught with complex technical problems but if successful it would provide a most compact method of producing a continuous supply of directly heated air of constant temperature.

The design based on this concept is shown in figure 7. Small solid particles of a suitable heat transfer medium are continuously melted in the upper chamber through which the hot gases from the m.h.d. duct flow. The molten material must then be pressurized before injection into the lower chamber where it is atomized before falling through the rising air flow, which is heated in the process. In this air heating chamber, molten droplets are solidified and then returned to the top of the upper chamber for recycling. Utilization of small particles presents a large surface area for heat transfer and thus provides an efficient and compact system.

For an oil fired unit, the medium used would be potassium sulphate, i.e. the seed material itself. This would pick up impurities from the oil combustion products until an equilibrium concentration is reached. For a coal fired unit, the medium could be molten coal ash although the separation of seed from coal ash would then require a separate operation. In either case, it is convenient to refer to the circulating medium as ‘slag’. These points are discussed further by Hart & Laxton (1965), who also describe the work on basic physical properties of the 'slag', an accurate knowledge of which is vital for the successful design of this system.

It is, however, essential to bear in mind that the overall approach to this design is based on an oil-fired m.h.d. unit and that the various detailed studies would require modification to cover the use of coal firing.

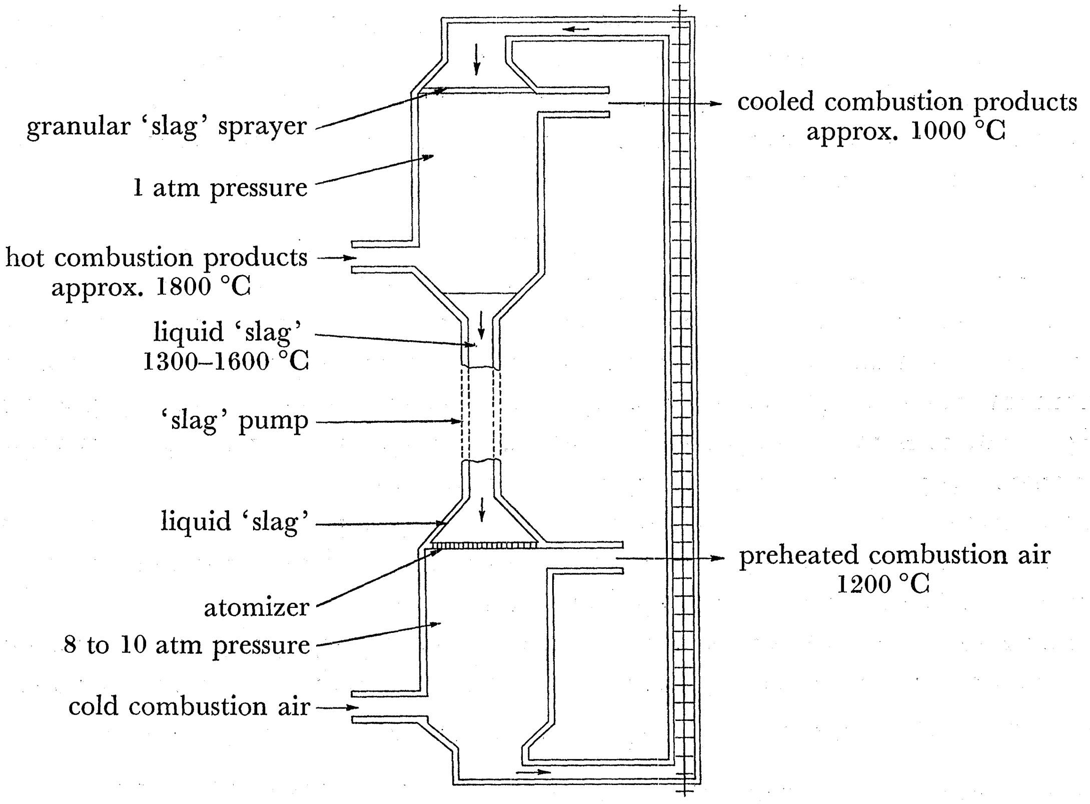


FIGURE 7. Schematic arrangement of liquid 'slag' regenerator

Before a prototype heater can be built to operate on this principle, basic information is required on:

(i) Heat and mass transfer between falling clouds of particles and vapour containing gas or air.

(ii) The atomization of liquid potassium sulphate at 1300 to 1600 °C to give a spray of correctly sized particles.

(iii) The development of a method of pressurizing slag at a temperature of 1300 to 1600 °C.

(iv) The uniform distribution of correctly sized particles into the top of the upper chamber.

(v) Aerodynamic design of both chambers to achieve satisfactory counter-current flow of gas/air and particles and avoiding excessive secondary flows.

(vi) Proving of materials for nozzles and lining.

In the following paragraphs an account is given of the research in progress on each of these topics.

2·3·1. *Heat and mass transfer between particles and gas/air*

The dimensions and performance of this air heater are critically dependent on the size distribution of the solid particles entering the upper chamber and of the spray entering the lower chamber.

The absence of detailed experimental data on the atomization of hot 'slag' and the incomplete analysis of the data from atomizer simulation tests make it impossible, at this stage, to state the mathematical expression describing the size distribution of the atomized 'slag'. In any event it will depend on the particular type of atomizer used. However, to illustrate quantitatively the effect of size distribution on heat exchange chamber dimensions the following analysis is presented which assumes that the slag particles are spherical and that their size distribution can be expressed by the Rosin–Rammler law

$$R = 1 - \exp\left[-(x/\bar{x})^{n}\right], \tag{1}$$

where R is the fraction of material having a size greater than x, and $\bar{x}$ and n are experimentally determined constants for any given particle population. Limited information is available on the spray characteristics of suitable fluid atomizers operating under hot conditions. For the purpose of this analysis a value of 3·75 was chosen for n which gives 90% of particles in the range 500 to 1500 μm diameter. In the event this may prove optimistic but is considered as the limit of achievement.

The height of air heating chamber is computed from a knowledge of the time taken for the heat to be transferred to or from the largest 'slag' particle and the terminal velocities of different sized particles falling through the chamber.

The heat transfer and residence times are computed by first calculating the heat transfer coefficient h which for forced convection to small spheres is given by the following equation (Ranz & Marshall 1952):

$$\mathrm{Nu} = 2 + 0{\cdot}6\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}, \tag{2}$$

where the symbols refer respectively to the Nusselt, Reynolds and Prandtl numbers.

The velocity term in the Reynolds number is the terminal velocity of the particle, which is calculated by equating the drag and buoyancy forces with the gravitational force. This equations is given as:

$$V_t = \sqrt{\frac{2gm_p\,(\rho_p - \rho)}{\rho\rho_p A_p C_p}}, \tag{3}$$

where m_p is the particle mass, A_p is the particle projected area in the direction of motion of the particle, ρ_p and ρ are the particle and fluid densities respectively, and C_p is the drag coefficient the value of which varies with Reynolds number.

The height of the heat exchange chamber is calculated by solution of the following enthalpy balance equations:

$$\left.\begin{array}{ccc} m_S(\mathrm{d}H_S/\mathrm{d}Z) & + \,\pi D^2 Nh(T_S - T_A) & = 0 \\ \text{(change of seed} & \text{(heat lost from} & \\ \text{enthalpy with} & \text{seed)} & \\ \text{chamber length)} & & \end{array}\right\}; \tag{4}$$

$$\left.\begin{array}{ccc} m_A C_{p_A}\,\mathrm{d}T_A/\mathrm{d}Z & + \,m_S C_{p_S}\,(\mathrm{d}T_S/\mathrm{d}Z) & = 0 \\ \text{(heat gained} & \text{(heat lost} & \\ \text{by air)} & \text{by seed)} & \end{array}\right\} \tag{5}$$

$$T_S = f(H_S), \tag{6}$$

where Z is distance along the chamber, H is enthalpy, N is the particle flux density, T is temperature, and suffixes A and S refer to air and slag, respectively.

This simplification avoids solution of the partial differential equation for unsteady state heat conduction in the particle for heat transferred to or from its surface in a changing environmental temperature and is valid because of the low internal resistance to heat transfer of the particle due to its small diameter compared with the high surface resistance brought about by the low heat transfer coefficient h. This simplification is confirmed by solving the partial differential equations for the unsteady state using an electrical analogue for three zones in the particle, i.e. $r' = 0$, $r' = \frac{1}{2}r$ and $r' = r$, where r is particle radius. The temperature variation in these three zones as the particle traversed the heat exchanger was found to be very small, therefore justifying the above approach.

The simultaneous equations (4) to (6) were solved by analogue computer for a size distribution, thus making it possible to follow the temperature history of individual particles as they fall through the heat exchanger. Although equations (4) to (6) as written refer to the air heating section of the regenerator, analogous equations allow calculations of the dimensions of the seed heating section to be made.

One typical calculation of the dimensions of the heat transfer region (minus entry and exit zones, which themselves could be large) of the air chamber for an air heater for a 2000 MW(T) m.h.d. steam plant is given in table 2, calculated for a configuration which will give constant gas velocity. This configuration gives minimum height.

TABLE 2. DIMENSIONS OF THE AIR HEATING CHAMBER HEAT TRANSFER ZONE FOR A 2000 MW (T) M.H.D. STEAM PLANT

	1 atm	5 atm	10 atm
height (ft.)	207	129	93
diameter (bottom) (ft.)	63	23	20
diameter (top) (ft.)	105	47	33

A constant gas velocity configuration may not be acceptable in practice because the walls will converge in the direction of the slag and seed particulate flow, thus tending to encourage wall deposition. A constant cross sectional area chamber based on optimum gas velocity at the top would be larger than the constant gas velocity configuration because of the lower than optimum gas velocity at the bottom of the chamber.

To decrease the chamber height it will be necessary to allow the larger particles to leave the chamber before reaching their optimum temperature level. For the same reason the smallest particles will be carried out of the chamber in the gas stream, separated by a hot running cyclone, and returned to the chamber whilst still in the molten state. Figure 8 shows the effect of elutriation of the small particles of 'slag' on the chamber height for various percentages of total mass of heat transfer 'slag' leaving the heat transfer zone before reaching their optimum temperature level. Also shown is the percentage of the enthalpy still remaining in the particle, which would have been transferred had the particle reached its optimum temperature level. This remaining enthalpy would not be lost; the particles leaving the heat transfer zone will then enter a fluidized bed where the remaining enthalpy will be transferred to the entering combustion air. The family of curves are calculated for an air pressure of 10 atm.

This method of reducing the chamber dimensions by elutriation reduces the size spectrum of the particles entering the gas chamber and hence its height, which to a first order of approximation, is similar to that of the air chamber. The diameter, of course, is larger because the gas pressure is close to atmospheric.

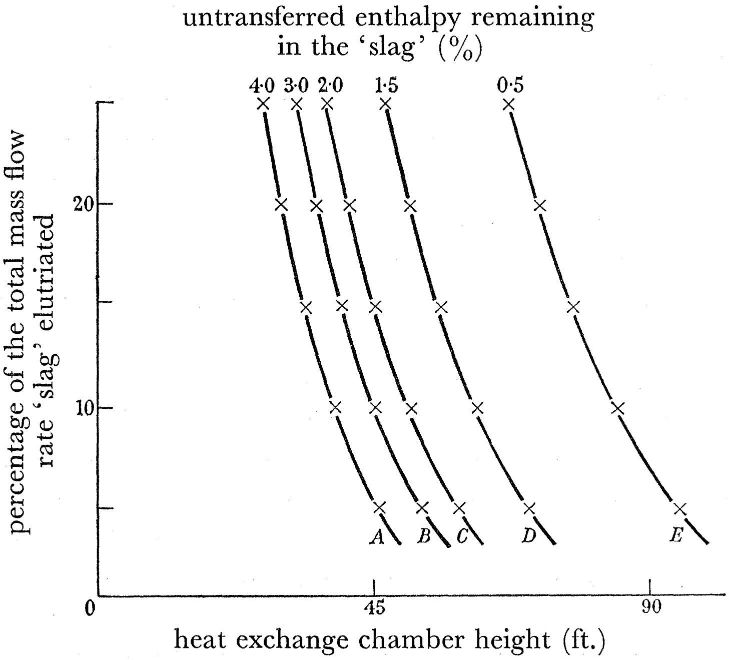


Figure 8. Graph showing the variation of air heating chamber height for various percentages of slag elutriated before attaining optimum temperature level. Percentage of the total mass flow rate of 'slag' leaving the heat transfer zone before attaining the optimum temperature level: *A*, 25; *B*, 20; *C*, 15; *D*, 10; *E*, 5.

2·3·2. *Atomization of molten slag*

The function of the atomizer is to produce a rain of molten droplets which, as they solidify, give up their heat rapidly to the incoming air at a pressure of some 8 atm. The atomization must be carried out with negligible pressure drop and the droplets must be closely sized about a mean diameter of 800 μm. The atomizer must be resistant to the effects of high temperature and corrosive slag, retaining its characteristics over long periods (see § 2·3·1). The two types of atomizer being investigated are the free fall atomizer and two fluid atomizer. In each case, the initial experiments have been with water which has a similar viscosity and surface tension at room temperature to that of potassium sulphate at 1300 °C.

(i) *Free fall atomizer.* It has been found that using the atomizer shown in figure 9 (*a*) and 9 (*b*), plate 26, single and stable droplets of water over the size range 4000 to 5000 μm can be produced without the subsequent formation of satellite or secondary drops. The advantage of this design is that it permits closely sized droplets to be formed, without the use of a secondary fluid. In practice a multiple array of atomizers will be required and further experiments have been carried out with a multiple dropper to test the behaviour

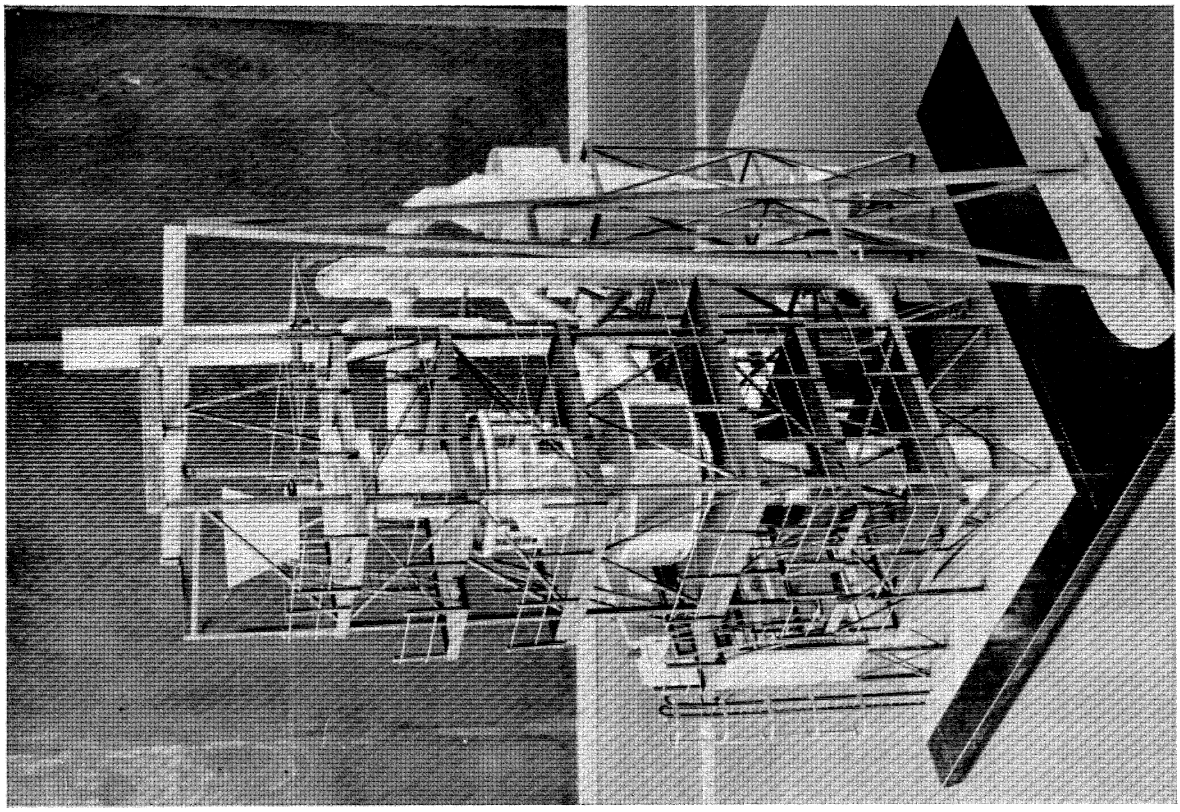


FIGURE 11. Model of the liquid slag atomizer test rig.

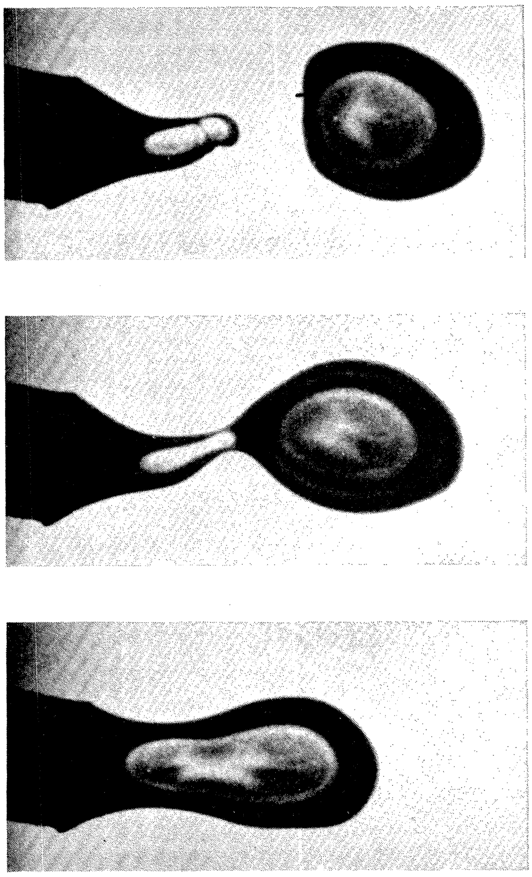


FIGURE 9 (B). Formation of stable drop of 0·18 in. diam. from stub of diameter 0·125 in. (Cine film, 750 frames/second.)

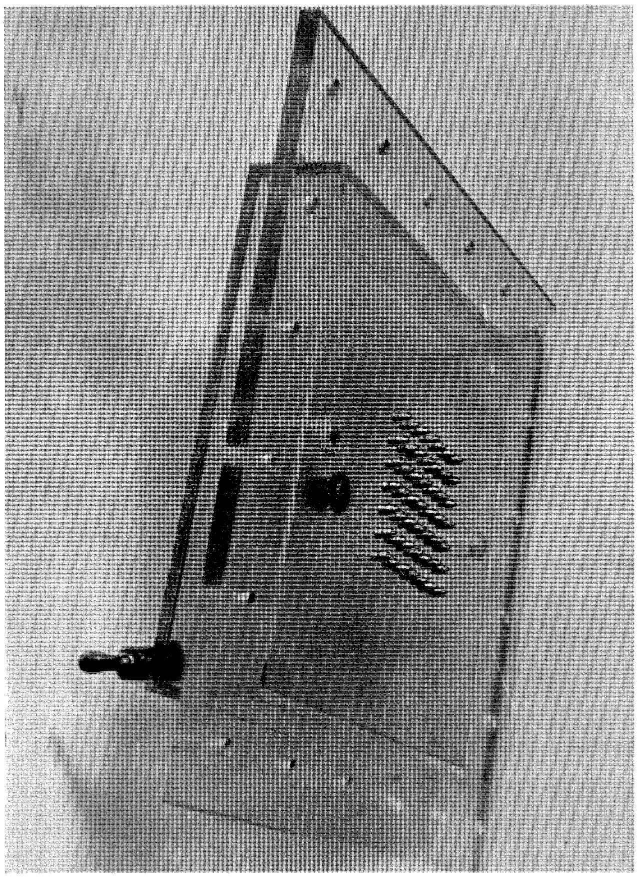


FIGURE 9 (A). Multiple dropper header supply tank with droppers at 0·65 in. centres.

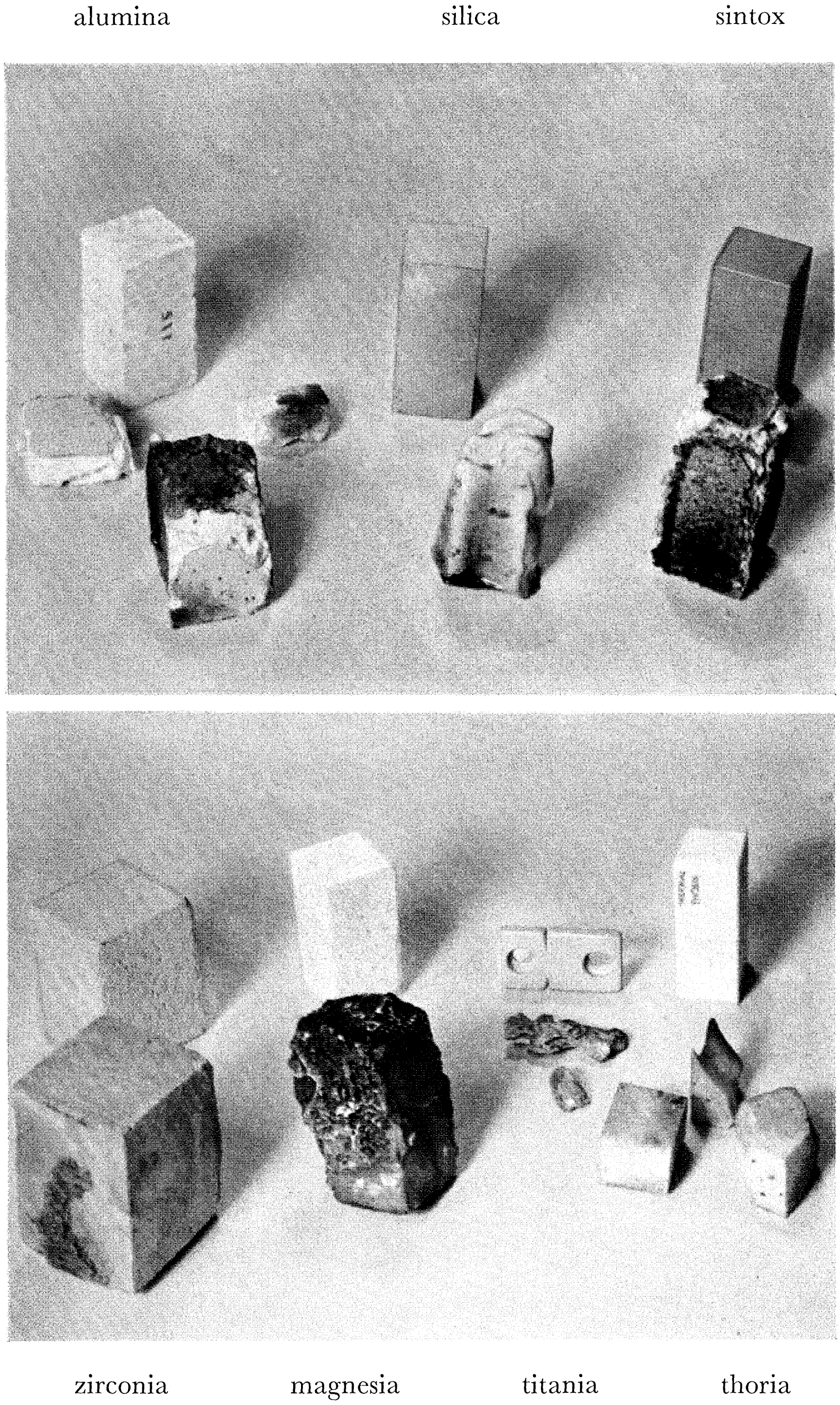


Figure 18. Refractory materials before and after exposure to hot seed vapour.

of droplets falling counter-current to an air stream of varying velocity. It is envisaged that the dropper will be constructed from a perforated ceramic plate with drop points at a suitable pitch to give the required flow rate with a minimum of interference and collisions between drops. Experimental work is continuing to give a design based on optimum drop size and tower dimensions.

(ii) *The two-fluid atomizer.* This devise makes use of inclined jets of air to break up a falling stream of molten slag. An impression of the practical form envisaged is shown in figure 10. Investigations have been carried out on a water model to assess the effects of flow and geometrical factors on the spray. Droplet sizes were measured by an electrostatic spray analyser in which the water droplets strike a wire charged by a high voltage source. On striking the wire, a drop takes up some of the charge and momentarily reduces the wire voltage by an amount which is a function of the droplet diameter. The voltage pulses so produced are sized and counted electronically.

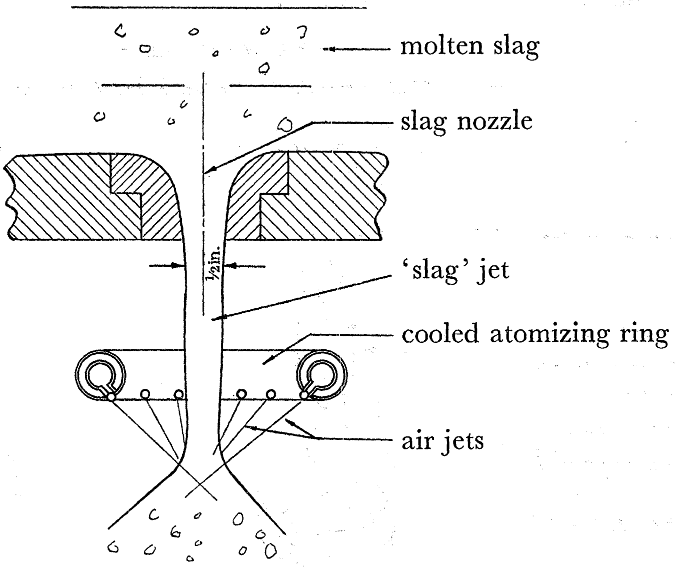


FIGURE 10. Diagrammatic arrangement of twin fluid 'slag' atomizer.

Analysis of the results of these tests showed that the significant factors affecting atomization, and the range over which the results could be correlated, were found to be:

W_1	liquid mass flow rate (lb./min) 8·98 to 46·05.
W_1/W_a	ratio of liquid mass flow rate to air mass flow rate 7·65 to 14·0.
θ	angle of incidence between the axes of the air and water jets (deg) 20 to 70°.
D_n	liquid nozzle diameter (in.) 0·25 to 0·5.

Experiments in a small high temperature crucible have shown that molten sulphate can be sprayed into air having a temperature above the melting point of the sulphate without formation of fibres. Owing to the difficulty of obtaining a representative sample of the spray, no quantitative conclusions have been drawn about the relation between the size distribution and the ratio of the slag to air mass flow rates. However, microscopic examination of samples of the slag spray shows as expected that there is a larger proportion of fine particles with lower ratio of slag to air mass flow rate. These results together with information provided by J. M. Rydderch of B.I.S.R.A. on the atomization of molten iron were sufficiently encouraging to warrant slag atomization experiments on a more realistic scale and these will be carried out in the plant shown in figure 11, plate 26. The effect of varying slag temperature over the range 1100 to 1600 °C will be observed as well as the flow and geometrical factors already investigated on the water model. The slag spray will fall under gravity against an upward current of air and the effect of the air stream on the shape of the spray and on the carry-over of fine particles will be observed. It will be possible to make measurements of temperatures and mass flows and obtain an experimental check on the method of design for heat transfer.

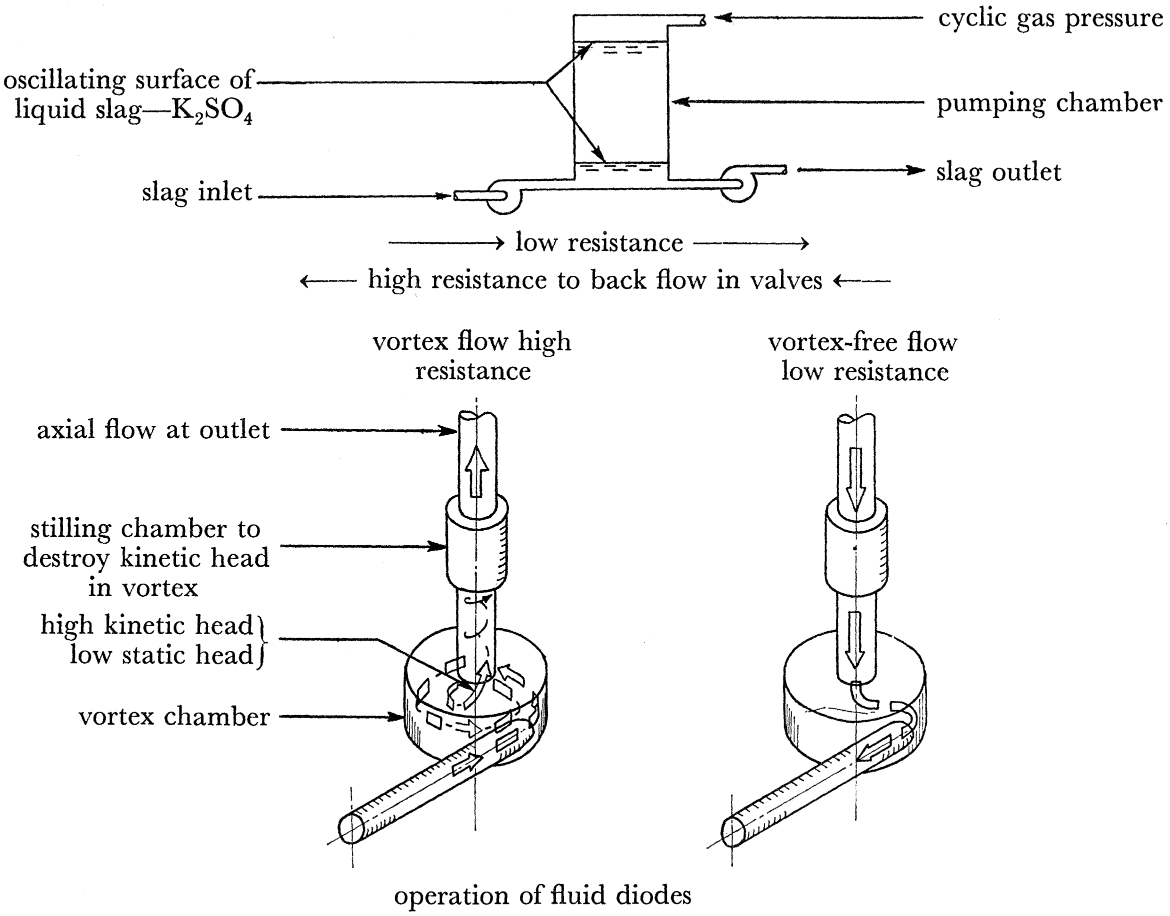


FIGURE 12. Schematic arrangement of the 'slag' pump using 'fluid diodes' as valves.

2·3·3. *The slag pump*

As has previously been discussed, many of the difficulties arising in the development of a suitable air heater for m.h.d. are due to the pressure difference between the air and the gas from which the heat is to be extracted. In the liquid slag air heater, this pressure difference will support a column of slag of the order of 100 ft. high. Thus, if one wishes to make use of gravitation to transfer the liquid from the bottom of the gas chamber to the top of the air chamber, there must be a vertical separation of approximately 100 ft. between the two chambers. The implications of this in terms of cost of supporting structure and ductwork provide a considerable incentive to develop a pump to provide the necessary transportation of liquid slag.

A survey of existing experience in this field shows that liquid metals have been pumped by centrifugal pumps at temperatures up to 800 °C. In this case, uncooled metal impellers have proved practicable. In the liquid slag regenerator the slag temperature will be at least 1300 °C and may be as high as 1600 °C. Under these conditions, it is not possible to cool the impeller sufficiently well to remove the heat that would be transferred to it by forced convection from the liquid. A coated or ceramic impeller is also impracticable because the only materials able to withstand the chemical attack of potassium sulphate do not have sufficient mechanical strength to resist the centrifugal forces. These considerations apply also to any form of mechanical positive displacement pump.

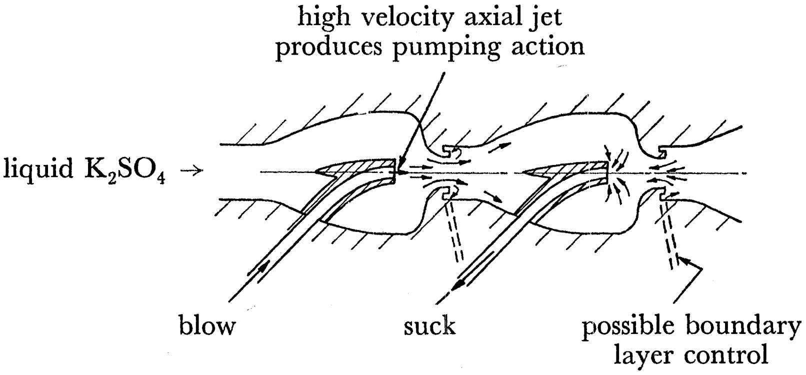


FIGURE 13. Schematic arrangement of the vector flow 'slag' pump

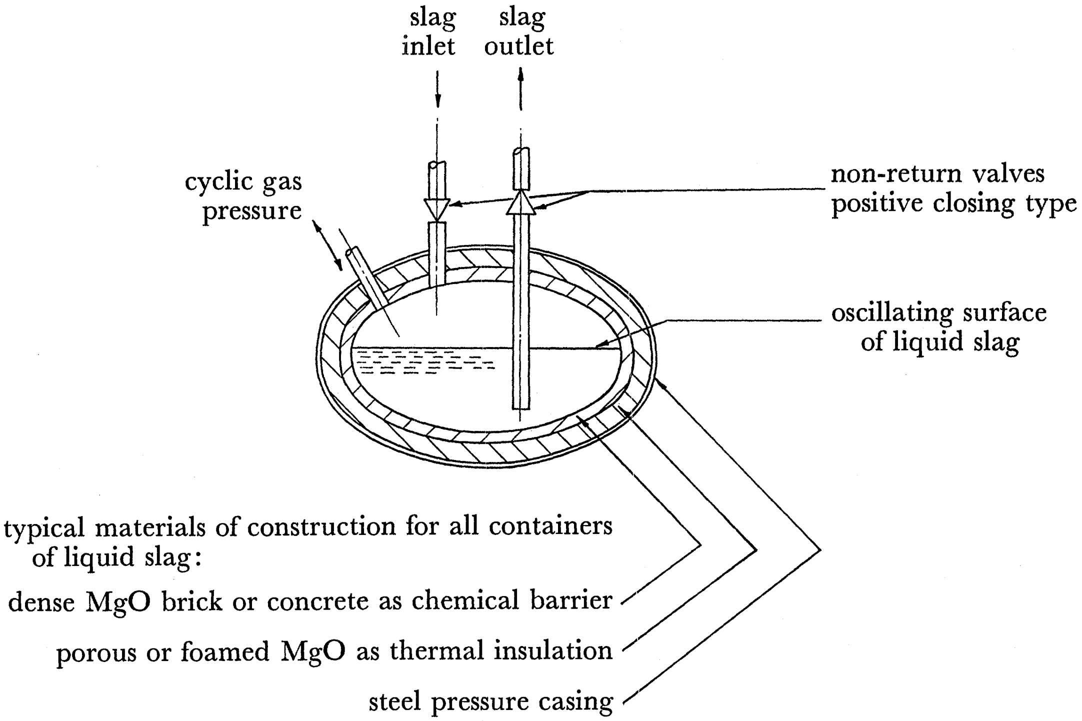


FIGURE 14. Schematic arrangement of the 'acid egg' pump.

Thus, the choice of practicable pump is restricted to a form in which a container is allowed to fill with liquid slag which is then expelled by a gas under pressure. Containment of the liquid is practicable and the gas forms a buffer between the hot liquid and the pumping prime mover.

In this form, there are two principles on which a pump could operate: (*a*) with valves of some sort to constrain the liquid flow in the desired direction—the ‘liquid diode’ and ‘acid egg’ pumps; (*b*) by making use of the change of liquid momentum to produce pressure difference—the ‘vector pump . The principle of each of these devices all of which are currently under investigation, is illustrated in figures 12, 13 and 14.

C_F, C_B coefficients of resistance for forward and backward flow where $\Delta P = \frac{1}{2}C\rho v^2$

P_o = outlet pressure = 8 atm
P_i = inlet pressure = 2 atm
P_S = suction pressure = 1 atm
P_P = pumping pressure = variable

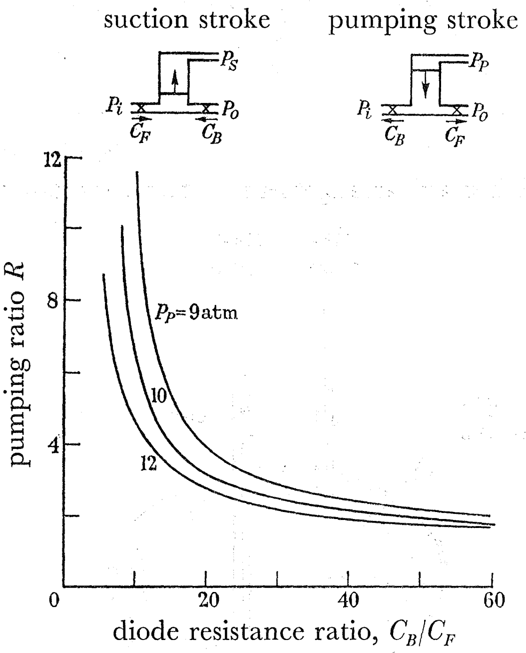


FIGURE 15. Variation of pumping ratio R (volumetric efficiency) with diode resistance ratio C_B/C_F for different pumping pressures.

In the ‘liquid diode’, the flow of liquid in one direction produces a vortex which is subsequently removed in a stilling chamber, whereas flow of liquid in the opposite direction does not produce a vortex. The flow of liquid in the vortex-producing direction is accompanied by an energy loss due to the vortex and therefore the resistance to flow is greater in this direction than in the direction where no vortex is generated. The initial experimental work is being carried out using Perspex models and water as the liquid. With the first model, a backward to forward resistance ratio of 23:1 has been measured and when a better understanding of the way in which the geometry of the vortex chamber is reached, it is hoped that higher resistance ratios will be achievable. Figure 15 shows the pumping ratios, i.e. the number of pumping cycles needed to transfer one swept volume plotted against liquid diode resistance ratio for various operating conditions.

The ‘acid egg’ pump requires the use of moving parts in contact with the slag. This type of pump is used in the chemical industry to handle corrosive fluids but its use is so far restricted to low temperatures. Design studies are proceeding on a high temperature version but selection of a suitable material must first be made.

The 'vector pump' makes use of the fact that liquid drawn from a reservoir into a jet has a multidirectional flow, whereas when it is ejected from the jet is has a unidirectional flow. It has been demonstrated that reciprocating operation of a single jet produces better pumping action than was originally expected from consideration of suction and ejection separately. Four elements arranged in series and suitably phased give five times the head produced by a single element.

The development of a suitable pump is considered vital to the economic application of the slag air heater principle. Although the experimental results so far achieved give some encouragement in so far as small pressure rises have been achieved, they should be treated with extreme caution until multiple arrays giving the complete pressure rise have been tested and it is also shown that the critical geometries can survive in high temperature conditions.

2·3·4. *Pellet distribution into upper chamber*

Particles of nominally uniform size must be distributed uniformly over the horizontal cross-section of the chamber at a constant feed rate. Feeders with moving parts are unacceptable due to the high temperature and the corrosive nature of the material. A number of gravity feed systems have been considered and it has been shown that a simple flat perforated plate is suitable. The minimum size of the perforations, to avoid blockage by the $\frac{1}{8}$ in. nominal diameter particles, has been shown to be a $\frac{3}{4}$ in. diameter hole. Measuring the mass flow rate of one such hole, by using the $\frac{1}{8}$ in. nominal diameter ceramic spheres of density 2·5 g/cm^3, indicates that the required full scale mass flow rate will be obtained by pitching the holes at the corners of equilateral triangles having $6\frac{1}{2}$ in. sides. The stream of particles issuing from each hole is distributed laterally by impingement on a 60° cone located with its apex about $\frac{1}{8}$ in. below the orifice.

While this solution is valid for the $\frac{1}{8}$ in. diameter ceramic spheres, the particles produced in the full scale plant are unlikely to be truly spherical and will cover a range of sizes. Furthermore, their temperature in the distribution zone is likely to be of the order of 500 °C. Under these conditions, the seed particle surface could well be sticky and it is proposed to extend this study to include tests at the elevated temperature on the correct material. These will check the flow properties of the hot particles and will indicate whether larger holes and or funnel-shaped entries to the holes are necessary.

2·3·5. *Aerodynamics*

Prediction of the flow behaviour and uniformity of particle dispersion through the two chambers is one of the most imponderable features of the design at the present time. Any analytical approach based on diffusion of particles in an isotropically turbulent system is of limited value as local temperature gradients are bound to exist and give rise to asymmetrical secondary flows. An empirical approach using models is therefore being adopted.

Preliminary theoretical and model studies have been made to determine the optimum inlet and outlet geometries to give uniform vertical flow in the upper chamber. As a result of these studies a model 20 in. diameter by 30 ft. long has been constructed for use with $\frac{1}{8}$ in. nominal diameter ceramic spheres and is shown in figure 16.

The distribution system for this rig is that evolved from the particle distribution tests. This arrangement gives the correct full scale flow rate of particles per unit of cross sectional area. Windows are provided in the chamber wall to permit the observation of any irregularities in the particle flow caused by collisions between particles or between particles and the wall. Instrumentation is provided to monitor air flow rate, air velocity distribution, particle flow rate, air inlet and outlet temperatures, particle inlet and outlet temperatures, air pressure distribution and particle trajectory. Particle distribution is measured by weighing the quantity collected in each of a series of 2 in. square compartments covering the chamber cross-sectional area in a rectangular array.

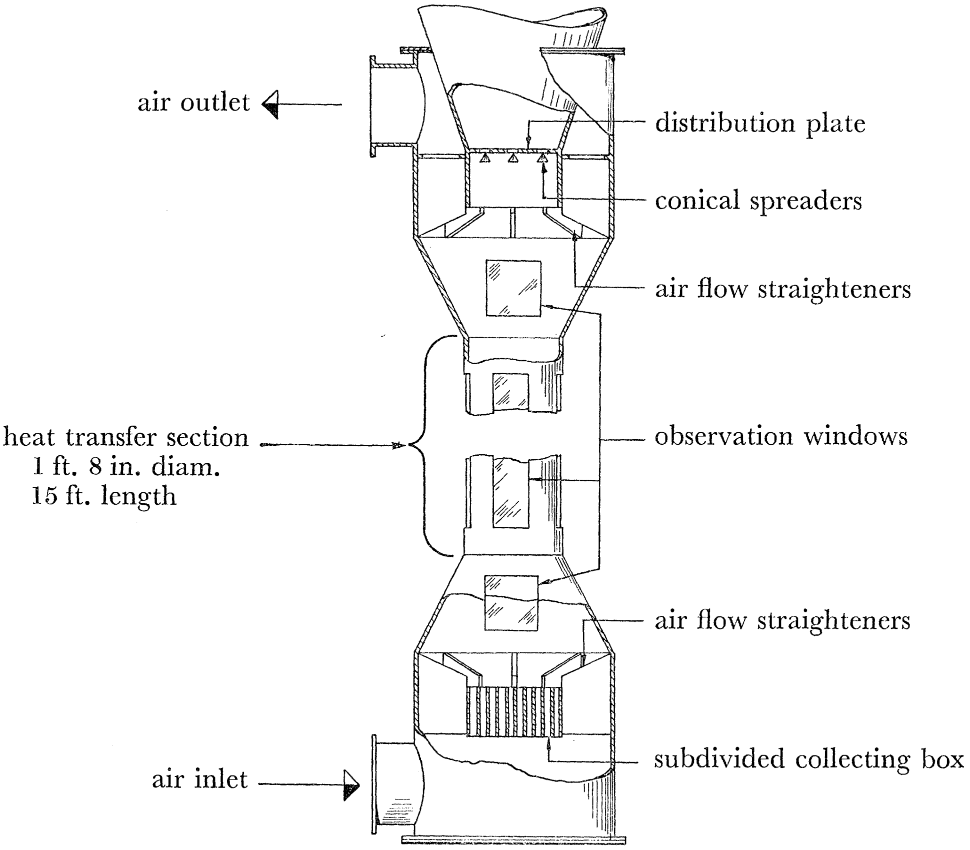


Figure 16. Test rig (upper chamber).

Stage 1 of the planned programme is intended to cover 'cold aerodynamics'—i.e. the achievement of satisfactory air flow conditions and particle distribution. Stage 2 will cover heat transfer characteristics of the chamber making use of hot air at a temperature of approximately 80 °C and cold particles. The third stage of the planned programme will check the operation of the chamber when a solid/liquid phase change of the particle material occurs, a material of suitably low melting point being used to simulate the seed.

Similar model studies are being carried out for the lower chamber, the first stage again being to cover the 'cold aerodynamics' of the system. A fluidized bed of the $\frac{1}{8}$ in. nominal diameter ceramic particles will form the lower end of the chamber and will assist in achieving a uniform air distribution as well as improving the heat transfer characteristics when the chamber is run hot. The second stage will be to use low melting point material, as in the final stage of the upper chamber work, to simulate seed droplets at the available temperature of 80 °C.

2·4. *Brick regenerator*

The brick regenerator is based on the established principle already used in the steel-making and glass-making industries for preheating air, generally to temperatures of the order of 900 to 1200 °C.

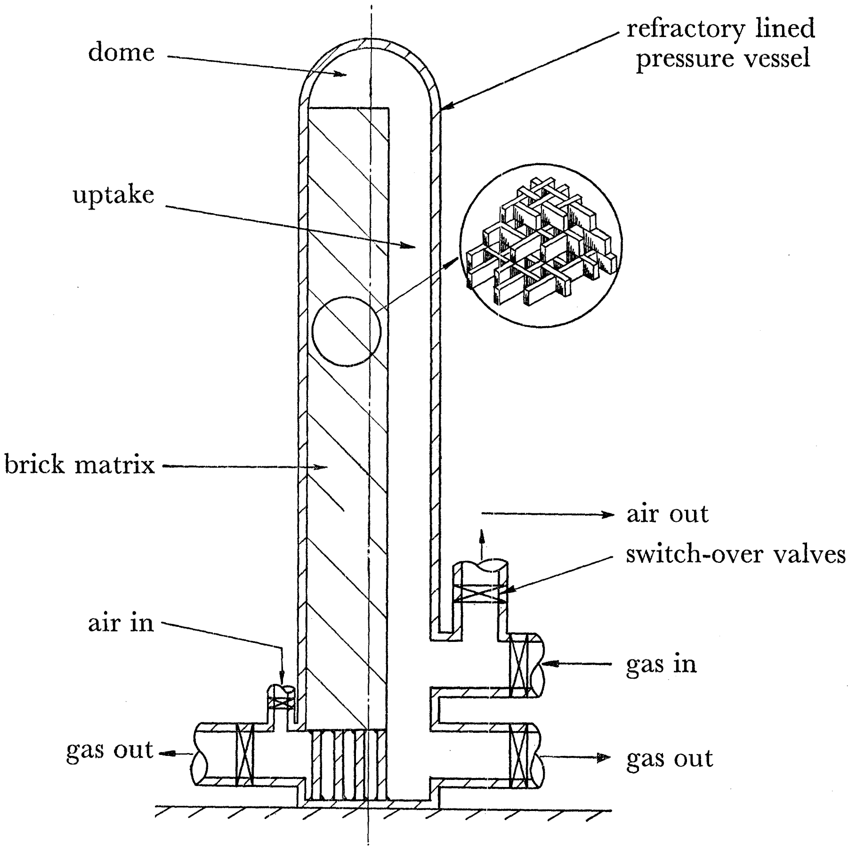


FIGURE 17. Sectional view of brick regenerator vessel.

This type of plant, illustrated in figure 17, is operated simply by heating a stationary ceramic matrix with, in this instance, the exit gases from the m.h.d. duct at a temperature of some 1650 to 1850 °C. After 20 to 30 min the matrix approaches equilibrium temperature and cold air is then passed over it. In order to ensure the continuous production of preheated air at relatively constant temperature, it would be necessary to arrange several suitably phased units in parallel.

The size of the units depends on the constitution of the matrix and more specifically on the minimum size of matrix gas passage which can be adopted without suffering excessive blockage by condensing gas constituents. Since the m.h.d. duct exhaust gases contain a large concentration of seed and fuel ash, this may require the use of large passages which could make this type of air heater prohibitively expensive for this application. The severity of this problem is best illustrated by table 3 where typical dust concentrations encountered in various industrial plants are given together with typical sizes of the matrix gas passages where regenerators form part of the plant.

An attempt has been made to predict the rate of seed deposition analytically for the case where molecular diffusivity equals thermal diffusivity and the effect of dynamic forces can be neglected.

It can be shown that the proportion of seed condensing on the wall surface to that sublimating in the main stream is

$$E \simeq \frac{T_{vg}}{T_s}\left[1-\frac{1}{2}\frac{A}{T_{vg}T_s}\Delta T+\frac{1}{6}\left(\frac{A}{T_{vg}T_s}\right)^2\Delta T^2\right], \tag{8}$$

where T_{vg} is seed saturation temperature, T_s is the condensing surface temperature, and $\Delta T = T_{vg} - T_s$.

TABLE 3. TYPICAL GAS DUST BURDENS IN INDUSTRIAL PLANTS

type of plant	dust burden (grains/cu.ft.)	minimum matrix gas passage size
p.f. coal fired boiler	10·4 (20% ash in coal, 20% excess air)	—
heavy oil fired boiler	0·02	—
hot blast stoves	0·05	1 in. diameter
glass melting tanks regenerators	1·50	6 in. × 6 in.
open hearth furnaces		
without O_2 lancing	2·0	6 in. × 6 in.
with O_2 lancing	5·0 to 7·0	9 in. × 9 in.
oil fired m.h.d./steam plant	16·9 (1 mol % K)	—
coal fired m.h.d./steam plant	29·2 (1 mol % K, 20% ash in coal)	—

Equation (8) indicates that fog and subsequent fume formation are promoted by a large temperature difference between the gas stream and containing surfaces. This is a simplified analysis of a most complex process, and experimental study of the seed deposition phenomenon is essential as much depends on the physical form of the seed as it condenses from the gas. Moreover, Hart has shown that the effect of radiative cooling can be considerable. An experimental regenerator test facility has therefore been set up in which this main parameter will be studied under conditions which simulate realistically those of a practical m.h.d. air heater.

A practical brick regenerator system for a 2000 MW plant would consist of a train of 12 units of which 2 will be on standby, 2 on pressurization and depressurization during switchover, 3 on air and 5 on gas. The cycle of operation of these units will be phased in order to reduce fluctuations in air temperature over the cycle time. The size of each unit cannot yet be determined until more is known about deposition rates, but if the blockage problem is similar to that encountered in glass melting tank regenerators, the external dimensions of each unit would be about 140 ft. in height and 30 ft. in diameter. Under these conditions this type of heater is likely to prove uneconomical because of the high initial cost of the bulky structure and the high heat losses from the extensive surface. The use of a matrix with smaller gas passages would lead to reduction in unit dimensions. To minimize heat losses, great attention must be paid to the layout of the gas and air ducting and one suggested design contains much of the ducting within the air heater vessels. During the intermittent operation of the regenerator units, the vessels will be alternately charged with gas at 1 atm pressure and air at 8 atm pressure. Large switchover valves will therefore be required, not only to isolate the fluids but to contain the very high differential pressure and these valves must operate under conditions of high dust burden and high temperature. Existing designs of valves in their present form would be unsuitable for m.h.d. air heater application. An improved design has therefore been evolved which best satisfied the requirements of gas tightness, minimum heat loss, adequate life and minimum cost requirements. The size of each valve would be 9 ft. diameter maximum aperture being dictated by the manufacturing size limitations. Since the maximum velocity of gas through the valve is restricted by pressure drop and erosion of the refractory walls, three valves will be required for controlling gas inlet and two for gas outlet. Water cooling of the switchover valves will be necessary, and since the amount of the thermal energy involved is considerable, it would have to be integrated with the steam plant feed heating system.

TABLE 4. PROPERTIES OF TYPICAL REFRACTORIES AVAILABLE IN TUBULAR FORM

material	recommended maximum service temperature in O_2 rich atm. (°C)	porosity (%)	density (g/cm^3)	thermal conductivity at 1000 °C*	coefficient of linear expansion, 400 to 1000 °C (10^{-6} degC^{-1})	mean specific heat, 0 to 1000 °C (cal g^{-1} degC^{-1})
1. lithium aluminium silicate (ceramic glass)	1000	†dense	2·00	12·5	0·6	0·25
2. mullite	1700	dense	2·68	15	5·0	0·23
3. alumina	1900	dense	3·80	40	8·1	0·32
4. magnesia	1900	dense	3·4	43·5	13·0	0·27
5. zirconia	2300	dense	5·4	14·4	11·5	0·17
6. silicon carbide (ceramic bonded)	1500	13	2·57	109	4·4	0·285
7. silicon nitride bonded silicon carbide	1750	8	2·87	113·5	4·4	0·29

* Measurements in Btu in. ft.$^{-2}$ h^{-1} degF^{-1}. † 'Dense' signifies porosity of under 5 %.

3. CERAMIC MATERIALS

All heating and containing surfaces for both direct and indirect high temperature stages must be made from ceramic materials, and a considerable experimental programme has been necessary to select satisfactory materials. Typical examples of the investigations are reported in this section.

3·1. *Indirect air heaters*

The tubular ceramic recuperator and rotary matrix regenerator are likely to be heated by flue gases from an oil fired combustor. The choice of refractories would be restricted by corrosive attack caused by the presence of oil ash constituents, in particular vanadium, sodium and sulphur compounds. The number of suitable materials available in tubular form of significant dimensions is very limited at the present time, the most promising of these are shown in table 4. Problems of leakage and vibration have been covered in a preceding section of the paper.

A programme of corrosion tests using these materials has been initiated in which tubular specimens of 1 in. internal diameter are suspended in a small oil fired furnace and are tested at varying levels of constant specimen temperature over the range 600 to 1600 °C with and without air cooling of the tubes.

A further series of tests is being carried out to check the extent of corrosion and blockage suffered by specially designed honeycomb matrices which are proposed as the basis for one rotary regenerator design (see §2·2).

3·2. *Direct air heaters*

The environmental conditions likely to obtain in the two forms of direct air heater, i.e. liquid slag and brick regenerators, are much more severe than those found in the indirect system. Containment problems are common to both forms of air heater but each has its special problems, e.g. erosion of atomizer nozzles and slag pump in the slag air heater, temperature cycling and valve design in the brick regenerator.

TABLE 5. TYPICAL PROPERTIES OF MAGNESIA AND ZIRCONIA BRICKS

property	MgO	ZrO$_2$
chemical composition	MgO 92 % Al$_2$O$_3$ 2 % SiO$_2$ 3 % CaO 1 % Fe$_2$O$_3$ 2 %	ZrO$_2$ 91 % HfO$_2$ 2 % SiO$_2$ 1 % CaO 5 % Fe$_2$O$_3$ 0·2 % Al$_2$O$_3$ 0·6 %
thermal conductivity, 500 to 1500 °C (cal cm^{-2} s^{-1} degC^{-1} cm^{-1})	0·06	0·005
specific heat, 500 to 1400 °C (cal g^{-1} degC^{-1})	0·27	0·17
coefficient of linear expansion, 50 to 1500 °C (degC^{-1})	11×10^{-6}	$5·5 \times 10^{-6}$
bulk density (g/cm^3)	2·8	4·5
apparent porosity (%)	18	20
limit of refractoriness (°C)	1650	1700

The experimental results obtained to date support the information available from the glass-making industry where regenerators operate with high temperature gases of high alkali content and indicate that the basic MgO refractories are attacked least. One other refractory material which exhibits promising chemical properties in this environment is zirconia stabilized by CaO or MgO but this is an inherently structurally unstable material, particularly under fluctuating temperature conditions, and moreover is much more expensive at present. All other known refractories, e.g. alumina, silica etc. are either chemically attacked by seed or are unsuitable as structural materials.

A wide range of magnesite bricks are commercially available, but for m.h.d. application only high grade materials, denoted by high MgO content are suitable. Other refractory compounds that are generally present as impurities are SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$ and CaO. The physical properties of the magnesite are dictated by the concentration of crystalline constituents, e.g. MgO, MgFe$_2$O$_4$, MgAl$_2$O$_4$, etc., which depend on the raw materials and the firing procedure adopted in their manufacture. Chemical stability of the refractory is reflected in minimum alteration of its crystalline constituents during operation. Typical properties of magnesite and zirconia refractories are summarized in table 5.

In order to select suitable containment materials for those areas exposed to vapour only, corrosion tests have been carried out using the equilibrium seed composition referred to by Hart (1965) over a range of steady temperatures. Typical results are shown in figure 18, plate 27. It can be seen that alumina, silica, titania were all severely attacked, zirconia suffered swelling and that thoria disintegrated due to thermal shock. The magnesia remained substantially intact, although it acquired a heavy surface deposit. It has been concluded that commercial high grade magnesite refractories should be suitable for containment materials in contact with vapour provided the surface temperature is not allowed to exceed 1600 °C.

The duties of refractories for lining vessels in contact with liquid seed are more onerous due to penetration of the material by the highly mobile liquid. A very dense refractory might appear at first sight to be a means of overcoming this problem although it has been found that molten potassium sulphate at 1200 °C diffuses rapidly through crucibles of high density, fusion-cast materials of only 3 to 5 % porosity. A further means of overcoming this problem under investigation is the treatment of the surface by high temperature flames or by plasma torch to produce an impermeable glaze, but this has not so far proved successful. A third approach is to rely on a 'frozen' layer of seed adjacent to the ceramic lining, maintained by the cooling effect of the wall. The structural stability of such a layer and the heat losses involved in such a system are being investigated.

In addition to corrosion resistance, the MgO refractories used for the brick regenerator matrix must exhibit good thermal shock resistance which is typified by such physical properties as coefficient of linear expansion, thermal diffusivity, Young's modulus, Poisson's ratio, rupture stress and shape. Since information available showed that basic bricks are more susceptible to thermal shock failure at high temperatures, tests were conducted by cycling the specimens every 20 min between 1100 °C and 1400 °C. The results which were obtained in an air atmosphere are shown in figure 19 and show that while considerable reduction occurs initially in cold crushing strength, it levels off and remains substantially constant for the limited number of cycles conducted. Additional tests over a similar temperature range are now being conducted on these materials to establish the effect of thermal cycling in a seeded atmosphere. Refractory bricks in contact with gas in which there is a high concentration of seed become saturated by the seed. This might be expected to lead to a change in such important properties as thermal conductivity and thermal diffusivity. However, as shown in figure 20, it has been established that seed penetration causes a 25 % decrease in diffusivity and a negligible change in thermal conductivity. This is due to the fact that heat transfer in the small pores is mainly by conduction and the conductivity of seed is similar to that of the air it replaces.

3·3. *High temperature ducting*

Transport of seeded, high temperature combustion products presents containment problems since the ducting must be constructed of insulating refractories that resist alkali attack. Magnesite refractories, which possess the best alkali corrosion resistance, are the only type economically viable but have relatively high thermal conductivity. A way of

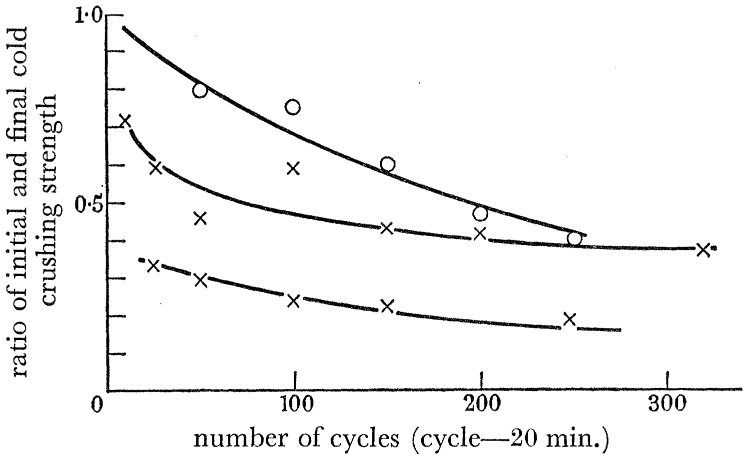
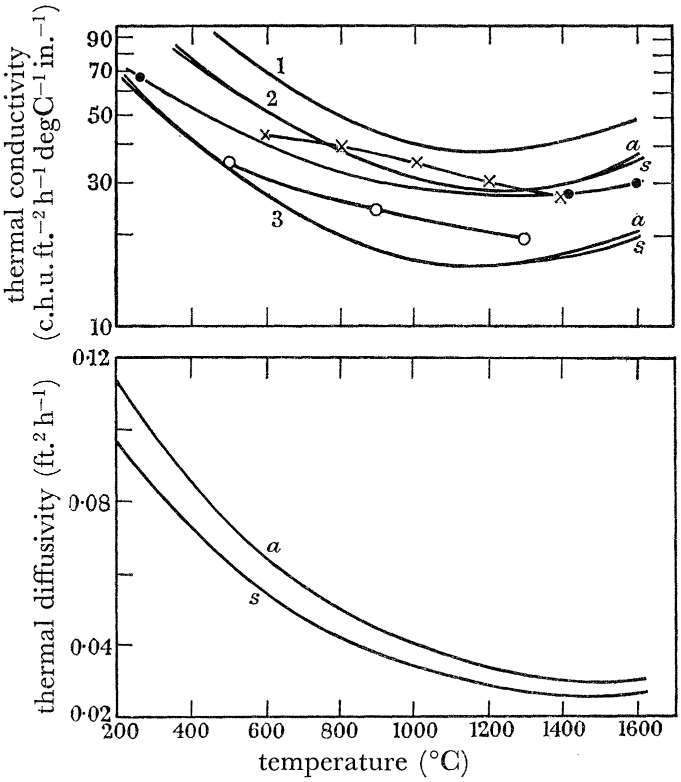


FIGURE 19. Effect of temperature cycling 1100 to 1400 °C on cold crushing strength of magnesite bricks.

	type	porosity	MgO	Fe_2O_3
×	A	21·6	95	< 0·1
+	B	18·6	94·9	0·6
○	C	13·8	96·2	1·5

atmosphere: air



1, MgO (0 porosity)
2, MgO (18 % porosity)
3, MgO (50 % porosity)
a, 0·1 in. air filled pores
s, seed filled pores

the plotting points show typical variations for commercial magnesite bricks (porosity 18 %)

a, air filled pores
s, seed filled pores

FIGURE 20. (Top) Thermal conductivity of magnesia and magnesite bricks, and the effects of porosity and seed penetration. (Bottom) Thermal diffusivity of magnesite bricks with seed penetration.

overcoming this difficulty is to adopt a composite duct lining. The inner lining would be of dense magnesite bricks ruffled backs followed by a second lining of high porosity magnesite refractory with compressible lining separating it from the pressure shell and allowing for any thermal expansion taking place.

4. Mass transfer and seed recovery

As the gaseous working fluid passes through the cycle: m.h.d. generator, air heater and conventional Rankine plant, its temperature falls continuously.

Simultaneously, with heat transfer, mass transfer of the condensable constituents of the working fluid can occur. In the oil fired plant these will be potassium sulphate plus certain ash constituents. The seed will deposit as condensate whose physical form will depend on the temperature difference between the gas and adjacent surfaces. It has been shown by Hart & Laxton (1964) that 90 % of the seed will condense as bulk liquid for a temperature difference of 20 °C. For a larger difference the proportion of bulk liquid condensate decreases and at 140 °C is typically of the order of 50 %, the remainder appearing as a gas borne smoke.

In any direct system (figure 1) mass transfer occurs irrespective of the type of air heater used, the rate depending on the physical properties of the seeded gas and particularly on the gas temperature and the saturation vapour pressure of potassium sulphate. Recent determinations of potassium sulphate saturation vapour pressure have been reported by Hart (1965).

One significant aspect of this data is that the saturation temperatures of 0·5 and 1·0 mol % potassium are 1300 and 1340 °C respectively, temperatures which may not be traversed in the air heater. Therefore, substantial quantities of seed (probably more than 50 %) will pass downstream of the air heater, aggravating the problem of boiler corrosion and seed capture. This effect is manifest in all directly fired heaters and thus the air heater can no longer be considered as a complete seed recovery device.

A detailed knowledge of mass transfer processes is particularly important for the slag air heater, where hot gas is brought into contact with large excess quantities of liquid seed. The extent to which seed from the m.h.d. gases will be carried through the slag air heater into the conventional Rankine plant is primarily dependent on the exit temperature of the hot gases. If this is 1300 °C, the seed concentration in the gases is approximately at the saturation level. Thus, at the very best the seed concentration in the gases leaving the air heater will be very close to 0·5 mol %, only a very small amount of seed will condense in the boundary layer adjacent to the slag particles and be thermally precipitated onto the particle surface. In the worst possible case the seed burden leaving the air heater would be saturation level plus smoke or fume from the seed evaporation taking place in the hotter part of the chamber without reprecipitation on to the slag particles. The seed concentration then carried through the air heater depends on the terminal temperatures of the air heater and might be of the order of 1·5 to 2 mol % potassium.

The extent of seed evaporation in the air heating chamber of the regenerator has been calculated for an air preheat of 1200 °C and initial seed temperature of 1300 °C. For these conditions only 0·019 mol % potassium was evaporated and would therefore be carried through with the preheated air as vapour into the m.h.d. combustion chamber. This quantity is much less than the optimum concentration of seed in the m.h.d. gases for ionization and therefore would not cause a reduction of efficiency in the generator.

The continuous deposition of seed as the gases pass through the cycle begins at the air heater and ends finally with the capture of fine gas borne particles in what will probably be a combination of electrostatic precipitator and bag filter. Since the seed is not recovered at a precise part of the plant, the whole process of seed recovery becomes difficult and is further complicated by the presence of acid phases in the potassium sulphate at temperatures below 500 °C. More detailed discussions of the chemical constitution and its corrosion nature are presented in the following paper by Hart & Laxton (1965). The mechanical engineering aspect of seed recovery is the subject of current study, which is not yet at a stage where final conclusions can be drawn.

5. Discussion

The preheating of combustion air to a temperature in excess of 1200 °C is an essential feature of m.h.d. power generation. The development of such an air heater to produce tonnage quantities of air at 1200 °C is complicated by the high pressure differential between the heat exchanging fluids and by the high concentration of corrosive seed chemicals present in the gas.

In an m.h.d. power station, the air heater can be arranged in two general ways. It can be heated directly by the exhaust gases from the duct or separately heated by an independent fuel supply. In the indirect system the high pressure differential can be avoided and seed excluded, although it would then be present in greater concentration in the remaining components downstream. Such a system is less efficient than its direct counterpart as part of the total fuel input is not utilized at the high temperature level of the m.h.d. process. Such a departure from thermodynamic ideality is bound to restrict the development potential of the system. However, the separately fired heater may prove less expensive to construct and the choice of arrangement, supposing a technical solution to be possible in both cases, will depend on the precise capital savings compared with the increased generating costs.

It will not be possible to say which of the four types of air heater under study will prove most suitable until certain key experiments have been performed and the results assessed.

The tubular ceramic recuperator and the rotary matrix regenerator can only be considered as separately fired systems. The second of these offers the prospect of the most compact unit, but the realization of this depends on the minimum size of honeycomb passage which will remain unblocked. It should prove possible to keep the tubular recuperator free from blockage and in this case the compactness will be governed by the effectiveness of joints to restrict cross leakage. Both forms of matrix are inherently fragile and ability to resist thermal and mechanical shocks and vibrational stresses must be demonstrated.

The principal attraction of the liquid slag regenerator is that it does not rely upon the integrity of a solid matrix to transmit heat but, accepting as it does, a molten heat exchange medium, opens up the prospect of further development beyond an air temperature of

1200 °C. However, this design is a longer term prospect because of the number and severity of the technological problems to be solved. The principal ones are considered to be the effective atomization of slag, correct aerodynamic flow in the two heat exchange chambers and the development of a slag pump, without which the structure would become impossibly expensive.

Of the four types under consideration the minimum development is required by the brick regenerator. The two main uncertainties are the minimum size of passage which can be used without excessive blockage and the development of suitable valves to withstand the high gas pressure differential. It is likely, however, that passage size will be such that the complete structure will be bulky, expensive and associated with unacceptable surface heat losses. Under these circumstances, the system can be usefully regarded as a fall back position.

The development of materials for reliable service under corrosive high temperature conditions is a key part of the air heater programme described. Existing materials may be expected to withstand the conditions of the separately fired system although the most satisfactory of them are not yet available in the correct geometries. For direct systems containment materials for the gaseous phases can be safely chosen from commercially available magnesites. For the liquid phases, however, there are less grounds for optimism and the production of dense materials or impermeable surfaces appear to offer the only hope. For atomizer nozzles of the slag air heater there are at present only limited prospects of success, although this is physically such a small component that a high specific cost could be tolerated.

Recovery of seed from an m.h.d. power station should not be regarded as the function of one individual piece of plant. The heat and mass transfer processes are intimately bound together and, as the gas gradually cools on its passage through the plant, so the seed will separate out and deposit on the heat transfer surfaces throughout. In the highest temperature zones, the air heater and the water cooled diffuser, the seed will deposit in liquid form and must be removed in the manner adopted for slag tapped boilers. In the cooler zones, solid deposits will form which may be loose and removable by soot blowers or at worst may combine with fuel ash to form hard bonded deposits. A proportion of the seed will remain in the coolest gas as fume and fine dust and must be removed by filters or electrostatic precipitators before discharge to atmosphere.

Development of the air heating systems described in this paper forms part of a collaborative research programme being undertaken by the Boiler and Electrical Plant Manufacturers, the National Coal Board and the Central Electricity Generating Board.

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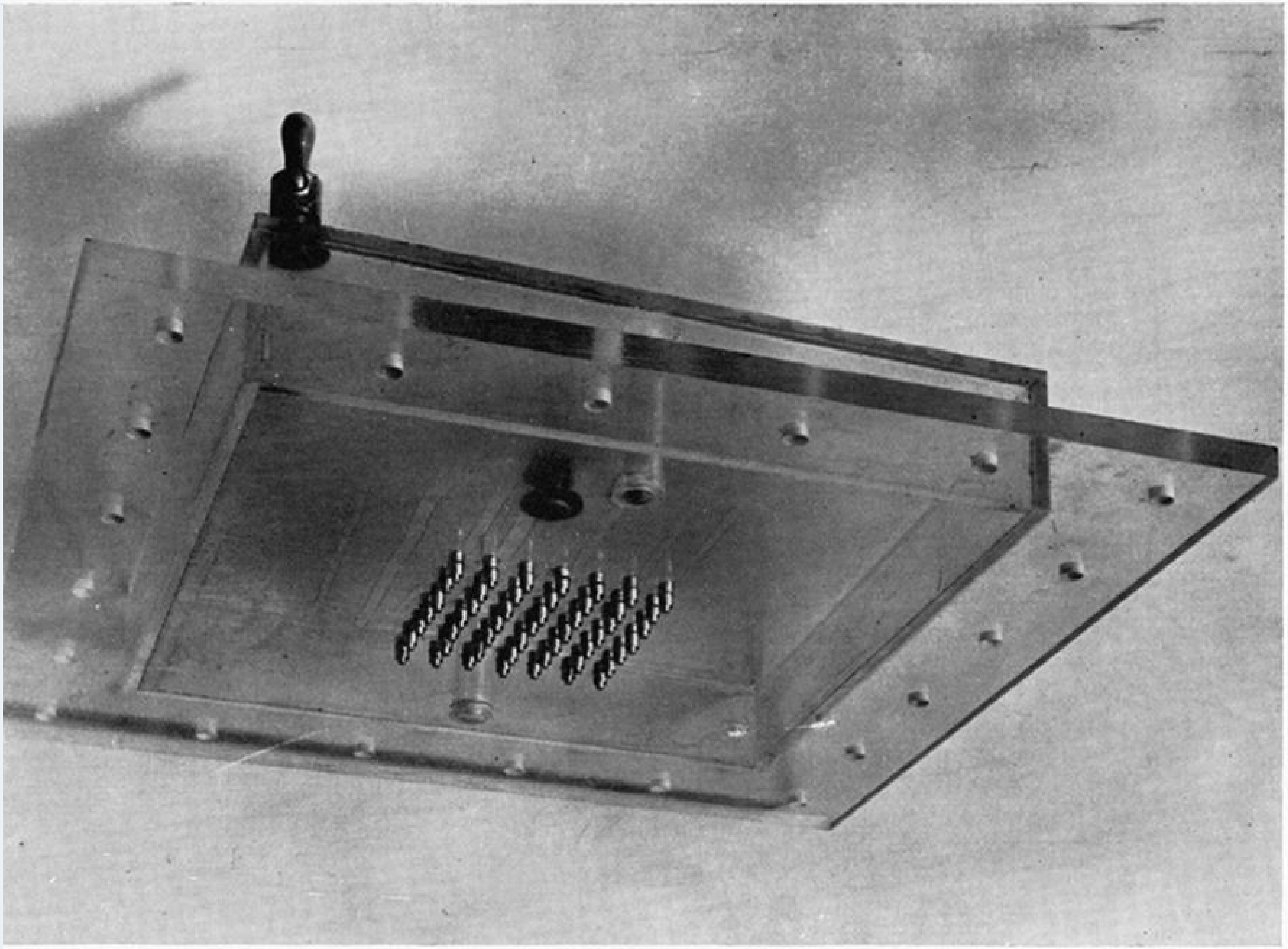
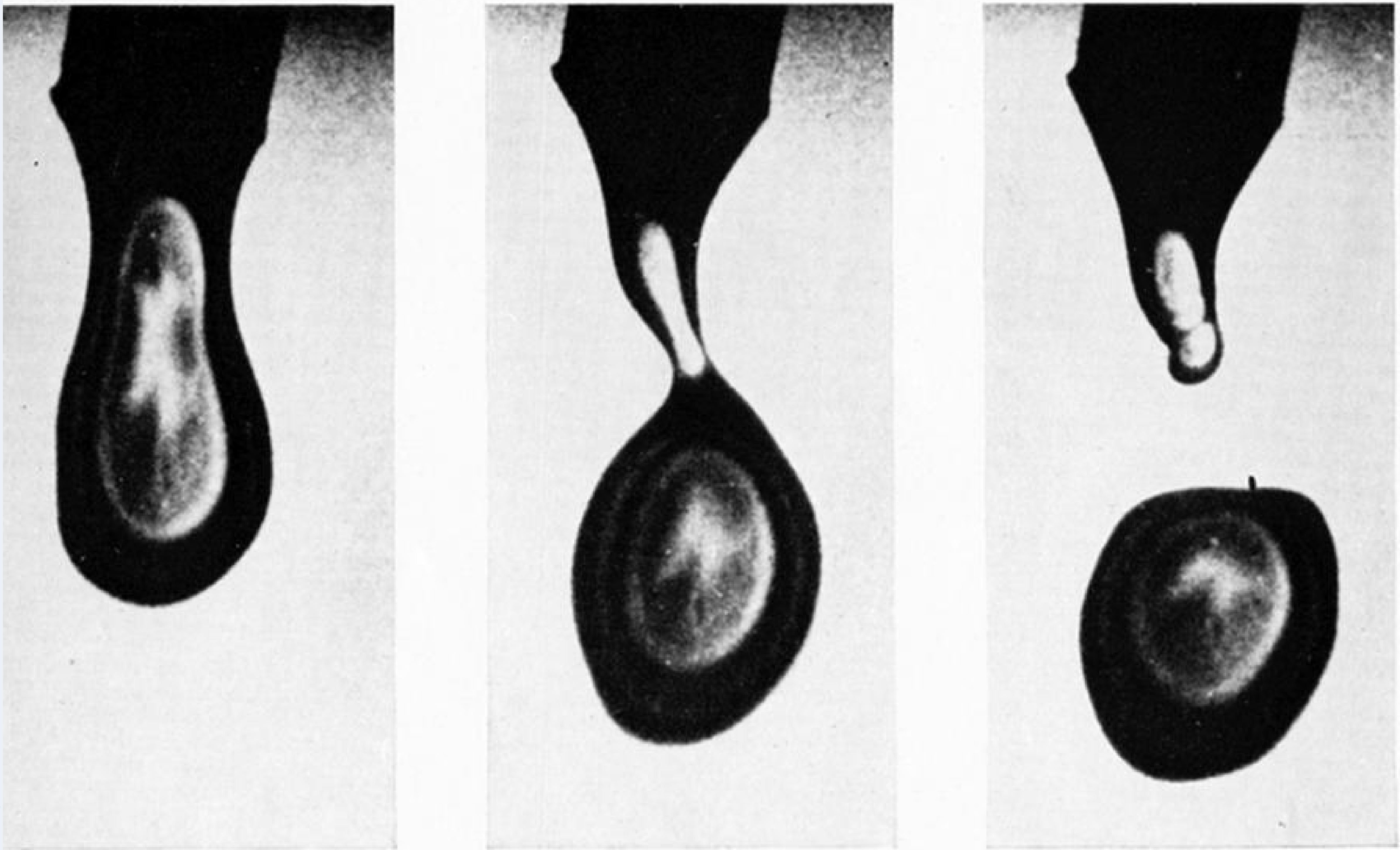


FIGURE 9 (A). Multiple dropper header supply tank with droppers at 0·65 in. centres.



IGURE 9 (B). Formation of stable drop of 0·18 in. diam. from stub of diameter 0·125 in. (Cine film, 750 frames/second.)

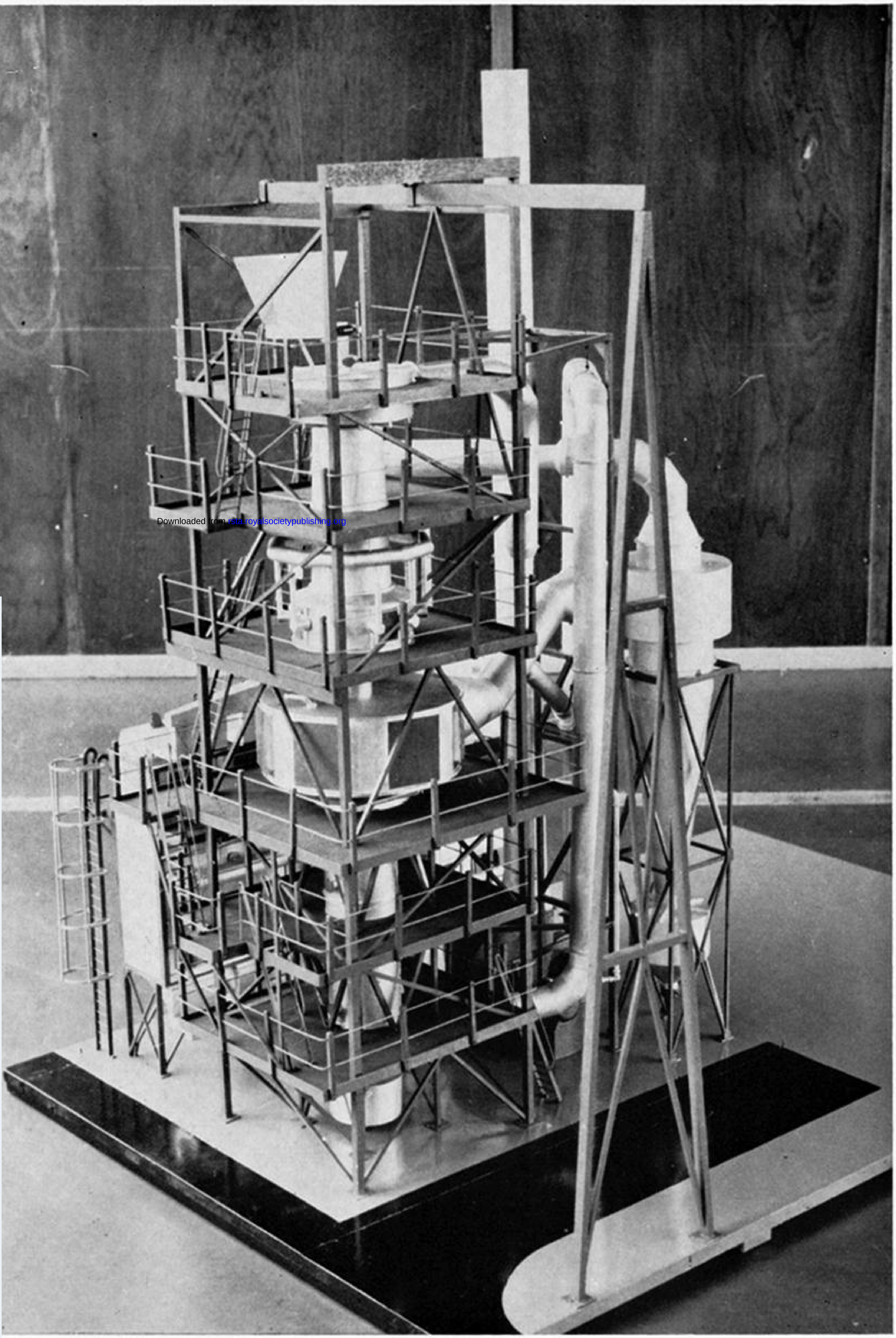


FIGURE 11. Model of the liquid slag atomizer test rig.

FIGURE 18. Refractory materials before and after exposure to hot seed vapour.