DESIGN OF HEAT-RECOVERY AND SEED-RECOVERY UNITS IN MHD POWER GENERATION

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Abstract

Crucial and limiting engineering and materials problems associated with the design of an MHD steam bottoming plant are discussed. Existing experimental and theoretical results on corrosion, fouling and deposits, potassium seed recovery and regeneration, are reviewed. The state of knowledge regarding the design of heat recovery and seed recovery units for coal-fired MHD plants is inadequate at the present time.

Introduction

A successful design of the heat recovery and seed recovery portions of a projected coal-fired MHD power plant will require the solution of several unique and challenging materials problems. These problems lie in the areas of corrosion, fouling and deposits, seed recovery, and seed regeneration. Corrosion and deposit formation are familiar areas of concern to the boiler industry; while the problems of seed collection and regeneration are essentially new problems peculiar to MHD technology.

Fouling of tubes, blockage of equipment passages, destruction of metal and refractory heat transfer surfaces, heavy losses of alkali seed into coal slag, and the inability to remove and regenerate the spent MHD seed, can have severe operational and economic consequences. A number of individuals with experience in the utility industry have expressed serious reservations about the ability of MHD researchers to surmount these problems (12,23). This paper discusses these problems and describes relevant Bureau of Mines experience in these areas.

Downstream Environment

Initially, we will seek to partially characterize the type of downstream environment to which candidate metals and refractories will be exposed. Fig. 1 displays a set of typical operating temperatures prevailing in various downstream components for both a separately and directly fired MHD powerplant. One mode of operation, which currently (2,18) is receiving serious consideration, is combustion of coal with 95% stoichiometric air, with an additional 6% introduced downstream in the superheat or reheat sections of the steam plant, in order to complete combustion. This procedure is carried out to reduce plant NO_x levels.

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As the MHD combustion plasma cools, a number of significant phase changes and chemical reactions take place. Within the MHD channel itself, molten coal slag condenses out of the MHD combustion gas, leading to the formation of a slag coating on the generator electrodes and insulators. At cooler downstream locations, molten slag and solid fly ash deposit out on the walls of the various components, as the gas phase is progressively depleted of its ash constituents. The composition of molten coal slag varies with temperature as a result of the differing volatilities of the various slag constituents. Each operating temperature range corresponds to a somewhat different slag environment. The portion of the coal ash which does not condense or freeze on component surfaces is blown through the system and ultimately collected as solid fly ash.

Unfortunately, the potassium MHD seed also reacts with coal slag to form insoluble potassium-aluminum-silicon-oxygen compounds. This fact has been verified both experimentally and theoretically (2,20,21). This reaction commences at temperatures encountered in the MHD channel and continues until substantial quantities of potassium are captured by the molten slag. Any seed trapped in such a manner has proved impossible to recover using conventional hot water extraction techniques. Fresh MHD seed must then be added to the combustor to compensate for this loss. However, below 1500°K a mixture of soluble potassium salts (K_2CO_3 , K_2SO_4 , K_2S , etc.) condenses out of the MHD exhaust gas. Fortunately, these salts are susceptible to recovery by hot water extraction.

At still cooler temperatures, the seed phase freezes, which would tend to prevent the corrosive attack on materials by the molten salt mixture. The seed phase, itself, is a rather complex mixture of potassium compounds. However, in many instances, two components may be dominant. Probably the three most common mixtures will be K_2S - K_2CO_3 , K_2CO_3 - K_2SO_4 and K_2S - K_2SO_4 . The prevalence of these mixtures are dependent on the fuel:air ratio. Phase diagrams for these systems are available (9,17,20). Freezing points as high as 1070°C and as low as 600°C have been reported.

Therefore, it becomes apparent that a knowledge of phase distributions and compositions within the downstream plant system is extremely important. The USEM High-Temperature Chemical Equilibrium Program (22), developed for the calculation of the chemical compositions and thermodynamic properties of complex multiphase equilibrium mixtures, has been employed to predict trends in these areas. It should be realized that the results of this program are dependent on the accuracy and availability of data from standard sources such as the JANAF Tables.

The following figures provide a few illustrations of its capabilities. Fig. 2 indicates the shift in composition with temperature of a typical potassium-containing MHD coal slag. For example, it is clear that the kind of slag forming in the MHD diffuser will be different from that forming in the low-temperature air heater. Fig. 3 displays the depletion of potassium from the gas phase on cooling, followed by an increase of potassium in the molten slag phase and finally, the development of a soluble seed phase. Fig. 4 illustrates

the importance of high slag rejection in the MHD combustor in lowering the loss of potassium into molten coal slag. Fig. 5 indicates the effect of reduced air operation on potassium compound formation. K_2S becomes quite prevalent as the air level is reduced; while K_2SO_4 is the dominant compound for operation with excess air. This fact becomes important in MHD seed regeneration, where the conversion of K_2SO_4 to K_2S demands the expenditure of a considerable quantity of energy.

The composition of actual wall deposits at a particular temperature depends upon fluid mechanical, heat transfer, and mass transfer considerations which are beyond the scope of this equilibrium model. However, the equilibrium program does provide a valuable guide as to what phenomena may be reasonably anticipated in the MHD-steam bottoming plant. For example, Spencer (21) has successfully correlated the predictions of this model with experimental data on potassium seed losses into slag, previously acquired from operation of the USBM pilot combustion facility. In summation, more basic information on component thermodynamics and phase behavior is urgently required to establish a firmer scientific basis for resolving the critical problems of corrosion, deposits, and seed recovery.

Corrosion

The problem of fireside corrosion of boiler and superheater tubes has had a profound impact on existing conventional steam plant construction. From 1930 onwards, maximum steam operating temperatures have been pushed continuously upwards from 850°F (454°C). By the mid-1950's, steam temperatures had ascended as high as 1200°F (649°C) in the Eddystone power plant of the Philadelphia Electric Company (19). Severe metal wastage by corrosive deposits was experienced in the high temperature zones of a number of units in the Eddystone plant (16). These deposits were related to the formation of complex alkali sulfates at 1050°F (566°C). As a result of this experience, design steam temperatures for utility boilers were lowered and have remained relatively static at 1000°F (538°C).

Metals in an MHD environment will face an extremely severe test because of the presence of high concentrations of alkali and sulfur. Alkali and sulfur in a fuel have been regarded as precursors of corrosion and deposit problems. Michel and Wilcoxson (15) found that alkali addition to a low alkali coal leads to increased fouling of superheater tubes. The presence of sulfur leads to SO_3 and complex sulfate formation; both of which are directly involved in corrosion reactions (19).

Only a limited amount of corrosion research related to MHD has been undertaken.

British workers (11) studied a number of representative superheater metals under oil-fired MHD conditions. Air-cooled tubular specimens were exposed to flue gases from a gas-oil burner at metal temperatures of 400-650°C (752-1202°F). Because of their interest in oil-fired MHD, vanadium and sodium were added to the fuel. Additional SO_2 was also added to yield 2000 ppm of SO_2 in the flue gas.

The tests were for periods of 70, 250, and 1000 hours at a seeding level of 0.01 atom % K. It was realized that this seeding level was substantially less than that to be expected in commercial MHD operations. However, earlier studies had shown that the deposit composition on metal surfaces was independent of seed level and that the rate of corrosion was not affected by the amount of deposit.

An average corrosion rate of 50 nanometers/hr was taken to indicate that a material was acceptable for plant use. It was found that corrosion rates were, in general, far above the acceptable level for potential superheater metal temperatures of 547-597°C (1012-1107°F). Only one steel, 60 Cr/40 Ni, was found to be suitable for temperatures up to 597°C (1107°F). Because of the cost and low creep strength of this steel, it was concluded that it could only be used as a coating or shielding material.

Corrosion rates at 250 hours were lower than those measured over 70 hours. In some cases, the rates measured over 1000 hours were still lower. Despite this, the conclusions regarding the suitability of the metals studied remained unaltered.

In some of the 70 hour tests, no vanadium was added to the fuel. This only resulted in about a 50% reduction in corrosion rates which still placed the materials tested (except 60 Cr/40 Ni) outside the range of acceptability.

Hals, Keefe, and El Bindari (10) studied corrosion of various steels and high-temperature alloys used in boiler tubes and conventional heat exchangers. An MHD atmosphere was simulated by injecting synthetic coal ash, sulfur, and potassium salts (K_2CO_3 or K_2SO_4) into the combustion products of a natural gas/enriched air mixture. The seed level of the resulting plasma was 0.2 mole-% potassium. Tube metal temperatures were controlled between 350°F (177°C) and 1760°F (960°C).

Severe corrosion after 100 hours and tube failures after 200 hours were experienced at tube-metal temperatures above 1550°F (843°C). The corrosion was attributed to formation of liquid mixtures of K_2SO_4 - Na_2SO_4 , a system which exhibited a minimum melting point of 1530°F (822°C). The molten sulfates attacked the iron and nickel in the tubes to form the sulfides, releasing alkali oxides into the gas phase to again form alkali sulfates by reaction with SO_2 and O_2 .

No metal corrosion was observed at temperatures below 1530°F (822°C). In particular, no corrosion was experienced by formation of complex alkali sulfates or pyrosulfates which have been reported to cause severe corrosion of superheater and reheater tubes at metal temperatures of 1025-1300°F (550-704°C), and of furnace wall tubes at 600-700°F (311-371°C) in coal-fired boilers. That no such corrosion occurred was attributed to the unique operating conditions of an MHD system; i.e., near-stoichiometric combustion, high combustion temperature, rapid cooling, and uniform gases tend to suppress SO_3 formation, which is a factor in formation of the pyrosulfates and complex alkali sulfates.

The Bureau of Mines investigated the corrosion characteristics of various boiler tube metals in a coal-fired combustion system (3). A cyclone combustor was built that was capable of burning 125 lbs/hr of coal and producing flame temperatures of 4000°F (2204°C). Ten different metals and alloys were studied ranging from inexpensive carbon steel to very expensive Haynes 25 (a high cobalt alloy). These results are reported in Table 1.

TABLE 1.- Metal Loss of Corrosion Specimens in Combustion Gas
With Unseeded Coal and in Combustion Gas with Coal
Seeded With Potassium Carbonate

Material	Metal temp., °F	Flue gas temp., °F	Metal loss while burning unseeded coal, inches	Metal loss while burning seeded coal, inches
Carbon steel (A 106)	800	1800	(1)	0.0075
Croloy 2½	800	1800	0.0000	0.0015
Croloy 5	800	1800	0.0025	0.0075
446 Stainless steel	1100	2100	0.0000	0.0000
406 Stainless steel	1100	2100	0.0055	0.0035
316 Stainless steel	1100	2100	0.0000	0.0000
310 Stainless steel	1100	2100	0.0000	0.0000
310 Stainless steel	1500	2500	0.0015	(2)
Nickel	1500	2500	0.0035	(2)
Inconel	1500	2500	0.0000	(2)
Haynes 25	1500	2500	(1)	0.0005

(1) Cooling air failure caused loss of specimen.

(2) Completely oxidized after 50 hours.

Test samples were located at various points in a refractory-lined tower following the combustor. Metal surface temperatures of 1500°F (816°C), 1100°F (593°C), and 800°F (427°C) were maintained by air flow through the tube specimens. Flue gas temperatures corresponding to these surface temperatures were 2500°F (1371°C), 2100°F (1149°C), and 1800°F (982°C), respectively. The design velocity of the gas through the tubes was 80 ft/sec.

In one experiment, coal containing 4.4% K₂CO₃ was burned over a 100 hour period at 105% of stoichiometric conditions. The results were compared with those of a similar experiment in which unseeded coal was used. The specimens exposed to the potassium-containing flue gas were more severely attacked than those exposed to the flue gas of the unseeded coal.

At metal temperatures of 1500°F (816°C) and at flue gas temperatures of 2500°F (1371°C), the 310 stainless steel, nickel, and Inconel samples were completely destroyed by the seeded gas. Haynes 25, although slightly attacked, would probably yield satisfactory service under the existing conditions.

No corrosion at 1100°F (593°C) metal temperature, in a 2100°F (1149°C) seeded flue gas, was found with 310, 316 and 406 stainless steels. However, 406 stainless steel was severely attacked in both the seeded and unseeded flue gas.

Both carbon steel and Croloy 5 were attacked at metal temperatures of 800°F (427°C) in a 1800°F (982°C) flue gas. It was concluded, though, that Croloy 2½ might fulfill short term use for these conditions.

Corrosion specimens of 310 stainless steel, Inconel, and nickel, exposed to 2500°F (1371°C) unseeded flue gas, were removed and weighed after 83 hours. Weight loss was directly proportional to the nickel content, the maximum being 14% for nickel and the minimum being 1% for the 310 stainless steel. Although the average diameter of the Inconel sample remained constant, the sample was furrowed and suffered a 9% weight loss. Electron-beam microprobe analysis revealed sulfur attack at the alloy grain boundaries. Sulfur-nickel reactions appear to increase the grain size and cause increased metal loss; the addition of alkali increases the corrosion rates.

It is apparent that the need exists for considerably more research in the area of metal corrosion under MHD conditions. The investigations carried out to date have been fragmentary and of relatively short duration. The studies of the British and Hals, et al., while offering some insight into potential problems, are not truly representative of coal-fired MHD conditions. The work of the Bureau of Mines, although simulating the MHD environment more closely, was limited in scope. Questions to be resolved include the effect of reduced air operation on corrosion, the enhanced destructive effects of an alkali-sulfur containing flue gas, the role of SO₃, alkali trisulfates and molten sulfates in metal wastage reactions, and the development of corrosion control methods.

The steam bottoming plant and metallic heat exchangers represent key components in the successful development of MHD combined cycle power generation. Only a greatly expanded research effort will elucidate the solutions to corrosion related problems involving these components.

Deposits

As previously indicated, the presence of solid deposits on heat transfer and refractory surfaces is a serious concern. Where and to what degree such deposits occur will have a substantial impact on corrosion, seed recovery, heat transfer, and equipment maintenance.

There is only a limited amount of evidence available from MHD experiments to date. Mawatari, et al. (14) studied seed deposition in metal shell-and-tube recuperative air heaters. In one series of experiments, kerosine was burned with preheated air and seeding was accomplished by injection of powdered K_2SO_4 or methanol solutions of KOH. Potassium concentrations in the working fluid ranged from 0.1 to 1 wt-%.

It was found that as long as the gas temperature was maintained above the melting point of the seed material, deposition in the air heaters was moderate. Even though the metal surfaces were at temperatures below the melting point, the deposits were of limited thickness since the surface of the deposit was molten. The thickness of the layer was about 3 mm.

In experiments where the gas temperatures were below the seed melting point, seed deposition was so severe as to nearly block the gas passages completely. The system could only be operated for short periods because of the rapid pressure build-up in the air heaters.

To overcome the seed deposition problems, a mechanical seed removal device was used. This device was simply a scraper that was operated intermittently. The periodic removal of deposits from tube surfaces permitted long term, steady-state operation of the system. However, it was necessary to water cool the seed removal device which resulted in considerable heat losses. When it was not cooled, sticky deposits formed on the device itself which were difficult to remove completely.

The Bureau of Mines has accumulated relevant experience with such deposits in their coal-fired combustor test facility. Following combustion, the MHD exhaust gas, passes through in succession an MgO brick chimney, an air-cooled Haynes 25 alloy heat exchanger, an MgO refractory crossover section, two air-cooled stainless steel heat exchangers, an air-cooled-carbon steel heat exchanger, and a set of baghouse filters. This system is depicted in Fig. 6, together with the approximate temperature levels existing in each section. This heat recovery system spans a temperature range of 350°F (177°C) to 4000°F (2204°C), and includes a number of pieces of equipment which undoubtedly will be encountered in an actual MHD steam-bottoming plant.

This system was run for several hundred hours under a wide range of operating conditions: fuels such as gas and coal, oxidizing and reducing conditions, together with a number of different seeding compounds and seeding levels. Thus, the deposits produced do not typify one definite operating condition, but a composite of many different operating conditions. When this system was disassembled to make way for a new system, several interesting observations were made. First, the MgO bricks in the high-temperature chimney were hardly attacked, except for a reddish deposit on the outside of the bricks. Fig. 7 is a picture which shows the outer surface and the inner cross-section of a typical brick.

Evidently, the temperatures were so high that a corrosive seed phase which could penetrate the bricks was absent. In addition, the fact that approximately 70% of the coal ash was rejected as slag in the MHD cyclone combustor may also have inhibited attack here. This encouraging result indicates that, at gas temperatures similar to those anticipated in the high-temperature MHD air preheater section, seed-slag blockage and attack may be preventable by careful design.

At the hot end of the Haynes 25 heat exchanger, pitting ensued on exposure to the 3000°F (1649°C) flue gas, while at the cold end no corrosion occurred on exposure to 2000°F (1093°C) flue gas. In sharp contrast to these conditions, profuse solid deposits formed on the wall of the uncooled refractory-lined crossover section. One such deposit is shown in Fig. 8. Interestingly enough, these heavy deposits caused no apparent damage to the refractory.

Some minor deposits were noted in the stainless-steel coolers, but again no damage was experienced at a wall temperature of 500°F (260°C). The flaking of these deposits led to the plugging of several of the 1-3/4" carbon steel tubes in the final air-cooled heat exchanger beneath the stainless steel coolers. Fig. 9 shows the fouling and blockage of a number of tubes. Narrow passages and small tubes should obviously be avoided.

Surprisingly, no sticky, glass-like deposits, characteristic of the formation of a molten seed phase were reported. From the powdery appearance of the deposits, it is perhaps possible that these deposits may have formed as a fine solid/liquid fume or mist impinging on the tube surface.

Seed Recovery

The MHD seed must be collected, recovered in a relatively pure form, regenerated to reduce its sulfur content, and recycled to the combustor. MHD seed losses beyond 2-5% have been generally deemed to be economically non-viable (2,13). The magnitude of this permissible seed loss depends on the price of potassium salts and coal, both of which have been rising dramatically of late.

Wall deposits in an MHD system can be blown off using air or steam as in conventional boiler practice, provided the deposits are not of the adherent glass-like variety. Special techniques would then be required. The seed-ash residue is either collected directly from each process unit or blown through the plant to appropriate dust collection equipment. Employing a baghouse filter, the USEM obtained a particulate collection efficiency of approximately 99.5%. The British, Japanese, and Avco have reported successful operation with electrostatic precipitators (7,10).

The particulates collected in the USBM system had a distribution of sizes in which about 90% (by wt) fell between 1 and 5 microns in diameter (1). This is an order of magnitude smaller than the fly ash from a conventional coal-fired power plant and should be borne in mind when selecting gas clean-up equipment. A typical photograph of such a fly ash collected in an unseeded run in the USBM experimental apparatus is shown in Fig. 10. Various combinations of gas-clean-up devices, such as mechanical cyclones, Venturi scrubbers, baghouse filters, and electrostatic precipitators could be tested.

Spent MHD seed leaving the plant will be either associated with the fly ash or the frozen coal slag. That portion associated with the slag is chemically locked into the frozen slag, and the chances of economic recovery are remote. On the other hand, fly ash-seed mixtures are amenable to treatment. The collected fly ash-seed mixture is initially subjected to a hot water extraction step in which two fractions result--a concentrated extract of soluble potassium salts and insoluble potassium-containing fly ash residue. The filtrate is fed to a vacuum crystallizer for water removal. The recovered potassium is collected and stored in lock hoppers. The insoluble residue can be recycled or discarded, depending on the fraction of potassium in it. The USBM seed recovery-sulfur removal system is shown in Fig. 11. For the purposes of simplicity, we have assumed the primary salt produced to be potassium sulfate, although other salts of potassium are undoubtedly present.

Raman spectra studies have disclosed the existence of water-unextractable potassium alumina silicate compounds interspersed in the fly ash. It has also been established experimentally that the level of seed extractability is directly proportional to the efficiency of slag removal from the MHD combustor. Potassium recoveries exceeding 99% were obtained for simulated slag rejections above 90% (2). This tends to accentuate the importance of clean combustion.

Losses of seed can take place in two ways: either as a direct loss to the MHD slag or as part of the unextractable seed-fly ash residue. Both possibilities should be minimized as much as is technically feasible. All of the steps outlined here are accepted unit operations, but they must be checked out on a reasonable scale prior to implementation.

Seed Regeneration

The Bureau of Mines has shown in earlier experimental work that open-cycle MHD has a self-contained sulfur removal system (2,4). The MHD seed itself is present in sufficient quantities to capture the sulfur contained in most American coals. In fact, SO_2 levels as low as that of natural gas combustion are achievable provided sufficient quantities of seed are added.

However, for this process to succeed, the seed regeneration step is a pivotal one. The sulfur-bearing spent seed must be regenerated to produce a partially sulfur-free seed, prior to being recycled back to the combustor. Earlier work has described some of the kinetics of the relevant reactions (8). The seed regeneration reaction proceeds at 1472°F (800°C) and essentially at atmospheric pressure. The kind of reactor to be adopted will be determined as part of the scale-up procedure.

The spent seed, rich in K_2SO_4 , reacts with a hot reducing gas mixture regenerating a partly sulfur-free seed and liberating gaseous H_2S . H_2 -steam, synthesis gas-steam, producer gas-steam are likely candidates for the reducing gas. If other potassium-sulfur compounds containing less oxygen such as K_2S or $KHSO_3$ are present, the energy and capital requirements for desulfurization will be correspondingly reduced. Enough sulfur is removed from the spent seed to balance the sulfur contained in the original coal. This leads to the complete elimination of SO_2 from the products of coal combustion.

The H_2S from the gases leaving the regeneration unit is recovered in a separate gas purification step using available absorption technology, and is then sent to a Claus unit for conversion to elemental sulfur. The partially desulfurized potassium salts, mainly KOH and K_2CO_3 are returned to the MHD combustor as fresh seed. Some rather comprehensive rate data has been recently obtained on the regeneration of spent seed and will be published shortly.

As far as materials are concerned, the desulfurization reactor tube was made from a 99.8% dense fine-grained alumina. A photograph of this reactor is shown in Fig. 12. This reactor has managed to withstand the action of molten potassium salts for hundreds of hours of operation. These favorable results further confirm the work of Kellogg and the University of Utah, with regard to gasifier vessel linings and air preheater refractories (5,6). Thus, the use of an alumina lined reactor can be recommended for the seed regeneration step.

Conclusions

The state of knowledge regarding the design of the MHD heat recovery and seed recovery system for a coal-fired plant leaves a great deal to be desired. The scientific basis for design has been improved somewhat through recent research. However, the prime deficiency remains; namely, a lack of hard experimental data on materials and components for coal-fired systems under simulated central-station power plant conditions. No definitive design study has ever been performed on the layout of a steam bottoming plant, while only a preliminary design has been prepared for the seed recovery-sulfur removal system (2). Hopefully, with increased funding and the construction of a pilot plant, these deficiencies will be remedied in the immediate future.

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Fig. 1. Temperatures of downstream components for separately and directly fired MHD cycles.

Fig. 2. Equilibrium composition of slag phase as a function of temperature.

Fig. 3. Equilibrium distribution of potassium between liquid and gas phases as a function of temperature.

Fig. 4. Fraction of total potassium lost in the slag phase as a function of slag rejection in the combustor.

Fig. 5. Effect of fuel to air ratio on equilibrium composition of molten seed phase.

Fig. 6. Heat recovery system for USBM experimental MHD combustor.

Fig. 7. Magnesia brick after several hundred hours exposure to seeded flue gas.

Fig. 8. Wall deposits in refractory-lined section after several hundred hours exposure to seeded flue gas.

Fig. 9. Blockage of tubes by deposits in carbon steel heat exchanger exposed to MHD combustion gas.

Fig. 10. Collected Specimen of unseeded MHD fly ash.

Fig. 11. Seed recovery-sulfur removal system for MHD power-plant.

Fig. 12. Alumina reactor tube used in bench scale desulfurization studies after 50 hours of operation.

Discussion

Perry Bergman. We need to know the controlling mechanism, thermodynamic or kinetic, for seed-slag interaction so that we can determine what component of the system the bulk of the seed will be collected from.

It would be extremely difficult to say anything about the kinetics of this process. Thermodynamics tells us how bad the problem might be. As I indicated during the talk, the presence of a few % SO_2 in the combustion gases may limit the concentration of K_2O dissolved in the slag to about 20 wt %. Rejection of 80-90% of the slag in the combustor would allow about 95% seed recovery. In the absence of SO_2 the problem appears more difficult. We plan additional experimental work at NBS on these problems.

R. De Saro. Is zero slag rejection unacceptable due to the large seed capture?

I believe so.

K. E. Tempelmeyer. Could you comment on the kinetics of seed/slag absorption process? Is it in your opinion fast or slow and do your experimental K_2O desorption tests give any evidence about the kinetics of desorption?

Our tests do not give any information about the kinetics of desorption. One could hope that the kinetics was not fast enough to keep the slag and seed at equilibrium.

J. Henry. Let me suggest the following in reference to kinetics being slow enough to result in reduced seed loss in slag capture: (1) Since the USBM experimental results are reasonably well modeled by an equilibrium assumption at a plausible temperature and (2) since the experimental unit had a more severe cooling profile than several suggested full-scale MHD plants, the kinetics of seed capture by slag may not be as slow as is hoped for effective slag separation from seed.

I think this is an important point. When considering an operational MHD unit it may be neither possible nor efficient to suddenly extract enough heat to freeze the equilibrium at some higher temperature.

A. L. Bement. Will hydrates of silicon be a significant factor under the conditions existing at various locations in the MHD system? What can you say about the degradation of SiO_2 -containing refractories in the combustor and preheater based upon your slag-seed reaction studies?

I presume you refer to gaseous Si(OH)_2 , Si(OH) , or perhaps $\text{H}_2\text{SiO}_3(\text{c})$. I do not think that any of these materials will be significant. I believe that silica containing refractories should be avoided. In addition, it might be wise to consult phase-equilibrium data for the $\text{K}_2\text{O-SiO}_2\text{-H}_2\text{O}$ system before considering the use of silica based refractories.

S. Way. The problems of injecting, mixing, and recovering seed will be less pronounced at lower seeding levels. Levels of 1% mole fraction of potassium are frequently mentioned. Cycle studies indicate that an acceptable level may be about 0.5% weight fraction or 0.4% mole fraction.

Yes, that is true.

M. Jones. What is a particle-gas time track across the chart of $P_{\text{K}}^2 \cdot P_{\text{O}_2}^{1/2}$ versus T^{-1} ?

I don't know but I would presume that the particle velocity would not be much different than the bulk gas velocity. This will depend on the distance from the nozzle.

F. E. Spencer. What was the O_2 pressure in your study? In HW work the $\text{N}_{\text{K}_2}\text{O}$ was not in the $\text{SiO}_2/\text{K}_2\text{SiO}_3$ phase. Was your two-liquid slide (for K_2SO_4 -slag) based upon experiment?

The oxygen pressure in equilibrium with $\text{K}_2\text{O-SiO}_2$ solution was about 1/4 the K pressure. In the HW work, the only condensed phase at equilibrium was the $\text{K}_2\text{O-SiO}_2$ solution. The two-liquid slide is based on data of Capps' at NBS and by E. Raask and R. Jessop, Phys. and Chem. of Glasses 7 200 (1966).