

POLLUTION CONTROL AND ENVIRONMENTAL MONITORING EFFORTS
AT DOE'S COAL-FIRED FLOW FACILITY¹

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ABSTRACT

Magnetohydrodynamics (MHD) involves interactions among an electromagnetic field and electrically conducting gases and liquids. The most developed application for MHD in the United States is for central station electric power generation using a coal-fired, combined cycle system. In such a system, the required electrical conductivity in the coal-derived combustion gases is obtained by seeding with about 1 wt. % potassium, usually as a sulfur-free compound. The combined cycle MHD system has the potential of increasing overall plant efficiency from <40% for conventional systems to 60%.

Proof-of-Concept (POC) scale demonstration of such technology is currently being carried out at the U.S. Department of Energy's (DOE's) Coal-Fired Flow Facility (CFFF), located at The University of Tennessee Space Institute (UTSI) in Tullahoma, Tennessee and at the Component Development and Integration Facility in Butte, Montana. The CFFF is dedicated to the evaluation of downstream (steam cycle) components and technology that may be considered for a full-scale MHD system. The objectives of the CFFF testing include the demonstration of various pollution control devices and techniques at a scale sufficient for future scale-up.

The CFFF offers a unique test environment in which emissions control techniques can be developed and evaluated through emissions and environmental monitoring. Results thus far have demonstrated the ability of sulfur oxide (SO_x), nitrogen oxide (NO_x) and particulate emissions well below the New Source Performance Standards (NSPS). Regeneration of the potassium sulfate to produce sulfur-free

compounds also has been demonstrated. The experimental program at the CFFF is now aimed at determining the optimum conditions for future commercial scale designs. Because of increased interests in Air Toxics, measurements of nitrous oxide (N_2O), a potential greenhouse gas, priority pollutants (inorganic as well as organics), and chlorine-containing species (Cl_2 and HCl) are also included in our ongoing efforts. Environmental monitoring activities are being pursued to develop an environmental impact assessment data base. These include the use of three ambient air sites to determine the impacts of gaseous and particulate emissions, five lake water sites to determine impacts due to process water discharges and seven sites to collect terrestrial data on possible soil contamination and tree growth.

In this paper, we will summarize the status of our ongoing environmental program.

INTRODUCTION

The University of Tennessee Space Institute (UTSI), located near Tullahoma, Tennessee, has been engaged in the development of coal-fired magnetohydrodynamics (MHD) for more than 20 years. Following the dedication of the Department of Energy's Coal Fired Flow Facility (CFFF) in the early 1980's, the UTSI effort has been directed toward development of technology and components for the MHD steam bottoming cycle. Pollution control has received priority as the CFFF construction and modification progressed throughout the 1980's.

The potential efficiency gains offered by the MHD concept also provides a direct benefit of reduced pollution. Even if the system emissions ($\text{lb}/10^6$ Btu) are the same as for conventional systems, the amount of pollution per kilowatt hour of electricity generated is reduced, because less fuel must be burned to generate the same number of units of electricity. The reduction of pollution levels because of

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efficiency gains promises to be substantial in advanced MHD power generation systems. For example, Weinstein and Boulay (1988) projected combined cycle efficiencies of up to 60.6% for a very advanced concept. However, achieving effective pollution control in an MHD system presents a number of challenges.

The early challenges addressed at UTSI were the control of NO_x, SO₂, and particulates. The first challenge was the very high combustion temperatures, approximately 5000°F [3033K], which result in equilibrium NO_x levels of up to 10,000 ppm. by volume. One of the early goals was to design MHD systems that could fire a wide range of coals, including those with high sulfur levels. Thus, another challenge was to burn high-sulfur coals while maintaining effluent compliance levels at the stack. The very high combustion temperatures and added potassium seed material required for MHD result in an increase in the dust loading of very fine particles. This presented a challenge in meeting New Source Performance Standards (NSPS) limits. All of these challenges have been met and these three pollutants can be controlled to levels well below NSPS for utility boilers. Recent efforts have been directed toward obtaining sufficient data on these pollutants to perform statistical analyses and on obtaining data on chloride emissions, air toxics and priority pollutants. Additional data are also required for designing commercial-sized equipment. This paper will review the potential for MHD systems to meet NSPS levels. Specifically, we will discuss the following subjects:

- Performance of pollution control devices and techniques used at the CFFF.
- Interpretation of measurements/results for priority pollutants, N₂O, and chlorides.
- Anticipated environmental impact, and
- Ability of MHD to meet current as well as anticipated future pollution standards.

THE MHD SYSTEM

Magnetohydrodynamics has had a long history. However, engineering development on systems for electrical power generation is relatively recent. For this purpose, an MHD system is a combined cycle including an MHD topping cycle and a steam bottoming cycle. A typical coal-fired open cycle system for generation of electricity is shown in Figure 1. The MHD topping cycle provides for direct energy conversion to electricity while the steam bottoming cycle generates electricity using a boiler and steam turbine. In the topping cycle, coal is seeded with a potassium salt and burned fuel rich at very high temperatures to produce an electrically conducting gas (plasma). Combustion temperatures approach 5000°F and pressures are 5 atmospheres or higher. The gas flows through a nozzle to a generator where flow velocities may reach 2500 ft/s (762m/s). The gases then

References are given in a Bibliography at the end of the paper.

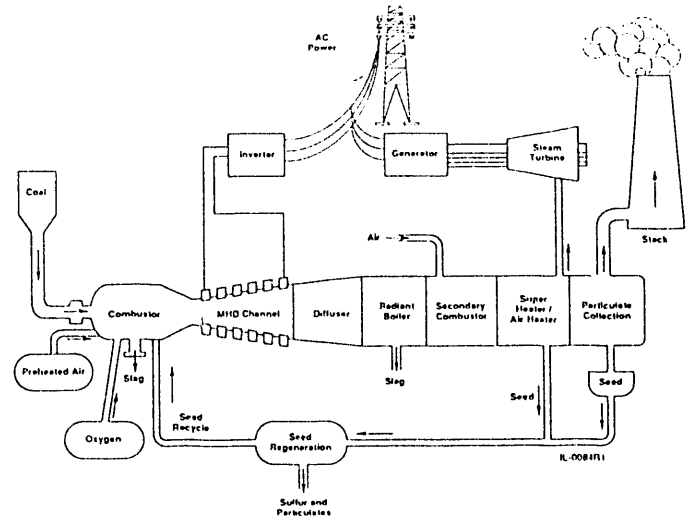


Figure 1. Schematic of Coal-Fired MHD Power System

pass through a diffuser to recover pressure and reduce velocity before entering the steam bottoming cycle. The MHD portion of the system is extremely efficient, with the generator reacting levels of almost 90% of theoretical over the temperature and pressure decreases in the generator.

In the steam generation cycle, the combustion gases are cooled from more than 3500°F (2200K) to less than 300°F (422K) to recover the thermal energy. The primary combustor is operated fuel rich. Heated secondary combustion air is used to burn the remaining combustible gases, primarily CO and H₂, after the gases have cooled to about 2500°F (1644K) in a boiler furnace. The gases are further cooled in a convection section that includes a superheater, reheater and intermediate- and low-temperature air heater surfaces. Steam generated and superheated in the bottoming cycle is used in a turbine-generator set to produce additional electricity. Some of the spent seed and the coal ash remaining after the slag tap deposits on tube surfaces, as occurs in conventional boilers. This material is collected after sootblowing and is then combined with the material collected from either a bag house or electrostatic precipitator.

The UTSI MHD Proof-of-Concept System

The early work done at UTSI was on small scale equipment. A larger facility, known as the DOE Coal Fired Flow Facility, was placed in operation in 1980. The facility at first included only a few components. Additional components were added throughout the 1980's. During this period, the University was actively engaged in both component design and construction, and in running short term tests to develop the technology for scale-up to commercial demonstration size. This phase of testing and construction was completed in 1987, when the facility was essentially complete and proof-of-concept (POC) testing was initiated with Illinois No. 6 coal. With the completion of testing of Illinois No. 6 bituminous coal, the facility is now being modified to pulverize and feed low rank coals.

The MHD system operating at UTSI is identified as the Low Mass Flow (LMF) test train. It contains all of the major components of a commercial system. The system has been

operated with topping cycle components, including an MHD generator and magnet, but is currently operated without a magnet and is using an aerodynamic duct in place of the generator. The development work at UTSI is now emphasizing steam bottoming or steam generation cycle components. However, to assure that conditions in these 'downstream' components are representative, the upstream components are operated at the high combustion temperatures required for MHD and the gases are seeded with potassium salt at levels expected in commercial systems. The current configuration is shown in Figure 2, with a photograph of the equipment in Figure 3. The downstream components consist of a furnace in which steam is generated at atmospheric pressure, followed by a secondary combustor, a superheater test module (SHTM) containing superheater and intermediate air heater materials test sections, water cooled surfaces to reduce gas temperatures and a low temperature air heater. The combustion gases can be split into three streams for spent seed and fly ash removal. The primary removal devices are an electrostatic precipitator (ESP) and a fabric filter baghouse. A venturi scrubber/cyclone was originally used as the sole clean up device when the gases were quenched following secondary combustion. This equipment was retained as backup and for at least partial particle removal when the other devices are operated off-design for performance evaluation.

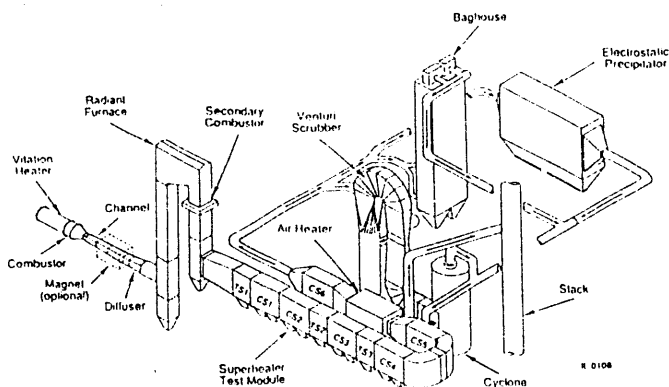


Figure 2. Low Mass Flow Train

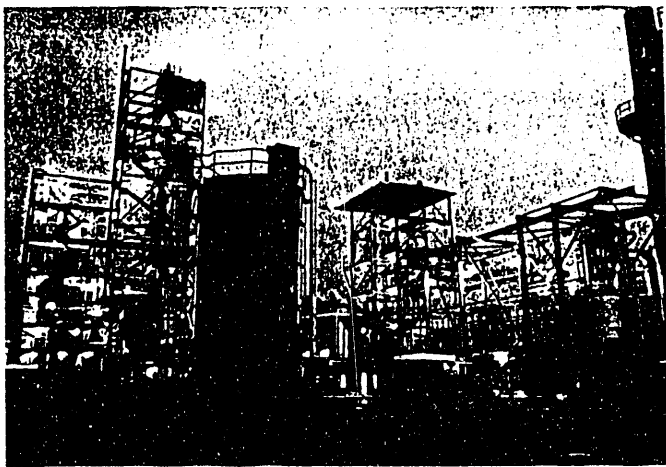


Figure 3. Low Mass Flow Train

The system is normally operated at a nominal thermal input of 20 megawatts (MW_t), and is capable of being operated at 28 MW_t . Coal and seed are pulverized together on site, fed to the combustor using dense phase flow, with a coal-to-nitrogen weight ratio of about 100 to 1. The coal is usually burned with some No. 2 fuel oil to provide sulfur and ash loading in the combustor that are similar to commercial units. Oxygen-enriched air is preheated by burning oil in the air-oxygen stream to raise the temperature to about 1800°F (1256K). The primary combustor is operated fuel rich to optimize MHD power generation and allow decomposition of NO_x . The combustibles remaining, largely carbon monoxide and hydrogen, are burned with heated secondary air in the secondary combustor. The very high combustion temperature and pressure result in complete carbon conversion, with no solid carbon found in the combustion gases. The gases are then cooled to about 300°F (422K) by passing over the superheater and intermediate temperature material test sections, the water-cooled tube banks and the low temperature air heater. The gas stream is then normally divided so that a little more than half of the volume passes through the ESP and the remainder passes through the baghouse. **Throughout the development, pollution control was a priority.** Control of NO_x was felt to be critical because equilibrium levels of up to 10,000 ppm are generated during primary combustion. Calculations made early in the program indicated that very long residence times under reducing conditions would be required to lower the nitrogen oxide to acceptable levels.

One of the goals of the MHD program was to burn high-sulfur coals. Thus, SO_2 control was also addressed early. The high combustion temperatures and presence of relatively large quantities of seed material meant that particle removal would be different from conventional boiler systems. Therefore, this aspect was important to the development of MHD technology.

NITROGEN OXIDE CONTROL

Early tests in the CFFF and a smaller apparatus, the Energy Conversion Facility, (ECF) preceding it are summarized in Crawford, et al., (1983). As early as the late 1970's, tests in the ECF showed that very low NO_x content could be achieved using cooling of the substoichiometric exhaust gases, albeit with oxidizer of a considerably higher oxygen content than currently is used in the CFFF. The results were confirmed in the CFFF as described in Crawford, et al., (1983). In addition, chemical kinetic calculations of several of the tests were described in Crawford, et al., (1983), together with the reaction rate set used to obtain NO_x contents close to those obtained experimentally.

Further refinements to the chemical kinetic results have been described in Crawford, et al., (1986), and more recent results and calculations in Crawford, et al., (1990). These references also cite other publications on the NO_x behavior in the CFFF, and projections made for commercial plants.

Generally speaking, it is efficacious in the CFFF to operate primary combustion near 85 percent stoichiometry

with secondary combustion to yield 5 percent excess oxygen. During CFFF test LMF4-V, performed in November 1990, several hours of the test were devoted to a variation of primary stoichiometry and of thermal input to examine the effects on NO_x. In this test, the coal used was an Illinois #6 coal, providing 55 percent of the thermal input, with the remainder provided by oil. The primary oxidizer was near 50 percent by mass oxygen; the remainder, nitrogen. The secondary combustion oxidant was preheated air.

The experimental results of the thermal input and stoichiometry variations in LMF4-V are illustrated in Table I. The fuel mass flows were varied such that, in the three sets of data, the thermal inputs were 15.0 MW_t, 18.9 MW_t, and 24.3 MW_t. In each set, primary combustion stoichiometries were set to values near 80, 84, and 90 percent. Secondary combustor air was set to give about 5 percent excess O₂.

Table I.

EFFECT OF THERMAL INPUT AND PRIMARY STOICHIOMETRY VARIATIONS ON NITROGEN OXIDE CONTENT DURING LMF4-V

Thermal Input (MW _t)	15.0	15.0	15.0	18.9	18.9	18.9	24.3	24.3	24.3
Stoichiometry (%)	80.3	83.9	89.3	80.7	84.0	88.9	81.0	84.3	90.2
T-diffuser (K)	2370	2420	2470	2430	2460	2490	2470	2490	2510
T-SCI (K)	1250	1265	1310	1360	1395	1435	460	1510	1535
T-inlet Trans. (K)	1490	1455	1390	1590	1565	1505	665	1655	1565
NO-SCI (ppmv)	40	45	90	60	60	140	110	120	400
NO _x -SCO (ppmv)	115	130	150	120	140	200	140	150	400
NO _x Emission index ng/J	34	37	43	37	40	57	42	43	119

Table I shows temperature at the diffuser, (T-diffuser) as measured by potassium line reversal, temperatures near the secondary combustor inlet (T-SCI) and at a point several meters downstream of the secondary combustor (T-inlet trans), as measured by thermocouples, NO content measured at the secondary combustor inlet (NO-SCI), and NO_x measured at the secondary combustor outlet (NO_x-SCO). Also shown is an emission index, calculated for the SCO-NO_x.

It is relevant to note that the diffuser temperature is highest at the highest stoichiometry, but does not change much with thermal input. At lower stoichiometries, the increment of diffuser temperature increase is larger with thermal input. The temperatures at the secondary combustor inlet (SCI) are highest for the highest stoichiometry, and increase significantly with thermal input. The temperature difference between the downstream thermocouple and that at the SCI is largest at the lowest stoichiometry, and the downstream temperature is highest at the lowest stoichiometry.

The NO content at the SCI is not very sensitive to stoichiometry at 80 and 84 percent, but is higher at 90 percent stoichiometry; similar observations are noted with the NO_x content at the secondary combustor outlet (SCO-NO_x). As thermal input is increased, the SCO-NO_x content increases slightly at the lower stoichiometries, but increases considerably at the highest stoichiometry. These results, at least at 19 MW_t, are in line with previously reported effects of stoichiometry. The study of thermal input variation is valuable as a guide to what might result in a plant going from full load to part load, from the point of view of NO_x emissions. The size of the furnace section, from the diffuser to the secondary combustor outlet region, is constant in all recent tests. Variations in thermal input and stoichiometry lead to different retention times in the furnace section, and hence, different temperature histories of the combustion products. The experimental results show that at 80-84 percent stoichiometry (upstream of the secondary combustor), the resultant NO_x emissions do not vary a great deal over a thermal input of ± 20 percent from the median thermal input.

A few comments are in order to understand the NO and NO_x values. At the various thermal inputs, fuel flow was maintained constant for the given input, while primary oxidizer flow was varied to obtain the cited stoichiometries. Thus, a lower total mass per unit of thermal input was obtained at lower stoichiometries. Therefore, although at 80 percent stoichiometry the SCI NO was almost the same as at 84 percent, the NO per unit of fuel input was lower. When secondary air was added, a considerable dilution occurred, greater at lower primary stoichiometries. Thus, if concentrations were the same at the SCI and the SCO, some NO would have been generated due to thermal effects of secondary combustion. In all cases but one downstream concentrations were considerably higher, indicating significant amounts of nitrogen oxide generation.

At low SCI temperature, such as occurred at 15 MW_t, values, since cooling rate could decrease as temperature decreased. The objective of the study was to find conditions leading to an emission index at or below 43 ng/J, hence calculations at higher cooling rates were not done for primary stoichiometry above 84 percent.

It is apparent that only at a primary stoichiometry of less than 88 percent would the low emission index be obtained for the cooling rates studied. A cooling rate of 360 K/s implies a primary furnace volume of 600-700 m³ for a flow at a thermal input of 250 MW.

Another nitrogen oxide of current concern is nitrous oxide (N₂O). Samples of gas from various ports in the downstream section of the CFFF have been analyzed for N₂O using a gas chromatograph with an electron capture detector. It is known (Kokinos, 1990) that NO, in the presence of SO₂ and O₂, can react to form N₂O in the sample container, unless the sample is very dry. In what are considered to be the most reliable samples, levels of 1-2 ppmv N₂O have been detected. This level is typical of coal-fired power plants (Kokinos, 1990). Samples have also been taken of venturi scrubber cyclone liquid, and allowed to cool; samples of the gas (originally air) over the liquid were then analyzed. N₂O

contents of several to over 20 ppmv have been observed in these gas samples, the higher values at higher NO contents in the gas approaching the scrubber. These latter results indicate that some NO and/or NO₂ dissolves with O₂ and SO₂, and reacts to form N₂O in the scrubber solution. As mentioned previously, the venturi scrubber is not used regularly as a particulate control device, but is used when temperatures or flows are outside specifications for the regular devices. It is not considered that the N₂O contents of the flue gas would cause significant environmental degradation, nor would the reaction in the scrubber.

SULFUR DIOXIDE CONTROL

As noted earlier, the use of a sulfur-free potassium appeared to provide an opportunity for inherent sulfur dioxide control. However, there was some concern that potassium would react with the coal ash constituents in the high temperature reducing zones, reducing the metal's effectiveness to create a plasma. This concern was minimized by specifying a multi stage combustor, with a slag tap in the first and at the lower stoichiometries, measurements and calculations Crawford, et al., (1986) indicate that significant amounts (up to 25 ppmv) of the NO are reduced to ammonia (NH₃) rather than to nitrogen. Since NH₃ oxidation can lead to significant NO formation, part of the NO generation is due to that effect, as well as to the thermal effect. Not much NH₃ would be formed at 24 MW_t, because of the higher SCI temperature.

In spite of the formation of NO during secondary combustion, the results obtained are very encouraging. A value of 150 ppm NO_x at the SCO, for the fuel and oxidizer mix used, translates to an emission index near 43 ng/J (nanogram NO + NO₂ expressed as NO₂/Joule), or 0.1 lb/10⁶ Btu (lb NO + NO₂ expressed as NO₂ per million Btu), much below current NSPS requirements of 0.6 lb/10⁶ Btu. In a commercial scale plant, cooling rates would be much lower than in the CFFF, and improved NO_x control is to be expected (see Table II).

TABLE II.
EFFECTS OF PRIMARY STOICHIOMETRY AND COOLING RATE ON NO_x EMISSIONS, PARAMETRIC STUDY

Primary Stoichiometry Percent	Primary Cooling Rate K/s	NO _x Emissions, ng/J	
		SCI	SCO
100	360	581	581
96	360	257	257
92	360	110	110
88	360	46	48
84	360	19	27
84	470	29	34
84	600	40	42

Table II shows the results of a parametric study of effects of primary stoichiometry and cooling rate in an MHD plant on NO_x emissions. An oxidizer with 38% O₂ by volume was used in primary combustion with an Illinois No. 6 coal. In

this study, a radiation heat transfer factor was caused to cool the gas from 2450K to 1533K, where upon air at 589K (corresponding to 5 percent excess O₂) was mixed adiabatically; the mixture then was allowed to react using the same heat transfer factor. Primary cooling rates are average stage, and initially establishing very high slag removal specifications (90%). However, the slag removal performance of the combustor selected by DOE has been much less (40-45%) than originally specified and requirements have been reduced to 60% (TRW, 1990). Furthermore, some of the early equilibrium calculations indicated that the concentration of K in the slag would be very high (Plante, et al., 1975). Another concern was the potassium-sulfur chemistry, which is complex throughout the MHD system. Although the system is operated fuel rich from the primary combustor to the secondary combustor, sulfur dioxide is the dominant sulfur compound present (Lanier, 1979 and Rasnake, et al., 1991). Hydrogen sulfide begins to form below gas temperatures of 3140°F (2000K) and about 10% by weight of the sulfur is present as SO₂ at 2780°F (1800K). (See Figure 4). At lower temperatures the SO₂ converts rapidly to H₂S. As shown in Figure 5, the reaction between potassium and SO₂ does not begin to occur under oxidizing conditions until the gases cool to about 2600°F (1700K). These figures indicate that the secondary combustor is located in a very critical region with respect to sulfur forms and the reaction of these forms with potassium. Therefore, SO₂ measurement in this region is very temperature sensitive and can vary significantly, depending on conditions (Rasnake, et al., 1991 and Li, et al., 1991).

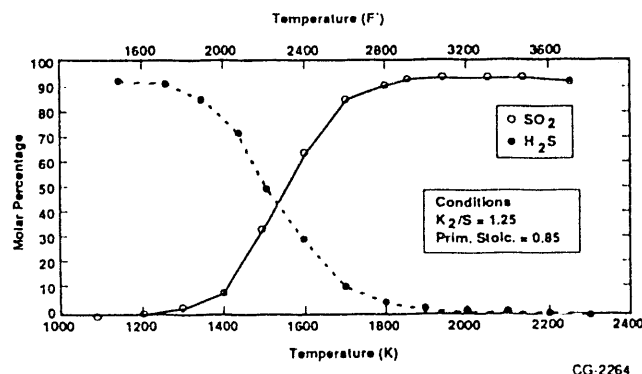


Figure 4. Sulfur Species Before Secondary Combustion

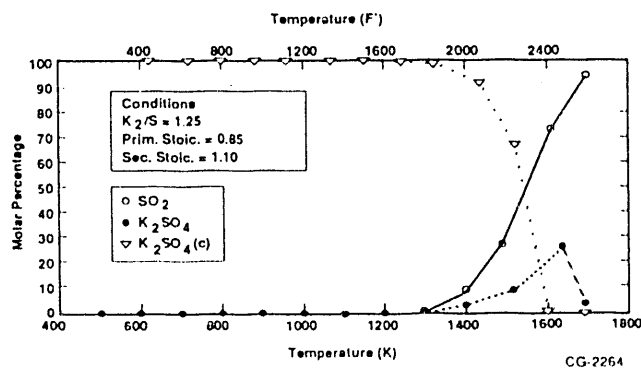


Figure 5. Sulfur Species After Secondary Combustion

The early concerns about slag-seed interaction were found to be less severe than predicted in tests at UTSI in a small MHD system during 1978 and 1979. These tests showed almost complete elimination of SO₂ (Lanier, et al., 1979) even though the UTSI system was operated with the slag tap at the entrance of the furnace, well downstream of the introduction of potassium seed. We are continuing to evaluate SO₂ removal effectiveness in tests at the CFFF. *This was an important aspect of MHD, because the seed has to be collected and recycled for economic reasons.* Furthermore, use of an 'inherent' SO₂ removal system would eliminate problems identified with current lime/limestone scrubbing systems. Scrubbing systems also reduce overall cycle efficiency from about 38% to 33-34% (Yeager, 1985). This efficiency loss results in the added combustion of millions of tons of coal a year and in emissions of millions of tons of CO₂ and other atmospheric pollutants.

The primary factor affecting SO₂ removal is the potassium-to-sulfur molar ratio. The effect of K₂/S molar ratio was confirmed again in recent tests. Figure 6 illustrates that NSPS levels for this coal can be met, even at K₂/S molar ratios only slightly above 1.

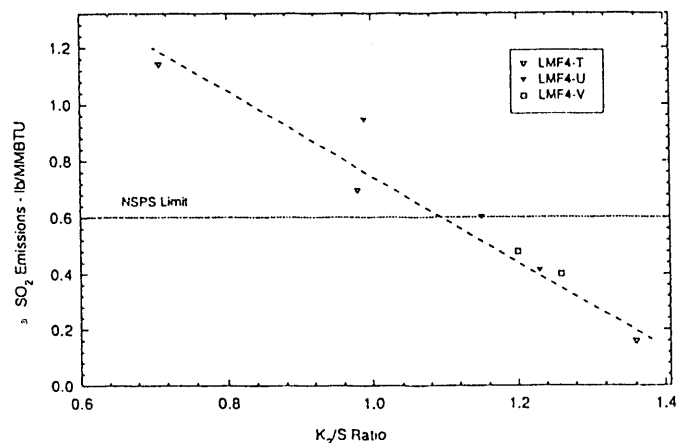


Figure 6. Effect of Potassium on SO₂ Removal

Tests at the CFFF have demonstrated almost complete removal of SO₂ while firing an Illinois No. 6 coal containing more than 3% sulfur. Concentrations of less than .02 lb/10⁶ Btu (<8.7ng/J) were measured for K₂/S molar ratios just under 1.4, and lower levels have been measured, well under the 0.6 lb/10⁶ Btu NSPS level.

For coals with sulfur contents of less than about 4%, the potassium carbonate seed levels can be adjusted to obtain SO₂ levels well below NSPS requirements, while maintaining total seed levels required for normal MHD power generation. All of the K₂SO₄ formed can be regenerated as carbonate, or a mixture of carbonate and sulfate can be recycled, depending on system economics and other requirements.

We noted earlier that some of the potassium reacts with the coal ash constituents forming insoluble potassium aluminosilicates. This reduces the amount of potassium available to react with the sulfur dioxide. However, an

extraction step developed at UTSI (Holt, et al., 1989) not only removes the potassium, but it can be integrated with the Formate seed regeneration process (Sheth, et al., 1988) to enhance the overall processing costs and efficiency. Thus, tests to date in both small and larger scale facilities confirm that potassium levels typically required for MHD power generation are effective in reducing SO₂ concentrations to levels well below NSPS requirements.

Radiant furnace slag as well as various process effluents from the seed recovery/regeneration operations based on the Formate Process were analyzed using EPA-toxicity tests. The results compared favorably with the maximum allowable EPA limits by the EPA, based on drinking water standards, and the toxicity results for the product (CaSO₃/CaSO₄) obtained from lime/limestone based spray dryer type flue gas desulfurization system (Sheth, et al., 1988). Because the concentrations of the leachable priority pollutants were found to be well below the maximum allowable concentration, all of the effluent streams as well as the slag will be considered non-hazardous. Therefore, they will be acceptable in a conventional landfill.

PARTICULATE CONTROL

Efficient collection of particles is essential in MHD systems, not only to meet NSPS and possible future emission limits, but also to assure maximum collection of spent seed that can be regenerated and recycled to the combustor. There are significant differences between the fly ash from conventional coal-fired plants and from an MHD system. The high combustion temperatures vaporize the potassium salt added for MHD power generation and some of the coal ash. The remainder of the coal ash is melted and the potassium salt added increases the dust loading. Therefore, early tests were run to characterize the ash so that effective particulate control devices could be specified. These tests indicated that the average particle size of the spent seed /fly ash mixture is typically less than 1 micrometer in diameter. Dust loading typically has been 6-7 grains/ft³ (14-16 g/m³) at 350°F (450K). Most of the coal ash is removed in the primary zone; thus 80-90% of the material reaching the collection devices is K₂SO₄ or a mixture of K₂SO₄ and K₂CO₃. The electrical resistivity of this mixture is lower than typical fly ash, in the range of 10⁹- 10¹⁰ ohm cm or lower, for normal operating temperatures. In some respects this material is similar to the fume generated in the pulp and paper industry's recovery boilers. Therefore, the technology for this equipment was reviewed carefully to provide input into the selection of equipment.

Based on characterization of the ash/spent seed mixture and review of applicable technology, it was decided to evaluate both a baghouse and an ESP. These components were installed to treat parallel flue gas streams, as shown in Figure 2. Normally, about 55% of the gas passes through the ESP, and the remainder passes through the baghouse. The ESP selected was a four field design, with rigid frame discharge electrodes and electrically operated gravity impact type rappers it has a maximum operating temperature of 750°F (672K), with a specific collection area of 375 at a flow rate of 8600 cfm (244m³/min). The bag-

house has 2 compartments, each with fifteen bags 11.5 in (29.2cm) diameter by 30ft (9.1m) length. Reverse gas flow is used to clean the bags in each compartment. Gore-Tex® filter bags are used to minimize blinding with the very fine particulate (< 1 µm) collected.

Both the baghouse and ESP have been operated throughout the POC program, over a range of conditions. The bags were removed after more than 800 hours of operation for inspection by the manufacturer and were found to be in excellent condition. Typical performance before bag removal reached an efficiency of well over 99%, with emissions of <0.01lb/10⁶Btu (4.3ng/J). After new bags were installed, collection efficiencies dropped, but have steadily improved as a permanent ash layer built up on the fabric. Emissions of .0093 lb/10⁶Btu (4ng/J) have been measured in recent tests. Residual pressure drop has been nominally 1.5 - 2 inches water column (374-498 pascals). The time between cleaning cycles is typically 1.5 to 2 hours or longer at a filtration velocity of 2 ft/min (0.6m/min).

The ESP has also achieved emission levels below NSPS requirements of 0.3 lb/10⁶ Btu. Figure 7 illustrates the performance of the ESP as a function of specific collection area (SCA). Levels as low as 0.003 lb/10⁶Btu have been measured. The performance of the ESP has not been consistent. To resolve this, we are working with Southern Research Institute to design and procure equipment to provide near real time measurement of particle loading and size distribution entering particulate control devices.

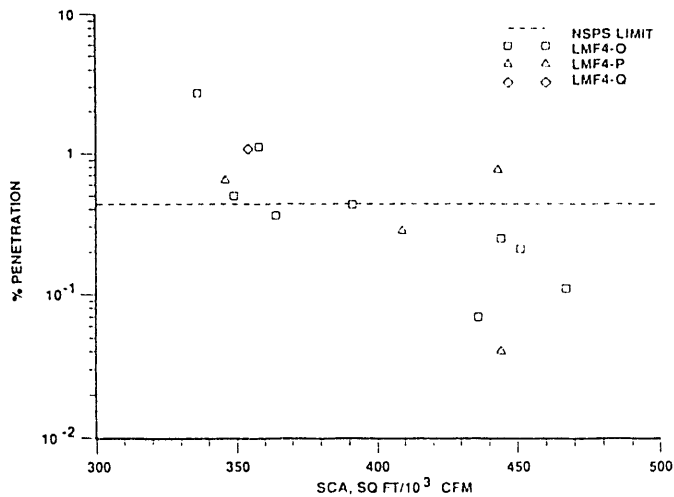


Figure 7. ESP Performance as a Function of Specific Collection Area

PRIORITY POLLUTANTS

In our assessment of the coal-fired MHD system, we have recently included an effort to investigate the concentration and behavior of various EPA-listed priority pollutants. These priority pollutants include 129 different organic and inorganic species which have been declared toxic to living organisms, and several of which are limited due to potential carcinogenic and mutagenic activities in humans. Of these 129 pollutants, to date we have focused on 88 organics (including purgeables, base/neutral and acid extractables)

along with 13 inorganic metals.

Our initial effort has been concentrated in the area of analyzing various solid (or condensed) combustion products that are derived from the CFFF with the following goals in mind:

- Comparison of the composition of solid combustion products collected from various locations along a prototypical MHD flow train during the firing of Illinois #6 and Montana Rosebud coals;
- Comparison of solid waste products generated from MHD and conventional power plant technologies, and
- Identification of a suitable disposal option for various MHD derived combustion products.

Details about the sample locations, analytical techniques, and comparison of results for the two coals as well as with results for conventional power plants are presented in Parks (1990). Due to high combustion temperature employed in the MHD system, no complex organic compounds are expected in the combustion products derived after secondary combustion. This reasoning has been confirmed in our study. Similarly, certain depositional trends were observed as the ash and gases being cooled in the downstream MHD components. Also, substantial fractionation (increase in concentration) in some priority pollutant elements was noticed. These results are well documented in Parks (1990). The specific conclusions derived are as follows:

- Similar depositional trends of priority pollutant inorganics are noted at various locations along the MHD flow train when comparing Illinois #6 and Montana Rosebud coal combustion products.
- In general, MHD solid combustion products contain lower concentrations of priority pollutant inorganics than those which have been quantified by others in combustion products from conventional coal-fired power plants.
- Other studies have confirmed the presence of priority pollutant organics in solid combustion products from conventional coal-fired facilities. So far, **no priority pollutant organics have been detected in similar wastes from the coal-fired MHD facility, even at 100 times the EPA protocol.**

To ascertain that there are no volatile, purgeable and/or semi-volatile toxic species in the MHD stack effluent, gaseous vapor and suspended particulate material from the CFFF stack will be collected and analyzed in future tests. Preliminary results indicate that any gas phase concentration of organic found in the MHD (CFFF) gaseous effluent will be lower than what has already been reported in the literature

on the stack gas composition from conventional coal-fired facilities.

CHLORIDE EMISSIONS

Chlorine generally occurs in coal in a form that is easily decomposed or vaporized during combustion. Similarly, chlorine in fresh (or make-up) seed can occur as chlorides of potassium and sodium. Under MHD conditions, a significant fraction of the chlorides introduced via the coal and/or seed can leave the stack as volatile hydrochloric acid gas/aerosol and/or as chlorine gas. Under the new Clean Air Act, emission of gaseous chlorides (measured as HCl) from a continuous source will be reduced from 17 tons/year (allowed in the past) to less than 10 tons/year. Potassium added in the MHD upstream for plasma conductivity and SO₂ removal also can control HCl-emissions, if added in sufficient quantities. However, the resulting chlorides of potassium and sodium collected with the spent seed materials will have to be removed or their concentrations be reduced during the seed recovery/regeneration operations. Control of chloride in the recycled seed is necessary to reduce any potential adverse effects caused by elevated levels of chlorides on MHD system components.

Hence, an effort has been initiated at UTSI to measure the gas phase chlorides at the SHTM outlet, baghouse outlet and electrostatic precipitator outlet by making necessary modifications to the EPA Method 17. Typical measured gas phase chloride concentrations for the SHTM and baghouse outlet locations are shown in Figures 8-10 as functions of gas temperature and potassium-to-sulfur (K₂/S) molar ratio. For comparison purposes, we have calculated equilibrium chloride disposition in the CFFF using the NASA-SP273 computer code (Sheth 1991). The calculated results, as functions of gas temperature and K₂/S ratio, are presented in Figures 11 and 12. By comparing Figures 11 and 12 with Figures 8 - 10, both calculated and measured data show a similar trend. The calculated results thus confirm that the gas phase chloride concentration (measured as HCl) will increase with gas temperature and will decrease as the K₂/S ratio increases.

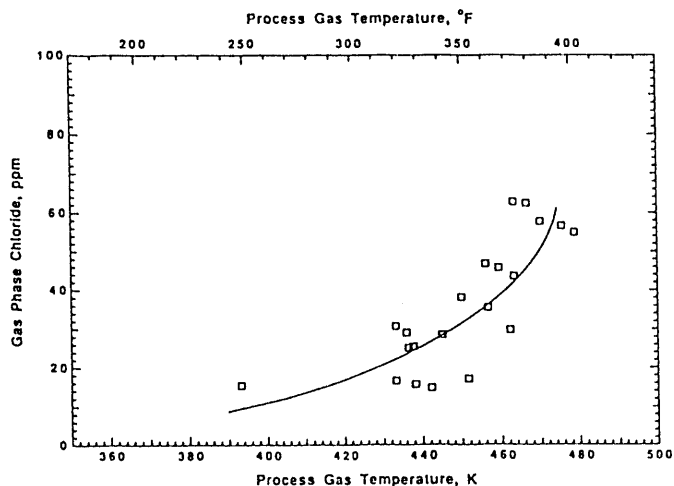


Figure 8. Effect of Gas Temperature on Measured Chloride Concentrations at the SHTM Outlet

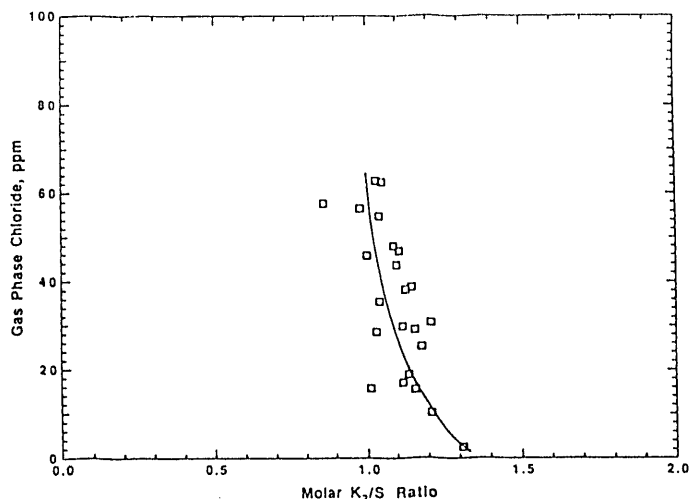


Figure 9. Effect of K₂ /S Ratio on Measured Chloride Concentrations at the SHTM Outlet

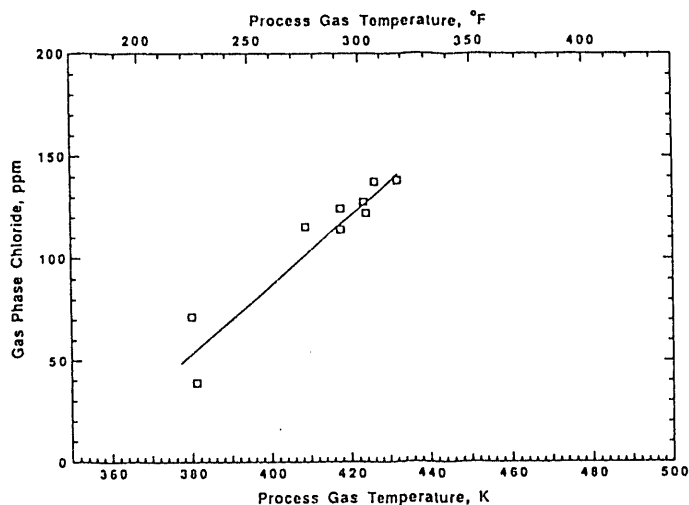


Figure 10. Effect of Gas Temperature on Measured Chloride Concentrations at the Baghouse Outlet

The relative measured concentrations at the three sampling locations did not agree with the calculated results and measured local temperatures. However, we believe this discrepancy is due to the sampling system with metal tubes being employed. This issue will be resolved in our ongoing efforts. From the work done so far, a significant quantity of chloride (~ 25 to 30% by weight of total incoming) leaves the CFFF stack at a K₂/S ratio of about 1.1. Our estimate shows that at this rate of chloride release, a commercial plant operating continuously (i.e. 365 days/year) could release more than 10 tons/year of HCl and would thus violate the Clean Air Act guidelines (based on the municipal solid waste incinerators). However, by increasing the K₂/S ratio to 1.2 or higher HCl-emission can be reduced significantly or avoided completely.

ENVIRONMENTAL MONITORING

As the plans for the CFFF MHD facility were made, the plans for environmental monitoring were also integrated. Located in rural Tennessee, approximately 10 miles from the

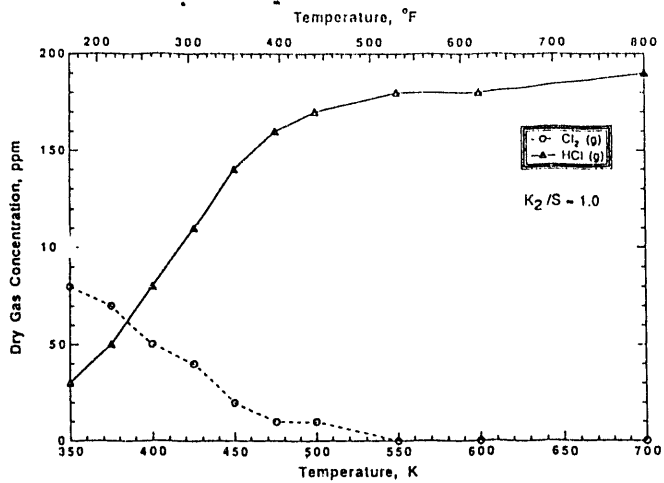


Figure 11. Equilibrium Gas Concentrations of HCl and Cl_2 as a Function of Gas Temperature

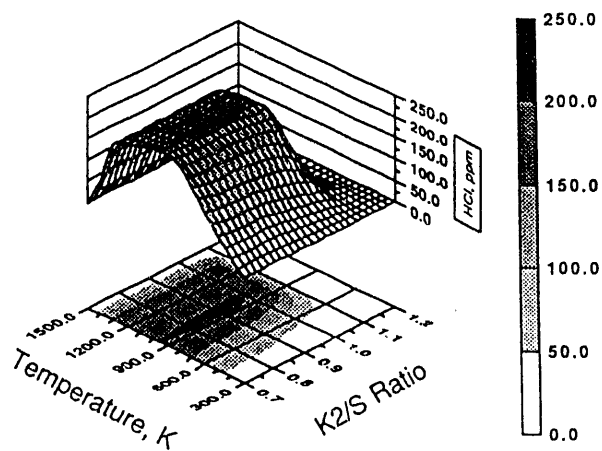


Figure 12. Effect of Temperature and K_2/S Ratio on Equilibrium HCl Gas Concentrations

nearest city, the location is a good one from the "Not in my back yard (NIMBY) Syndrome" viewpoint. However, as the facility is located on the shoreline of a recreational lake, and adjacent to 40,000 acres of game forest, it is important to control effluents and to evaluate its potential for environmental impact of this facility. As shown in Figure 13, the CFFF is surrounded by sites for monitoring air, water, vegetative and terrestrial impact. The locations were selected to provide baseline conditions and to assess maximum potential impact of the CFFF activities. Animal health is not part of the program (except for occasional aquatic investigations).

Baseline ambient air data have been collected for approximately 10 years along with data during test periods. Figure 14 shows the SO_2 and NO_x levels at a site located about 900m from the CFFF during MHD testing. The increases occurred while the ambient air site was downwind from the source. Concurrently, the flow train was operated with relatively high SO_2 emissions of 900 ppm and 500 ppm. The respective SO_2 levels are shown in Figures 14 and 15. Ambient SO_2 levels at the Ambient 1 site were reduced from nearly 40 ppb to less than 15 ppb when the SO_2 levels at the stack were reduced from 900 ppmv to 500 ppmv. These

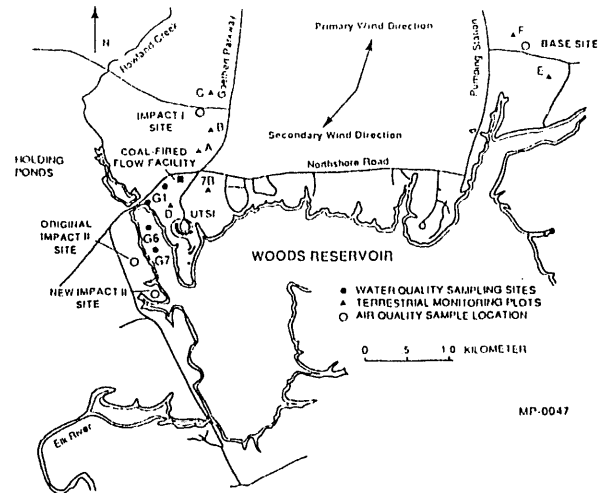


Figure 13. CFFF Environmental Monitoring Sites

levels are well below the $365 \mu g/m^3$ 24-hour National Ambient Air Quality Standard. For reference, excursions to nearly 40 ppb NO_x were observed before the CFFF was operational, and similar excursions are observed for SO_2 from distant sources.

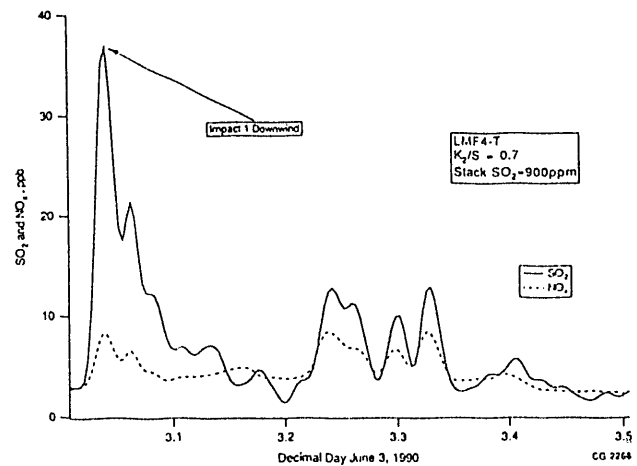


Figure 14. Ambient Concentrations at Impact 1 Site (900 meters from CFFF)

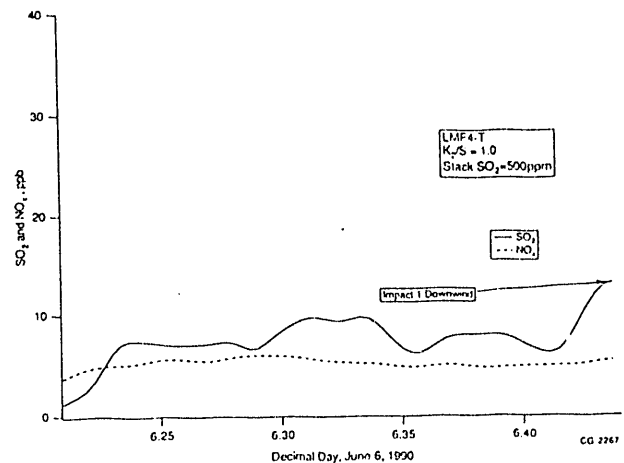


Figure 15. Ambient Concentrations at Impact 1 Site (900 meters from CFFF)

Similar monitoring of process effluents, lake water plus some vegetation and soil are being performed. The results thus far show no significant impact from the operations at the CFFF (Casey, et al., 1990). Since a potassium compound is used as the seed material in the MHD flow train, this material can act as a 'tracer' material in evaluating impact on the environment. For example, as shown in Table III, potassium and sulfur levels in the effluent from the holding pond to the lake are frequently higher than in the incoming stream feeding the lake at the CFFF.

TABLE III.
WATER QUALITY DATA FOR 1990 (mg/l)

CONSTITUENT	MONTH	EFFLUENT	INLET STREAM	LAKE SITE
Potassium	Jan	36.3	1.1	1.1
	May	18.9	0.5	1.0
	Sep	1.6	1.3	1.3
	Jan	108.	10.	10.6
Sulfate	May	43.3	3.6	7.8
	Sep	10.0	5.7	7.4
	Jan	2.5	2.7	2.8
Silica	May	1.8	3.2	1.6
	Sep	1.6	2.0	1.5

However, no build up of these elements has been measured in the lake near the effluent discharge. Furthermore, the higher levels in the CFFF discharge result primarily from the part time operation of the venturi scrubber. This equipment, however, will not be used in a commercial system and all of the recovered potassium will be recycled through a seed regeneration plant.

SUMMARY AND FUTURE WORK

The ability of an open-cycle, coal-fired MHD system to meet current contaminant emission limits and ever tighter pollution standards that are anticipated in the future has been demonstrated. Nitrogen oxide (NO_x) levels of less than 0.1 lb/10⁶ Btu have been achieved by operating the primary combustor with a stoichiometry of about 0.85 and completing combustion at a temperature of 2500°F (1644K) or lower. Analytical modeling efforts have shown that similar levels can be achieved in commercial MHD systems. Nitrous oxide (N_2O) levels of less than 2 ppmv, typical of conventional power plants, have been measured in the flue gases from the CFFF flow train.

Sulfur dioxide levels of well under 0.1 lb/10⁶ Btu (<43 ng/J) can be readily met through the use of the potassium compound used to ionize the gas for MHD power generation. The potassium sulfate formed will be collected and regenerated as a sulfur-free material and recycled to the combustor. Depending on the regeneration scheme selected, the sulfur can be recovered as a usable product. The remaining coal ash, an insoluble product is reduced to minimum volume and can be landfilled. Current work is directed toward refining measurement and analytical techniques, exploring the effects of additional variables such as thermal input (load), analyzing the data base already collected and compiling additional

data to provide a larger statistical base for greater confidence in extrapolating to commercial units.

The use of a potassium compound in an MHD system does increase the particulate loading, but the potassium provides an inherent SO_2 control eliminating the need for a scrubber. The overall effect of the added solids is minimized in most MHD concepts by tapping most of the coal ash upstream of boiler surfaces. The remaining spent seed/fly ash mixture has 85% or more K_2SO_4 when it reaches the collection equipment. This mixture is also very fine, typically less than 1 micrometer average particle diameter. In spite of this, dust loadings well under NSPS requirements have been achieved and levels of less than 0.01lb/10⁶Btu have been measured. Current work in this area is directed toward optimizing performance of the ESP and in developing sufficient information to complete an economic analysis of the particle collecting equipment. We are also exploring the potential of using a wet ESP, since most of the seed regeneration schemes use a slurry or solution as the inlet stream to the process.

The high MHD combustion temperatures destroy organic priority pollutants. In our measurements of 88 organic compounds in solid samples collected along the flow train, none was detected, using EPA analytical protocols. Some of the inorganics were concentrated in various parts of the MHD flow train, indicating vaporization during combustion and deposition downstream. However, even with the inorganics, concentrations were within the range of conventional boiler samples. We plan to continue work in this area to attempt a material balance. We are also in the initial stages of measuring volatile, purgeable and semi-volatile toxic species in the stack effluent. There is a need to make a direct comparison with other firing techniques while burning the same coal, but this is currently beyond the scope of our present effort.

Chlorides will receive increased attention in future coal fired plants. Therefore, control of chlorides is important in an MHD system. Measurements made at UTSI while firing Illinois coal indicate that gas-phase chloride emissions make up about 25-30% of the incoming chlorides. Emissions can be reduced significantly or eliminated by operating with a K₂S ratio of about 1.2 or higher. Further work is underway to refine analytical techniques and more fully evaluate the effect of potassium levels on chloride concentration.

In summary, years of testing of a relatively large MHD proof-of-concept system at UTSI has shown that the pollutants of concern can be controlled to levels below regulated limits.

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