

MASTER

FINAL REPORT

**THE EFFECTS OF COAL CLEANING
AND SLAG REJECTION ON THE
MASS AND COMPOSITION OF
SLAG AND SEED IN AN
MHD GAS FLOW TRAIN**

Prepared for

**The United States Department of Energy
Division of Magnetohydrodynamics
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GILBERT ASSOCIATES, INC.
READING, PENNSYLVANIA

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TABLE OF CONTENTS

	<u>PAGE</u>
1.0 EXECUTIVE SUMMARY	1
1.1 Findings and Conclusions	1
1.2 Recommendations	2
2.0 INTRODUCTION	4
3.0 LITERATURE ON PHYSICAL COAL CLEANING OF MHD REFERENCE COALS	6
4.0 RESULTS	14
4.1 Prediction of the Composition of Cleaned MHD Montana Rosebud Coal	14
4.2 Calculation of MHD Slag and Seed Equilibrium Compositions	14
5.0 IMPACTS ON THE DESIGN OF THE MHD GAS FLOW TRAIN	37
5.1 Solid Loadings in the Gas Flow Train	37
5.2 Slagging and Viscosity Parameters	39
5.3 Flame Temperature	46
6.0 MATERIAL IMPLICATIONS OF COAL CLEANING AND SLAG REJECTION	47
6.1 General	47
6.2 Channel	48
6.3 Radiant Boiler	50
6.4 Afterburner	51
6.5 Heat Recovery/Seed Recovery Components	52
7.0 CONCLUSIONS AND RECOMMENDATIONS	53
7.1 Findings and Conclusions	53
7.2 Recommendations	55
8.0 REFERENCES	57

LIST OF FIGURES

<u>FIGURE NUMBER</u>	<u>TITLE</u>	<u>PAGE</u>
1	CONCEPTUAL MHD TOPPING CYCLE	18
2	PERCENT ASH IN COAL VERSUS MASS FRACTION OF SLAG AND SEED	38

LIST OF TABLES

<u>TABLE NUMBER</u>	<u>TITLE</u>	<u>PAGE</u>
1	MHD REFERENCE COALS	7
2	DATA FROM ISGS ON ASH COMPOSITION	9
3	DATA FROM BCR ON ASH COMPOSITION	10
4	COAL ASH COMPOSITION AT EQUIVALENT WEIGHT RECOVERY	12
5	ENRICHMENT FACTOR	13
6	COAL ANALYSES	15
7	CASES STUDIED	16
8	CONDENSED SLAG/SEED PROPERTIES PRIMARY COMBUSTOR (A)	19
9	CONDENSED SLAG/SEED PROPERTIES DIFFUSER EXIT (C)	20
10	CONDENSED SLAG/SEED PROPERTIES RADIANT BOILER EXIT (D)	21
11	CONDENSED SLAG/SEED PROPERTIES AFTERBURNER EXIT (E)	22
12	CONDENSED SLAG/SEED PROPERTIES SUPERHEATER EXIT (F)	23
13	CONDENSED SLAG/SEED PROPERTIES LOW TEMPERATURE AIR HEATER EXIT (G)	24
14	CONDENSED SLAG/SEED PROPERTIES LOW TEMPERATURE ECONOMIZER EXIT (J)	25
15	CONDENSED SLAG/SEED PROPERTIES PRIMARY COMBUSTOR (A)	29
16	CONDENSED SLAG/SEED PROPERTIES DIFFUSER EXIT (C)	30
17	CONDENSED SLAG/SEED PROPERTIES RADIANT BOILER EXIT (D)	31
18	CONDENSED SLAG/SEED PROPERTIES AFTERBURNER EXIT (E)	32

LIST OF TABLES

<u>TABLE NUMBER</u>	<u>TITLE</u>	<u>PAGE</u>
19	CONDENSED SLAG/SEED PROPERTIES SUPERHEATER EXIT (F)	33
20	CONDENSED SLAG/SEED PROPERTIES LOW TEMPERATURE AIR HEATER EXIT (G)	34
21	CONDENSED SLAG/SEED PROPERTIES LOW TEMPERATURE ECONOMIZER (J)	35
22	SLAG/SEED CARRYOVER - ROSEBUD COAL	36
23	MHD SUPERHEATER GRAIN LOADINGS	39
24	FOULING AND SLAGGING DEFINITIONS	42
25	PARAMETER CALCULATION RESULTS	43
26	FLAME TEMPERATURE OF CLEANED FRACTIONS	46

1.0 EXECUTIVE SUMMARY

As part of the MHD program, DOE is sponsoring efforts to define the design criteria and performance requirements for components downstream of the diffuser in an MHD gas flow train. The objectives of this study are to assess the effects of coal cleaning and combustor slag rejection on the mass flow rate and composition of the slag and seed in an MHD flow train. Included in this assessment is an evaluation of the impacts on the design and material selection for the downstream components.

This assessment was done by using equilibrium calculations to define the mass fraction, chemical composition, and properties of the slag carryover as a function of coal type, coal cleaning method, and slag temperature. Until experimental data are available, equilibrium calculations provide the best indication of the environment in the downstream components.

From a survey of the literature on physical cleaning of coals, the effect of cleaning on the ash composition of the MHD reference coals was correlated and this information was used to predict the composition of a cleaned MHD coal. Equilibrium calculations of the carryover from a raw and cleaned Montana Rosebud coal were made at selected state points of a specific MHD flow train (the DOE 200 MWe Baseline ETF cycle). In addition, three different levels of slag rejection were considered for the raw coal.

Slag rejection was assumed to take place only at the first stage of the combustor. Liquid slag will be present in the radiant boiler and, in practice, some portion of the slag may be removed there. However, for this scoping study, no slag rejection in the radiant boiler was assumed.

1.1 Findings and Conclusions

Both slag rejection and coal cleaning reduce the absolute weight and weight fraction of the slag being carried over from the combustor. Grain loadings in the gas train, even for high slag rejection, are

considerably higher than in conventional coal-fired systems due primarily to the seed addition, and are largely independent of coal cleaning, especially at high slag rejection rates. For Montana Rosebud coal, conductivity considerations determine the seed requirements. Hence, coal cleaning and slag rejection have little effect on the amount of seed needed. Coal cleaning does reduce seed regeneration requirements by removing sulfur from the coal.

Liquid slag is present and can be tapped until the upstream portion of the radiant boiler. The slag will be solid at the radiant boiler exit. Seed first condenses in the afterburner and remains liquid into the superheater. Liquid alkali salts attack protective oxide films, thus selection of appropriate superheater materials to resist accelerated corrosion is critical. The seed will be solid at the superheater exit. All condensed species are expected to be solid downstream of the superheater. If the salts are "sticky" at temperatures around 1350°F, fouling in the Low Temperature Air Heater (LTAH) may occur and sootblowing techniques might not remove the condensed salts.

Afterburner materials must be able to withstand alternating reducing and oxidizing conditions, in relatively high sulfide vapor pressures, and oxide fluxing molten sulfates. In terms of materials of construction, the afterburner is therefore the most critical component of the flow train downstream of the MHD channel.

1.2 Recommendations

- o The slagging, fouling, and flow properties of slags from Montana Rosebud coal should be experimentally investigated as functions of cleaning level and combustor slag rejection.

- o The surface properties (e.g. adhesion, cohesion, friability, etc.) of potassium salts should be experimentally investigated at LTAH and reheater temperatures. Admixtures of sodium salts and flyash oxides in the $K_2SO_4.K_2CO_3$ system should be included to simulate operating conditions.
- o The use of coal cleaning as a supplement to slag rejection and as a means of reducing seed regeneration requirements should be considered. Both results can lead to a reduced cost of electricity through lowered costs or increased efficiency.
- o Development of materials resistant to the conditions in the afterburner and superheater should be accelerated.
- o Radiant boiler, afterburner, and superheater design studies incorporating new materials and direct-fired air heater materials should be initiated as soon as possible.

2.0 INTRODUCTION

As part of the MHD program, DOE is sponsoring efforts to define the design criteria and performance requirements for components downstream of the diffuser in an MHD gas flow train. To accomplish this, the mass fraction, chemical composition, and properties of the slag carryover must be identified as a function of coal type, coal cleaning method, and slag temperature. Until experimental data are available, equilibrium calculations can be used to provide an indication of the environment in the downstream components.

The objectives of this study are to assess the effects of coal cleaning and combustor slag rejection on the mass flow rate and composition of the slag and seed in an MHD flow train. Included in this assessment is an evaluation of the impacts on the design and material selection for the downstream components.

The effect of cleaning on the ash composition of the MHD reference coals was correlated from a survey of the literature on physical cleaning of coals. This information was used to predict the composition of a cleaned MHD coal. Equilibrium calculations for raw and cleaned Montana Rosebud coal were made at selected state points of a specific MHD flow train (the DOE 200 MWe Baseline ETF cycle). In addition, three different levels of slag rejection were considered for the raw coal.

Slag rejection was assumed to take place only at the first stage of the combustor. Liquid slag will be present in the radiant boiler and, in practice, some portion of the slag may be removed there. For this scoping study, however no slag rejection in the radiant boiler was assumed in order to keep the computer runs to a manageable level. Since seed is not condensed in the radiant boiler, slag rejection there will have little, if any, effect on the seed being carried over.

The equilibrium calculation results were used to assess the impacts of coal cleaning and slag rejection on determining the design criteria and performance requirements of the MHD gas flow train. Additionally, the impacts are evaluated and material selection implications are discussed.

3.0 LITERATURE ON PHYSICAL COAL CLEANING OF MHD REFERENCE COALS

The MHD program has been using two reference coals for its design studies; a high sulfur bituminous coal, Illinois No. 6, and a low sulfur subbituminous coal, Montana Rosebud. The composition of these coals are listed in Table 1. Washability data presenting the effects of physical coal cleaning of these types of coals have been published.¹ However, only the Btu and weight yields, sulfur and ash contents for various gravity separations are usually tabulated. Very little data are available on the ash composition of coal after physical coal cleaning.

In order to determine impacts on the MHD gas train components, washability data is not sufficient; ash compositional data must also be obtained. The following quotation² is presented to emphasize this point. "The selective removal of mineral matter by coal preparation depends on the differences in density between the coal substance and the mineral matter as well as the size consist and the distribution of the inorganic matter in the coal. Washability data, as shown by the yield of float coal as a function of specific gravity and the amount of ash in the float coal, do not distinguish between the various mineral constituents appearing finally in a proximate analysis as 'ash'.³

"Washability curves also fail to identify the real parameters involved in ash fusion. Although the float product may be examined at several specific gravities by the ASTM cone-fusion test, such data are virtually useless in predicting the behavior of the ash when the coal is burned in a central station power plant. The cone-fusion test is at best a rough indicator of ash characteristics and is almost useless for predicting the behavior of coal blends.

TABLE 1

MHD REFERENCE COALS⁴

<u>SPECIES</u>	<u>Montana Rosebud</u> <u>(Weight %)</u>	<u>Illinois No. 6</u> <u>(Weight %)</u>
C	63.00	65.07
H ₂	4.20	4.60
N ₂	1.00	1.25
S	1.10	3.44
O ₂	15.86	9.64
H ₂ O	5.00	5.00
Al ₂ O ₃	2.14	2.29
CaO	1.36	0.65
Fe ₂ O ₃	0.62	2.65
MgO	0.49	0.04
Na ₂ O	0.38	0.08
K ₂ O	0.06	0.25
P ₄ O ₁₀	0.05	0.02
SiO ₂	4.66	4.92
TiO ₂	<u>0.08</u>	<u>0.10</u>
	100.00	100.00
Total Ash (including SO ₃)	12.00	11.88
HHV (Btu/lb)	10760	11752

"Although there are many gaps in our understanding of the relationship between ash fusability and ash composition as shown by analysis, those relationships are far more useful than cone-fusion determinations. The chemical composition of the inorganic matter does provide a good indication of ash behavior at high temperatures. This chemical analysis of the ash in a washed product permits prediction of ash fusion characteristics better than any other existing procedure. It is particularly useful when different products must be blended. Unfortunately, chemical analyses of the ash are not usually made, mainly because of cost."

Thus, washability data, as defined in the above quotation, showing ash and sulfur content of the float-and-sink fractions give little indication of the behavior of the coal when burned as far as slagging and fouling are concerned. However, if such analyses are available, correlational methods, such as those given in Reference 5, can be used to predict trends. Quantitative prediction of the amounts and properties of slag carried over from an MHD combustor to the Heat Recovery/Seed Recovery system could possibly be made using these methods.

Data on the effects of physical coal cleaning on the chemical composition of the ashes of Illinois No. 6 and Montana Rosebud coal were obtained from two sources, Illinois State Geological Survey^{6,7} (ISGS) and Bituminous Coal Research, Inc.⁸ (BCR). Tables 2 and 3 summarize these data for the two coals. It is apparent that the changes in ash composition depend not only on the level of cleaning, but also upon the coal sample, even for samples taken from the same seam. On the average, sink ash fusion temperature is slightly higher than that of the feed coal and the Hardgrove Grindability Index (an indicator for ease of size reduction) is higher for the sink than for the feed.⁹ Exceptions occur, however, to both generalizations.

TABLE 2 - DATA FROM ISGS ON ASH COMPOSITION^{6,7}

Specific Gravity Fraction	% of Raw Coal	% Ash										Ash	S	Btu/lb
		Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	Na ₂ O	P ₂ O ₅	SiO ₂	TiO ₂				
Illinois No. 6														
3/8 x 28M	90.7	21.5	4.3	22.8	1.4	1.0	0.3	0.2	51.4	1.0	14.1	4.9	11355	
1.29 F	34.3	25.8	5.7	22.8	2.2	1.1	0.6	0.1	60.8	1.5	4.4	2.85	13397	
1.33 FS	25.9	24.6	3.5	17.9	2.1	1.3	0.5	0.1	59.1	1.3	8.0	3.16	11060	
1.40 FS	18.6	23.5	1.9	15.3	1.8	1.0	0.3	0.1	54.6	1.0	13.1	3.77	12022	
1.60 FS	12.5	21.6	2.7	13.7	1.3	0.8	0.3	0.1	53.8	0.8	21.9	4.88	10595	
1.60 S	8.7	18.0	6.1	32.8	0.7	0.9	0.2	0.1	43.1	0.7	61.1	20.15	3849	
Rosebud														
3/8 x 28 M	94.3	22.3	14.2	5.6	0.4	1.5	0.2	0.3	47.1	0.9	10.0	0.9	11607	
1.29 FS	36.8	19.3	21.9	1.6	0.3	12.4	0.4	0.4	31.4	0.9	4.8	0.6	12263	
1.32 FS	24.4	21.0	21.6	1.6	0.3	12.7	0.3	0.3	38.0	1.0	5.5	0.6	12042	
1.35 FS	13.1	38.8	17.2	1.5	0.2	10.0	0.3	0.3	40.0	0.9	7.1	0.6	11872	
1.40 FS	12.3	23.6	13.6	1.6	0.2	7.5	0.2	0.2	50.9	0.8	9.3	0.5	11525	
1.60 FS	10.4	23.4	6.9	1.8	0.3	3.7	0.1	0.1	66.8	1.0	17.8	0.5	10308	
1.60 S	3.0	15.1	6.6	22.3	1.0	0.8	0.1	0.1	50.6	0.7	54.9	8.5	5023	

M = mesh

F = float fraction

FS = floats on listed specific gravity liquid, sinks in next lighter specific gravity liquid

S = sink fraction

TABLE 3
DATA FROM BCR ON ASH COMPOSITION⁸

	SPECIFIC GRAVITY FRACTION	% OF RAW COAL	% ASH										
			<u>AL₂O₃</u>	<u>CAO</u>	<u>FE₂O₃</u>	<u>K₂O</u>	<u>MGO</u>	<u>NA₂O</u>	<u>P₂O₅</u>	<u>SI₂O₂</u>	<u>TI₂O₂</u>	<u>ASH</u>	<u>S</u>
ILLINOIS #6		100	20.90	2.72	17.07	2.24	0.91	1.04	0.23	50.76	1.05	16	2.73
	1.60 F	89.6	23.86	1.90	13.12	2.17	0.89	1.28	0.07	54.66	1.21	8.39	1.66
ROSEBUD		100	24.15	6.02	7.75	0.85	3.31	0.21	0.12	53.98	1.15	15.8	1.18
	1.60 F	87	27.86	10.20	3.01	0.54	5.10	0.30	0.18	50.57	1.13	9.83	0.61

F = FLOAT FRACTION

The two independent sets of data from ISGS and BCR were obtained using different coal samples (although from the same type of coal) and slightly different cleaning and analytical procedures. The individual fractions reported in the ISGS data were combined into a single analysis at the fraction which gave approximately the equivalent weight recovery as reported for the BCR data (Table 4). The ratio of the ash composition of the washed coal to the ash composition of the feed coal (the enrichment factor) was used to compare the two sets of data (Table 5). For all ash constituents, both sets of data agreed on whether an individual ash compound was enriched (enrichment factor >1) or depleted (enrichment factor <1). There were some differences in the magnitude of the enrichment factors but the agreement was good considering the differences in sampling, washing, and analysis. This good agreement gives confidence in applying these enrichment factors to predict the composition of cleaned coal for any Montana Rosebud or Illinois No. 6 coal. In this study, the ISGS data for Montana Rosebud coal was used to predict the composition of the cleaned Montana Rosebud MHD reference coal.

TABLE 4
COAL ASH COMPOSITION AT EQUIVALENT WEIGHT RECOVERY

	ROSEBUD				ILLINOIS NO. 6			
	ISGS		BCR		ISGS		BCR	
	RAW	WASHED	RAW	WASHED	RAW	WASHED	RAW	WASHED
SULFUR	0.9	0.6	1.2	0.5	4.9	3.4	2.7	1.7
ASH	10.0	5.0	15.8	9.8	14.1	9.6	16.0	8.4
SiO ₂	47.1	39.0	53.9	50.5	51.4	56.6	50.7	54.6
Al ₂ O ₃	22.3	24.2	24.2	27.9	21.5	23.6	20.9	23.9
Fe ₂ O ₃	5.6	1.6	7.8	3.0	22.8	16.7	17.1	13.1
TiO ₂	0.9	0.9	1.2	1.1	1.0	1.1	1.1	1.2
P ₂ O ₅	0.3	0.4	0.1	0.2	0.2	0.1	0.2	0.1
CaO	14.2	19.1	6.0	10.2	4.3	3.2	2.7	1.9
MgO	7.5	11.0	3.3	5.1	1.0	1.0	0.9	0.9
Na ₂ O	0.2	0.3	0.2	0.3	0.3	0.5	1.0	1.3
K ₂ O	0.4	0.3	0.8	0.5	1.4	1.8	2.2	2.2
COAL								
BTU/LB	11607	12037	10990	11816	11355	12070	11902	13111
BTU RECOVERY (%)	100	86.6	100	87.0	100	91.3	100	89.6
WEIGHT RECOVERY (%)	100	89.8	100	93.5	100	97.0	100	98.7

TABLE 5
ENRICHMENT FACTOR
ASH COMPOSITION, WASHED
ASH COMPOSITION, FEED

	<u>ROSEBUD COAL</u>		<u>ILLINOIS COAL</u>	
	<u>ISGS</u>	<u>BCR</u>	<u>ISGS</u>	<u>BCR</u>
SiO ₂	0.83	0.94	1.10	1.08
Al ₂ O ₃	1.09	1.15	1.10	1.14
Fe ₂ O ₃	0.29	0.38	0.73	0.77
TiO ₂	1.00	0.92	1.10	1.09
P ₂ O ₅	1.33	2.00	0.50	0.50
CaO	1.35	1.70	0.74	0.70
MgO	1.47	1.55	1.00	1.00
Na ₂ O	1.50	1.50	1.67	1.30
K ₂ O	0.75	0.63	1.29	1.00

4.0 RESULTS

4.1 Prediction of the Composition of Cleaned MHD Montana Rosebud Reference Coal

The composition of a cleaned Rosebud coal was predicted using the ISGS coal cleaning data. Cleaning factors (based on whole coal analyses) were obtained by dividing the value for each constituent in the clean coal by its analysis value in the raw coal. The cleaning factors are expressed on a whole coal, 5% moist basis. These cleaning factors were then applied to the MHD Montana Rosebud reference coal to obtain the cleaned coal analysis (Table 6). The analyses in Table 6 were used as inputs to the chemical equilibrium calculations for determining slag behavior in an MHD plant.

4.2 Calculation of MHD Slag/Seed Equilibrium Compositions

Equilibrium calculations of the weight and composition of the condensed slag/seed compounds were made at the MHD plant state points. Calculations were made for both raw and cleaned Montana Rosebud coal. For the raw coal, three levels of slag removal were considered; 0, 50, and 90 percent of the slag condensed in the primary combustor. Since all the slag had not condensed in the primary combustor, this corresponded to 0, 35, and 62.5 percent of the ash fed to the combustor, respectively. For the clean coal, only the 90% slag removal (75% of the ash fed), case was considered. In this case, the heat loss from the primary combustor was increased so that the resulting gas temperature matched that obtained in the 90% removal raw coal case. Table 7 summarizes the cases studied.

TABLE 6
COAL ANALYSES

<u>SPECIES</u>	<u>COAL*</u>	<u>CLEANING FACTOR</u>	<u>PREDICTED CLEANED COAL*</u>
C	63.00	1.04	65.52
H	4.20	1.07	4.49
N	1.00	1.00	1.00
S	1.10	0.66	0.73
O	15.86	1.09	17.29
H ₂ O	5.00	1.00	5.00
Al ₂ O ₃	2.14	0.67	1.43
CaO	1.36	0.82	1.12
Fe ₂ O ₃	0.62	0.18	0.11
MgO	0.49	0.90	0.44
Na ₂ O	0.38	1.00	0.38
K ₂ O	0.06	0.50	0.03
P ₄ O ₁₀	0.05	0.60	0.03
SiO ₂	4.66	0.51	2.38
TiO ₂	0.08	0.56	0.05
ASH	12.00	0.50	6.00
HHV (BTU/LB)	10,760	1.04	11,238

%YIELD (WT) 86.6
 %RECOVERY (BTU) 89.8

*WEIGHT PERCENT

TABLE 7
CASES STUDIED

<u>ROSEBUD COAL</u>	<u>FRACTION OF CONDENSED SPECIES REMOVED</u>	<u>% ASH REJECTION</u>
RAW	0	0
	50	35
	90	62.5
CLEANED	90	75

DEFINITIONS:

% ASH REJECTION = $\frac{\text{WEIGHT SLAG REMOVED}}{\text{WEIGHT ASH FED}}$

WEIGHT SLAG REMOVED = FRACTION OF COND. SPECIES REMOVED X WEIGHT SLAG
CONDENSED

FIRST STAGE COMBUSTOR STOICHIOMETRY = 55%

The MHD cycle used in this evaluation was the DOE 200 MWe Baseline cycle for the Engineering Test Facility (ETF).¹⁰ This system uses an oxygen enriched, open cycle, direct fired MHD power plant concept operating as a combined cycle with a steam bottoming plant. A schematic of the MHD topping cycle is shown in Figure 1. The state points were obtained using a Gilbert/Commonwealth proprietary computer code. The equilibrium computations were done with a Gilbert/Commonwealth modified Chemical Equilibrium Code (CEC) based on the NASA code.¹¹

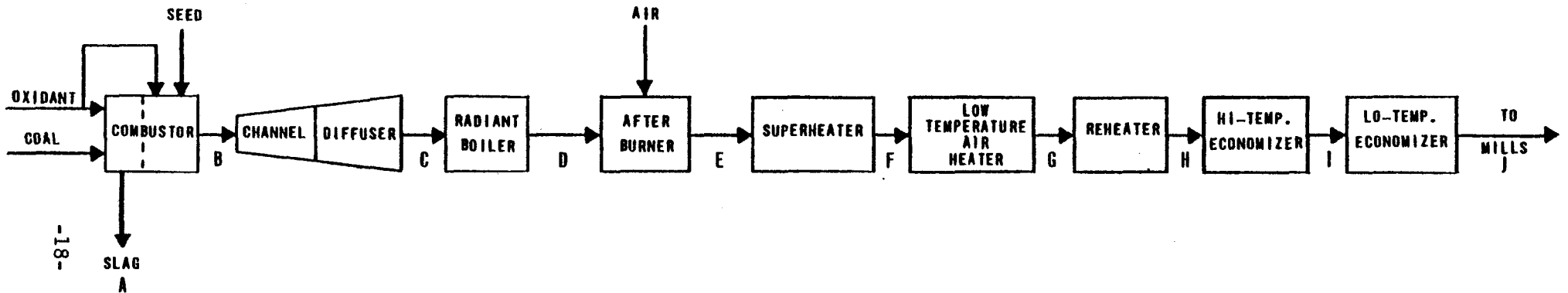
In the operation of the MHD topping cycle, oxidant and fuel are fed at pressure (5.7 atm) and produce a reducing atmosphere from the combustor into the radiant boiler. The pressure is let down in the diffuser, but the atmosphere remains reducing. These conditions persist into the afterburner, where after air injection the atmosphere changes to oxidizing. Conditions remain oxidizing and at ambient pressure through the low temperature economizer. Pressure, temperature, and atmosphere changes throughout the system are indicated in Figure 1.

Tables 8 to 14 present the condensed slag and seed weights and compositions calculated for raw and cleaned coal at 90% removal of the slag condensed. Tables 15 to 21 present the same data from raw coal runs at varying slag removal levels.

Since the clean coal contains less ash and much less iron than the raw coal, the amount of slag condensed in the primary combustor is less and contains no iron oxide when clean coal is burned. Iron acts to lower the melting point, therefore slag from cleaned coal can be expected to be higher melting and more viscous than the slag from the raw coal.

FIGURE 1

CONCEPTUAL MHD TOPPING CYCLE



-18-

STATE POINT	A	B	C	D	E	F	G	H	I	J
TEMPERATURE (°F)	3650	4575	3528	2110	2400	1555	1258	751	550	320
PRESSURE (STD. ATM)	5.69	5.69	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
ATMOSPHERE	RED.	RED.	RED.	RED.	OX.	OX.	OX.	OX.	OX.	OX.



TABLE 8
 CONDENSED SLAG/SEED PROPERTIES
 PRIMARY COMBUSTOR (A)
 TEMP. 3650°F/2283 K

<u>COAL</u>	<u>RAW</u>	<u>CLEANED</u>
SLAG WT. (LB/LB COAL)		
REJECTED	0.075	0.045
CARRYOVER	0.008	0.005
TOTAL CONDENSED WT (LB/LB COAL)	0.083	0.050
TOTAL SYSTEM MASS FLOW RATE*	3.603	3.737
SPECIES (SLAG WT. %)		
AL ₂ O ₃	S** 25.55	S 28.82
CAO	S 15.66	S 21.54
FE0	L 1.31	-
MgSiO ₃	L 14.22	L 21.46
SiO ₂	L 43.25	L 28.17

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

L = LIQUID

TABLE 9
 CONDENSED SLAG/SEED PROPERTIES
 DIFFUSER EXIT (C)
 TEMP. 3528°F/2216 K

<u>COAL</u>	<u>RAW</u>	<u>CLEANED</u>
SLAG WT. (LB/LB COAL)	0.012	0.004
SEED WT. (LB/LB COAL)	0	0
TOTAL CONDENSED WT (LB/LB COAL)	0.012	0.004
TOTAL SYSTEM MASS FLOW RATE*	5.414	5.623
SPECIES (SLAG WT. %)		
AL ₂ O ₃	S**17.27	S 34.29
CaO	S 12.73	S 32.86
FeO	L 10.45	-
MgSiO ₃	L 10.45	L 32.86
SiO ₂	L 49.55	-

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

L = LIQUID

TABLE 10
 CONDENSED SLAG/SEED PROPERTIES
 RADIANT BOILER EXIT (D)
 TEMP. 2110°F/1428 K

<u>COAL</u>	<u>RAW</u>	<u>CLEANED</u>
SLAG WT. (LB/LB COAL)	0.018	0.011
SEED WT. (LB/LB COAL)	0	0
TOTAL CONDENSED WT. (LB/LB COAL)	0.018	0.011
TOTAL SYSTEM MASS FLOW RATE*	5.414	5.623
SPECIES (SLAG WT. %)		
Al ₂ O ₃	S** 11.68	S 12.73
CaS	S 12.72	S 18.56
FeO	S 25.62	S 8.69
MgSiO ₃	S 8.00	S 12.20
SiO ₂	S 37.50	S 43.20
TiO ₂	S 4.48	S 4.62

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 11
 CONDENSED SLAG/SEED PROPERTIES
 AFTERBURNER EXIT (E)
 TEMP. 2400°F/1589 K

<u>COAL</u>	<u>RAW</u>	<u>CLEANED</u>
SLAG WT. (LB/LB COAL)	0.018	0.010
SEED WT. (LB/LB COAL)	0.059	0.061
TOTAL CONDENSED WT. (LB/LB COAL)	0.076	0.072
TOTAL SYSTEM MASS FLOW RATE*	6.637	6.894
SPECIES (SLAG WT. %)		
AL ₂ O ₃	S** 2.69	S 1.92
CAO	S 2.34	S 2.21
FE ₃ O ₄	S 6.42	S 1.44
MgSiO ₃	S 1.91	S 1.82
SiO ₂	S 8.77	S 6.52
TiO ₂	S 1.04	S 0.67
K ₂ SO ₄	L 76.82	L 85.52

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

L = LIQUID

There was no Page 23 in this document.

TABLE 13
 CONDENSED SLAG/SEED PROPERTIES
 LOW TEMPERATURE AIR HEATER EXIT (G)
 TEMP. 1258⁰F/954 K

<u>COAL</u>	<u>RAW</u>	<u>CLEANED</u>
SLAG WT. (LB/LB COAL)	0.028	0.020
SEED WT. (LB/LB COAL)	0.118	0.123
TOTAL CONDENSED WT. (LB/LB COAL)	0.146	0.143
TOTAL SYSTEM MASS FLOW RATE*	6.637	6.894
SPECIES (SLAG WT. %)		
AL ₂ O ₃	S** 1.43	S 0.96
CACO ₃	S 2.17	S 1.95
FE ₃ O ₄	S 3.38	S 0.71
MgSiO ₃	S 0.98	S 0.92
NA ₂ SO ₄	S 5.84	S 5.94
SiO ₂	S 4.60	S 3.27
TiO ₂	S 0.55	S 0.35
K ₂ SO ₄	S 71.32	S 77.44
K ₂ CO ₃	S 9.73	S 8.45

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 14
 CONDENSED SLAG/SEED PROPERTIES
 LOW TEMPERATURE ECONOMIZER EXIT (J)
 TEMP. 320°F/433 K

<u>COAL</u>	<u>RAW</u>	<u>CLEANED</u>
SLAG WT. (LB/LB COAL)	0.028	0.021
SEED WT. (LB/LB COAL)	0.118	0.123
TOTAL CONDENSED WT. (LB/LB COAL)	0.146	0.143
TOTAL SYSTEM MASS FLOW RATE*	6.637	6.894
SPECIES (SLAG WT. %)		
AL ₂ O ₃	S** 1.43	S 0.96
CACO ₃	S 2.16	S 1.94
FE ₃ O ₄	S 3.37	S 0.71
MgSiO ₃	S 0.98	S 0.92
NA ₂ SO ₄	S 5.90	S 6.01
P ₄ O ₁₀	S 0.32	S 0.19
SiO ₂	S 4.59	S 3.26
TiO ₂	S 0.55	S 0.35
K ₂ SO ₄	S 71.02	S 77.21
K ₂ CO ₃	S 9.70	S 8.44

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

The behavior of the slag at the diffuser exit is also influenced by the chemical composition. Up to this point, the raw coal slag is more acidic than the clean coal slag, but the former becomes more basic in the diffuser. After seed begins to condense in the afterburner, similar comparisons are no longer possible since no data are available for potassium salts contaminated with slag.

At the radiant boiler exit, iron appears in slags from both raw and cleaned coals, but at a lower concentration and amount from that in the cleaned coal. Since iron acts to lower the melting point, the cleaned coal slag can be expected to be higher melting. Calcium sulfide is present in both slags. If this slag is removed and water quenched, toxic hydrogen sulfide will be evolved. Also, the free calcium hydroxide formed when water reacts with calcium sulfide could react with the silicates and aluminosilicates in the slag to form large clinkers which would interfere with slag handling.

In the afterburner, conditions change from reducing to oxidizing, which poses a materials selection problem. Additionally, liquid potassium sulfate, condensing from the gas stream, is very corrosive and poses a serious materials selection problem.

The slag continues to condense and solidifies in the superheater and remains solid thereafter. However, portions of the superheater will contain liquid potassium sulfate. The calcium oxide has been converted to calcium carbonate and the FeO to Fe_3O_4 , increasing the mass flow of solids.

Sodium sulfate condenses in the low temperature air heater. This unit may be subject to plugging since mixtures of sodium and potassium sulfate at temperatures around 1000 K are known to be sticky.

At the low temperature economizer, phosphorous condenses. Since phosphorous has a deleterious effect on plasma conductivity, it should not be recycled. Either slag arriving at this point should be discarded or a seed regeneration process that rejects phosphorous should be used.

In the second set of calculations for the raw coal runs at varying slag removals (Tables 15-21), decreasing amounts of potassium salts are required to attain the specified 1% potassium in the plasma as the amount of slag rejection from raw coal increases, because total mass flow decreases. The composition of the slags in the primary combustor are identical.

Not shown in the tables is the fact that the absolute temperature in the secondary combustor decreases about 1% as carryover increases from 37.5 to 100%, which is sufficient to condense calcium oxide and magnesium silicate. However, in the downstream components, the compositions change in that aluminum oxide, calcium oxide, and silicon dioxide increase while iron oxides decrease as carryover decreases.

All of the comments concerning the chemical composition of the slag made in the raw-cleaned coal comparison apply here also, but they become of increasing concern as the amount of slag carryover increases.

Table 22 summarizes the results showing the weight of the slag rejected and the weight of the slag and seed carried over for the four cases. As the slag rejection increases, the weight of the total slag accounted for (slag rejected plus slag carried over) decreases. This is due to the fact that the slag rejection takes place under reducing conditions, leaving smaller amounts to convert to higher oxides and thus increase in weight due to the downstream oxidizing conditions. Also, the ash sulfur transfers to the seed component. The seed weight recovered exceeds that fed due to the

conversion of potassium carbonate to sulfate. In the clean coal case, the weight of slag accounted for exceeds the weight of the ash fed because there is only a small amount of sulfur present in the cleaned coal ash and the increase in the weights of the higher oxides overbalances the loss of sulfur. In both cases, the small amount of potassium in the ash is included with the seed.

TABLE 15
 CONDENSED SLAG/SEED PROPERTIES
 PRIMARY COMBUSTOR (A)
 RAW COAL
 TEMP. 3650°F/2283 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)			
REJECTED	0	0.042	0.075
CARRYOVER	0.083	0.042	0.008
TOTAL COND. WT. (LB/LB COAL)	0.083	0.084	0.084
TOTAL SYSTEM MASS FLOW RATE*	3.678	3.636	3.603
SPECIES (SLAG WT. %)			
Al_2O_3	S**25.55	S 25.55	S 25.55
CaO	S 15.66	S 15.66	S 15.66
FeO	L 1.31	L 1.31	L 1.31
$MgSiO_3$	L 14.22	L 14.22	L 14.22
SiO_2	L 43.25	L 43.25	L 43.25

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

L = LIQUID

TABLE 16
 CONDENSED SLAG/SEED PROPERTIES
 DIFFUSER EXIT (C)
 RAW COAL
 TEMP. 3528⁰F/2216 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)	0.087	0.045	0.012
TOTAL COND. WT. (LB/LB COAL)	0.087	0.045	0.012
TOTAL SYSTEM MASS FLOW RATE*	5.491	5.448	5.414
SPECIES (SLAG WT. %)			
Al ₂ O ₃	S**24.40	S 23.38	S 17.27
CaO	S 15.28	S 14.87	S 12.73
FeO	L 2.52	L 3.72	L 10.45
MgSiO ₃	L 13.65	L 13.19	L 10.45
SiO ₂	L 44.09	L 44.84	L 49.55

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

L = LIQUID

TABLE 17
 CONDENSED SLAG/SEED PROPERTIES
 RADIANT BOILER EXIT (D)
 RAW COAL
 TEMP. 2110°F/1428 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)	0.093	0.051	0.018
TOTAL COND. WT. (LB/LB COAL)	0.093	0.051	0.018
TOTAL SYSTEM MASS FLOW RATE*	5.491	5.448	5.414
SPECIES (SLAG WT. %)			
AL ₂ O ₃	S**22.87	S 20.70	S 11.68
CAO	S 12.32	S 9.96	-
CAS	S 2.89	S 4.80	S 12.72
FE0	S 5.96	S 9.76	S 25.62
MgSiO ₃	S 13.00	S 12.03	S 8.00
SiO ₂	S 42.10	S 41.20	S 37.50
TiO ₂	S 0.86	S 1.56	S 4.48

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 18
 CONDENSED SLAG/SEED PROPERTIES
 AFTERBURNER EXIT (E)
 RAW COAL
 TEMP. 2400°F/1589 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)	0.093	0.051	0.018
SEED WT. (LB/LB COAL)	0.060	0.059	0.059
TOTAL COND. WT. (LB/LB COAL)	0.154	0.111	0.076
TOTAL SYSTEM MASS FLOW RATE*	6.714	6.672	6.637
SPECIES (SLAG WT. %)			
Al ₂ O ₃	S**13.90	S 9.64	S 2.69
CaO	S 8.83	S 6.33	S 2.34
Fe ₃ O ₄	S 3.89	S 4.88	S 6.42
MgSiO ₃	S 7.91	S 5.60	S 1.91
SiO ₂	S 25.57	S 19.16	S 8.77
TiO ₂	S 0.52	S 0.72	S 1.04
K ₂ SO ₄	L 39.38	L 53.73	L 76.82

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 19
 CONDENSED SLAG/SEED PROPERTIES
 SUPERHEATER EXIT (F)
 RAW COAL
 TEMP. 1555⁰F/1119 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)	0.093	0.051	0.018
SEED WT. (LB/LB COAL)	0.118	0.117	0.117
TOTAL COND. WT. (LB/LB COAL)	0.212	0.169	0.134
TOTAL SYSTEM MASS FLOW RATE*	6.714	6.672	6.637
SPECIES (SLAG WT. %)			
AL ₂ O ₃	S**10.09	S 6.31	S 1.55
CAO	S 6.43	S 4.17	S 1.32
FE ₃ O ₄	S 2.83	S 3.20	S 3.66
MgSiO ₃	S 5.74	S 3.67	S 1.06
SiO ₂	S 18.58	S 12.56	S 4.99
TiO ₂	S 0.38	S 0.47	S 0.60
K ₂ SO ₄	S 50.14	S 62.32	S 77.66
K ₂ CO ₃	S 5.81	S 7.29	S 9.16

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 20
 CONDENSED SLAG/SEED PROPERTIES
 LOW TEMPERATURE AIR HEATER EXIT (G)
 RAW COAL
 TEMP. 1258°F/954 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)	0.112	0.065	0.028
SEED WT. (LB/LB COAL)	0.120	0.119	0.118
TOTAL COND. WT. (LB/LB COAL)	0.232	0.184	0.146
TOTAL SYSTEM MASS FLOW RATE*	6.714	6.672	6.637
SPECIES (SLAG WT. %)			
Al ₂ O ₃	S**9.20	S 5.79	S 1.43
CaCO ₃	S 10.46	S 6.83	S 2.17
Fe ₃ O ₄	S 2.58	S 2.93	S 3.38
MgSiO ₃	S 5.23	S 3.36	S 0.98
Na ₂ SO ₄	S 3.66	S 4.62	S 5.84
SiO ₂	S 16.94	S 11.52	S 4.60
TiO ₂	S 0.34	S 0.44	S 0.55
K ₂ SO ₄	S 45.48	S 56.83	S 71.32
K ₂ CO ₃	S 6.10	S 7.69	S 9.73

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 21
 CONDENSED SLAG/SEED PROPERTIES
 LOW TEMPERATURE ECONOMIZER (J)
 RAW COAL
 TEMP. 320°F/433 K

% SLAG REJECTION	0	35	62.5
SLAG WT. (LB/LB COAL)	0.113	0.066	0.028
SEED WT. (LB/LB COAL)	0.120	0.119	0.118
TOTAL COND. WT. (LB/LB COAL)	0.233	0.185	0.146
TOTAL SYSTEM MASS FLOW RATE*	6.714	6.672	6.637
SPECIES (SLAG WT. %)			
AL ₂ O ₃	S**9.18	S 5.77	S 1.43
CACO ₃	S 10.43	S 6.80	S 2.16
FE ₃ O ₄	S 2.57	S 2.92	S 3.37
MGSIO ₃	S 5.22	S 3.35	S 0.98
NA ₂ SO ₄	S 3.71	S 4.67	S 5.90
P ₄ O ₁₀	S 0.20	S 0.25	S 0.32
SI O ₂	S 16.89	S 11.48	S 4.58
TIO ₂	S 0.34	S 0.43	S 0.55
K ₂ SO ₄	S 45.37	S 56.64	S 71.02
K ₂ CO ₃	S 6.09	S 7.68	S 9.70

* INCLUDES FUEL, AIR, OXYGEN, AND SEED LESS SLAG REJECTED (LB/LB COAL)

** S = SOLID

TABLE 22
SLAG/SEED CARRYOVER - ROSEBUD COAL

COAL	<u>% REJECTED</u>	<u>SLAG WEIGHT REJECTED*</u> <u>(LB/LB COAL)</u>	<u>SLAG/SEED CARRYOVER</u> <u>THROUGH ECONOMIZER*</u> <u>(LB/LB COAL)</u>		
			<u>SLAG</u>	<u>SEED</u>	<u>TOTAL</u>
RAW	0	0	0.113	0.120	0.233
	35	0.042	0.066	0.119	0.185
	62.5	0.075	0.028	0.118	0.146
CLEANED	75	0.045	0.021	0.123	0.144

* ASSUMES NO SLAG/SEED REMOVAL FROM SYSTEM BEYOND COMBUSTOR

5.0 IMPACTS ON THE DESIGN OF THE MHD GAS FLOW TRAIN

5.1 Solid Loadings in the Gas Flow Train

Both slag rejection and coal cleaning reduce the absolute weight and the weight fraction of the slag being carried over into the gas flow train. The reduced carryover due to coal cleaning is equivalent to 72% of the condensed species being removed at the combustor (50% of the ash fed) for the Montana Rosebud coal.

Figure 2 shows the mass fraction of the condensed species (both slag and seed) downstream of the HR/SR system versus the amount of ash originally in the raw coals. At high ash rejection rates, coal cleaning has a relatively small impact on the mass fraction since the seed fraction is much larger than the slag fraction. However, at low ash rejection rates, the seed and slag fractions are about equal and coal cleaning has a higher proportional effect.

Table 23 shows the grain loadings (weight of condensed species per standard cubic foot of gas) in the superheater section. Also shown are the grain loadings in the superheater section of a typical pulverized coal-fired boiler. The grain loadings shown assume that no slag or seed has been rejected beyond the combustor (i.e. in the radiant boiler, superheater, etc.).

The higher condensate loadings in the MHD system are due primarily to the seed. The amount of seed compared to slag in the system ranges from 51% for zero slag rejection to 86% for the combination of high slag rejection and cleaned coal. These higher solid loadings can be expected to result in increased fouling and erosion as compared to conventional furnaces. The amount of seed in the HR/SR system is set by either conductivity (for low sulfur coals) or sulfur removal requirements (for high sulfur coals). Slag rejection and coal cleaning will not significantly affect the former amount.

FIGURE 2
PERCENT ASH IN COAL VERSUS
MASS FRACTION OF SLAG AND SEED

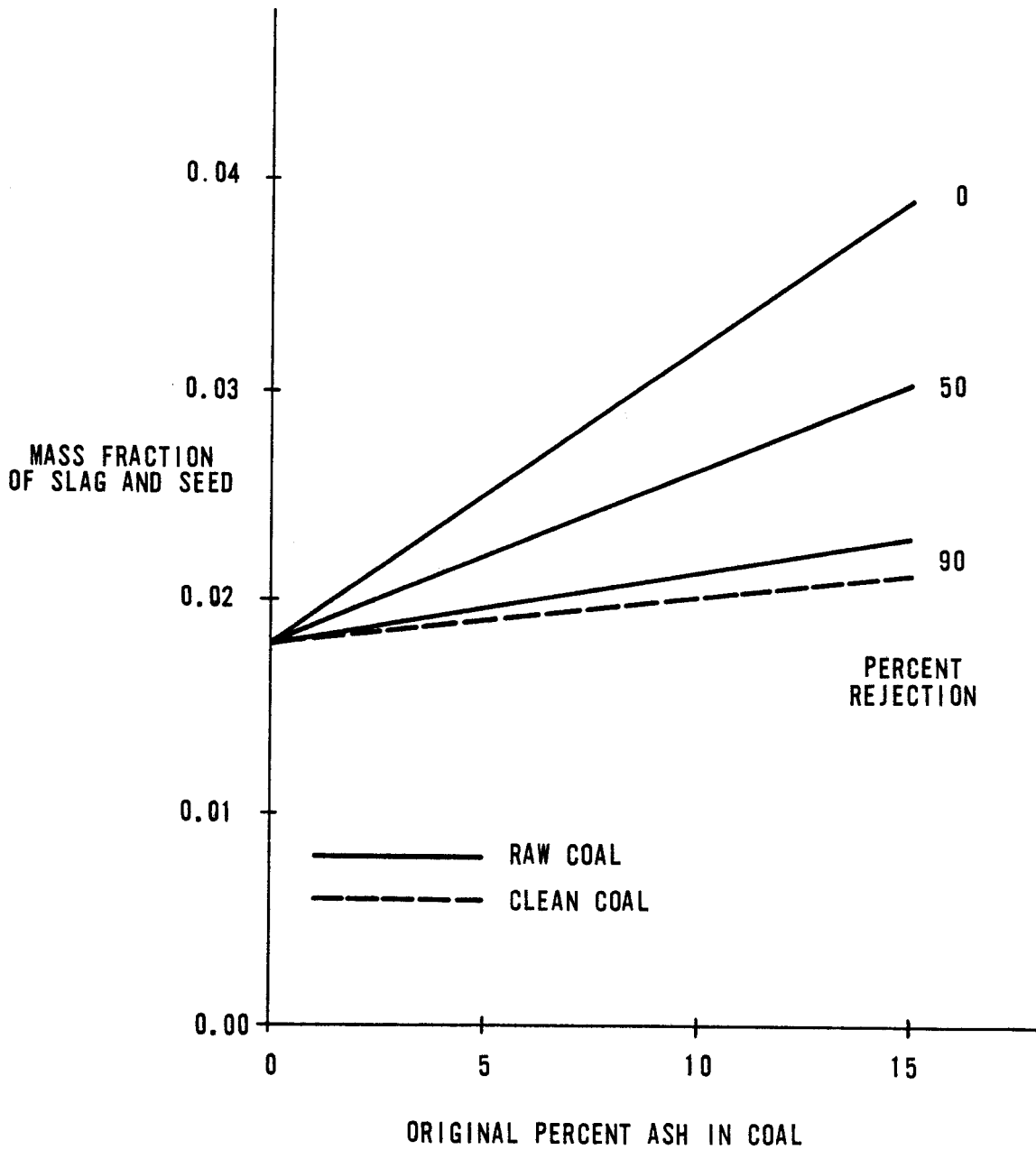


TABLE 23

MHD SUPERHEATER GRAIN LOADINGS

<u>Rosebud Coal</u>	% Ash Rejected at the Combustor	<u>Grain Loading (gr/scf)</u>		
		<u>Total</u>	<u>Slag</u>	<u>Seed</u>
Raw	0	19.6	9.6	10.0
	35	15.6	5.6	10.0
	62.5	12.4	2.4	10.0
Clean	75	11.8	1.6	10.2
Conventional Dry Bottom PC Boiler	15	3-5	3-5	-

However, coal cleaning, reduces the amount of sulfur in the coal and thereby reduces seed regeneration requirements (in this case from 47% of the seed to 26%).

5.2 Slagging and Viscosity Parameters

The chemical and physical behaviors of the inorganic (ash) constituents in coal during gasification (reducing conditions) and combustion (oxidizing conditions) are extremely important factors in the design and performance of coal-fired MHD systems. Excessive or widely fluctuating pressure drops occur when fly ash and slag accumulate in critical gas passages. Unsteady, non-uniform heat absorption by furnace walls and other heat exchange surfaces occur when such surfaces are covered with varying fly ash and slag deposits. The operability of slag removal mechanisms depends significantly upon the physical and chemical behavior of the fly ash and slag formed during gasification and combustion.

No single test has yet been devised that will provide a reliable index of the behavior of ash and slag under any stated operating conditions. This is due to the complexity of the physical and chemical reactions that occur when the inorganic constituents of coal are heated to high temperatures. The composition of the ash and slag from coal burned in suspension differs in various parts of the MHD system. Coal ash and slag are complex substances consisting primarily of compounds of aluminum, calcium, iron, magnesium, potassium, silicon, sodium, and titanium. Predicting the effect of change in any one constituent on the properties of slag is extremely difficult because variation in any one constituent changes the effect of all the other constituents. Thus, when studying systems of this complexity, the practice has become to fix certain variables, the effects of which either are negligible or are known to range normally between rather narrow limits.

In studying the effects of composition, only the compounds previously mentioned have been considered. Thus, ash constituents are grouped together as inputs for calculating certain parameters, of which there seems to be a rather confusing array. A publication¹² of ASME attempts to bring them all together in one convenient place. All of these parameters are acceptable within the framework of the observations made in deriving them. In general, someone observed a recurring problem and searched out a test, analysis, or combination thereof, which could explain their observations. None of these observations or correlations are incorrect; however, there exists considerable doubt as to the applicability of some of these correlations to all coals and all systems.¹³ The differences between the MHD slags and the slags used in developing the correlations introduces uncertainties into the interpretations of the calculated results.

Table 24 presents definitions from Reference 12 that are commonly used in presenting slagging and viscosity parameters. Although it is not generally stated explicitly, slag behavior parameters are based on fully oxidizing conditions. The MHD system has a reducing atmosphere up to the afterburner, consequently, the parameter interpretations are subject to considerable doubt up to that point in the system.

For this study, the FeO which appears in computer outputs has been used directly in place of Fe_2O_3 , which appears in some parameters. The fusion characteristic of slag depends greatly on the iron content in it¹⁴ and FeO lowers the fusion temperature more than does Fe_2O_3 .¹³ If the viscosity is similarly affected, the temperature of critical viscosity, T_{cv} , may be too high and the critical viscosity, η_{cv} , as well as the viscosity at the statepoint, η_{sp} , may be too small. The assumption that CaS would act like CaO should not introduce serious error, since the difference in equivalent weights will tend to be balanced by the difference in basicities.

Potassium concentrations expected in MHD systems will cause a slight increase (10 to 30 percent) in viscosity.¹⁵ These increases are not reflected in Table 25. The changes are relatively independent of slag type and temperature.

With the above provisos in mind, the temperatures of critical viscosity and of 250 poise viscosity, the viscosity at the critical temperature, at the statepoint temperature, and at 2600°F were calculated. This temperature of 2600°F, which is a convenient slag tapping temperature, occurs only in the combustor and the radiant boiler. For those slags shown to be of Eastern type by their base to acid ratio, the slagging potential, R_s , was also calculated. R_s gives a reasonable correlation with slagging problems. Low values indicate low accumulations of deposits on heat exchange surfaces. This parameter is not applicable to Western type slags. The calculations, shown in Table 25, were made for three cases: 1) raw coal with 0 percent slag removal from the primary combustor, 2) raw coal with 90 percent condensed slag removal, and 3) cleaned coal with 90 percent condensed slag removal.

TABLE 24

FOULING AND SLAGGING DEFINITIONS¹²

- o Acid Constituents of Ash: Al_2O_3 , SiO_2 , and TiO_2 .
- o Base Constituents of Ash: CaO , Fe_2O_3 , K_2O , Na_2O , and MgO .
- o Eastern Type Coal: One whose ash contains more Fe_2O_3 than $\text{CaO} + \text{MgO}$. Also, one whose base to acid ratio is less than 0.4^5 .
- o Slagging Factor, R_s , is a parameter empirically developed to relate coal ash analyses to fused slag deposits that form on surfaces exposed to predominately radiant heat. It is not applicable to western type coals.
- o Temperature of Critical Viscosity, T_{cv} : That temperature at which the viscosity properties of a molten slag changes on cooling from those of a Newtonian fluid to those of a Bingham plastic. As slag is cooled, the logarithm of its viscosity increases linearly with decreasing temperature. At some temperature, the increase deviates from a straight line and the viscosity increases more rapidly as cooling proceeds. This is believed to occur at the temperature where solid phases start to crystallize from the melt.
- o T_{250} : The temperature at which the viscosity of the slag is 250 poises. The maximum viscosity at which a molten slag can be tapped readily is 250 poises. If T_{250} is lower than T_{cv} , the slag will not flow well, since it is in the plastic range.
- o Western Type Coal: One whose ash contains more $\text{CaO} + \text{MgO}$ than Fe_2O_3 . Also, one whose base to acid ratio is greater than 0.4^5 .

TABLE 25

PARAMETER CALCULATION RESULTS

COAL	% SLAG REMOVAL	STATEPOINT	Tsp	η_{sp}	Tcv	η_{cv}	η_{2600}	T250	Rs
Raw	0	Combustor	3648	3.2	2374	608	170	2480	Low
		Radiant Boiler Entrance	3528	4.2	2318	994	160	2470	Low
		Radiant Boiler Exit	2110	1888	2255	427	86	2330	Low
Raw	90	Combustor	3648	3.2	2374	608	170	2480	Low
		Radiant Boiler Entrance	3528	3.4	2654	103	100	2275	Low
		Radiant Boiler Exit	2110	511	2966	5.2	8	<2000	IA
Clean	90	Combustor	3651	0.8	2925	4.4	21	2230	Low
		Radiant Boiler Entrance	3528	0.03	4766	0.01	<1	<4766	IA
		Radiant Boiler Exit	2110	742	3335	2.4	36	2130	IA

Tsp = Temperature ($^{\circ}$ F) at statepointTcv = Critical temperature ($^{\circ}$ F)T250 = Temperature ($^{\circ}$ F) at which viscosity is 250 poises η_{sp} = Viscosity (poise) at statepoint temperature η_{cv} = Critical viscosity (poise) η_{2600} = Viscosity (poise) at 2600 $^{\circ}$ F

Rs = Slagging potential

IA = Inapplicable

The raw Montana Rosebud coal without slag rejection yields an Eastern type slag in the primary combustor. Its slagging potential is low. The combustor statepoint temperature is sufficiently above T_{250} and T_{cv} so that slag removal should not be a problem from the standpoints of high viscosity or plastic behavior.

The temperature at the entrance of the radiant boiler is sufficiently high such that slag can be removed. T_{250} will be reached before the exit of the radiant boiler, so slag removal will be difficult in the downstream portion of the boiler. The slag will be a solid at the exit so that other types of removal rather than slag tapping will be required if slag is to be removed at the exit. The slagging potential is low throughout.

Conditions when 90 percent of the slag condensed in the primary combustor is removed are very similar to the 0 percent rejection case. Slag removal from the primary combustor should not be a problem but removal from the upstream portion of the radiant boiler may be difficult due to the plastic behavior. Again, the downstream and exit portions of the radiant boiler may show poor slag handling properties. The exit slag is of the Western type so that the slagging parameter, low to this point, becomes inapplicable.

Cleaning the Montana Rosebud coal increases the base to acid ratio making its slag more Western-like. This is reflected in the inapplicability of the slagging parameter at the entrance of the radiant boiler. T_{cv} and T_{250} are very high, but the associated viscosities are very low, which does not seem reasonable. Plastic behavior normally means high viscosity. It could be concluded that slag removal from the combustor is possible, but the slag in the radiant boiler will not flow well. However, a better conclusion is that the parameters do not apply to the slag from a clean coal, since its constituent makeup is quite different from the slags upon which the parameters are based.

The slagging and viscosity parameters cannot be applied to any of the remaining downstream components of the heat recovery - seed recovery subsystem since the solids formed there are mostly potassium salts contaminated with slag. Mention has previously been made of the possible corrosivity of such mixtures. Additionally, they can be expected to have high fouling potential due to the presence of mixed alkali sulfates. The temperature range over which high corrosion rates are attributable to effects of alkali-iron trisulfates is a maximum near a sodium to potassium ratio of 1.¹² In the MHD system, the alkali ratio is approximately 0.08 so the extension of $(\text{Na},\text{K})_3\text{Fe}(\text{SO}_4)_3$ corrosion to lower temperatures by the inclusion of Na^+ should not be significant.

The coal parameter calculations can only indicate gross trends since the cases studied departed from the conditions under which the parameters were obtained. The MHD conditions represent an extrapolation into new conditions where insufficient background information is available upon which to correlate informative parameters. However, the consistently low slagging potentials, in the cases in which they can be applied, and the generally good flow properties calculated for the raw Montana Rosebud coal slag indicates little impact on the design of the MHD gas flow train up to the afterburner. Beyond the afterburner, however, the presence of seed may require that tube spacings and arrangements be more widely spaced than that usually used in conventional pulverized coal furnaces. Additionally, more erosion and corrosion resistant materials may be needed. Cleaned coal results in slags that are less familiar and of higher viscosities, so that operability of conventional designs is less certain, even without considering seed effects.

5.3 Flame Temperature

The flame temperature of the raw and clean coal fractions were calculated for the Rosebud coal using the ISGS cleaning data.^{6,7} The Gilbert/Commonwealth modified CEC code was used for these calculations and the results are shown in Table 26. While coal cleaning increases the heating value (a maximum of 14%), the increase in flame temperature is much less (less than 5%). The higher heating value fuel requires more oxidant. The inert N₂ in the oxidant tends to reduce dampen the effect of the higher heating value of the fuel. Thus the effect of coal cleaning on flame temperature, while a small percentage change, is significant in absolute terms and thus could have a pronounced effect on plasma conductivity.

TABLE 26

FLAME TEMPERATURE OF CLEANED FRACTIONS
ROSEBUD COAL - ISGS DATA

Specific Gravity	1.29	1.32	1.35	1.40	1.60	Raw Coal
Weight Recovery, %	36.8	61.2	74.3	86.6	97.0	100.0
HHV, Btu/lb	12263	12175	12121	12037	11851	10760
T _F , °F	4787	4785	4782	4784	4779	4575

6.0 MATERIAL IMPLICATIONS OF COAL CLEANING AND SLAG REJECTION

6.1 General

It is to be expected that the properties of slags and their interactions with materials of construction will be sensitive to changes in slag composition. The origins of such changes might be different coal types or pretreatment (e.g., cleaning) of the coal to deplete some ash components. It seems likely that the range of differences between various coals is larger than the difference in a single coal as a result of washing. This is confirmed by calculations of the temperatures required to achieve specified slag viscosities. The differences between Montana Rosebud and Illinois #6 coal slags were found to be greater than the differences between the slags from the natural and washed states of either coal.

The following comparisons are based on computations of the equilibrium composition of the products of combustion at various points in the MHD flow train. Assumptions relating K^+ additions to sulfur content and their governing slag removal were consistent. However, compositional calculations based on equilibrium in the mainstream flow do not represent the non-equilibrium conditions on water-cooled walls. Therefore, the following discussion is qualitative, assuming that variations in wall condensate correspond to changes in equilibrium composition. It is necessary to remember, however, that components that do not occur in the equilibrium condensed phase at a given location can and will condense on relatively cool surfaces. Thus, even relatively volatile species, such as K_2O , are found on the walls of high temperature regions of the system.

The principle differential effects of coal cleaning are depletion of the oxides of iron and aluminum. The reduction in total ash content is about 50% in Montana Rosebud coal. This difference is reflected in the various amounts of slag rejected in the combustor, and in

different condensation rates for individual slag components downstream. The following discussion of slag properties and potential materials interactions in the channel/diffuser and radiant boiler is based on the equilibrium computations. Downstream of the afterburner, the alkali salts dominate the condensed phase of the products of combustion and the differences between any of the conditions studied with respect to materials interactions are expected to be small. The discussion of these downstream components, then, applies in general.

6.2 Channel/Diffuser

The equilibrium calculations indicate that the slag entering the channel is essentially Al_2O_3 , and the condensate in the stream leaving the channel contains SiO_2 , CaO , and FeO (in the unwashed coal case) as well. Presumably, these other components condense out of the cooling plasma. It might then be reasonable to assume that the slags deposited on the channel walls would match the equilibrium compositions at the extremes and would reflect a smooth transition in between. This, however, would not be in accord with experimental results or the conclusions of slag layer theory analyses. Rather, it is preferable to envision a steady state slag layer in which the liquid surface is depleted by flow along the channel and re-evaporation, and simultaneously renewed by upstream flow along with condensation. The flow is driven by shear/drag forces at the plasma-slag interface. The slag layer adjusts itself such that the surface temperature corresponds to a slag viscosity allowing flow under the applied shear force. Since the shear force is approximately uniform along the channel, so, then, are the slag surface viscosity and temperature.⁵ The further implication is that because of uniform temperature and flow along the channel, along with continuous condensation and re-evaporation, the slag composition is close to uniform along the channel.

Given a fixed (by water cooling) wall temperature and a steady state plasma temperature distribution, the slag layer surface temperature is maintained by variation in layer thickness along the channel. Perpendicular to the channel axis, the slag layer temperatures vary from the fixed wall temperature to the slag surface temperature. Therefore, the slag layer can contain all species from the plasma that are condensable at temperatures above that of the wall.

The major calculated effects of coal cleaning are a greatly decreased FeO content in the slag and an increased ratio of SiO_2 to Al_2O_3 . However, at the diffuser exit, the washed coal slag is Al_2O_3 rich as compared to unwashed coal slag. These changes should be reflected by changes in thermophysical properties and in chemical/electrochemical properties. Using Capp's¹⁶ modification of the Watt-Fereday¹⁷ equation empirically relating the viscosity-temperature characteristics of slags to their compositions, it is seen that decreased FeO content is dominated by decreased SiO_2 to Al_2O_3 ratio giving a net tendency to lower the temperature at which the slag will flow. It is estimated that these changes in composition will decrease the slag surface layer temperature 800° to 1,000°F with corresponding decreases in slag layer thickness.

The decrease in FeO content decreases electrochemical corrosion effects. Both the ionic conductivity of the slag and the presence of a relatively easily reduced oxide are lessened. There will be less propensity for reduction of FeO to the metal and for intergranular attack at the cathodes. There is a lowered rate of oxygen formation causing cavitation/erosion at the anodes¹⁸ and less dissolution corrosion. In addition, the relative decrease in SiO_2 suggests a decrease in chemical capture of K_2O by the slag.¹⁹ Quantitative assessment of the relative magnitudes of these effects requires additional data. In addition, SiO_2 depletion implies a decrease in seed loss in the power train and improved seed recovery downstream.

6.3 Radiant Boiler

The MHD system radiant boiler is intended to serve two functions: enthalpy extraction and slag removal. These dual purposes require sufficient design flexibility to accommodate changes in one area without major perturbations in the other. In particular, changes in slag properties must be handled without producing major changes in steam conditions or production rates.

The major effect of the change in slag composition due to coal cleaning is, in this component, a decrease in fluidity, or a shift upstream in the position at which slag ceases to flow. This results from the removal of FeO and a simultaneous relative increase in SiO₂. The consequence of these changes is the need for higher temperatures to achieve the same degree of fluidity; it is estimated²⁰ that flow of washed coal slag will require surface temperatures 240° to 360°F higher than similar flow of slag from the unwashed coal. The design implications include lower heat fluxes, thicker refractory linings, and increased heat transfer surface areas. Thus, boiler design must be specific to a particular slag or incorporate heat transfer control features to accommodate a range of slags.

The question of slag compatibility with boiler materials cannot be unambiguously resolved. Again, the composition of the slag collecting on relatively cool slag screen and boiler wall surfaces is not the same as the equilibrium slag composition at flue gas temperatures. Virtually all condensable species present in the gas, including seed, appear on the surfaces despite their volatility at gas temperatures. Little experimental or analytical work has directly addressed interactions between slag/seed and boiler materials. However, research into the survivability and durability of directly-fired air preheater refractories is applicable. The results^{15,21} of such work suggests that the decrease in FeO concentration in washed coal slags could be advantageous, but the

mechanisms of refractory degradation relative to FeO concentration are not known nor are the data quantitative.

6.4 Afterburner

In terms of materials of construction, the afterburner is the most critical component of the flow train downstream of the MHD channel. Afterburner materials must be able to withstand both reducing and oxidizing conditions, possibly in alternation, relatively high sulfide vapor pressures; and oxide fluxing molten sulfates. Unfortunately, the transitions from reducing to oxidizing and from sulfide to sulfate do not occur at a precise, clearly defined interface. They occur, rather, throughout zones of transition that could fluctuate as a result of minor perturbations in air injection, mixing, and combustion conditions.

The composition of the gas entering the afterburner is capable of reducing ferrous metal oxides to the metals at water-cooled wall temperatures. This reduction can eliminate the effectiveness of protective oxide films on structural metals, exposing fresh metallic surfaces to subsequent corrosion. At the same time, the relatively high sulfur partial pressure in the gas can allow conversion of oxides to sulfides. This process seems to be kinetically favored where microscopic discontinuities in the solid provide initiating sites. The resulting phenomena, typically, are pitting and grain boundary penetration. In both cases, impairment of protective oxide films leave surfaces vulnerable to subsequent oxidation.

In the afterburner, most of the sulfur and sulfide in the stream is converted to sulfate. The predominant condensed phase component becomes K_2SO_4 liquid. On the surfaces of metal components, the sulfate can act as a fluxing agent, melting and stripping off protective oxide films and thereby exposing fresh metal surfaces to an aggressively oxidizing atmosphere. Alloys and/or coatings for this service must be carefully selected for resistance to sulfate attack.

Little effect of coal cleaning is expected in the afterburner. If most of the coal ash components carried through the MHD channel are removed in the radiant boiler, the rate at which entrained condensate will enter the afterburner is relatively low. Thus, the higher fluidity of the raw coal slag, due largely to its higher iron content, is of secondary importance. K_2SO_4 quickly becomes the dominant component of the condensed phase under oxidizing conditions.

6.5 Heat Recovery/Seed Recovery Components

The superheater, oxidant preheater, and economizers downstream of the afterburner are heat exchangers designed for coolant flow in metal water walls and tubes over which the hot gas is passed. The equilibrium calculations indicate that for the 90% slag rejection cases, the seed containing constituents account for 80 to 85% of the mass of condensate carried into and condensing in this series of components. Thus, collection of the condensate for subsequent recovery of the seed material is planned. With the condensate so dominated by seed compounds, the variation in coal ash components is of relatively minor significance.

The principal materials considerations in these components are corrosion enhanced by sulfates and carbonates at the higher temperatures (as described above), and acid/dew point corrosion at the low temperature end. The dew point, at which aqueous acids condense, is largely a function of the initial coal hydrogen and moisture contents. Thus, the downstream dew point temperature varies with coal type and with the extent of pre-combustion drying, but is not very sensitive to coal cleaning. The equilibrium calculations show a marginally higher (by about 2.4%) water vapor pressure in the cleaned coal cases. This changes the dew point by only a few degrees. For the conditions of the calculations, the dew point temperature would be expected to occur in the ESP or the stack. The severity of acid corrosion also depends on trace amounts of components, such as chloride ion, which were not included in the calculations.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Findings and Conclusions

This study was conducted using a computer model based on equilibrium calculations. Until more data are available, these calculations give the best indication of the effect of coal cleaning and slag rejection on the mass flow rate and composition of slag and seed in the gas train components of a MHD power plant. The general findings and conclusions drawn from this assessment are as follows.

7.1.1 Solid Loadings in the Gas Flow Train

- o Both slag rejection and coal cleaning reduce the weight and weight fraction of the slag being carried over from the combustor. Grain loadings in the gas train, even for high slag rejection, are considerably higher than in conventional coal-fired systems due primarily to the seed addition, and are largely independent of coal cleaning, especially at high slag rejection rates.
- o Rejection rates of 90, 50, and 0 weight percent of the condensed slag in the first stage of the combustor is equivalent to rejection rates of 62.5, 35, and 0 percent of the ash content in the coal fed to the combustor.
- o For Montana Rosebud coal, conductivity considerations determine the seed requirement. Hence, coal cleaning and slag rejection have little effect on the amount of seed needed. Coal cleaning does reduce seed regeneration requirements by removing sulfur from the coal.

7.1.2 Slagging and Fouling Characteristics of the Gas Flow Train

- o Liquid slag is present and can be tapped until the upstream portion of the radiant boiler. The slag will be solid at the radiant boiler exit.
- o Upstream of the afterburner, the condensed species consists only of slag constituents, whereas downstream of the afterburner, the predominate specie is potassium sulfate in all cases, with varying amounts of slag.
- o All condensed species are expected to be solid downstream of the afterburner. If the salts are "sticky" at temperatures around 1350°F, fouling in the Low Temperature Air Heater (LTAH) may occur and sootblowing techniques might not remove the condensed salts.

7.1.3 Material Selection and Design Implications for the Gas Flow Train

- o Seed first condenses in the afterburner and remains liquid into the superheater. Liquid alkali salts attack protective oxide films, thus selection of appropriate superheater materials to resist accelerated corrosion is critical. The seed will be solid at the superheater exit.
- o Afterburner materials must be able to withstand alternating reducing and oxidizing conditions, in relatively high sulfide vapor pressures, and oxide fluxing molten sulfates. In terms of materials of construction, the afterburner is therefore the most critical component of the flow train downstream of the MHD channel.

- o The major effects in the channel of cleaning Montana coal are to greatly decrease FeO content in the slag and to decrease the ratio of SiO_2 to Al_2O_3 . These changes are dominated by the changing ratio and tend to lower the temperature at which the slag will flow.
- o The major effects in the radiant boiler of cleaning the Montana coal are a greatly decreased FeO content in the slag and an increased ratio of SiO_2 to Al_2O_3 . These changes, now both acting in the same direction, tend to raise the temperature at which the slag will flow.
- o The above mentioned compositional changes affect the design and operation of components which are constrained by the need to maintain slag flow on their walls.
- o Materials data supporting direct fired high temperature air heater development are applicable to radiant boiler refractory selection.

7.2 Recommendations

- o The slagging, fouling, and flow properties of slags from Montana Rosebud coal should be experimentally investigated as functions of cleaning level and combustor slag rejection.
- o The surface properties (e.g. adhesion, cohesion, friability, etc.) of potassium salts should be experimentally investigated at LTAH and reheater temperatures. Admixtures of sodium salts and flyash oxides in the $\text{K}_2\text{SO}_4\text{-K}_2\text{CO}_3$ system should be included to simulate operating conditions.
- o The use of coal cleaning as a supplement to slag rejection and as a means of reducing seed regeneration requirements should be considered. Both results can lead to a reduced cost of electricity through lowered costs or increased efficiency.

- o Development of materials resistant to the conditions in the afterburner and superheater should be accelerated.

- o Radiant boiler, afterburner, and superheater design studies incorporating new materials and direct-fired air heater materials should be initiated as soon as possible.

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