Seed Regeneration System Integration Issues And Economics

Author(s): J. R. Lance

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SEED REGENERATION SYSTEM INTEGRATION ISSUES AND ECONOMICS

J. R. LANCE
WESTINGHOUSE SCIENCE & TECHNOLOGY CENTER
1310 BEULAH ROAD
PITTSBURGH, PA 15235

ABSTRACT

Westinghouse Electric Corporation, through Contract No. DE-AC22-87PC79668 funded by U.S. DOE/PETC, is conducting a conceptual design study to evaluate a coal-fired magnetohydrodynamic (MHD) retrofit of a utility plant of sufficient size to demonstrate the technical and future economic viability of an MHD system operating within an electric utility environment. The objective of this study is to prepare a site-specific conceptual design of a coal-fired MHD system or retrofit to the Scholz Generating Station, Sneads, Florida.

The objective of this technical paper is to document continuing seed regeneration system application studies and the definition of seed system integration requirements for the Scholz MHD retrofit plant design. Development of a seed regeneration process with the DOE MHD Proof-of-Concept program is being accomplished by the TRW Applied Technology Division. This TRW program included the definition of a design basis for an ECONOSEED process suitable for a 300 MWt coal-fired MHD power plant.

The 300 MWt ECONOSEED design basis was used to prepare a mathematical model for quantifying interface requirements between the Scholz MHD retrofit plant design and an integrated ECONOSEED regeneration system. The mathematical model was validated by comparison with the ECONOSEED 300 MWt design basis and includes:

- Capital, operating, maintenance, and consumable cost
- Cost algorithms for the seed regeneration system and the seed injection system to permit evaluations of capital and operating costs as a function of plant size and operating conditions.

As expected, the most significant cost driver for the seed regeneration system is the coal sulfur content and therefore the amount of sulfur that the seed system removes from the process. The seed system operating cost in mills/kWh is also sensitive to the overall power plant efficiency. For example, the seed regeneration cost for an advanced, fully commercial 953 MWe MHD plant with an efficiency of 60% is about 3 mill/kWh with a coal sulfur content of one percent. The seed regeneration cost for the same plant burning coal with a four percent sulfur content is about 10 mill/kWh. The above numbers are based on a coal sulfur removal rate of 90%.

INTRODUCTION

MHD power plants require the addition of a seeding material in the form of potassium to enhance the ionization of the high temperature combustion gas in the MHD channel. This process has an added environmental advantage compared to other types of coal-fired power plants in that the potassium combines with the naturally occurring sulfur in the coal to form a potassium sulfate flyash (K_2SO_4) which can be removed from the process by appropriate particulate control equipment. Up to 100% of the Sulfur in the coal can be removed by this process thereby providing environmentally clean power plant operation that is better than required by present and anticipated future New Source Performance Standards (NSPS).

Given the above, the development of MHD technology and power plant designs to the point where electric utility companies will construct and operate coal-fired MHD power plants will also provide coal utilization benefits of economic importance to the U.S. Particularly with high sulfur eastern coals, MHD provides the capability to utilize this existing energy resource in an environmentally clean manner while contributing to U.S. national economic growth.

The Scholz Generating Station is owned and operated by Gulf Power Company, a member of the Southern Company. In the earlier tasks of this study, the Westinghouse design team was comprised of the following members: Southern Electric International (the architectural engineering arm of the Southern Company), University of Tennessee Space Institute (UTSI), SeiTec, Inc., HMJ Corporation, STD Research Corporation, and the Westinghouse Science & Technology Center. A previous contract deliverable report[1] documented the efforts of this team over the period of performance from October 1987 through April 1989.

SEED REGENERATION SYSTEM DESIGN BASIS

The design basis[2] for the ECONOSEED system is based on the regeneration of spent MHD seed material (flyash) in a 300 MWt MHD power plant using Illinois No. 6 coal. The spent seed material is primarily potassium sulfate (K_2SO_4) flyash which reacts in the ECONOSEED process with calcium formate ($Ca(COOH)_2$) to form potassium formate (KCOOH) and calcium sulfate ($CaSO_4$). Any potassium carbonate (K_2CO_3) in the spent seed flyash also reacts with calcium formate to form potassium formate and calcium carbonate ($CaCO_3$). Sulfur is removed from the process as gypsum by settling and filtration. Insoluble flyash and metal salts are removed with the gypsum and the calcium carbonate. The end product of the ECONOSEED process is a regenerated seed material consisting of a potassium formate solution which can be injected directly into the MHD combustor.

A 300 MWt/100 MWe MHD power plant was used as the basis for defining seed material and new material flow rates for the above ECONOSEED process. The requirements and assumptions used by TRW to formulate the design basis are:

Coal Combustion

- Illinois No. 6 Coal (3.62% sulfur)
- Higher Heating Value (HHV) used for coal flow rate
- 95% theoretical oxygen for combustion
- 70% slag/flyash rejection in combustor
- Combustion air enriched to 35% oxygen

Seed Requirements

- 1.5% potassium by weight in the MHD channel
- a molar ratio of injected seed carbonate to coal sulfur equal to 1.0
- sodium in the recycled seed material is allowed to build-up to a level of one mole Na per six moles of K or Na/K = 0.167 for the combined recycled and makeup seed materials at the combustor injection point.

The Illinois No. 6 coal ash contains both potassium and sodium which would be recovered in the spent seed as K_2SO_4, K_2CO_3, Na_2SO_4 and Na_2CO_3. TRW assumed that the ECONOSEED process does not separate potassium and sodium salts and cannot reduce the Na/K ratio by the selective rejection of sodium. As a result, the ratio of sodium to potassium in the regenerated seed after repeated recycling would approach the sodium to potassium ratio of the coal ash (Na/K = 1.5) if no recovered seed material is rejected or there is no sodium separation. A similar build-up of other contaminants will also occur after repeated seed recycling unless the contaminants are selectively removed or rejected. The ECONOSEED approach to preventing the build-up of contaminants is to purge a portion of the recovered flyash at a rate equal to the contaminant input from the coal. For the 300 MWt design basis this means the rejection of 4.8% of the soluble flyash seed to limit the build-up of sodium. Additional sodium is lost in the insoluble seed slag which is not input to the ECONOSEED process. This flyash/slag rejection also results in a corresponding loss of potassium which must be made up by an external supply of K_2SO_4/K_2CO_3.

Figure 1 shows the inputs and outputs of the ECONOSEED process for the 300 MWt design basis. Thermal energy equivalent values are shown for: the input natural gas; the required 150/175 psia saturated steam; the output gases; and the 600 psia steam. In Figure 1, only those ECONOSEED internal components involving the gas and boiler feedwater streams are shown.

K_2/S Molar Ratio

The ECONOSEED design basis[2] assumes 100% sulfur removal at an effective K_2/S molar ratio of 1.0. Actually, since both K_2CO_3 and Na_2CO_3 are injected as seed materials and sodium is assumed to have the same affinity for sulfur as potassium, the alkali metal to sulfur molar ratio should be used. Therefore, in the design basis case:

$$(K_2 + Na_2)/S = CO_3/S = 1.0$$

But test data[3] has shown that a CO_3/S ratio greater than 1.0 is needed for 100% sulfur removal. It is also noted[3] that gas phase chloride emissions (measured as HCl) can be significantly reduced or eliminated by using an effective K_2/S ratio of 1.2 or greater. As a result of the above, the following

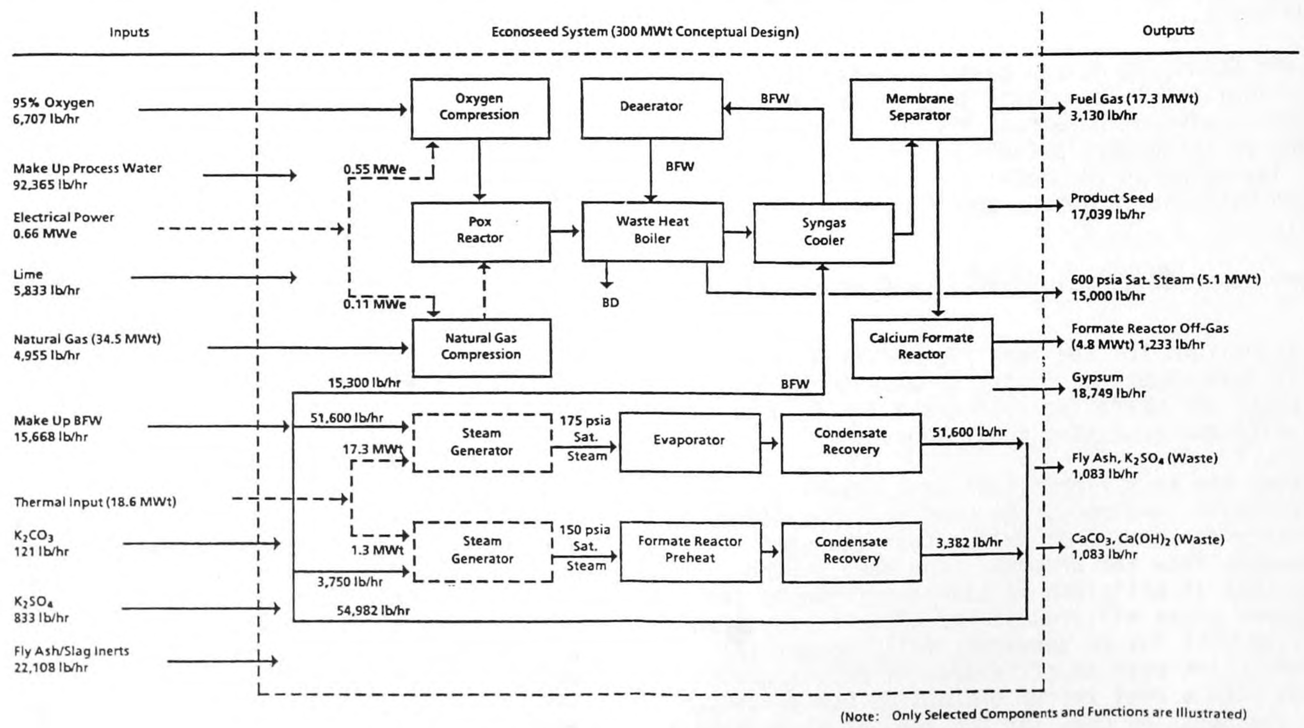


Figure 1. ECONOSEED Design Basis-Input and Output Interfaces.

equation is used herein to calculate the sulfur removal percentage for high sulfur coals:

$$\% \text{ S removal} = 50\ (CO_3/S) + 30$$

With the above equation, a CO_3/S ratio of 1.0 results in 80% sulfur removal and a CO_3/S of 1.4 is required for 100% sulfur removal.

Carbonate Bypass

With a carbonate to sulfur ratio greater than 1.0, the recovered flyash will contain both K_2CO_3 and K_2SO_4. If the K_2SO_4 can be separated, the K_2CO_3 can be bypassed around the seed regeneration system and reinjected as seed material at the combustor. Two recent technical papers[4,5] have addressed the separation of K_2CO_3 and K_2SO_4 flyash.

The Reference (5) uses a different approach for K_2SO_4/K_2CO_3 separation and potassium carbonate bypass. This approach is based on the use of a wet electrostatic precipitator (WESP) as a fractionator to separate K_2CO_3 and K_2SO_4. With this approach, a filtrate solution of recovered K_2CO_3 flyash is recycled back to the MHD combustor after concentration (by evaporation or the addition of K_2CO_3 dry makeup powder). The separated K_2/SO_4 and other insolubles are then the input to the seed regeneration process.

MODEL DESCRIPTION

MATHCAD software was used to define an ECONOSEED model for seed regeneration system integration evaluations. The basis of this model is a mass balance (on a molar basis) through the ECONOSEED system. Internal ECONOSEED processes are not modeled. Consumable input quantities and by-product output quantities are assumed to be a function of the molar sulfur input after a portion of the recovered flyash is rejected to control sodium build-up. Therefore, the size and operating cost of the ECONOSEED system will be a function of the coal sulfur content, the amount of sulfur removed, and the prepared coal heating value as well as the desired coal thermal input to the combustor.

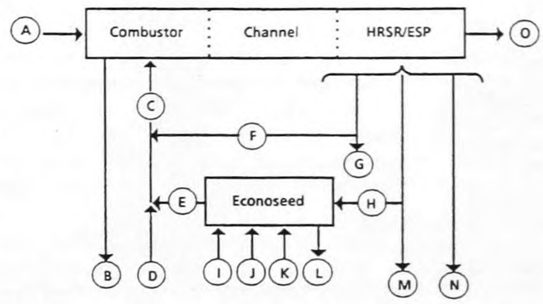
A schematic of the ECONOSEED model and the interfacing MHD combustor, channel, and HRSR/ESP interfacing components is shown in Figure 2. A carbonate spent seed bypass loop for operating at a high K_2/S ratio has been included in the model.

All of the flow rates that interface the seed regeneration system with the rest of the MHD plant are calculated by the model and these include K_2CO_3, K_2SO_4, and other flow rates as follows:

- Combustor seed injection
- Combustor slag/ash rejection
- Recovered spent seed
- Lost spent seed
- Bypassed spent seed
- Regeneration system input/output
- Make up seed
- Consumables and wastes.

Capital and Operation and Maintenance Costs

The ECONOSEED system operation and maintenance cost, capital cost, and the capital costs of a storage facility, seed handling, and seed injection were represented in the seed system model as a function of size by using modified algorithms from reference (6). When these algorithms are used in the seed system model, the process and project contingency percentages and other capital requirements are specified input parameters, so the model calculates the total capital cost requirement.



State Point	Description
A	Coal Input, lb/hr
B	Slag/Ash Rejection, lb/hr
C	Seed Input, lb/hr
D	Make up Seed Materials, lb/hr
E	Econoseed Seed Output, lb/hr
F	Carbonate Spent Seed Bypass, lb/hr
G	Carbonate Spent Seed Loss, lb/hr
H	Sulfate Spent Seed Input, lb/hr
I	Lime Input, lb/hr
J	Electrical Input, MWe
K	Net Thermal Input, MWt
L	Gypsum Output, lb/hr
M	Rejected Sulfate Flyash, lb/hr
N	Rejected Slag/Inerts, lb/hr
O	Stack Sulfur, lb/MMBtu

Figure 2. Simplified ECONOSEED Model and State Points.

Consumable/Waste Costs and By-Product Credits

The Table 1 consumable/waste costs and by-product credit values are used in the seed system model. These values are the same as the ECONOSEED base case except for: the natural gas costs; the values for the formate reactor off-gas and the combustor fuel gas; and the steam values. The natural gas cost of 5.00$/MMBtu has been reduced to 3.50$/MMBtu to reflect current price levels. The formate reactor off-gas and combustor fuel gas have lower heating values than natural gas. Since it is assumed that these gases will be used on-site, there will be no pipeline transmission cost penalty due to their lower heating value. For this reason, the assumed value of the formate/combustor gases is \$3.50\$/MMBtu or the same as natural gas. The steam values are based on the thermal input, the natural gas cost, and a boiler efficiency of 85 percent.

Operating Conditions

Both the CO_3/S ratio and the potassium seed percentage required for ionization are input parameters for the seed system model. The latter input parameter is based on the weight of potassium as a percentage of the total combustor outlet flow rate before seed injection. Therefore the weight percentage of potassium in the channel (after seed injection) will be a slightly lower value than the input percentage and can be adjusted upward if necessary. The model incorporates logic that compares the input CO_3/S ratio

TABLE 1
CONSUMABLE/WASTE COSTS AND BY-PRODUCT CREDITS

CONSUMABLE	UNIT COST
Boiler Feed Water	0.70 $/1000 lb
Process Water	0.40 $/1000 gallon
175 PSIA Steam	4.72 $/1000 lb
150 PSIA Steam	4.71 $/1000 lb
Lime	40 $/ton
K_2CO_3	36 $/100 lb
K_2SO_4	150 $/ton
Natural Gas	3.5 $/MMBtu
Power	0.06$/kwh
Oxygen	50 $/ton
WASTE DISPOSAL	**UNIT COST**
$CACO_3/CA(OH)_2$	8.35 $/ton
Flyash/K_2SO_4	8.35 $/ton
Gypsum	5.00 $/ton
BY-PRODUCTS	**CREDIT VALUE**
Formate Reactor Off-Gas	3.5 $/MMBtu
Combustor Fuel Gas	3.5 $/MMBtu
600 PSIA Steam	4.75 $/1000 lb

and the input potassium seed requirement for ionization. If a CO_3/S ratio greater than one is specified, the model calculates a total seed injection flow rate for K_2CO_3 to provide the required amount of carbonate. This required K_2CO_3 flow rate can be provided by a combination of the seed regeneration system output, make up K_2CO_3, and recovered K_2CO_3 flyash bypassed around the seed regeneration system. For low sulfur coals, ionization requirements (1.5% K by weight for example) will result in very high CO_3/S ratios and higher seed regeneration system cost if only K_2CO_3 is used as the seed material.

However, if the additional potassium is supplied by bypassed K_2SO_4 recovered as fly ash, then the methods proposed in references (4) and (5) do not need to achieve complete K_2SO_4/K_2CO_3 separation of the recovered fly ash prior to seed regeneration system input.

COST AND PERFORMANCE STUDIES

The cost/performance study of seed regeneration issues was conducted in three parts. First, a base case was defined in order to determine the effect of individual parameters on seed regeneration costs and performance. Second, the effect of coal sulfur content over the range from 1-5% was evaluated. Third, the model was used to calculate seed regeneration system costs for: the Scholz retrofit MHD plant; early commercial, Advanced Power Train plants; and a high efficiency, advanced commercial MHD power plant.

Base Case Cost/Performance

The base case was defined to measure the impact of individual parameters on seed system cost and performance. Table 2 summarizes the key parameters of the base case.

Figure 3 shows the impacts of coal sulfur content, CO_3/S ratio and, spent seed loss on the base case seed regeneration system operating cost. The operating cost is most sensitive to the coal sulfur content when the sulfur content is varied over the 1-5% range (with the base case value of $CO_3/S = 1.2$, S removed = 90%, and spent seed loss = 5% held constant).

The coal sulfur content determines the amount of sulfur that must be rejected by the seed regeneration system during the conversion of sulfate to carbonate.

TABLE 2
MHD PLANT BASE CASE FOR
SEED REGENERATION SYSTEM SENSITIVITY STUDY

Plant Size	300 MWt
Plant Output	100 MWe
Overall Efficiency	33.3%
Annual Capacity Factor	65%
Coal Sulfur	3%
CO_3/S Ratio	1.2
Sulfur Removed	90%
Potassium Required (By Weight)	1.5%
Prepared Coal Moisture	2.5%
Prepared Coal Heating Value	11900 Btu/lb
Combustor Stoichiometry	0.88
Slag/Ash Rejection	70%
Spent Seed Lost (K_2CO_3/K_2SO_4 by Weight)	5%
SEED REGENERATION SYSTEM	
Sulfur Rejected	6609 tons/year
Project/Process Capital Cost Contingency	19.4%
IDC/Working Capital Multiplier	1.2
Total Capital Requirement	23,340,000 (89$)
Fixed Charge Rate	15.5%
Operating Costs	
Capital	6.34 Mills/kwh
Operation & Maintenance	2.07 Mills/kwh
Consumable/Waste Disposal	9.55 Mills/kwh
By-Product Credits (Gases & Steam)	2.63 Mills/kwh
Total System Operating Cost	15.33 Mills/kwh
K_2CO_3 Production Cost	0.179 $/lb

The size, capital cost, and consumable costs are thus directly related to the amount of sulfur rejected in the regeneration process.

In Figure 3, a single curve represents the cost sensitivity of both the sulfur removal percentage and the CO_3/S ratio because they are not independent variables. The curve shows that an increase in sulfur removal from 90% to 100% increases the base case operating cost by 1.7 mills/kwh or about 11%. The spent seed loss curve shows the least cost sensitivity in that a loss increase from 5 to 10% (necessitating additional potassium make up) results in 0.6 mills/kwh (4%) increase in operating cost.

Figure 4 shows the cost sensitivity to the combustor slag/ash rejection rate.* When the slag/ash rejection rate is reduced, the operating cost is increased by a higher seed injection flow rate and by a higher rate of sulfur rejection in the seed regeneration process.

The effect of the plant capacity factor on the seed system operating cost is shown in Figure 5. The physical size of the seed system (in terms of the rate** of sulfur rejection) does not change with capacity factor, but the number of tons of sulfur rejected per year is increased at higher capacity factors. The consumable, operation, and maintenance costs and the value of the by-product credits are also shown in Figure 5.

Combustor stoichiometry has very little effect on the seed regeneration system operating cost. Increasing the combustor thermal input decreases the operating cost slightly due to economy of scale benefits in the

*See the Addendum Note at the end of this paper.
**The Seed System is always sized for the maximum sulfur rejection rate that occurs when the plant operates at full rated power output.

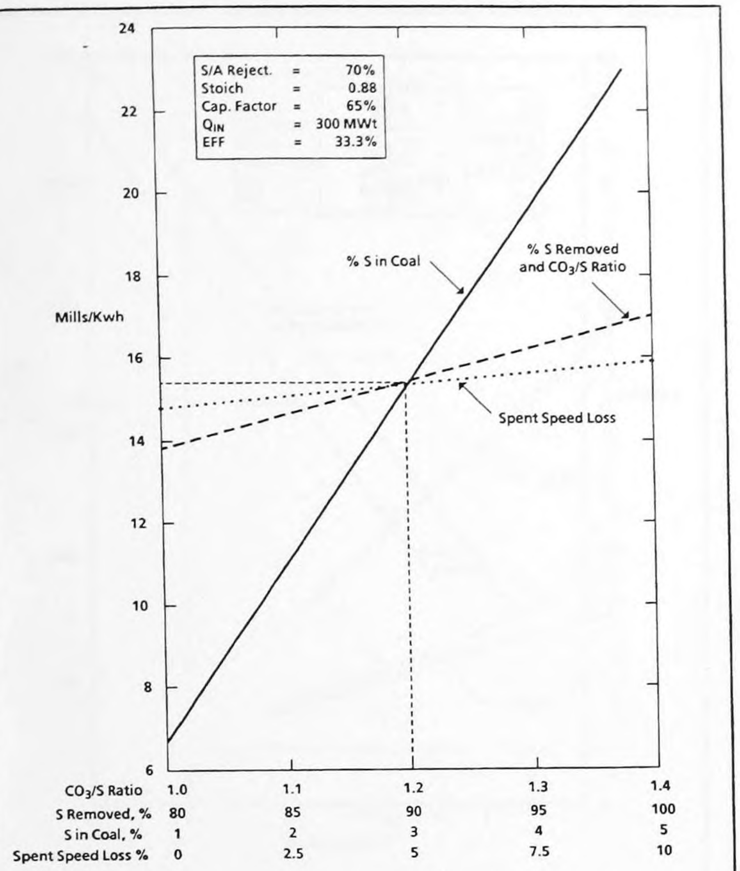


Figure 3. Effect of CO_3/S, Coal Sulfur Content, and Spend Seed Loss.

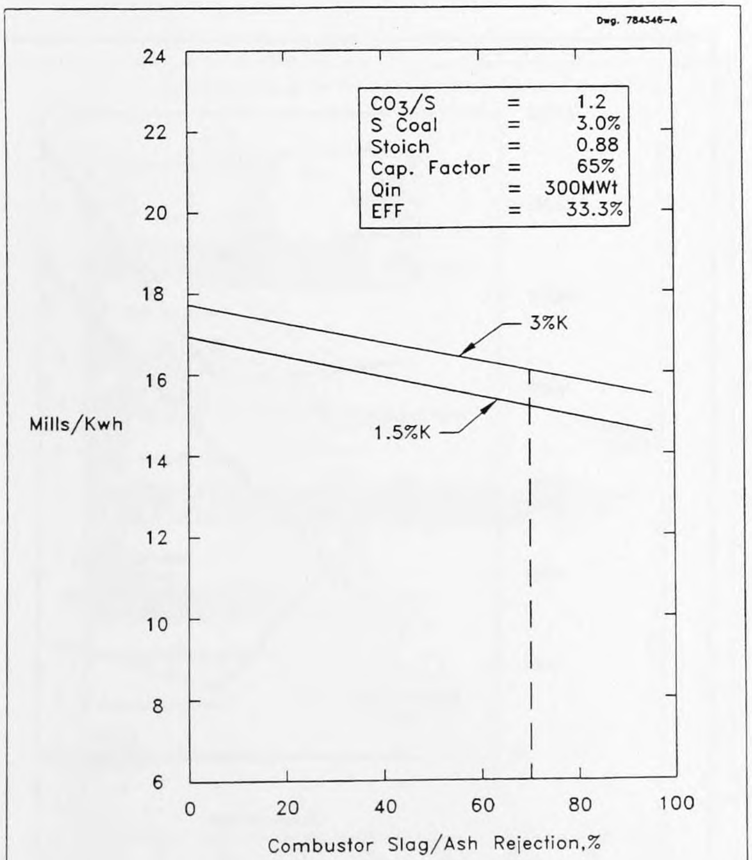


Figure 4. Effect of Combustion Slag/Ash Rejection.

seed regeneration system capital cost. Increasing the overall efficiency, as shown in Figure 6, significantly reduces the operating cost due to increased annual kilowatt-hour production.

Effect of Coal Sulfur Content

The seed regeneration operating cost is directly proportional to the sulfur rejected by the process and the coal sulfur content at a given CO_3/S ratio as shown in Figure 7. The amount of recovered spent seed that can be bypassed around the seed regeneration system to reduce the operating cost by reducing the throughput* is shown in Figure 8. A significant fraction of the required total seed injection flow rate is provided by the bypassed spent seed especially when the coal sulfur content is low. For the data shown in Figure 9, the CO_3/S ratio is fixed at 1.2 so that any additional potassium required for ionization is supplied by K_2SO_4 and not more expensive K_2CO_3. At coal sulfur contents above 3 percent, consumable and waste disposal costs are more than sixty percent of the total operating cost. A breakdown of the consumable and waste disposal costs on a relative basis is shown in Figure 10 for a coal sulfur content of 3%. The highest consumable costs in order of importance are:

- Natural gas
- 175 PSIA steam
- Oxygen
- Lime
- Make up K_2CO_3

Coal can replace natural gas as the feed stock for the ECONOSEED carbon monoxide production (at the expense of slightly higher capital cost) to reduce this feed stock cost by about one-third. It may be possible to reduce the oxygen and 175 PSIA steam costs somewhat by close integration with the balance of plant but the lime and make-up K_2CO_3 costs cannot be reduced.

Design and Operating Options

For most of the study, a potassium seed concentration of 1.5 percent by weight of the combustor outlet flow before seed addition was specified. The potassium seed concentration must be related to the amount of carbonate in the seed material required for sulfur removal. A CO_3/S ratio of 1.2-1.4 is required for 90-100% sulfur removal. When the potassium seed requirement for ionization is compared to the CO_3/S ratio, a coal sulfur content of 3% represents a break point between two methods of designing and operating the seed regeneration system which are summarized in Table 3.

When the coal sulfur content is above 3%, the need for "excess" carbonate dominates. Then, if K_2CO_3 is used to provide the required amount of carbonate, the actual concentration of potassium in the MHD channel will be significantly higher than the 1.5% specified for ionization requirements. This factor should be examined in future MHD channel performance calculations with high sulfur coal. At a coal sulfur content of 3% or higher, recovered spent seed in the K_2CO_3 form can be bypassed around the seed regeneration system and reinjected at the combustor, but no spent seed in the K_2SO_4 form can be bypassed.

*The total amount of sulfur removed is not changed by the bypass itself.

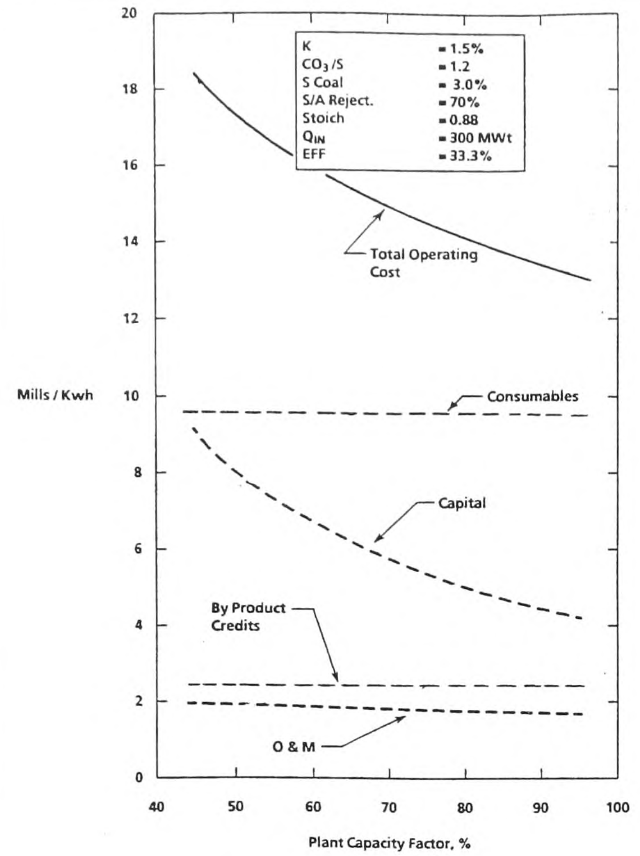


Figure 5. Effect of Plant Capacity Factor.

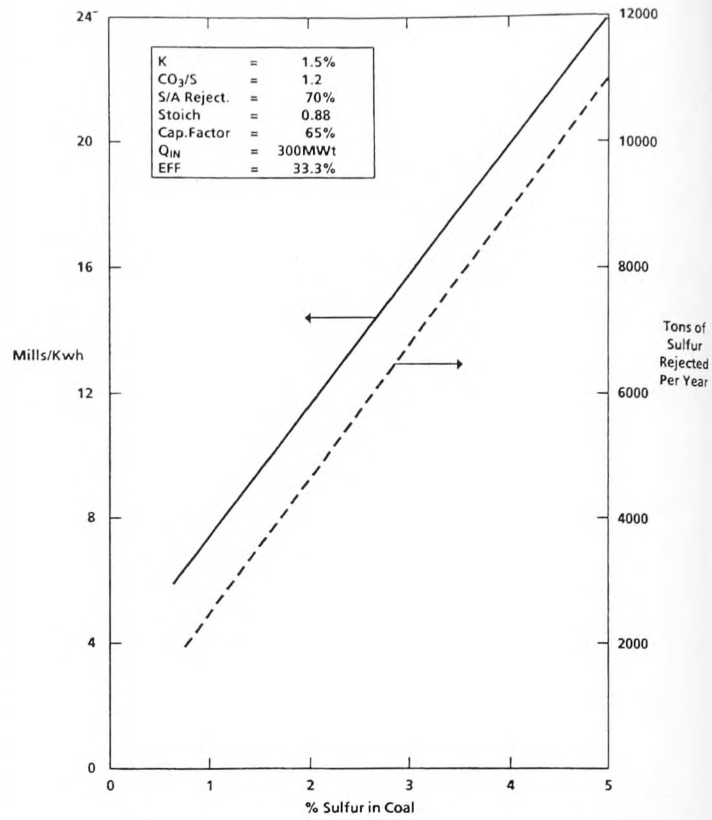


Figure 7. Operating Cost and Sulfur Rejected per Year vs Sulfur Content.

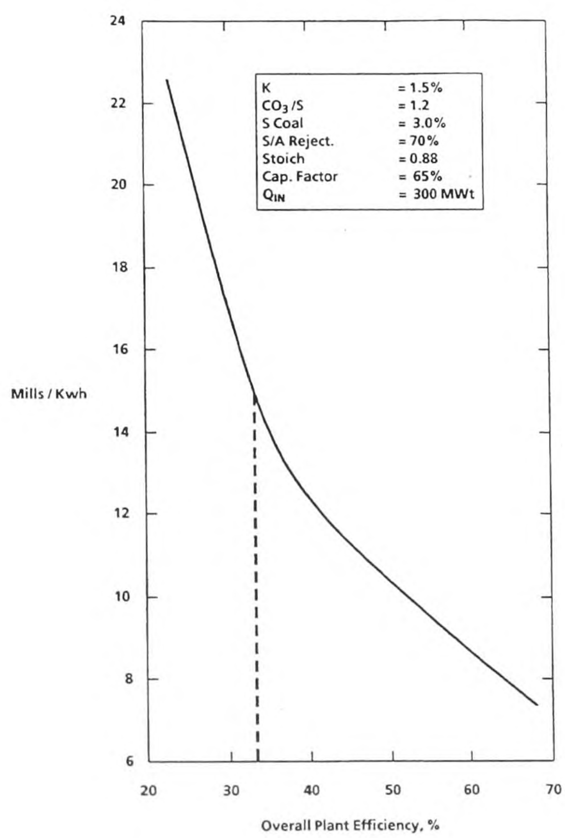


Figure 6. Effect of Overall Plant Efficiency.

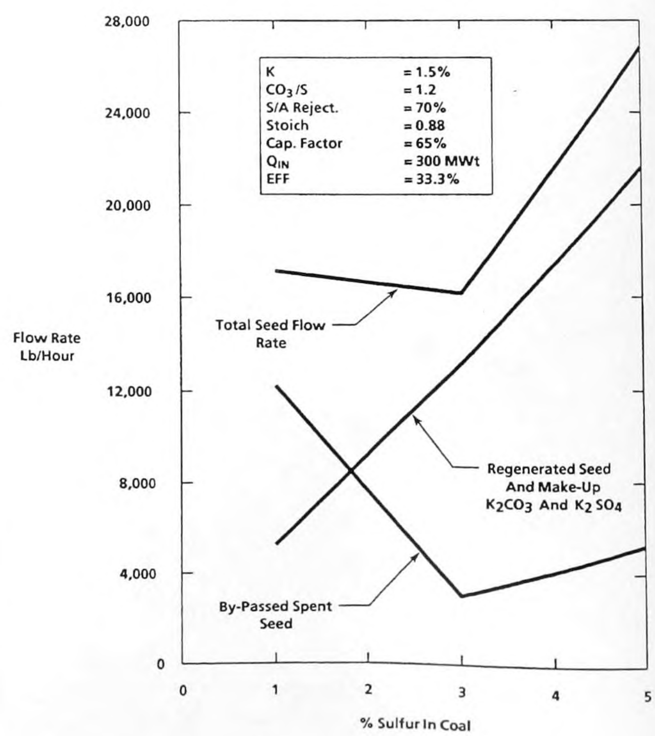


Figure 8. Total Seed Injection, By-Passed Spent Seed, Regenerated, and Make-Up Seed Flow Rates vs Coal Sulfur Content.

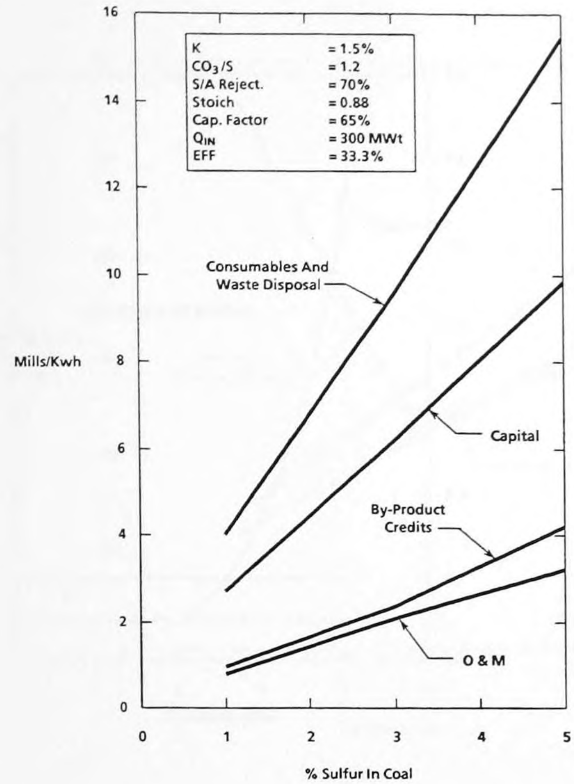


Figure 9. Operating Cost Breakdown vs. Coal Sulfur Content.

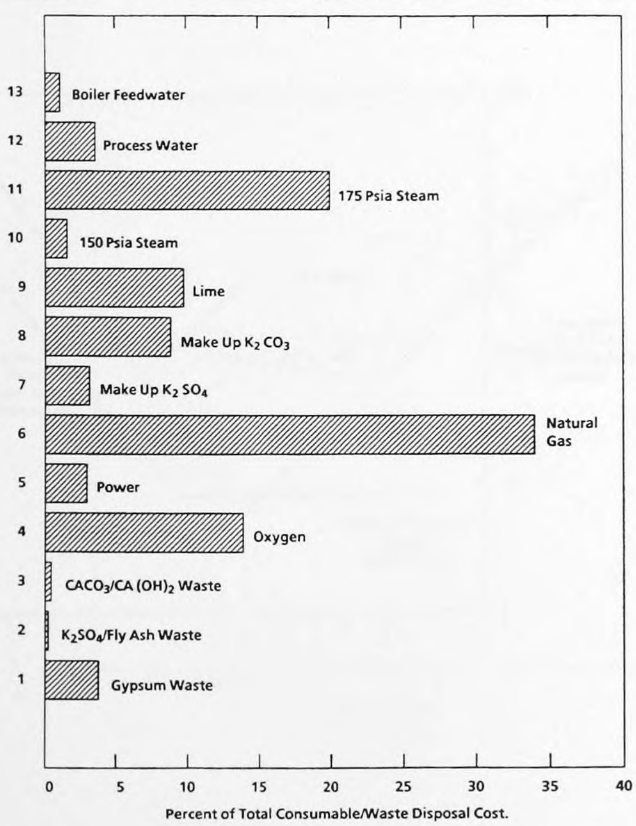


Figure 10. Relative Consumable and Waste Disposal Costs at S = 3%, CO_3/S = 1.2, K_2 = 1.5%.

TABLE 3 SEED REGENERATION SYSTEM DESIGN/OPERATING OPTIONS

Less than 3% Coal Sulfur Content	Greater than 3% Coal Sulfur Content
% K For Ionization Dominates	CO_3/S For Sulfur Removal Dominates
"Excess" Carbonate If Only K_2CO_3 is used	"Excess" %K Available For Ionization
<u>Spent Seed Bypass</u>	<u>Spent Seed Bypass</u>
• Bypass only K_2CO_3 means: - High CO_3/S Ratio - High % Separation of Spent K_2CO_3/K_2SO_4 Required - Higher Operating Cost	• Only Recovered K_2CO_3 Can Be Bypassed - High % Separation Of Spent K_2CO_3/K_2SO_4 Required
• Bypass Mix of K_2CO_3/K_2SO_4 means: - CO_3/S = 1.2-1.4 - High % Separation of Spent K_2CO_3/K_2SO_4 <u>Not</u> Required - Up To 90% Of Bypass Can Be K_2SO_4 - Lower Operating Cost	- CO_3/S = 1.2-1.4

<u>Effects of K_2CO_3/K_2SO_4 By Pass</u>

When the coal sulfur content is below 3%, the need for "excess" potassium dominates and there are two design options for supplying sufficient potassium for ionization. A CO_3/S ratio can be specified for a desired amount of sulfur removal and the specific CO_3/S ratio is then achieved by injecting a corresponding amount of seed in the K_2CO_3 form. But for low sulfur coals, additional potassium is needed for ionization. The additional potassium can be supplied by using one of the following options:

(1) The additional potassium can be supplied in the K_2SO_4 form by bypassing some of the K_5O_4 from recovered spent seed around the seed regeneration system and reinjecting the K_2SO_4 at the combustor. This option limits the CO_3/S ratio to the specified value and reduces seed regeneration cost since the total seed system flow rate is reduced and some of the make-up potassium can be supplied as K_2SO_4. This option was used in the analyses discussed above.

(2) The additional potassium is supplied as K_2CO_3 by bypassing only K_2CO_3 and using only K_2CO_3 for make-up. As a result, seed regeneration and potassium make-up costs are higher than in option (1). The sulfur concentration in the channel is minimized but the CO_3/S ratio will be higher than that required for sulfur removal.

Note that the amount of sulfur removed from the process (in tons per year, for example) by the seed regeneration system is the same in both options if the option (1) CO_3/S ratio is high enough for 100% sulfur removal.

The above options were examined using the following conditions for the results shown in Figures 11 through 14:

Minimum Potassium Requirement*	= 1.5%
Combustor Slag/Ash Rejection	= 70%
Combustor stoichiometry	= 0.88
Capacity factor	= 65%
Thermal Input	= 300 MWt
Efficiency	= 33.3%
Spent Seed Loss	= 5%

*Weight percent of the combustor outlet flow before seed addition.

Figure 11 shows the impact of using option (2) on the CO_3/S ratio. With option (2) only the recovered spent seed in the K_2CO_3 form is bypassed and all of the K_2SO_4 spent seed is recycled through the seed regeneration system. As a result the CO_3/S ratio is much higher than needed for sulfur removal when the coal sulfur content is lower than 2.5%. However, the potassium concentration in the channel is the same for both options when the coal sulfur content is low as shown in Figure 12. At higher coal sulfur levels, the carbonate requirement dominates. Since the carbonate is supplied as K_2CO_3, the potassium concentration in the channel is higher than the specified 1.5% K at the combustor outlet for ionization. The impact of this "excess" potassium on plasma conductivity should be considered in MHD channel performance calculations.

At low coal sulfur levels, both K_2CO_3 and K_2SO_4 spent seed can be bypassed. If option (2) is selected and no K_2SO_4 is bypassed, the bypass flow rate consists only of K_2CO_3 spent seed and the total flow rate is reduced. When the coal sulfur content is high, the CO_3/S ratio constraint permits only K_2CO_3 bypass flow and all recovered K_2SO_4 spent seed must be recycled through the seed regeneration system.

Minimizing the amount of K_2CO_3 make up that is required is desirable since K_2CO_3 is about five times more expensive than K_2SO_4 on a per pound basis. Figure 13 shows the impact of the bypass options on the K_2CO_3 make up requirement. With 1% coal sulfur, bypassing K_2SO_4 can reduce the K_2CO_3 makeup requirement by a factor of five. For a 300 MWt plant operating at a 65% capacity factor, this is an operating cost reduction of about $1 M per year.

At a coal sulfur content of 1%, the seed system total operating cost when no K_2SO_4 is bypassed is about 1 mill/kWh higher than the CO_3/S = 1.4 case. However, this cost differential disappears when the coal sulfur content is above 3% when no K_2SO_4 can be bypassed.

Figure 14 shows the sulfur concentration in the MHD channel with and without bypassed K_2SO_4. When the coal sulfur content is low, bypassing K_2SO_4 significantly increases the channel sulfur concentration. But the sulfur concentration does not exceed 0.6% by weight when the coal sulfur content is below 3%. For higher sulfur eastern coals, the channel will operating with 0.6 to 0.96% sulfur concentration.

Retrofit, APT Early Commercial, and Advanced Plants

Coal-fired MHD power plant designs from retrofit through advanced plants have a wide size and efficiency range as shown in Table 4. The seed system operating cost over the coal sulfur range for these plant designs was calculated and is shown in Figure 15.

The APT[9] early commercial plants were also examined with the original design assumptions which included the following:

Coal sulfur content = 0.85%
Combustor Stoichiometry = 0.90
Slag/ash rejection = 85%

A coal fuel cost of 1.5 $/MMBtu was used and the cost estimates were adjusted from 1982 dollars to 1989 dollars using the Handy-Whitman Index.[8] The levelizing factor (2.004) was taken out of the fuel and O&M costs of APT early commercial plants so they

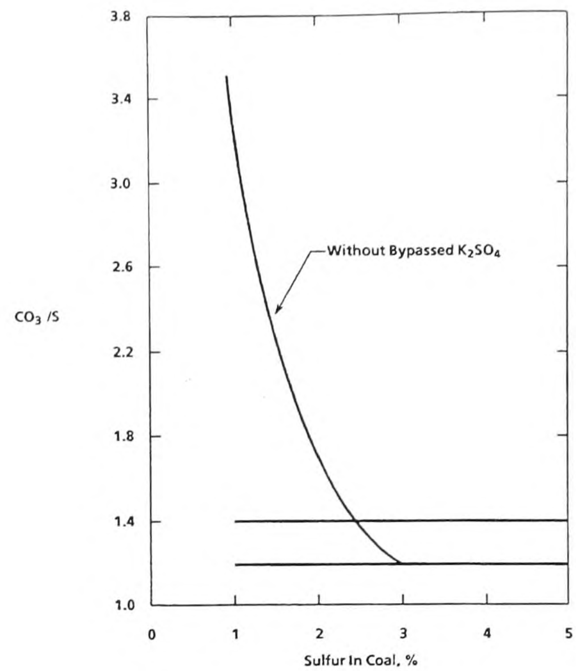


Figure 11. Impact of K_2SO_4 Bypass on CO_2/S Ratio.

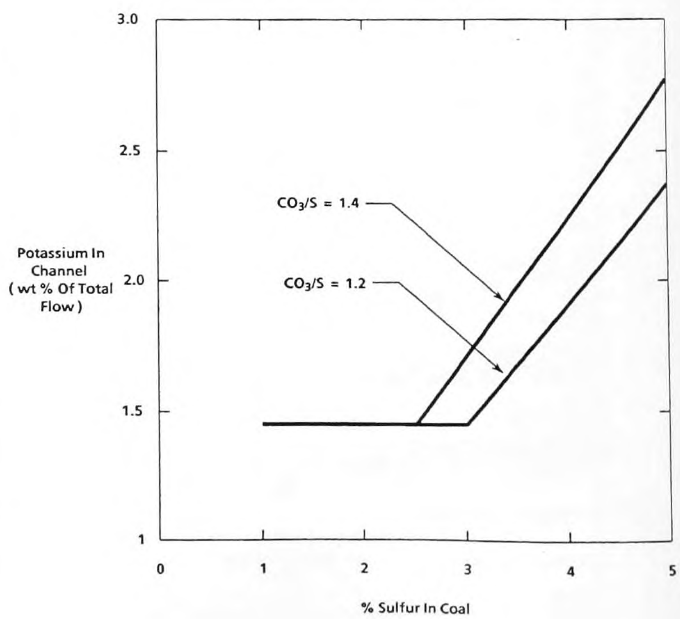


Figure 12. Potassium Concentration in the MHD Channel.

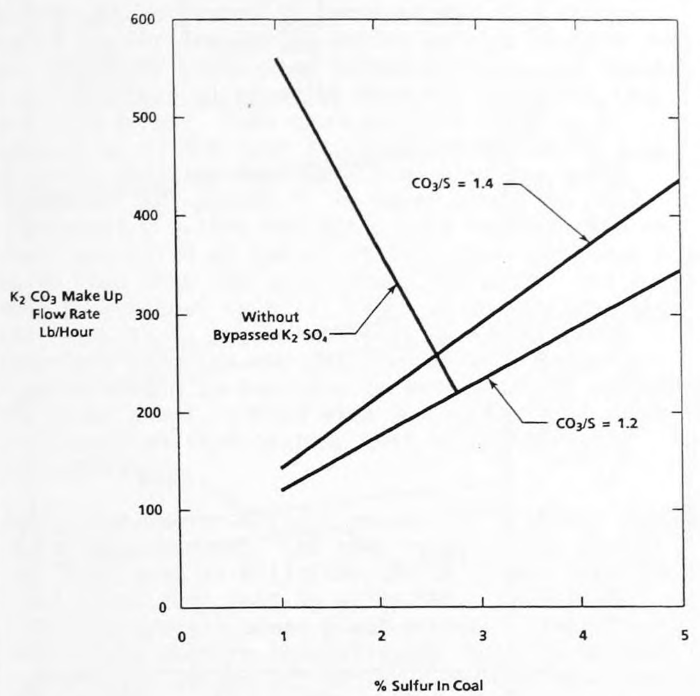


Figure 13. K_2CO_3 Make Up Requirements.

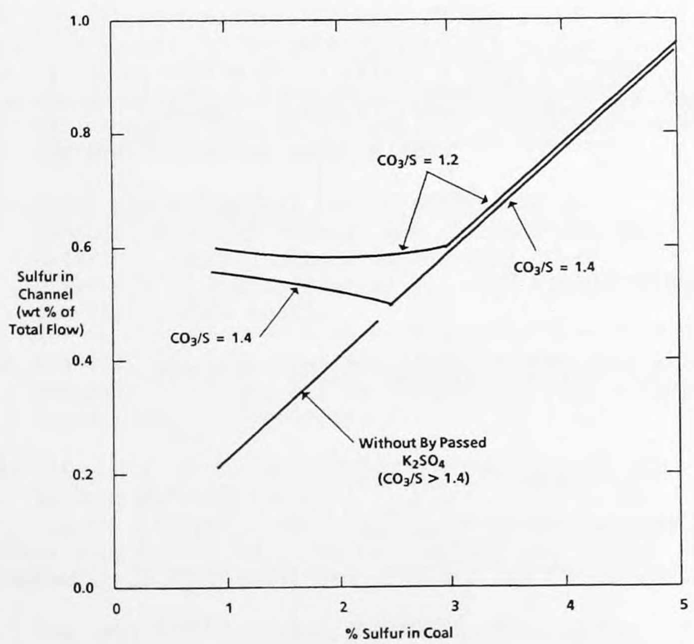


Figure 14. Sulfur Concentration in the MHD Channel.

TABLE 4
DATA FOR RETROFIT, APT EARLY COMMERCIAL, AND ADVANCED COAL-FIRED MHD POWER PLANTS

	Scholz[1] Retrofit	APT Early Commercial[9]		Advanced[10]
		200	500	
Thermal Input, MWt	192	483	1163	1578
Net Output, MWe	59.6	195	495	953
Efficiency, %	31.0	40.4	42.6	60.4

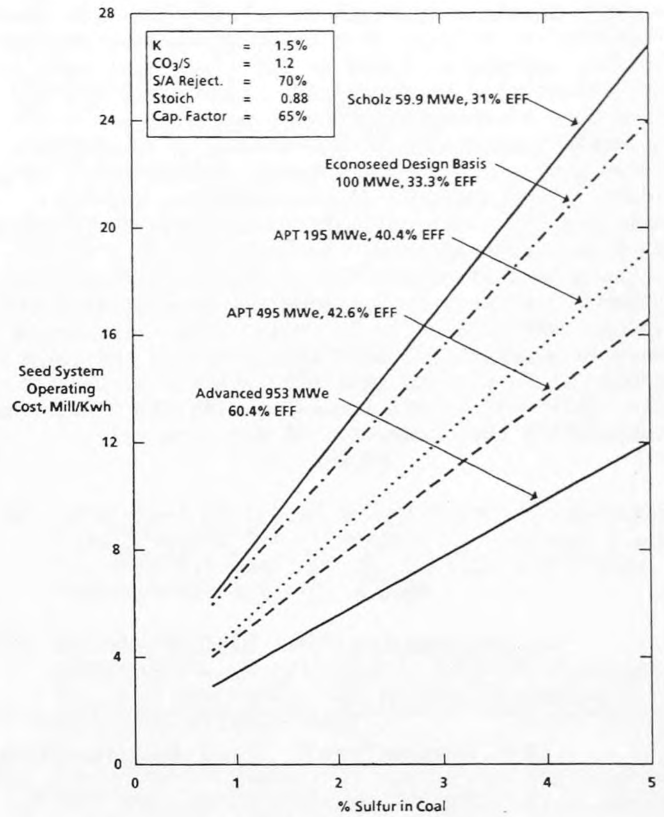


Figure 15. Seed System Operating Costs for Retrofit, APT Early Commercial and Advanced Coal-Fired MHD Power Plants.

could be compared directly with the first year operating costs for the seed system. Capital cost estimates (installed cost plus contingency) for the APT seed systems were also updated to 1989 dollars. The basic ECONOSEED capital cost estimate was more detailed than the APT seed system cost estimates which are 13-21 percent higher. This indicates that the APT seed system capital cost estimates were conservative. However, the net operating cost of the ECONOSEED based system (for fuel, consumable, O&M, and by-product credit) indicates that O&M and consumable costs for the APT seed systems may have been underestimated.

Addendum Note

Most of the results presented in this paper were discussed at the 1992 DOE MHD Contractors' Review Conference.[11,12] At that Conference it was suggested that low combustor slag/ash rejection rates required higher concentrations of Potassium for plasma ionization. This issue was addressed parametrically by calculating the seed system operating cost with the Potassium concentration increased from 1.5 to 3% (see

Figure 4 herein). The Figure 4 calculation assumes a small coal-fired MHD power plant of 300 MWt and 33% efficiency. Seed system capital and operating costs were also calculated for a larger (1578 MWt), higher efficiency (60%) MHD power plant[10] with the results shown in Figure 16. The resulting conclusion is that the combustor slag/ash rejection rate (and the related Potassium concentration) is a minor issue relative to the high cost of "conventional" seed regeneration with high sulfur coals. It may be possible to reduce this high cost by improvements in the ECONOSEED process for high sulfur applications or by development of the proposed ion exchange seed regeneration process.[5] Another possible approach is to eliminate the seed regeneration process as a means for sulfur removal. Several approaches based on DOE clean coal initiatives are illustrated in Figure 17. Approaches (B) and (D) have been examined previously, notably by Gilbert/Commonwealth,[13] but should be re-examined because of recent developments. For example, it was found[13] that approach (D) was $190/KWe and 5.7 mill/KWh higher in cost than a coal-fired MHD plant with seed regeneration. However, the Pure air advanced wet limestone FGD system being demonstrated under DOE's clean coal technology program at Northern Indiana Public Service Co.'s Bailly station could be used in approach (D) with K_2SO_4 used as the recycled seed. It is claimed that the Pure Air AFGD will cost less ($160/KWe versus $300/KWe) with far lower power consumption than conventional wet scrubbers.

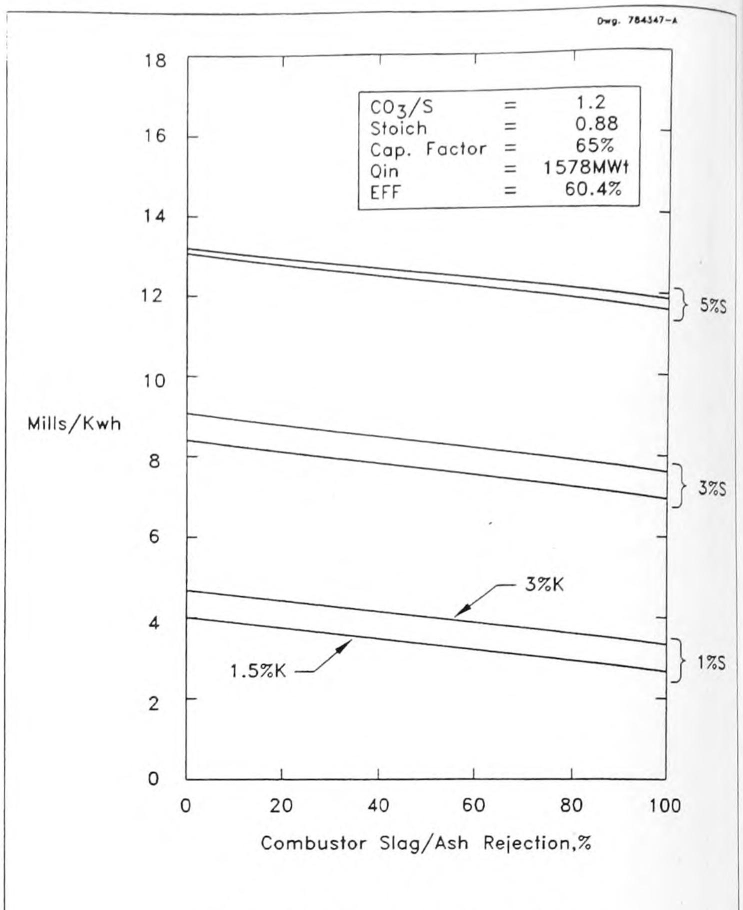


Figure 16. Effect of Slag/Ash Rejection Rate

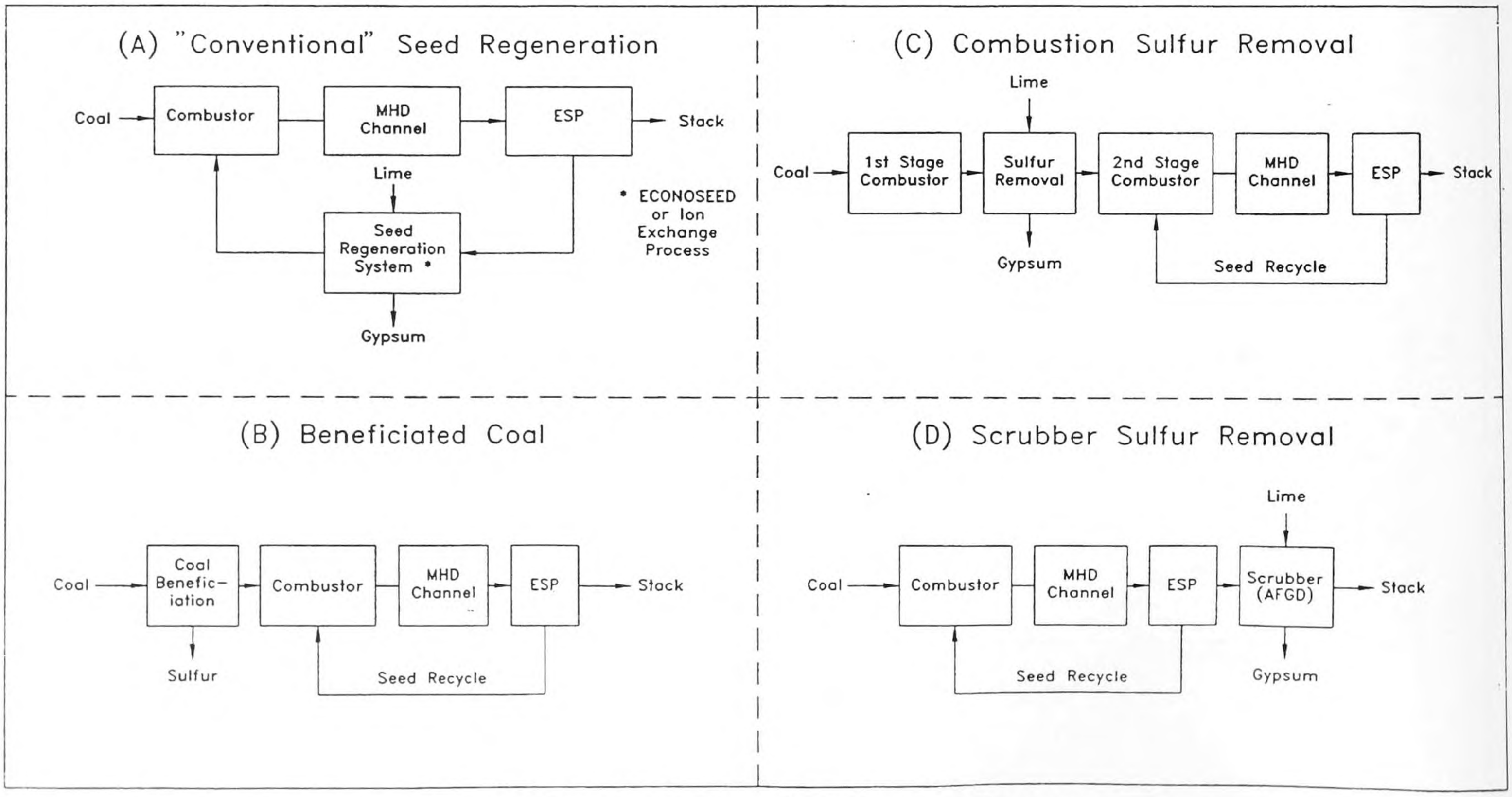


Figure 17. Seed Regeneration and Sulfur Removal Approaches

CONCLUSIONS

The seed regeneration issue for coal-fired MHD power plants can be framed in terms of the coal sulfur content. For low (~ 1%) sulfur content western coals, the ECONOSEED based seed regeneration system appears to be a viable alternative when the operating costs are considered. This conclusion is based on a comparison of the seed regeneration operating cost with the fuel and O&M costs predicted for early commercial APT plants.[9] In these cases the seed regeneration system operating cost in mills/kWh is about one third of the plant fuel cost and about equal to or less than the total plant O&M cost. While the seed system cost is still high, it is possible that cost reductions can be achieved by evolutionary technical progress and detailed plant integration. Then it should be possible to design a high efficiency MHD power plant, fueled with low sulfur coal and with an integrated seed system, that is economically competitive.

For higher sulfur eastern coals with a sulfur content above three percent, the seed regeneration system operating cost in mills/kWh can be higher than the total plant fuel cost in mills/kWh. Therefore, achieving overall power plant economic viability will most likely require revolutionary advances in seed regeneration technology and/or alternate approaches for removing sulfur and recovering the potassium seed. It appears unlikely that detailed integration of an ECONOSEED based seed regeneration system with the balance of a coal-fired MHD power plant will result in a major operating cost reduction with high sulfur content coals because only marginal reductions in consumable costs can be achieved with this approach. Since the consumables represent more than 60 percent of the seed system operating cost, any design or process improvements or technical advances which reduce the consumable costs are highly desirable and worthy of investigation. Some other approaches that should be evaluated include:

- The use of beneficiated coal as the plant fuel. Coal beneficiation methods for high sulfur coals should be evaluated to select a candidate method and to determine if the coal beneficiation method yields advantages when technically integrated with the coal-fired MHD power plant.
- Other new clean coal technologies such as combustion sulfur removal and advanced FGD for emissions control should be examined as an alternate to sulfur removal via seed regeneration for high sulfur coals.
- Off-site seed regeneration if there is a possible economic advantage due to integration with a large scale chemical processes.
- Alternate seed regeneration methods such as ion exchange processes.

Other conclusions relative to "conventional" seed regeneration from this study include the following:

- The combustor slag/ash rejection rate can be reduced below 70 percent (with lower combustor thermal loss as a benefit) without a severe seed system economic penalty.
- Since excess carbonate or a CO_3/S ratio of 1.2-1.4 is desirable for sulfur removal rates of 90-100 percent, a significant amount of recovered spent seed can be bypassed around the seed regeneration system and re-injected into the combustor.
- Above a 3 percent coal sulfur content, the bypass flow should be near 100% K_2CO_3, so high degree of separation of K_2SO_4 from K_2SO_4 spent seed is needed.
- At low coal sulfur contents, the bypass flow rate can be as high as 90% by weight of K_2SO_4. This holds the CO_3/S ratio to a maximum of 1.4 or less and does not require complete separation of K_2SO_4/K_2CO_3 flyash. Seed system operating costs are minimized by maximizing the amount of K_2SO_4 which is bypassed.
- Controlling the build-up and rejection of sodium, chlorine, etc. was not a subject of this study and remains an issue. The build-up of these elements could be limited somewhat by rejecting higher amounts of recovered flyash at the expense of higher seed system operating costs. This is the approach recommended[2] for limiting sodium buildup in the ECONOSEED System since the system as presently designed cannot separate sodium from potassium. Direct removal of soluble chlorides, fluorides and nitrates from the recovered flyash is one of the stated advantages[5] of the Ion Exchange seed regeneration process.

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