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NOV 26 1993

93-9TK0-MHDCR-R1

Conceptual Design of a
Coal-Fired MHD Retrofit Plant
Topical Report
Seed Regeneration System Study (II)

Prepared for
U.S. Department of Energy
Pittsburgh Energy Technology Center
Contract No. DE-AC22-87PC79668
November 1992

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LIST OF ACRONYMS

APT	Advanced Power Train
CAD	Computer Aided Drafting
CDIF	Component Development and Integration Facility (DOE)
CFFF	Coal-Fired Flow Facility (UTSI)
COE	Cost-of-Electricity
DAS	Data Acquisition System
DOE	Department of Energy
EPRI	Electric Power Research Institute
FY	Fiscal Year
ITC	Integrated Topping Cycle
MHD	Magnetohydrodynamics
MSE	Mountain States Energy, Inc.
NASA	National Aeronautics and Space Administration
O&M	Operating and Maintenance
PETC	Pittsburgh Energy Technology Center (DOE)
POC	Proof-of-Concept
SCS	Southern Company Services
SEI	Southern Electric International
SEAM	Symposium-Engineering Aspects of MHD
SPA	Systems Performance Analysis
TTIRC	Technology Transfer & Integration Review Committee
UTSI	University of Tennessee Space Institute
WAES	Westinghouse Advanced Energy Systems
WSTC	Westinghouse Science and Technology Center

1.0 EXECUTIVE SUMMARY

Westinghouse Advanced Energy Systems (WAES), 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 Utility plant considered in this study is the Scholz Generating Station which 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), SelTec, 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.

The objective of this project is to prepare a site-specific conceptual design of a coal-fired MHD system for retrofit to the Scholz Generating Station, Sneads, Florida.

As documented, to date, the conceptual design(I) includes: process, system and equipment descriptions, interface identification and requirements, equipment handling arrangements, an overall plant layout, and costs and schedule for the design, fabrication, installation and initial operation of the MHD retrofit system.

The objective of this topical report is to document continuing seed regeneration system application studies and the definition of seed system integration requirements for the Scholz MHD retrofit plant design. 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. Existing U.S. resources of both high sulfur eastern and low sulfur western coals represent a significant low cost energy source.

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 conceptual MHD retrofit design⁽¹⁾ is intended for the Scholz Generating Station which utilizes high sulfur eastern coal. The MHD system flyash resulting from the potassium seed addition and the removal of the coal sulfur consists primarily of K_2SO_4 . Previous studies have shown that it is more economical to recover and utilize the K_2SO_4 flyash than it is to purchase fresh seed in the preferred forms of either potassium carbonate (K_2CO_3) or potassium formate (KCOOH). Utilizing the K_2SO_4 requires a seed regeneration process which converts the flyash into the K_2CO_3 or KCOOH forms. Development of a seed regeneration process with the DOE MHD Proof-of-Concept program is being accomplished by the TRW Applied Technology Division. The TRW ECONOSEED development program has been focused on eastern coal flyash regeneration. This program included the definition of a design basis⁽²⁾ for an ECONOSEED system suitable for a 300 MWt coal-fired MHD power plant.

BACKGROUND

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 initial version of the mathematical model and its validation by comparison with the ECONOSEED design basis⁽³⁾ was documented in a previous Topical Report⁽³⁾. A summary of the previous Topical Report results are included herein as Appendix A.1 to provide continuity.

This Topical Report includes a significantly upgraded version of the previous seed system mathematical model⁽³⁾ and uses the model to investigate seed system integration and application issues. Upgrades to the model include the following:

- Capital, operating, maintenance, and consumable cost data from reference⁽²⁾ has been incorporated in the model. In all cases described herein, 80.7% of the sulfur input to the ECONOSEED system as flyash is removed and rejected. This is consistent with the 300 MWt ECONOSEED design basis⁽²⁾.
- Cost algorithms from reference⁽⁴⁾ for the seed regeneration system and the seed injection system were applied to the cost data to permit evaluations of capital and operating costs as a function of plant size.
- Combustor outlet stoichiometry is now a specified input parameter used to compute oxidant flow rate.

The upgraded model has been used to evaluate several of the issues identified in reference⁽³⁾ and the results are documented herein.

STUDY RESULTS

The results from this study are summarized in the following paragraphs.

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. For a small Scholz size retrofit plant (59.6 MWe, 31% efficiency), the regeneration cost with 1% sulfur coal is 7.5 mill/kWh and 22 mill/kWh with 4% sulfur coal. The above numbers are based on a coal sulfur removal rate of 90%.

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 CONS ratio of 1.2-1.4 is required for 90-100% sulfur removal. When the potassium seed requirement for ionization is compared to the CONS 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 1.1.

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.

TABLE 1.1
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
Spent Seed Bypass	Spent Seed Bypass
<ul style="list-style-type: none"> • Bypass only K_2CO_3 means: <ul style="list-style-type: none"> - High CO_3/S Ratio - High % Separation of Spent $\text{K}_2\text{CO}_3/\text{K}_2\text{SO}_4$ Required - Higher Operating Cost • Bypass Mix of $\text{K}_2\text{CO}_3/\text{SO}_4$ means: <ul style="list-style-type: none"> - $\text{CO}_3/\text{S}=1.2-1.4$ - High % Separation of Spent $\text{K}_2\text{CO}_3/\text{K}_2\text{SO}_4$ Not Required - Up To 90% Of Bypass Can Be K_2SO_4 - Lower Operating Cost 	<ul style="list-style-type: none"> • Only Recovered K_2CO_3 Can Be Bypassed <ul style="list-style-type: none"> - High % Separation Of Spent $\text{K}_2\text{CO}_3/\text{K}_2\text{SO}_4$ Required • $\text{CO}_3/\text{S} = 1.2-1.4$

When the coal sulfur content is below 3%, the need for "excess" potassium dominates and there are two design options. The "excess" potassium requirement can be supplied by either K_2CO_3 or K_2SO_4 . If K_2CO_3 alone is used, the CONS ratio will increase (with 1% sulfur coal, $\text{CO}_3/\text{S} = 3.5$ under these conditions). If a mix of K_2CO_3 and K_2SO_4 is used, then the CO_3/S ratio can be fixed at a specified value of 1.2-1.4. Also, the required amount of K_2SO_4 can be recovered from the spent seed and bypassed around the seed regeneration system and reinjected. This latter option results in the lowest seed regeneration system operating cost. In addition, the weight percentage of K_2SO_4 in the bypass can be high (90% K_2SO_4 and 10% K_2CO_3 at 1% coal sulfur) so that complete separation of the K_2SO_4 and K_2CO_3 in the recovered spent seed is not necessary. By passing the K_2SO_4 increases the sulfur concentration in the MHD channel to as high as 0.6% by weight of the total flow. This is the same sulfur concentration that occurs when 3% sulfur coal is used without any K_2SO_4 bypass.

The sensitivity of the seed regeneration system operating cost to several other parameters was determined with the coal sulfur content fixed at three percent. The plant size (300 MWt) and overall plant efficiency (33.3%) were also held constant.

Varying the combustor stoichiometry over the 0.8-1.0 range had a negligible effect on the seed system operating cost.

The spent seed loss (in the 0-10% range examined) had only a minor impact on the system operating cost.

The effect of the combustor slag/ash rejection rate was also examined and it was found that the effect of a substantial reduction in the rejection rate (from 70% to zero) resulted in only a small increase in seed regeneration cost. A combustor designed for zero slag/ash rejection should have the advantages of simplicity and reduced thermal losses. These advantages could be partially affected if 100 percent carryover into the MHD channel requires an increase in the potassium seed concentration to maintain the plasma conductivity at the desired level. The results cited herein were based on a fixed level of potassium seed over the entire range of slag/ash rejection rates (1.5% K by weight of the combustor outlet flow before seed addition).

The seed regeneration system operating cost decreases with increasing capacity factor^{*} as would be expected. While the consumable and by-product credit portions of the

^{*}The capacity factor is the annual kilowatt-hour output of the power plant divided by the maximum kilowatt-hour output that could be produced if the plant were operated at its full rated output continuously for the entire year (8760 hours). Operating plant capacity factors are often used erroneously as a direct measure of power plant economic value and/or reliability. The daily and annual load duration curves of a given utility system and the mix of sizes and types of generating units it contains, combined with economic factors, define the plant load profile requirements. As a result, even large, so-called "base load" power plants must often operate in a load follow mode in order to satisfy system requirements (the large nuclear power plants in the Commonwealth Edison system are a good example of "base load" units which must load follow). Therefore, identical power plants of equal reliability can have different capacity factors when operating in different utility systems. They can also have the same annual capacity factor while operating with different load profiles and periods of time. However, if (continued)

operating cost are constant with capacity factor, the capital and operation and maintenance portions of the cost decrease with increasing capacity factor. In this analysis, the seed regeneration system was always sized for the maximum sulfur rejection rate when the plant operates at the full rated power output.

A breakdown of the operating cost for the seed regeneration system was developed. In percentage terms, the breakdown is as follows:

Consumables/Waste Disposal	=	62.3%
Capital Charges	=	41.4%
Operation & Maintenance	=	13.5%
By-Product Credits	=	-17.2%
Total	=	100.0%

The highest consumable costs in order of importance are:

Natural Gas
175 psia steam
Oxygen
Lime
 K_2CO_3

The by-product credits are for; 600 psia steam, combustor fuel gas, and formate reactor off-gas.

(continued)

variations in efficiency with operating power level are taken into account, the two identical power plants with the same annual capacity factor could have different average annual energy costs (in mills per kilowatt-hour). A plant cost of electricity calculation which took such factors into account would have to be a utility system — specific analysis or based on some assumed or arbitrary annual load profile for the plant. Such an analysis is beyond the scope of the present study. Generally, most initial power plant economic evaluations assume full load efficiency at a given capacity factor and that approach is used herein.

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.

- 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 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 significant seed system economic penalty. With low sulfur (1%) coals, the economic penalty due to zero rejection or 100 percent slag/ash carry over will be negligible.
- Since excess carbonate or a CO₂/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% K₂CO₃, so high degree of separation of K₂SO₄ from K₂SO₄ spent seed is needed.
- At low coal sulfur contents, the bypass flow rate can be as high as 90% by weight of K₂SO₄. This holds the CO₂/S ratio to a maximum of 1.4 or less and does not require complete separation of K₂SO₄/K₂CO₃ flyash. Seed system operating costs are minimized by maximizing the amount of K₂SO₄ 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.

2.0 INTRODUCTION

This Topical Report includes a significantly upgraded version of the previous seed system mathematical model⁽³⁾ and uses the model to investigate seed system integration and application issues. Upgrades to the model include the following:

- Capital, operating, maintenance, and consumable cost data from reference⁽²⁾ has been incorporated in the model.
- Cost algorithms from reference⁽⁴⁾ for the seed regeneration system and the seed injection system were applied to the cost data to permit evaluations of capital and operating costs as a function of plant size.
- Combustor outlet stoichiometry is now a specified input parameter used to compute oxidant flow rate.

The upgraded model has been used to evaluate several of the issues identified in reference⁽³⁾ and the results are documented herein.

The previous Topical Report⁽³⁾ defined a step by step approach which consisted of the following subtasks:

- (1) Evaluate the ECONOSEED system given the 300 MWt design basis, assumptions, and data given in reference (2).
- (2) Prepare an input/output mathematical model of the ECONOSEED system and verify the model by comparison with the reference (2) data at the 300 MWt size level.
- (3) Use the model to evaluate differences in coal properties, operating conditions, and plant design approaches and new DOE POC program developments.
- (4) Scale to the Scholz plant size and evaluate integration approaches specific to the Scholz MHD retrofit plant design.

Subtasks (1), (2) and (3) have been completed. New program developments^{(5),(6)} have been incorporated. The work subsequent to this report will focus on:

- Integration with the Scholz MHD retrofit plant design.
- Evaluation of alternate approaches to reducing seed regeneration system operating costs for high sulfur coal.
- Review and incorporation of new POC program developments.

3.0 SEED REGENERATION SYSTEM APPLICATION STUDIES

The previously described⁽³⁾ mathematical model of the seed regeneration system (based on the ECONOSEED⁽²⁾ process) has been upgraded to include: consumable and waste costs; operation and maintenance costs; and capital cost. Section 3.1 describes these and other changes in the model which permit the calculation of the total operating cost (in mills/kWh) for seed regeneration with various operating conditions. A cost/performance sensitivity study was then conducted and the results are reported in Section 3.2. The model was also used in Section 3.3 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.

3.1 UPGRADED MODEL DESCRIPTION

Cost data from the ECONOSEED system base case⁽²⁾ and information from other sources was used to upgrade the seed system model. Overall combustor stoichiometry is now a model input parameter and is used to compute the oxidant flow rate. Algorithms were incorporated so the seed system can be scaled to different MHD plant sizes. The model can now be used to examine costs and operating conditions over a wide range of coal sulfur content (a 1-5% range was used). 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.

A sample print-out for the upgraded model is included herein as Appendix A.2.

3.1.1 Seed System Capital Cost

The ECONOSEED system base case⁽²⁾ capital cost for a unit removing 8418 tons of sulfur per year at a 65 percent capacity factor is:

Installed Cost	=	\$18,732,000
Process & Project Contingency @ 19.4%	=	3,635,000
Total Plant Cost	=	22,367,000
Other Capital*	=	4,553,000
Total Capital Required	=	\$26,920,000

The above costs were represented in the seed system model as a function of size by using modified algorithms from reference (4) per plant code of Account number as follows:

ACCOUNT NO. 317.6.1, SEED REGENERATION SYSTEM

$$C_{srs} = F_E K (W)^{0.9}$$

where C_{srs} = installed cost (89\$)
 F_E = experience cost factor (use $F_E = 1.0$)
 $K = 45.5 \times 10^6$
 W = sulfur removal rate in Kg/S

For the base case ECONOSEED system, the sulfur removal rate is 0.373 Kg/S (8418 tons of sulfur per year at a 65% capacity factor)

ACCOUNT NO. 317.6:2, SEED INJECTION, HANDLING, STORAGE

* Includes interest during construction, royalty allowance, preproduction costs, working capital, and land cost.

$$C_{srs} = K_1 (W)^{0.8} + K_2$$

where C_{srs} = installed cost (\$)

K_1 = 4.92×10^5

K_2 = 8.71×10^5

W = seed injection flow rate in Kg/S

the seed injection flow rate for the base case ECONOSEED system is 17,039 lb/hr or 2.147 Kg/S.

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 requirement for both of the above accounts.

3.1.2 Operation and Maintenance Cost

The annual operation and maintenance cost (not including consumable costs) for the base case ECONOSEED system removing 8418 tons of sulfur per year is \$1,448,000. This cost is represented in the seed system model by the following algorithm:

$$C_{O\&M} = K (S_R)^{0.85}$$

where $C_{O\&M}$ = annual O&M cost (\$)

K = 667

S_R = annual sulfur removed, tons/year

3.1.3 Consumable/Waste Costs and By-Product Credits

The Table 3.1 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.

TABLE 3.1
CONSUMABLE/WASTE COSTS AND BY-PRODUCT CREDITS

<u>CONSUMABLE</u>	<u>UNIT COST</u>
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 ₂ CO ₃	36 \$/100 lb
K ₂ SO ₄	150 \$/ton
Natural Gas	3.5\$/MMBtu
Power	0.06\$/kwh
Oxygen	50 \$/ton
<u>WASTE DISPOSAL</u>	<u>UNIT COST</u>
CACO ₃ /CA(OH) ₂	8.35 \$/ton
Flyash/K ₂ SO ₄	8.35 \$/ton
Gypsum	5.00 \$/ton
<u>BY-PRODUCTS</u>	<u>CREDIT VALUE</u>
Formate Reactor Off-Gas	3.5 \$/MMBtu
Combustor Fuel Gas	3.5 \$/MMBtu
600 PSIA Steam	4.75 \$/1000 lb

3.1.4 Operating Conditions

For the seed system model as described in the previous Topical Report⁽³⁾, the oxidant flow rate was an input parameter derived from the Scholz operating condition⁽¹⁾ or used as is from the ECONOSEED 300 MWt design basis⁽²⁾. In the updated model, the overall combustor stoichiometry is the input parameter and the oxidant flow rate is calculated from the coal ultimate analysis properties. The study results reported herein assume that the oxidant is 40 oxygen percent by volume, but this oxygen percentage can be changed for other plant designs.

The seed system model has also been modified to accept a wide range of coal sulfur content (1-5%) and both the CO_3/S ratio and the potassium seed percentage required for ionization are input parameters. 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 updated model incorporates logic that compares the input CO_3/S ratio 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 (5) and (6) do not need to achieve complete $\text{K}_2\text{SO}_4/\text{K}_2\text{CO}_3$ separation of the recovered fly ash prior to seed regeneration system input (see section 3.2.3).

3.1.5 Coal Properties

The coal properties used in the Scholz⁽¹⁾ Corette⁽⁷⁾ retrofit designs and in the ECONOSEED 300 MWt design basis⁽²⁾ are summarized in Table 3.2.

3.2 COST/PERFORMANCE SENSITIVITY

The cost/performance study of seed regeneration issues was conducted in two 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.

3.2.1 Base Case Cost/Performance

The base case was defined to measure the impact of individual parameters on seed system cost and performance. Table 3.3 summarizes the key parameters of the base case. The complete seed system model and all of the base case input/output data is included herein as Appendix A.2 (Run 3).

Figure 3.1 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 $\text{CO}_3/\text{S} = 1.2$, 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. The size, capital cost, and consumable costs are thus directly related to the amount of sulfur rejected in the regeneration process. At a fixed rate of 90% of sulfur removed from the combustion products, we have the following:

TABLE 3.2
SUMMARY OF COAL PROPERTIES

		CORETTE	ECONOSEED	SCHOLZ
PROXIMATE, AS RECEIVED				
Moisture	%	25.3	9	12
Ash	%	9.1	12.52	8.7
Carbon	%	36.6	68.49	47.8
Volatile Material	%	29	41.7	31.5
Heating Value	Btu/lb	8600	11925	11241
ULTIMATE, DRY, ASH FREE				
Carbon	%	65.99	68.49	77.16
Sulfur	%	1.28	3.62	4.29
Oxygen	%	14.51	9.22	1.12
Hydrogen	%	5.21	4.83	5.19
Heating Value	Btu/lb	11508	12400	12774
ASH ANALYSIS				
K ₂ O	%	0.33	2.3	1.9
Na ₂ O	%	0.39	2.3	0.6
SO ₃	%	14.76	0	3.5
PREPARED COAL				
Moisture	%	5	0	2
Heating Value	Btu/lb	10933	12400	12520

TABLE 3.3
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 ₂ CO ₃ /K ₂ SO 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 ₂ CO ₃ Production Cost	0.179\$/lb

<u>Coal Type/S Content</u>	<u>S, tons/year</u>	<u>Mills/kwh</u>
Corette/Rosebud/1.28% S	2820	8
3.0% S	6609	15.3
Scholz/IL, No. 6/4.29% S	9451	21

In Figure 3.1, 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 3.2 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 3.3. 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 3.3.

As shown in Figure 3.4, combustor stoichiometry has very little effect on the seed regeneration system operating cost. In Figure 3.5, increasing the combustor thermal input decreases the operating cost slightly due to economy of scale benefits in the seed regeneration system capital cost. Increasing the overall efficiency, as shown in Figure 3.6, significantly reduces the operating cost due to increased annual kilowatt-hour production.

^{*}The Seed System is always sized for the maximum sulfur rejection rate that occurs when the plant operates at full rated power output.

Figure 3.1. Effect of CO₃/S, Coal Sulfur Content, and Spent Seed Loss.

Figure 3.2. Effect of Combustor Slag/Ash Rejection.

Figure 3.3 Effect of Plant Capacity Factor.

Figure 3.4. Effect of Combustor Stoichiometry.

Figure 3.5 Effect of Combustor Thermal Input.

Figure 3.6 Effect of Overall Plant Efficiency.

3.2.2 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 3.7. 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 3.8. 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 3.8, 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 . Given this scenario, a breakdown of the operating cost is given in Figure 3.9. 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 3.10 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.

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

Figure 3.7. Operating Cost and Sulfur Rejected per Year vs Sulfur Content.

Figure 3.8 Total Seed Injection, By-Passed Spent Seed, Regenerated, And Make-Up Seed Flow Rates Vs Coal Sulfur Content

Figure 3.9 Operating Cost Breakdown Vs Coal Sulfur Content

Figure 3.10. Relative Consumable and Waste Disposal Costs at $S = 3\%$, $CO_3/S = 1.2$, $K_g = 1.5\%$.

3.2.3 Effect of K_2CO_3/K_2SO_4 By Pass Options

There are two options for supplying sufficient potassium for ionization when low sulfur coal is used. 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_2SO_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 . However, the sulfur concentration in the MHD channel will be higher than in option (2). This option was used in the analyses of Sections 3.2.1 and 3.2.2.
- (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 (1) and (2) 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 3.11 through 3.17.

$$\text{Minimum Potassium Requirement}^* = 1.5\%$$

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

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

Figure 3.11 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 3.12. 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.

Figure 3.13 shows the total bypass flow rate as a function of coal sulfur content for the two options. 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. Figure 3.14 shows the weight percentage of K_2SO_4 in the bypass flow. When the CO_2/S ratio is reduced, the K_2SO_4 concentration increases because less K_2CO_3 is available from the spent seed.

Potassium and carbonate losses in the overall system are made up by a mix of K_2SO_4 and K_2CO_3 . Minimizing the amount of K_2CO_3 make up that is required is desirable since

Figure 3.11 Impact of K_2SO_4 Bypass on CO_3/S Ratio.

Figure 3.12 Potassium Concentration In The MHD Channel

Figure 3.13. Total Bypass Flow Rate.

Figure 3.14. Percentage of K_2SO_4 in Bypass Flow.

K_2CO_3 is about five times more expensive than K_2SO_4 on a per pound basis. Figure 3.15 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. A spent seed loss rate of 5% by weight was assumed for the Figure 3.15 data.

Figure 3.16 shows the seed system total operating cost for the bypass options. At a coal sulfur content of 1%, the 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 % when no K_2SO_4 can be bypassed.

Figure 3.17 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.

3.3 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 3.4. The seed system operating cost over the coal sulfur range for these plant designs was calculated and is shown in Figure 3.18.

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%

Figure 3.15 K_2CO_3 Make Up Requirements

Figure 3.16. Total Seed System Operating Cost for By Pass Options.

Figure 3.17. Sulfur Concentration in the MHD Channel.

TABLE 3.4
DATA FOR RETROFIT, APT EARLY COMMERCIAL, AND
ADVANCED COAL-FIRED MHD POWER PLANTS

		APT Early Commercial ⁽⁹⁾		
	Scholz ⁽¹⁾			
	Retrofit	200	500	Advanced ⁽¹⁰⁾
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 3.18. Seed System Operating Costs for Retrofit, APT Early Commercial and Advanced Coal-Fired MHD Power Plants.

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 could be compared directly with the first year operating costs for the seed system. The results are shown in Table 3.5 for the nominal 200, 500 and 1000 MWe APT plants. Capital cost estimates (installed cost plus contingency) for the APT seed systems were also updated to 1989 dollars separately and are shown in Table 3.5. The scaled capital costs for the ECONOSEED based seed system are also shown in Table 3.5. The basic ECONOSEED capital cost estimate was more detailed than the APT seed system 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) ranges from 2.28 to 2.57 mills/kWh over the plant size range. Comparison of these operating costs with the total O&M cost for the APT plants indicates that O&M and consumable costs for the APT seed systems may have been underestimated.

TABLE 3.5
APT⁽⁹⁾ EARLY COMMERCIAL MHD POWER PLANT
WITH WESTERN COAL (SULFUR CONTENT = 0.85%)

APT PLANT DATA	200	500	1000
Efficiency, %	40.4	42.6	43.4
Net Output, MWe	195	495	989
Total Capital Req'd, (89 \$M)	350	665	1126
(COE) _{capital} Mill/kWh	48.7	36.5	30.9
(COE) _{fuel} Mill/kWh	12.7	12.0	11.8
(COE) _{O&M} Mill/kWh	8.6	5.1	3.8
(COE) _{total} Mill/kWh	70.0	53.6	46.5
<u>SEED SYSTEM COMPARISON</u>			
APT Seed System Capital Cost (89 \$M)	12.5	26.2	47.0
ECONOSEED BASED SEED SYSTEM COSTS			
Capital Cost (89 \$M)	10.3	22.6	41.4
(COE) _{capital} Mill/kWh	1.96	1.63	1.47
(COE) _{consumable} Mill/kWh	2.67	2.53	2.49
(COE) _{O&M} Mill/kWh	0.62	0.52	0.46
(COE) _{by-product cred.} Mill/kWh	-0.72	-0.69	-0.67
(COE) _{total} Mill/kWh	4.53	4.00	3.75

APT PLANT ASSUMPTIONS: Fuel Cost = 1.5 \$/MMBtu, no levelizing factors in fuel or O&M COEs, Capacity Factor = 65%, Fixed Charge Rate = 15.46%, Construction Period = 5.5 years at 10% Interest Rate and a 6.5% Escalation Rate. Combustor Stoichiometry = 0.90, Slag/Ash Rejection Fraction = 0.85.

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APPENDIX A.1

SEED SYSTEM DESIGN BASIS EVALUATION

A.1 SEED SYSTEM DESIGN BASE EVALUATION

The design basis⁽¹⁾ 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. The potassium formate reacts exothermally with oxygen in the combustor per the following reaction:

As an alternate, the potassium formate may be oxidized to form K_2CO_3 if a solid rather than a solution is preferred as a seed product material.

The calcium formate needed in the process is produced by the reaction of slaked lime and carbon monoxide (CO). The required carbon monoxide is produced by the partial oxidation of natural gas although other methods of carbon monoxide production could also be used.

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 to formulate the design basis were the following:

Coal Combustion

- Illinois No. 6 Coal
- 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 relative to the combined flow rate of combustion products and inerts.
- a molar ratio of injected seed carbonate to coal sulfur equal to 1.0 (with the assumption that 100% of the sulfur will be captured with $CONS = 1.0$)
- 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 . It was 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. Such an uncontrolled build-up of sodium in the regenerated seed would have two negative effects. First, a high Na/K ratio is likely to reduce the electrical conductivity of the combustion gas since the sodium ionization potential is about 20% higher than that of potassium (5.14 eV versus 4.34 eV). Second, a high concentration of sodium is known to contribute to hot corrosion failures of metal tubes⁽²⁾. A similar build-up of other contaminants will also occur after repeated seed recycling unless the contaminants are selectively removed or rejected. One such contaminant, chlorine, can attack both metals and ceramics⁽²⁾. 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 . Further details are provided in reference (1) and Table A.1-1 shows a breakdown of the resulting seed materials for the 300 MWt design basis.

Figure A.1-1 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 A.1-1, only those ECONOSEED internal components involving the gas and boiler feedwater streams are shown.

Table A.1-1
INPUT/OUTPUT SEED MATERIALS FOR 300 MWt DESIGN BASIS (IN LB/HR)

Material	Seed ⁽¹⁾ Slag	Flyash Slag	Recycle Output	Make Up Amounts	Total Seed Required
K_2CO_3	-	-	10,918	121	11,039
K_2SO_4	-	17,810 ⁽²⁾	3,207	833	4,040
Na_2CO_3	-	-	1,411	-	1,411
Na_2SO_4	-	2,583 ⁽²⁾	549	-	549
Na	13	-	-	-	-
K	126	-	-	-	-
Slag (inerts)	1,253	1,735 ⁽¹⁾	-	-	-
Totals	1,392	22,108	18,085	954	17,039

(1) Not Input to ECONOSEED (2) Before 4.8% Flyash Rejection

(Note: Only Selected Components and Functions are Illustrated)

Figure A.1-1. Econoseed Design Basis-Input and Output Interfaces.

Coal Properties

While both the Scholz MHD Retrofit design(3) and the 300 MWt ECONOSEED design basis use Illinois No. 6 coal, the coal properties (Tables A.1-2 and A.1-3) are significantly different for each. The ECONOSEED and Scholz coal properties are compared in Table A.1-4 at the 300 MWt level and with the amount of flyash rejection necessary to control sodium buildup. It is assumed that any coal-fired power plant, over its operating lifetime, would be supplied with a range of properties similar to that of the ECONOSEED/Scholz Illinois No. 6 coals. It is also assumed that the ECONOSEED system and component capacities and the material and energy consumable are directly related to the sulfur input in lb-moles/hr (in the form of K_2SO_4 and Na_2SO_4). From Table A.1-4, this means an 18% increase in ECONOSEED system size is required to switch from the ECONOSEED coal to the Scholz coal. If the same approach to limiting the recycle build-up of sodium is used for both coals, much less flyash must be rejected (0.8% versus 4.8%), to maintain the Na/K molar limit of 0.167 when the Scholz coal is used. As a result, the amount of seed make up materials (K_2CO_3 , K_2SO_4) will be reduced significantly. The conclusion is that the seed regeneration system must operate over a range of coal property conditions and integration of the seed system with the MHD retrofit plant must allow a necessary degree of flexibility in seed system inputs and outputs.

K_2/S Molar Ratio

The ECONOSEED design basis⁽¹⁾ 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:

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

TABLE A.1.2
ECONOSEED⁽¹⁾ COAL ANALYSIS (ILLINOIS NO. 6)

Ultimate Analysis	
96%, Moisture Free	
Hydrogen	4.83
Carbon	68.49
Nitrogen	1.32
Oxygen	9.22
Sulfur	3.62
Ash	<u>12.52</u>
	100.00
Ash Analysis, %	
SiO ₂	44.7
Al ₂ O ₃	20.9
CaO	5.8
Fe ₂ O ₃	24.1
MgO	1.8
TiO ₂	1.0
K ₂ O	2.3
Na ₂ O	2.3
P ₂ O ₅	0.12
Chloride	0.2
Zinc	0.12
Lead	0.03
Proximate Analysis, Moisture Free	
Volatile	41.7
Fixed Carbon	45.8
Moisture, as Received, %	9.0
Heating Value	
Dry Btu/lb	12,400
Fusions	
Initial Deformation Temp, °F	1,960
Softening Temp, °F	2,030
Fluid Temp, °F	2,260

TABLE A.1-3
SCHOLZ⁽³⁾ COAL ANALYSIS (ILLINOIS NO. 6)

Proximate Analysis - "As Received" (wt %)

Moisture	12.0
Ash	8.7
Fixed Carbon	47.8
Volatile Material	<u>31.5</u>
	100.0

Ultimate Analysis - Dry, Ash-Free (wt %)

Carbon	77.16
Hydrogen	5.19
Oxygen	11.12
Nitrogen	1.39
Sulfur	4.29
Chlorine	<u>0.13</u>
	100.00

Ash Analysis - High Temperature Ashing (wt %)

SiO ₂	45.0
Al ₂ O ₃	18.0
Fe ₂ O ₃	20.0
TiO ₂	1.0
CaO	7.0
MgO	1.0
SO ₃	3.5
K ₂ O	1.9
Na ₂ O	0.6
P ₂ O ₅	0.2
Unknown	<u>1.8</u>
	100.0

TABLE A.1-3
SCHOLZ⁽³⁾ COAL ANALYSIS (ILLINOIS NO. 6)
(Continued)

Ash Fusion Analysis

	<u>Reducing</u> <u>Atmosphere</u>	<u>Oxidizing</u> <u>Atmosphere</u>
Initial Deformation, °F	1,950	2,250
Softening Temp., °F	2,030	2,300
Hemispherical Temp., °F	2,140	2,430
Fluid Temp., °F	2,150	2,450

Heat Value

Higher Heating Value (HHV) = 11,241 Btu/lb (As Received)
 = 12,774 Btu/lb (Dry)

TABLE A.1-4
IMPACT OF DIFFERENT ILLINOIS NO. 6 COAL
PROPERTIES ON ECONOSEED SYSTEM

Property/Quantity	300 MWt With ECONOSEED Coal	300 MWt With Scholz Coal
Sulfur, wt %	3.62	4.29
K ₂ O, wt %	2.3	1.9
Na ₂ O, wt %	2.3	0.6
K, lb-mole	0.0244	0.0217
Na, lb-mole	0.0371	0.0097
Na/K molar ratio in ash	1.521	0.48
Na/K ECONOSEED Limit	--	0.167
Flyash Rejection Required ⁽¹⁾ , wt %	4.8	0.8
Sulfur ⁽²⁾ , lb-mole/hr	115	135

NOTES: (1) For Na/K limit of 0.167.

(2) ECONOSEED input after flyash rejection.

But test data⁽⁴⁾ has shown that a CO_3/S ratio greater than 1.0 is needed for 100% sulfur removal. It is also noted⁽⁴⁾ 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 equation is used herein to calculate the sulfur removal percentage for high sulfur coals:

$$\% \text{ S removal} = 50 (\text{CO}_3/\text{S}) + 30$$

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^(5,6) have addressed this issue.

Reference (5) notes that solubility data available in the literature suggests that an aqueous separation of K_2CO_3 from K_2SO_4 may be possible for solid mixtures of K_2CO_3 and K_2SO_4 when the weight ratio of K_2CO_3 to K_2SO_4 is 2.0 or greater. A laboratory experiment was conducted and showed that aqueous separation of the K_2CO_3 from the mixed flyash was a promising approach. The reference (5) discussion addresses the use of the ECONOSEED process in an MHD plant using low sulfur western coal (Rosebud with 1.1% sulfur content). Since the weight % of potassium needed in the MHD channel for ionization is in the range of 1.0 - 1.5%, the low sulfur content of the Rosebud coal means that the flyash will contain a high weight ratio of carbonate to sulfate. For this reason, the above mentioned aqueous separation experiment was conducted with a modified sample of UTSI supplied spent seed from high sulfur Illinois No. 6 coal tests. The spent seed sample was modified by adding potassium carbonate to increase the carbonate to sulfate weight ratio to about 2.1 in order to simulate the lower sulfur

Rosebud coal case. Based on the laboratory experiment, it is then concluded that separation and bypass of the potassium carbonate will significantly reduce the ECONOSEED system capital and operating cost relative to the case where all of the spent seed (recovered flyash) is processed through the ECONOSEED system. The cost reductions are due to the reduced size of the ECONOSEED calcium formate reactor and the carbon monoxide (CO) gas generation components and their consumable inputs (calcium formate and natural gas). These cost reductions are only partially offset by the cost additions to the ECONOSEED system to bypass the CO_2 (dissolvers, solid-liquid separators, evaporator).

Reference (6) uses a different approach for $\text{K}_2\text{SO}_4/\text{K}_2\text{CO}_3$ 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 . The WESP uses continuous liquid irrigation to clean the electrostatic collection surfaces and is said to have a lower operating cost and higher sub-micron particle collection efficiency than alternative gas cleaning systems. Using an aqueous solution of potassium salts as the irrigating liquid allows the WESP to be used to separate K_2CO_3 , K_2SO_4 , and insoluble flyash. Application to MHD power plants fired by either high sulfur eastern coals (low K_2/S ratio) and low sulfur western coals (high K_2/O ratio) is addressed by changing the solution strength of the WESP irrigating liquid. Bench scale tests of K_2SO_4 and K_2CO_3 co-solubilities at various concentrations and temperatures were conducted. These tests demonstrated that the co-solubility of K_2SO_4 in a K_2CO_3 solution decreased rapidly as the K_2CO_3 concentration increases and would allow effective separation even at elevated temperatures.

As a result, two approaches were proposed for potassium salt and solid-liquid separation. For a low K_2/S ratio, the recovered spent seed will be primarily K_2SO_4 and flyash. By keeping the WESP irrigating solution at the saturation limit for K_2/SO_4 , the insoluble flyash can be separated from the soluble K_2SO_4 . As shown in Figure A.1-2, the filtrate from the rotary drum filter consists of a K_2SO_4 solution. A portion of the

Figure A.1-2. Wet ESP Operation Scheme for Low K_2/S Ratio.

solution, with makeup water, is recycled back to the WESP and the blown-down portion becomes the K_2/SO_4 input to the seed regeneration process. Figure A.1-3 illustrates the approach for high K_2/S ratio. The irrigating solution strength is maintained at the co-solubility of K_2CO_3 and K_2/SO_4 . Most of the K_2CO_3 can then be maintained in the solution form and the K_2SO_4 is in an insoluble form. The filtrate from the rotary drum filter is primarily a K_2CO_3 solution which is recycled back to the WESP. The blowdown portion of the filtrate 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.

The rotary drum filter only acts on a fraction of the total WESP recycle solution to control the build-up of solids in the system. Since this filter is an inherent part of the WESP system, all of the K_2SO_4/K_2CO_3 separation is accomplished by the WESP, and either of the Figure A.1-2 or Figure A.1-3 schemes can interface with the ECONOSEED or other type of seed regeneration system without the need for additional process equipment. However, some additional work will be required to represent either the Reference (5) or (6) approaches in the seed regeneration and bypass model. For example, the filtrate stream of K_2SO_4 in Figure A.1-2 will be much larger (in lb/hr) than the K_2CO_3 filtrate stream in the Figure A.1-3 scheme, and rotary drum filter capacity will be different. But since a K_2/S ratio greater than 1.0 is desirable even for high sulfur coals in order to achieve a high percentage of sulfur removal, the scheme illustrated in Figure A.1-3 is the preferred scheme for either high or low sulfur coals.

Model Description and Benchmark Results

MATCAD software was used to define an ECONOSEED model for seed regeneration system integration evaluations. A printout of the model is provided in the Appendix. 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

Figure A.1-3. Wet ESP Operation Scheme for High K_2/S Ratio.

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 HRSG/ESP interfacing components is shown in Figure A.1-4. A carbonate spent seed bypass loop for operating at a high K_2/S ratio has been included in the model. An efficiency calculation was also included in the model to estimate the effect on overall MHD power plant efficiency of the ECONOSEED system (unintegrated). The ECONOSEED design basis assumed an MHD power plant of 300 MWt coal thermal input with an electrical output of 100 MWe with an overall efficiency of 0.333. With the ECONOSEED system included, the overall plant efficiency is:

$$\text{Plant Efficiency} = \frac{100 - J}{300 + K}$$

where J is the electrical input to the ECONOSEED system and K is the net thermal input, as indicated in Figure A.1-4. Referring to Figure A.1-1, the electrical input J is the power required for oxygen and natural gas compression. Also referring to Figure A.1-1, the net thermal input to the ECONOSEED system is the algebraic sum of the following thermal inputs and outputs.

- natural gas input
- 150 and 175 psia steam inputs
- 600 psia steam Output
- fuel gas output
- formate reactor off-gas output

A series of ten cases or operating conditions have been examined to "Benchmark" with the ECONOSEED model, and the resulting data is presented in Table A.1-5. All ten cases assumed a 300 MWt coal thermal input, five with the ECONOSEED design basis coal

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 A.1-4. Simplified Econoseed Model and State Points.

properties and five with the Scholz coal properties. As in the ECONOSEED design basis, it was assumed that the only potassium losses in the overall system consisted of potassium lost in the slag and insoluble sulfate flyash and the soluble flyash rejected to control sodium build-up.

Case 1E for the ECONOSEED coal properties in Table A.1-5 is a "benchmark" case to compare the model results with the ECONOSEED design basis. Comparison of the design basis data with the Case 1E results show only minor differences (on the order of 1% or less) for key flow rates. Therefore, it was assumed that the model was a sufficiently accurate representation of the ECONOSEED process and could be used to evaluate other operating conditions.

The ECONOSEED design basis and case 1E assume 100% sulfur removal when $\text{CO}_3/\text{S} = 1.0$. Cases 2E, 3E and 4E show the effect of less than 100% sulfur removal and higher CO_3/S ratios and require the separation and bypass of spent carbonate seed.

It is interesting to compare Cases 1E and 4E. Both cases assume 100% sulfur removal, but a higher CONS ratio is required in Case 4E. The assumption, by itself, that a higher CO_3/S ratio (1.4 as opposed to 1.0) is required for the same sulfur removal has no impact on the ECONOSEED system or the makeup seed requirements. A higher combustor seed input flow rate is required, but the increase is offset by the bypassed carbonate seed. This situation would change somewhat if significant potassium losses occur in the spent seed carbonate/sulfate separation process.

Cases 1E through 4E assume a sodium build-up limit of $\text{Na}/\text{K} = 0.167$ for the combustor seed input which is achieved by rejecting a sufficient quantity of soluble sulfate flyash (4.7% by weight). Case 5E shows how much this method of controlling sodium build-up will increase the percentage of flyash rejection, and the makeup seed required if the Na_2/K_2 limit is reduced by a factor of ten to 0.0167.

STATE POINT	MATERIAL/PROCESS	QUANTITY	ECONOSEED COAL PROPERTIES S = 3.62%, Na ₂ O = 2.3%, 300 MWt						SCHOLZ COAL PROPERTIES S = 4.29%, Na ₂ O = 0.6%, 300 MWt				
			DESIGN BASIS	1E	2E	3E	4E	5E	1S	2S	3S	4S	5S
A	Coal	lb/hr	82548	82620	82620	82620	82620	82620	81840	81840	81840	81840	81840
B	Slag/Ash Rejection	lb/hr	7233	7239	7239	7239	7239	7239	5550	5550	5550	5550	5550
C	Seed, K ₂ CO ₃ (Equivalent)	lb/hr	11039	11040	11070	13260	15460	17760	12960	12970	15530	18100	20600
C	Seed, K ₂ SO ₄	lb/hr	4040	4014	3159	3566	4014	2657	4132	3297	3714	4132	4265
C	Seed, Na ₂ CO ₃	lb/hr	1411	1441	1417	1712	2007	248	1665	1658	1990	2322	272
C	Seed Na ₂ SO ₄	lb/hr	549	540	429	487	545	39	561	448	505	561	58
C	Seed Total	lb/hr	17039	17040	16070	19050	22030	20900	19310	18370	21740	25120	25390
D	Makeup K ₂ CO ₃	lb/hr	121	124	265	195	124	4963	44	89	67	44	1580
D	Makeup K ₂ SO ₄	lb/hr	833	835	657	746	835	518	283	226	254	283	254
F	Bypass K ₂ CO ₃	lb/hr	0	0	2214	3321	4428	5082	0	2572	3858	5144	5903
F	Bypass Na ₂ CO ₃	lb/hr	0	0	283	424	566	65	0	329	493	657	75
G	Lost K ₂ CO ₃	lb/hr	0	0	0	0	0	0	0	0	0	0	0
G	Lost Na ₂ CO ₃	lb/hr	0	0	0	0	0	0	0	0	0	0	0
I	Lime Input	lb/hr	5833	5833	4591	5212	5833	3618	6879	5491	6185	6879	6189
J	Electrical Input	MWe	0.60	0.60	0.472	0.536	0.60	0.372	0.708	0.565	0.636	0.708	0.637
K	Net Thermal Input	MWt	26	26	21	23	26	16	31	25	28	31	28
-	Net Plant Efficiency	-	0.305	0.305	0.31	0.308	0.305	0.315	0.30	0.306	0.303	0.30	0.303
L	Gypsum Output	lb/hr	18749	18750	14760	16750	18750	11630	22110	17650	19680	22110	19690
M	Rejected Flyash	lb/hr	978	966	966	966	966	6764	175	175	175	175	2053
N	Rejected Slag/Inerts	lb/hr	3127	3103	3103	3103	3103	3103	2379	2379	2379	2379	2379
O	Stack Sulfur	lb/MMBtu	0	0	0.716	0.367	0	0	0	0.816	0.417	0	0
-	CO ₂ /S Molar Ratio	-	1.0	1.0	1.0	1.2	1.4	1.4	1.0	1.0	1.2	1.4	1.4
-	Sulfur Removed	%	100	100	80	90	100	100	100	80	90	100	100
-	Combustor Slag Rejection	%	70	70	70	70	70	70	70	70	70	70	70
-	Seed Na ₂ /K ₂ Molar Ratio	-	0.167	0.167	0.167	0.167	0.167	0.0167	0.167	0.167	0.167	0.167	0.0167
-	Wt % of Flyash Rejection	%	4.8	4.7	5.9	5.3	4.7	35.4	0.8	0.9	0.8	0.8	8.9

Table A.1-5. COMPARISON OF CALCULATED SEED SYSTEM PARAMETERS WITH ECONOSEED DESIGN BASIS

Cases 1S through 5S shown in Table A.1-5 duplicate the Case 1E to 5E conditions, but the higher sulfur, lower sodium Scholz coal properties are used. The model results are consistent with the change in coal properties:

Higher prepared coal HHV - lower coal flow rate

Higher sulfur content - higher combustor seed flow rate
 - higher bypass flow rate
 - increase in ECONOSEED input and output quantities

Lower Sodium Content - reduced soluble flyash rejection
 - reduced makeup seed requirements

APPENDIX A.1 REFERENCES

- (1) DOE/PC/79675-T1, MHD Seed Recovery and Regeneration, Final Report, DOE/PETC Contract No. AC22-87PC79672, TRW Applied Technology Division, October 1988.
- (2) DOE/PC/79671-T2, MHD Seed Recovery and Regeneration Based on the Formate Process, Phase I Final Report, DOE/PETC Contract No. AC22-87PC79671, University of Tennessee Space Institute, October 1988.
- (3) Conceptual design of a Coal-Fired MHD Retrofit Plant (Scholz Plant, Sneads, FL), Volumes I and II, DOE/PETC Contract No. DE-AC22-87PC79668, Westinghouse AES, April 1989.
- (4) "Preliminary Summary of Results of the 2000 Hour POC Tests on Illinois NO. 6 Coal", R. C. Attig, et al., the University of Tennessee Space Institute, 30th Symposium on Engineering Aspects of Magnetohydrodynamics, Baltimore, Maryland, June 29 - July 2, 1992.
- (5) "ECONOSEED Process for Regeneration of Spent Seed for Magnetohydrodynamic Power Generation", J. L. Anastasi, et al., TRW Applied Technology Division, 30th Symposium on Engineering Aspects of Magnetohydrodynamics, Baltimore, Maryland, June 29-July 2, 1992.
- (6) "The Role of the Wet Electrostatic Precipitator in the Coal-Fired Magnetohydrodynamic System", A. C. Sheth, et al., The University of Tennessee Space Institute, 30th Symposium on Engineering Aspects of Magnetohydrodynamics, Baltimore, Maryland, June 29 - July 2, 1992.

APPENDIX A.2

UPGRADED SEED SYSTEM MODEL

MHD RETROFIT SEED SYSTEM

SRS1

J. R. LANCE

DAY = 16

MONTH = 12

YEAR = 92

RUN = 3

MHD PLANT ACCOUNT NO 3176, SEED REGENERATION AND
AND INJECTION SYSTEM MODEL-ECONOSEED BASIS

INDEPENDENT VARIABLES

CO3S = 12	CO3/S MOLAR RATIO	
SCF = 0.3	SULFUR CAPTURE FACTOR	
PK2 = 0.015	DESIRED K2 IN CHANNEL FLOW, %/100	
QI = 300	COMBUSTOR THERMAL INPUT, MWT	
MP = 0.025	MOISTURE IN PREPARED COAL, %/100	MPP = 100 MP
STOICH = 0.88	OVERALL COMBUSTOR STOICHIOMETRY	
CGF = 0.01	COAL CARRIER GAS FRACTION	
SAR = 0.70	SLAG/ASH REJECTION FRACTION	

COAL ANALYSIS/ILLINOIS NO 6 (ECONOSEED COAL)

PROXIMATE AS RECEIVED

MAR = 0.1715	MOISTURE, %/100
ASH = 0.106	ASH, %/100
CARB = 0.525	CARBON, %/100
VOLAT = 0.354	VOLATILE MTL, %/100
HVAR = 10500	HEATING VALUE, BTU/LB

ULTIMATE, DRY, ASH FREE

PS = 0.03	SULFUR IN COAL, %/100	PSP = 100 PS
PC = 0.7156	CARBON, %/100	
PH = 0.0502	HYDROGEN, %/100	
PO = 0.1187	OXYGEN, %/100	
HVD = 12141	HEATING VALUE, BTU/LB	

ASH ANALYSIS

PKASH = 0.0132	WT %/100 OF K2O IN ASH	PKASP = 100 PKASH
PNASH = 0.0135	WT %/100 OF NA2O IN ASH	PNASP = 100 PNASH
PSASH = 0.0738	WT %/100 OF SO3 IN ASH	PSASP = 100 PSASH

OTHER DATA

MWK2 = 78.2	MOLECULAR WT OF K2
MWNA2 = 45.982	MOL. CULAR WT OF NA2

MWCO ₃ = 60	MOLECULAR WT OF CO ₃
MWS = 32	MOLECULAR WT OF S
PK ₂ C = 0.56585	WT %/100 K ₂ IN K ₂ CO ₃
PK ₂ S = 0.449	WT %/100 K ₂ IN K ₂ SO ₄
PS ₂ S = 0.184	WT %/100 S IN K ₂ SO ₄
PSO ₃ = 0.40	WT %/100 S IN SO ₃
PSO ₄ = 0.3333	WT %/100 S IN SO ₄
PNA ₂ O = 0.7419	WT %/100 NA ₂ IN NA ₂ O
PNAS = 0.3239	WT %/100 NA ₂ IN NA ₂ SO ₄
PNAC = 0.434	WT %/100 NA ₂ IN NA ₂ CO ₃
PSNS ₄ = 0.2254	WT %/100 S IN NA ₂ SO ₄
PK ₂ O = 0.830	WT %/100 K ₂ IN K ₂ O

ECONOSEED PROCESS PARAMETERS

SRSC = 0.1927	RATIO OF RECYCLED S TO FLYASH S
NA ₂ K ₂ = 0.1667	MOLAR RATIO OF NA ₂ /K ₂ IN RECYCLED SEED
K ₂ L = 0.01992	MOLAR LOSS RATIO FOR K ₂ IN INSOLUABLE SLAG
NA ₂ L = 0.01951	MOLAR LOSS RATIO FOR NA ₂ IN INSOLUABLE SLAG
LCRE = 0.05	MOLAR LOSS FRACTION FOR K ₂ AND NA ₂ IN FLY ASH RECOVERY
BETA = 0.8357	MOLAR SULFUR MAKE UP FRACTION
CF = 0.65	POWER PLANT ANNUAL CAPACITY FACTOR

ECONOSEED BASE CASE PARAMETERS

EP _{IB} = 0.6	ELECTRICAL POWER,MWE
O _{IB} = 6707	OXYGEN(95%),LB/HR
NG _{IB} = 4995	NATURAL GAS, LB/HR
HVNG = 23764	NATURAL GAS HHV,BTU/LB
BFW _{IB} = 15668	MAKE UP BOILER FEED WATER,LB/HR
PW _{IB} = 92365	MAKE UP PROCESS WATER,LB/HR
LIME _B = 5833	LIME,LB/HR
BSRYR = 8417.6	SULFUR REMOVED IN TONS PER YEAR
QS175B = 17.34	THERMAL INPUT FOR 175 PSIA STEAM,MWT
MS175B = 51600	175 PSIA STEAM,LB/HR
QS150B = 1.26	THERMAL INPUT FOR 150 PSIA STEAM,MWT
MS150B = 3750	150 PSIA STEAM,LB/HR

OUTPUTS

GYPSMB = 18749	GYPSUM,LB/HR
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PREPARED COAL FLOW RATE

$$COI = QI \frac{3415}{HVP} \frac{1000}{HVP}$$

$$COI = 8.608 \cdot 10^4$$

COAL CARRIER GAS FLOW RATE

$$CCG = CGF \cdot COI$$

$$CCG = 860.795$$

MASS FRACTIONS IN PREPARED COAL

$$LI = ASH + CARB + VOLAT$$

$$MT = \frac{LI}{(1 - MP)}$$

$$MT = 1.01$$

$$MFP = \frac{(MT - LI)}{MT}$$

$$MFP = 0.025$$

$$ASHP = \frac{ASH}{MT}$$

$$ASHP = 0.105$$

$$CARBP = \frac{CARB}{MT}$$

$$CARBP = 0.52$$

$$VOLTP = \frac{VOLAT}{MT}$$

$$VOLTP = 0.35$$

$$CARVOL = CARBP + VOLTP$$

$$DPC = PC \cdot CARVOL$$

$$DPCM = \frac{DPC}{12}$$

$$DPH = PH \cdot CARVOL$$

$$DPHM = \frac{DPH}{2}$$

$$DPO = PO \cdot CARVOL$$

$$DPOM = \frac{DPO}{32}$$

$$DPS = PS \cdot CARVOL$$

$$DPSM = \frac{DPS}{32}$$

$$THEO_2 = DPCM + DPHM + DPSM - DPOM$$

$$THEO_2 = 0.071$$

$$COAM = DPC + DPH + DPS + DPO$$

$$COAM = 0.796$$

ASSUME OXIDANT IS 40% O₂ BY VOLUME OR THE MIXTURE IS 29.6 LB/LB-MOLE

THEORETICAL O₂ WEIGHT

$$OTCO = THEO_2 \text{ STOICH} \frac{29.6}{(0.4324 \cdot COAM + (1 - MP))}$$

$$OTCO = 5.267$$

THEN GIVEN THE PREPARED COAL INCLUDING ASH AND MOISTURE, THE

OXIDANT FLOW RATE IN LB/HR IS

$$MO = OTCO \cdot COI$$

$$MO = 4.534 \cdot 10^5$$

SLAG/ASH REJECTION FLOW RATE

$$\text{SARF} = \text{SAR ASHP COI}$$

$$\text{SARF} = 6.322 \cdot 10^3$$

SULFUR IN SLAG/ASH REJECTION FLOW RATE, LB/HR

$$\text{SSR} = \text{SARF PSASH PSO3}$$

$$\text{SSR} = 186.633$$

NET COMBUSTER OUTLET FLOW RATE WITHOUT SEED

$$\text{CFWOS} = \text{COI} + \text{CCG} - \text{SARF} + \text{OXD}$$

$$\text{CFWOS} = 5.34 \cdot 10^5$$

SLAG/ASH CARRYOVER FLOW RATE

$$\text{SACF} = (1 - \text{SAR}) \text{ ASHP COI}$$

$$\text{SACF} = 2.71 \cdot 10^3$$

K AND NA FLOW RATES IN SLAG/ASH CARRYOVER, LB/HR

$$\text{K1} = \text{SACF PKASH PK2O}$$

$$\text{K1} = 29.686$$

$$\text{NA1} = \text{SACF PNASH PNA2O}$$

$$\text{NA1} = 27.138$$

SULFUR FLOW RATE IN SLAG/ASH CARRYOVER

$$\text{S1} = \text{SACF PSASH PSO3}$$

$$\text{S1} = 79.986$$

SULFUR FLOW RATE IN REMAINDER OF COAL

$$\text{S2} = (\text{CARBP} + \text{VOLTP} + \text{ASHP}) \text{ PS COI}$$

$$\text{S2} = 2.518 \cdot 10^3$$

TOTAL SULFUR FLOW RATE FROM COAL, LB/HR AND LB-MOLE/HR

$$\text{STC} = \text{S1} + \text{S2}$$

$$\text{STC} = 2.598 \cdot 10^3$$

$$\text{SCM} = \frac{\text{STC}}{\text{MWS}}$$

$$\text{SCM} = 81.182$$

AFTER SEED INJECTION THE SULFUR REMOVAL (%/100) BASED ON UTSI TESTS IS

$$\text{SREM} = 0.5 \text{ CO3S} + \text{SCF}$$

$$z = \text{SREM} - 1.0$$

$$f(z) = z$$

$$\text{SREM} = 0.9$$

$$n(z) = \text{if}(f(z) > 0, 1.0, \text{SREM})$$

$$N = n(z)$$

$$N = 0.9$$

$$\text{NP} = 100 \cdot N$$

FOR ONLY THE ECONOSEED PORTION OF THE SYSTEM.

THE TOTAL AMOUNT OF CO3 IN THE SEED IN MOLES IS

$$\text{TM2} = (\text{SCM})$$

$$\text{TM2} = 81.182$$

MOLES OF K2 IN THE K2CO3 SEED FORM

$$\text{CK2} = \frac{\text{TM2}}{(1 + \text{NA2K2})}$$

$$\text{CK2} = 69.582$$

MOLES OF NA2 IN THE NA2CO3 SEED FORM

$$TNA2C = TM2 \frac{NA2K2}{(1 + NA2K2)} \quad TNA2C = 11.599$$

MOLES OF K2 AND NA2 IN SLAG /ASH CARRYOVER

$$IK2 = \frac{K1}{MWK2} \quad IK2 = 0.38$$

$$IN2 = \frac{NA1}{MWNA2} \quad IN2 = 0.59$$

MOLES OF K2 AND NA2 LOST IN INSOLUBLE SLAG

$$K2LF = \left[\frac{PKASH}{0.023} K2L \right] (IK2 + CK2) \quad K2LF = 0.8$$

$$NA2LF = \left[\frac{PNASH}{0.023} NA2L \right] (IN2 + TNA2C) \quad NA2LF = 0.14$$

MOLES OF NA2 THAT MUST BE REJECTED FROM SO4 FLY ASH

$$NA2RR = IN2 - NA2LF \quad NA2RR = 0.451$$

TOTAL S IN MOLES REMOVED FROM THE COAL BY THE CO3 IS

$$RTS = SCM \cdot N \quad N = 0.9 \quad RTS = 73.063$$

THE AMOUNTS OF S REMOVED BY CONVERSION TO NA2SO4 AND K2SO4 ARE

$$NRTS = RTS \frac{TNA2C}{TM2} \quad NRTS = 10.439$$

$$KRTS = RTS \frac{CK2}{TM2} \quad KRTS = 62.624$$

THE MOLES OF ECONOSEED CO3 REMAINING IN THE NA2CO3 AND K2CO3 FORMS

$$RNCO3 = TNA2C - NRTS \quad RNCO3 = 1.16$$

$$RKCO3 = CK2 - KRTS \quad RKCO3 = 6.958$$

THE MOLES OF UNUSED ECONOSEED CO3 THAT CAN BE BYPASSED BACK TO FEED IN NA2CO3 AND K2CO3 FORMS ARE

$$NNCO3 = RNCO3 (1 - LCRE) \quad LCRP = 100 \text{ LCRE} \quad NNCO3 = 1.102$$

$$NKCO3 = RKCO3 (1 - LCRE) \quad NKCO3 = 6.61$$

THE RATIO OF NA2 TO K2 IN THE SO4 FLY ASH IS DIFFERENT THAN IN THE SEED SO WE NEED A NEW VALUE FOR NA2K2 WHICH IS

$$R1 = \frac{1}{NA2CO3} \quad R2 = \frac{1}{(K2CO3)}$$

$$NNNA2K2 = \frac{(SCM \ B2 - NA2LF + IN2)}{(SCM \ B1 \ B2 - K2LF + IK2)}$$

$$NNNA2K2 = 0.174$$

THE MOLES OF K2 THAT ARE LOST IN THE SO4 FLY ASH REJECTION ARE

$$KS4RM = \frac{NA2RR}{NNNA2K2}$$

$$KS4RM = 2.586$$

THEN THE TOTAL K2 LOSS IS

$$TK2LM = K2LF + KS4RM$$

$$TK2LM = 3.386$$

BUT WE GET SOME K2 FROM THE COAL SO THE MAKE UP K2 IS

$$MUK2 = TK2LM - IK2$$

$$MUK2 = 3.006$$

THE S IN MOLES REJECTED FROM THE SO4 FLY ASH IS

$$SRJ = KS4RM + NA2RR$$

$$SRJ = 3.037$$

THE S IN MOLES GOING UP THE STACK IS

$$SST = SCM (1 - N) \quad MUPS = (1 - SRSC) \text{ BETA } \frac{MUK2}{(SCM - SST - SRJ + \text{BETA } MUK2)}$$

$$SST = 8.118$$

$$MUPS = 0.028$$

THE S IN MOLES COMING OUT OF THE ECONOSEED SYSTEM IS

$$SEO = \frac{(SCM - SST - SRJ)}{\left[\frac{1}{SRSC} (1 - MUPS) - 1 \right]}$$

$$SEO = 17.315$$

THE S IN MOLES INTO THE ECONOSEED SYSTEM IS

$$SEI = \frac{SEO}{SRSC}$$

$$SEI = 89.854$$

$$SI = SCM - SST - SRJ$$

$$SI = 70.027$$

THE MAKE UP S IN MOLES THAT MUST BE ADDED IN K2SO4 FORM IS

$$SMU = MUPS \ SEI$$

$$SMU = 2.512$$

THEN THE MOLES OF S IN THE SEED INPUT IS

$$SS = SEO + SMU$$

$$SS = 19.827$$

THE REMAINDER OF THE K2 IN MOLES THAT MUST BE ADDED TO THE ECONOSEED OUTPUT IN THE K2CO3 FORM IS

$$MKCE = MK2 - SMU$$

$$MKCE = 0.494$$

THE ECONOSEED OUTPUT OF MOLES OF K2 IN THE K2SO4 FORM IS

$$KSE = \frac{(TNA2C + SEO - NA2K2 (SMU + CK2))}{(1 + NA2K2)}$$

$$KSE = 14.482$$

THEN THE TOTAL SEED INPUT IN MOLES OF K2 IN THE K2SO4 FORM IS

$$SK2 = SMU + KSE$$

$$SK2 = 16.994$$

THE ECONOSEED OUTPUT IN MOLES OF NA2 IN THE NA2SO4 FORM IS

$$NSE = SEO - KSE$$

$$NSE = 2.833$$

WE NEED ANOTHER NEW VALUE FOR NA2K2 AT THE ECONOSEED INPUT

$$NNK = \frac{(SCM \cdot B2 - NA2LF + IN2 - NA2RR)}{(SCM \cdot B2 \cdot B1 - E2LF + IK2 - KS4RM)}$$

$$NNK = 0.174$$

THEN THE MOLAR K2 AND NA2 INPUTS TO THE ECONOSEED SYSTEM ARE

$$KSI = \frac{SEI}{(1 + NNK)}$$

$$KSI = 76.522$$

$$NSI = SEI \cdot \frac{NNK}{(1 + NNK)}$$

$$NSI = 13.332$$

AND THE K2 AND NA2 MOLAR OUTPUTS IN CO3 FORM ARE

$$KCE = KSI - KSE$$

$$KCE = 62.04$$

$$NCE = NSI - NSE$$

$$NCE = 10.499$$

A CLOSING RATIO GREATER THAN 1.0 IS REQUIRED TO CAPTURE THE SULFUR. IF AN ADDITIONAL BYPASS FLOW IS REQUIRED IT IS ASSUMED THAT THE EXCESS CO2 IS SUPPLIED BY F2CO3

$$CKE = SCM \cdot (CO3S - 1)$$

$$CKE = 16.236$$

TO FIND THE TOTAL MOLES OF K2 IN THE CHANNEL ARE

$$KA = CKE + SE2 + CK2 \quad PK2 = 0.015$$

$$KA = 102.813$$

BUT WE MUST HAVE ENOUGH K2 FOR IONIZATION WITH LOW S COALS, WHICH IS

$$KD = PK2 \cdot \frac{CFWOS}{MWK2}$$

$$CPR2 = KA \cdot \frac{MWK2}{CFWOS}$$

$$CPR2 = 0.015$$

$$KD = 102.435$$

$$CPR2 = 0.015$$

$$CPR2 = 0.015$$

$$CPR2 = 0.015$$

$$CPR2 = 0.015$$

ADD ANY ADDITIONAL K2 IN THE K2SO4 FORM
SO THE TOTAL MOLAR FLOW RATES INTO THE SEED/CHANNEL OF RECYCLED
AND BYPASSED MATERIALS PLUS MAKE UP AMOUNTS ARE

K2CO3	$MKCS = MKCE + KCE + NKCO3 + CKE$	$MKCS = 85.38$
K2SO4	$MKSS = SMU + KSE + EKS$	$MKSS = 16.994$
NA2CO3	$MNCS = NCE + NNCO3$	$MNCS = 11.601$
NA2SO4	$MNSS = SEO - KSE$	$MNSS = 2.833$

IF THERE ARE LOSSES IN THE BYPASSED K2CO3 AND NA2 THE TOTAL MAKEUP
AMOUNTS IN MOLES ARE

K2CO3	$MKCET = MKCE + LCCE (RKCO3 + CKE)$	$MKCET = 1.654$
NA2CO3	$MNCT = LCCE (RNCO3)$	$MNCT = 0.058$
K2SO4	$MKST = SMU + LCCE (EKS)$	$MKST = 2.512$

THE TOTAL S IN THE CHANNEL AFTER SEED INJECTION IN MOLES IS

$TS = SCM + SS + EKS$	$STCO = TS \cdot MWS$	$TS = 101.009$
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TOTAL MOLES OF CO3 IN THE CHANNEL AFTER SEED INJECTION

$MCCO3 = MKCS + MNCS$	$MCCO3 = 96.982$
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THE TOTAL S IN MOLES THAT IS REMOVED FROM THE COAL BY THE CO3 IS

$RTS = SCM \cdot N$	$N = 0.9$	$RTS = 73.063$
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THE TOTAL MOLES OF NA2 AND K2 IN THE CHANNEL ARE

$CTNA2 = MNCS + MNSS + \frac{NA1}{MWNA2}$	$CTNA2 = 15.024$
$CTK2 = MKCS + MKSS + \frac{K1}{MWK2}$	$CTK2 = 102.754$

REQUIRED COMBUSTOR INPUT FLOW RATES OF SEED MATERIALS IN LB/HR ARE

$FNA2S = MNSS \frac{MWNA2}{PNAS}$	$FNA2S = 402.178$
$FK2S = MKSS \frac{MWK2}{PK2S}$	$FK2S = 2.96 \cdot 10^3$
$FNA2C = MNCS \frac{MWNA2}{PNAC}$	$FNA2C = 1.229 \cdot 10^3$

$$FK2C = MKCS \frac{MWK2}{PK2C}$$

$$FK2C = 118 \cdot 10^4$$

TOTAL RECYCLED SEED FLOW RATE IN LB/HR IS

$$FTRS = FNA2S + FK2S + FNA2C + FK2C$$

$$FTRS = 1639 \cdot 10^4$$

THEN THE TOTAL CHANNEL FLOW RATE IN LB/HR IS

$$FTC = CFWOS + FTRS$$

$$FTC = 5504 \cdot 10^5$$

THE WT % OF NA2K2 AND S IN THE CHANNEL ARE

$$CNA2P = 100 \frac{CTNA2}{FTC} \frac{MWNA2}{FWK2}$$

$$CNA2P = 0.126$$

$$CK2P = 100 \frac{CTK2}{FTC} \frac{MWK2}{FWK2}$$

$$CK2P = 1.46$$

$$CTSP = 100 \frac{TS}{FTC} \frac{MWS}{FWK2}$$

$$CTSP = 0.587$$

THE RECOVERED FLY ASH/SLAG FLOW RATES OF NA2SO4 AND K2SO4 IN LB/HR

$$FSNA2S = (NRTS + MNSS) \frac{MWNA2}{PNAS}$$

$$FSNA2S = 1884 \cdot 10^3$$

$$FSK2S = (KRTS + MKSS) \frac{MWK2}{PK2S}$$

$$FSK2S = 1387 \cdot 10^4$$

$$TFAR = FSNA2S + FSK2S$$

$$TFAR = 1575 \cdot 10^4$$

THE WT%/100 OF THE RECOVERED SO4 FLY ASH WHICH IS NA2SO4 IS

$$WPNS = \frac{FSNA2S}{TFAR}$$

$$WPNS = 0.12$$

THE AMOUNT OF NA2SO4 THAT MUST BE REJECTED FROM THE SO4 FLY ASH LB/HR

$$NASO4R = NA2FR \frac{MWNA2}{PNAS}$$

$$NASO4R = 63968$$

THE AMOUNT OF K2SO4 THAT MUST BE REJECTED IS

$$KS4R = KS4FR \frac{MWK2}{PK2C}$$

$$KS4R = 450431$$

THE TOTAL AMOUNT OF SO4 FLY ASH THAT MUST BE REJECTED LB/HR

$$WFAR = NASO4R + KS4R$$

$$WFAR = 514399$$

THE WEIGHT % OF THE SO4 FLY ASH REJECTED IS

$$WPAR = \frac{WFAR}{TFAR}$$

$$WPAR = 3.56$$

THE LB/HR FLOW RATES OF THE FLY ASH K_2CO_3 , K_2SO_4 AND Na_2CO_3 THAT BYPASS THE ECONOSEED PROCESS ARE

$$K_2CB = (NKCO_3 + CKE (1 - LCRE)) \frac{MWK_2}{PK_2C} \quad K_2CB = 3.045 \cdot 10^3$$

$$N_2CB = (NNCO_3) \frac{MWNA_2}{PNAC} \quad N_2CB = 116.75$$

$$K_2SB = EKS (1 - LCRE) \frac{MWK_2}{PK_2S} \quad K_2SB = 0$$

THE TOTAL RECOVERED SPENT SEED FLOW RATE IN THE BYPASS IS

$$TSSBP = K_2CB + N_2CB + K_2SB \quad TSSBP = 3.162 \cdot 10^3$$

THE PERCENT OF K_2SO_4 IN THE BYPASSED SPENT SEED IS

$$PK_2SB = 100 \frac{K_2SB}{TSSBP} \quad PK_2SB = 0$$

THE LB/HR FLOW RATE OF THE CONVERTED Na_2CO_3 IS

$$N_2CF = NCE \frac{MWNA_2}{PNAC} \quad N_2CF = 1.112 \cdot 10^3$$

AND THE LB/HR FLOW RATE OF THE PROCESSED Na_2SO_4 IS

$$N_2SF = NSE \frac{MWNA_2}{PNAS} \quad N_2SF = 402.178$$

ECONOSEED SYSTEM INPUT/OUTPUT CONDITIONS-TONS OF S REMOVED/YEAR

$$FSRYR = SEI (1 - SRSC) MWS CF \left[\frac{8760}{2000} \right] \quad SEI = 89.854 \quad FSRYR = 6.609 \cdot 10^3$$

$$SR = \frac{(0.65 FSRYR)}{(CF BSRYR)} \quad CF = 0.65 \quad SR = 0.785$$

OTHER INPUTS ARE

$$\begin{aligned} EPI &= SR EPIB & EPI &= 0.471 \\ OI &= SR OIB & OI &= 5.266 \cdot 10^3 \\ NGI &= SR NGIB & NGI &= 3.922 \cdot 10^3 \\ BFWI &= SR BFWIB & BFWI &= 1.23 \cdot 10^4 \\ PWI &= SR PWIB & PWI &= 7.252 \cdot 10^4 \\ LIME &= SR LIMEB & LIME &= 4.579 \cdot 10^3 \end{aligned}$$

QS175 = SR QS175B
 MS175 = SR MS175B
 QS150 = SR QS150B
 MS150 = SR MS150B

QS175 = 13 614
 MS175 = 4 051 10^4
 QS150 = 0 989
 MS150 = 2 944 10^3

OUTPUTS

GYPSUM = SR GYPSMB
 PWAST = SR PWASTB
 CFG = SR CFGB
 FROG = SR FROGB
 QS600 = SR QS600B
 MS600 = SR MS600B

GYPSUM = 1 472 10^4
 PWAST = 850 256
 CFG = 2 457 10^3
 FROG = 968 02
 QS600 = 3 98
 MS600 = 1 178 10^4

UNCONDENSED THERMAL INPUTS MWt

$$NGIT = NGI \frac{HVNG}{(3415 \cdot 1000)}$$

NGIT = 27 289

$$SNTI = NGIT + QS175 + QS150$$

SNTI = 41 892

ECONOSEED THERMAL OUTPUTS MWt

$$FRGT = FROG \frac{HVFRG}{(3415 \cdot 1000)}$$

FRGT = 3 793

$$CFGT = CFG \frac{HVCFG}{(3415 \cdot 1000)}$$

CFGT = 13 566

$$SNTG = FRGT + CFGT + QS600$$

SNTG = 21 339

NET PLANT THERMAL INPUT WITH ECONOSEED MWE

$$NPO = EFPB \cdot QI$$

NPO = 99 999

NET ECONOSEED MAE

$$NPOE = NPO - EPI$$

NPOE = 99 528

CONDENSANT THERMAL INPUT WITH ECONOSEED MWt

$$GQIE = QI + SNTI - SNTG$$

GQIE = 320 552

NET PLANT EFFICIENCY WITH ECONOSEED

$$EFE = \frac{NPOE}{GQIE}$$

EFE = 0 31

ECONOSEED EFFICIENCY DELTA

$$EFED = 100 (EFE - EFFB)$$

$$EFED = -2.284$$

NSPS/EMISSION CALCULATIONS

TOTAL SULFUR IN ASH INPUT LB/HR

$$SII = ASHP COI PSASH PSO3$$

$$SII = 266.619$$

TOTAL SULFUR IN COAL/ASH INPUT LB/HR

$$STI = SII \cdot S2$$

$$STI = 2.784 \cdot 10^3$$

TOTAL THERMAL INPUT IN MMBTU IS

$$QIB = QI3415 \frac{1000}{10^6}$$

$$QIB = 1.025 \cdot 10^3$$

THE WT FRACTION OF S IN SO2 IS 0.5

SO THE EQUIVALENT S AND SO2 INPUTS PER MMBTU ARE

$$STIB = \frac{STI}{QIB}$$

$$STIB = 2.718$$

$$SOTIB = \frac{STIB}{0.5}$$

$$SOTIB = 5.436$$

THE CHANNEL/HRSR INPUT S AND SO2 INPUTS PER MMBTU ARE

$$STCB = \frac{STCO}{QIB}$$

$$STCB = 3.155$$

$$SOCB = \frac{STCB}{0.5}$$

$$SOCB = 6.31$$

THEN THE SULFUR CAPTURED IN THE HRSR/ESP/BH LB/HR

$$STCC = N \cdot STCO$$

$$STCC = 2.909 \cdot 10^3$$

AND THE S AND SO2 STACK EMISSIONS ARE

S LB/HR

$$STCE = (1 - N) \cdot STCO$$

$$STCE = 323.229$$

S LB/MMBTU

$$SCEB = \frac{STCE}{QIB}$$

$$SCEB = 0.315$$

SO2 LB/MMBTU

$$SOCE = \frac{SCEB}{0.5}$$

$$SOCE = 0.631$$

MISCELLANEOUS CALCULATIONS

$$K = K2LF \cdot MWK2$$

$$K = 62.547$$

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FOR ANNUAL O&M COSTS W/O CONSUMEABLES, USE

$$AOMC := 667.357 (\text{FSR}^{\text{YR}})^{0.85}$$

$$AOMC = 1.179 \cdot 10^6$$

CALCULATED ANNUAL CONSUMEABLE COSTS

$$YOT := CF \cdot 8760$$

$$YOT = 5.694 \cdot 10^3$$

$$CBFW := VBFW \cdot BFWI \cdot \frac{YOT}{1000}$$

$$CBFW = 4.903 \cdot 10^4$$

$$CPW := VPW \cdot PWI \cdot YOT \cdot \frac{7.481}{(62.4 \cdot 1000)}$$

$$CPW = 1.98 \cdot 10^4$$

WATER SUBTOTAL

$$CWST := CBFW + CPW$$

$$CWST = 6.883 \cdot 10^4$$

$$C175S := V175S \cdot MS175 \cdot \frac{YOT}{1000}$$

$$C175S = 1.089 \cdot 10^6$$

$$C150S := V150S \cdot MS150 \cdot \frac{YOT}{1000}$$

$$C150S = 7.901 \cdot 10^4$$

STEAM SUBTOTAL

$$CSST := C175S + C150S$$

$$CSST = 1.168 \cdot 10^6$$

$$CLIME := VLIME \cdot LIME \cdot \frac{YOT}{2000}$$

$$CLIME = 5.215 \cdot 10^5$$

$$CKCO3 := VKCO3 \cdot FKCO3 \cdot \frac{YOT}{100}$$

$$CKCO3 = 4.849 \cdot 10^5$$

$$CKSO4 := VKSO4 \cdot FKSO4 \cdot \frac{YOT}{2000}$$

$$CKSO4 = 1.869 \cdot 10^5$$

CHEMICAL SUBTOTAL

$$CHST := CLIME + CKCO3 + CKSO4$$

$$CHST = 1.193 \cdot 10^6$$

$$CNG := VNG \cdot NGI \cdot YOT \cdot \frac{HVNG}{1000000}$$

$$CNG = 1.857 \cdot 10^6$$

$$CPOW := VEP \cdot EPI \cdot YOT \cdot 1000$$

$$CPOW = 1.609 \cdot 10^5$$

$$COX := VOX \cdot OI \cdot \frac{YOT}{2000}$$

$$COX = 7.496 \cdot 10^5$$

OTHER SUBTOTAL

$$COST := CNG + CPOW + COX$$

$$COST = 2.768 \cdot 10^6$$

$$CPWAS := VPWAS \cdot PWAST \cdot \frac{YOT}{2000}$$

$$CPWAS = 2.021 \cdot 10^4$$

$$CKS4W := VKSO4W \cdot WFAR \cdot \frac{YOT}{2000}$$

$$CKS4W = 1.223 \cdot 10^4$$

$$CGYPW = VGYPG \text{ GYPSUM } \frac{YOT}{2000}$$

$$CGYPW = 2.095 \cdot 10^5$$

$$\text{WASTE SUBTOTAL} \quad CWAST = CPWAS + CKS4W + CGYPW$$

$$CWAST = 2.42 \cdot 10^5$$

COST OF CONSUMEABLES AND WASTE SUBTOTAL

$$CCWST = CWST + CSST + CHST + COST + CWAST$$

$$CCWST = 5.44 \cdot 10^6$$

$$CFGAS = VFROG \text{ FROG } HVFRG \frac{YOT}{1000000}$$

$$CFGAS = 2.581 \cdot 10^5$$

$$CCGAS = VCFG \text{ CFG } HVCFG \frac{YOT}{1000000}$$

$$CCGAS = 9.233 \cdot 10^5$$

$$C600S = V600S \text{ MS600 } \frac{YOT}{1000}$$

$$C600S = 3.185 \cdot 10^5$$

$$\text{BY-PRODUCT SUBTOTAL} \quad CBPST = CFGAS + CCGAS + C600S$$

$$CBPST = 15 \cdot 10^6$$

CONSUMEABLE, WASTE, AND BY-PRODUCT TOTAL

$$CCWBYT = CCWST - CBPST$$

$$CCWBYT = 3.94 \cdot 10^6$$

CAPITAL, OPERATING, AND UNIT COSTS

ANNUAL ELECTRICITY PRODUCTION, KWH

$$AE = NPO \text{ YOT } 1000$$

$$AE = 5.694 \cdot 10^8$$

ANNUAL K2CO3 PRODUCTION, LB/YEAR

$$AKC = K2CF \text{ YOT}$$

$$AKC = 4.882 \cdot 10^7$$

ANNUAL CAPITAL COST IN \$/YEAR AND MILLS/KWH

$$ACCD = FXCR \text{ C3176C}$$

$$ACCD = 3.608 \cdot 10^6$$

$$ACCM = ACCD \frac{1000}{AE}$$

$$ACCM = 6.337$$

OTHER ANNUAL COSTS/CREDIT IN MILLS/KWH

$$\text{O\&M} \quad COMM = AOMC \frac{1000}{AE}$$

$$COMM = 2.07$$

$$\text{CONSUMEABLES/WASTE} \quad COCWM = CCWST \frac{1000}{AE}$$

$$COCWM = 9.554$$

$$\text{BY-PRODUCTS} \quad \text{CCBPM} = \text{CBPST} \frac{1000}{\text{AE}}$$

$$\text{CCBPM} = 2.634$$

TOTAL COST IN MILLS/KWH AND \$/YEAR

$$\text{TOCM} = \text{ACCM} + \text{COMM} + \text{COCWM} - \text{CCBPM}$$

$$\text{TOCM} = 15.327$$

$$\text{TOCD} = \text{ACCD} + \text{AOMC} + \text{CCWST} - \text{CBPST}$$

$$\text{TOCD} = 8.727 \cdot 10^6$$

PRODUCTION COST OF K₂CO₃ IN \$/LB

$$\text{PCARB} = \frac{\text{TOCD}}{\text{AKC}}$$

$$\text{PCARB} = 0.179$$

RATIO OF PRODUCTION COST TO MARKET PRICE FOR K₂CO₃

$$\text{PMCR} = \frac{\text{PCARB} \cdot 100}{\text{VKCO}_3}$$

$$\text{PMCR} = 0.497$$

$$\text{DOLKW} = \frac{\text{C3176C}}{(1000 \text{ NPO})}$$

$$\text{DOLKW} = 233.38$$

DATA SUMMARY

SRS1

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DAY = 16

MONTH = 12

YEAR = 92

RUN = 3

CO3S = 12

CO3/S MOLAR RATIO

SCF = 03

QI = 300

COMBUSTOR THERMAL INPUT,MWT

OXD = 4534 10⁵

OXIDANT, LB/HR

STOICH = 0.88

MPP = 25

WT % MOISTURE IN PREPARED COAL

HVP = 119 10⁴

HIGHER HEATING VALUE OF PREPARED COAL BTU/LB

CCI = 8608 10⁴

PREPARED COAL, LB/HR

PSP = 3

WT % SULFUR IN COAL (DRY, ASH FREE)

PKASP = 1.32

WT % K2O IN ASH

PNASP = 1.35

WT % NA2O IN ASH

PSASP = 7.38

WT % SO3 IN ASH

SAR = 0.7

SLAG/ASH REJECTION FRACTION

SARF = 6322 10³

SLAG/ASH REJECTION FLOW RATE

CFWOS = 534 10⁵

COMBUSTOR FLOW RATE WITHOUT SEED, LB/HR

RECYCLED SEED INPUT FLOW RATES IN LB/HR

FK2C = 118 10⁴

K2CO3 (EQUIVALENT)

FNA2C = 1229 10³

NA2CO3

NA2K2 = 0.167

FK2S = 296 10³

K2SO4

FNA2S = 402.178

NA2SO4

FTRS = 1639 10⁴

TOTAL RECYCLED SEED FLOW RATE, LB/HR

FTC = 5504 10⁵

TOTAL CHANNEL FLOW RATE, LB/HR

CONCENTRATIONS IN THE CHANNEL

CK2P = 1.46

K2, WT %

PK2 = 0.015

CPK2 = 0.015

X = -0.378

CTSP = 0.587

SULFUR, WT %

CNA2P = 0.126

NA2, WT %

DATA SUMMARY

SRS1

PAGE 2 OF 5

DAY = 16

MONTH = 12

YEAR = 92

RUN = 3

RECOVERED FLY ASH/SLAG FLOW RATES IN LB/HR

FSK2S = $1.387 \cdot 10^4$

K2SO4

FSNA2S = $1.884 \cdot 10^3$

NA2SO4

NNNA2K2 = 0.174

RECOVERED CO3 AND SO4 FLY ASH IN LB/HR (THAT BYPASS THE SEED SYSTEM)

K2CB = $3.045 \cdot 10^3$

K2CO3

N2CB = 116.75

NA2CO3

K2SB = 0

K2SO4

X = -0.378

TSSBP = $3.162 \cdot 10^3$

TOTAL BYPASS FLOW RATE

PK2SB = 0

PERCENT OF K2SO4 IN BYPASSED SPENT SEED

TOTAL SO4 FLY ASH REJECTED AND K, NA LOST IN INSOLUBLE SLAG IN LB/HR

WFAR = 514.399

K2SO4, NA2SO4

K = 62.547

NA = 6.419

NNK = 0.174

INERTS REJECTED FROM SLAG/ASH CARRYOVER IN LB/HR

SACF = $2.71 \cdot 10^3$

ECONOSEED OUTPUTS IN LB/HR

BETA = 0.836

NA2K2 = 0.167

K2CF = $8.574 \cdot 10^3$

CONVERTED K2CO3 (EQUIVALENT)

N2CF = $1.112 \cdot 10^3$

CONVERTED NA2CO3

K2SF = $2.522 \cdot 10^3$

PROCESSED K2SO4

N2SF = 402.178

PROCESSED NA2SO4

DATA SUMMARY

SRS1

PAGE 3 OF 5

DAY = 16

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MAKE UP FLOW RATES IN LB/HR

IF K₂CO₃/NA₂CO₃ MIX IS USEDIF ONLY K₂CO₃ IS USED

FKCET = 228.538

K₂CO₃

FKC = 236.553

FMNCT = 6.145

NA₂CO₃

FMNC = 0

FKSET = 437.587

K₂SO₄

FKSET = 437.587

LCRP = 5

PERCENT OF K₂ OR NA₂ LOSS IN CO₃ FLY ASH RECOVERY

OTHER ECONOSEED CONSUMEABLES

LB/HR

MWE or MWT

DEFINITION

EPI = 0.471

ELECTRICAL POWER

OI = 5.266 10²

OXYGEN(95%)

NGI = 3.922 10³

NGIT = 27.289

NATURAL GAS

BFWI = 1.23 10⁴

MAKE UP BOILER FEED WATER

PWI = 1.852 10⁴

MAKE UP PROCESS WATER

LIME = 4.579 10³

LIME

MS175 = 4.051 10⁴

QS175 = 13.614

175 PSIA STEAM

MS150 = 2.944 10³

QS150 = 0.989

150 PSIA STEAM

FSRSTR = 6.609 10³

ECONOSEED SULFUR REMOVAL TONS OF S/YEAR

SR = 11.785

S REMOVED/S REMOVED IN ECONOSEED BASE CASE

DATA SUMMARY

SRS1

PAGE 4 OF 5

DAY = 16

MONTH = 12

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RUN = 3

ECONOSEED OUTPUTS/BY PRODUCTS

LB/HR

MWE OR MWT

DEFINITION

GYPSUM = $1.472 \cdot 10^4$

GYPSUM

PWAST = 850.256

WASTE(CACO₃, CA(OH)₂)CFG = $2.457 \cdot 10^3$

CFGT = 13.566

COMBUSTOR FUEL GAS

FROG = 968.02

FRGT = 3.793

FORMATE REACTOR OFF GAS

MS600 = $1.178 \cdot 10^4$

QS600 = 3.98

600 PSIA STEAM

OVERALL POWER PLANT IMPACT

WITHOUT ECONOSEED

WITH ECONOSEED

TOTAL THERMAL INPUT,MWT

QI = 300

GQIE = 320.552

NET PLANT OUTPUT,MWE

NPO = 99.999

NPOE = 99.528

OVERALL EFFICIENCY

EFFB = 0.333

EFE = 0.31

ECONOSEED EFFICIENCY DELTA, %

EFED = -2.284

NP = 90

WT % SULFUR REMOVED IN HRSR/BH/ESP

QIB = $1.025 \cdot 10^3$

THERMAL INPUT,MMBTU/HR

STI = $2.784 \cdot 10^3$

SULFUR IN COAL INPUT, LB/HR

STIB = 2.718

SULFUR IN COAL INPUT, LB/MMBTU

STCO = $3.232 \cdot 10^3$

TOTAL SULFUR IN CHANNEL, LB/HR

STCC = $2.909 \cdot 10^3$

SULFUR CAPTURED IN HRSR/BH/ESP

STCE = 323.229

SULFUR UP THE STACK, LB/HR

SCEB = 0.315

SULFUR UP THE STACK, LB/MMBTU

DAY = 16

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YEAR = 92

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CAPITAL COSTS BY CODE OF ACCT NO.(1989\$)

C61 = $1799 \cdot 10^7$

317.61 SEED REGENERATION SYSTEM(W CONT.)

C61C = $2159 \cdot 10^7$

317.61 SEED REGENERATION SYSTEM(TCR)

C62 = $175 \cdot 10^6$

317.62 SEEDHANDLING,STORAGE AND INJECTION

C3176C = $2334 \cdot 10^7$

317.6 COMPLETE SEED SYSTEM

DOLKW = 233.38

CAPITAL COST IN DOLLARS PER KWE.

FXCR = 0.155

FIXED CHARGE RATE FOR CAPITAL

CF = 0.65

ANNUAL CAPACITY FACTOR

PSRYR = $6609 \cdot 10^3$

ANNUAL SULFUR REMOVAL TONS OF S/YEAR

AKC = $4882 \cdot 10^7$ ANNUAL K₂CO₃ PRODUCTION, LB/YEARAE = $5694 \cdot 10^8$

ANNUAL ELECTRICITY PRODUCTION KWH/YEAR

\$/YEAR	MILLS/KWH	OPERATING COST COMPONENT
ACCD = $3608 \cdot 10^6$	ACCM = 6.337	CAPITAL(TOTAL CAPITAL REQUIREMENT)
AOMC = $1179 \cdot 10^6$	COMM = 2.07	OPERATION & MAINTENANCE
CCWBYT = $394 \cdot 10^6$	COCWM = 9.554	CONSUMEABLES,FUEL,WASTE DISPOSAL
CBPST = $15 \cdot 10^6$	CCBPM = 2.634	BY-PRODUCT CREDITS(GAS&S&STEAM)
TOCD = $8727 \cdot 10^6$	TOCM = 15.327	TOTAL SYSTEM OPERATING COST

PCARB = 0.179

PRODUCTION COST OF K₂CO₃\$/LB

PMCR = 0.497

RATIO OF PRODUCTION COST TO MARKET PRICE OF K₂CO₃

PPCNT = 0.194

PROJECT AND PROCESS CONTINGENCY(ACCT NO 317.6.1)

TCMM = 1.2

IDC WORKING CAPITAL MULTIPLIER

**DATE
FILMED**

12 / 27 / 93

END