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Modeling of a Combined Cycle MHD/Steam Power Plant

Edward H. Kiessling III

University of Tennessee - Knoxville

Recommended Citation

To the Graduate Council:

I am submitting herewith a thesis written by Edward H. Kiessling III entitled "Modeling of a Combined Cycle MHD/Steam Power Plant." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

Y.C.L. Wu, Major Professor

We have read this thesis and recommend its acceptance:

R.L. Young, James N. Chapman

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
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B. L. Young

James J. Chapman

Accepted for the Council:

The Graduate School
MODELING OF A COMBINED CYCLE
MHD/STEAM POWER PLANT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Edward H. Klessling III
August 1984
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ABSTRACT

The objective of this effort was to develop an improved process model of a prototype MHD/steam central station power plant. This model was designed to perform a first law thermodynamic analysis for steady state plant operation. An existing MHD topping cycle model was modified to provide predictions of mass flows and energy requirements associated with topping cycle equipment for coal processing and oxidant preparation. This topping cycle is characterized by full slag carryover to the heat and seed recovery system, and by direct fired oxidant preheating. New models were developed for the potassium formate seed regeneration process, and for the heat and seed recovery system. PRESTO II, a program for analyzing the performance of regenerative, superheated steam-turbine cycles, was added to the existing model structure to provide a detailed steam cycle model. The resulting model was executed for a specified design condition and the results reported herein.
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CHAPTER I

INTRODUCTION

The electric power industry is on the verge of a crisis. The United States of America is an advanced industrial society which requires large amounts of electric power. This electric power is produced by generating plants which use coal, oil, natural gas, nuclear fission, and hydro power as their primary energy sources. (Unconventional energy sources such as solar power, wind power, and geothermal produce a negligible fraction of the total electric power generation and are not considered in this analysis). Given the present state of the art of energy conversion technology and the constraints of resource availability, it appears that the five primary energy sources, either individually or collectively, will be unable to satisfy future electric power demand in a satisfactory manner. The next ten paragraphs consider the problems associated with each of the five primary energy sources.

Hydro power is probably the most desirable source for generating electric power. The environmental impact of dam construction is relatively minor and normally includes only local alteration of river flow behavior, silt transportation patterns, and biological ecosystems. The reservoirs created by dams are often popular recreation lakes. Since the ultimate source of hydro power is rainfall, this source is continually renewed. Hydro power is a very inexpensive source of electric power because there is no cost associated with allowing river water to flow through turbines (i.e., no fuel cost). Unfortunately, there are
relatively few sites suitable for constructing hydro power dams and nearly all these sites have already been developed and put into service. At present, hydro power furnishes about 15% of the nation's electric power output. There will be no significant hydro power additions to the nation's electric power generation capacity.

During the 1960's, nuclear fission reactors were promoted as a safe, clean, and inexpensive means for generating electric power. Nuclear power advocates predicted that nuclear power plants would eventually generate most of the nation's electric power at very low cost. "Too cheap to meter", was the description of electricity to be produced by nuclear fission plants. In 1984, years later, the nuclear power industry is a troubled industry. Nuclear fission plants produce only about 10% of the nation's electric power. Many plants ordered in the early 1970's have been cancelled. Many of the plants under construction are experiencing costly construction delays due to modifications required by the Nuclear Regulatory Commission (NRC). What went wrong? The nuclear power industry has three major problems: public distrust, disposal of radioactive plant wastes, and an assured fuel supply.

The environmental conservation movement of the early 1970's publicly raised the issue of nuclear power plant safety and painted a frightening picture of the potential disaster associated with a nuclear power plant malfunction. In 1979, the accident at the Three Mile Island Nuclear Plant seemed to elevate the level of fear and suspicion. In response, the Nuclear Regulatory Commission tightened its control on the nuclear power industry in an attempt to assuage public fears and restore credibility and acceptance to the nuclear power program. These added
controls extended the time required to license and construct a nuclear power plant. They increased the amount of analysis, record keeping, and testing associated with nuclear plant construction. Furthermore, the NRC conducted extensive design reviews which resulted in required modifications for both operating and under construction plants. All of these actions greatly increased the cost of developing nuclear power and utilities began to lose interest. The 1979-1983 recession with its decrease in electric power demand and its high interest rates exacerbated the utilities' position.

The lack of a well developed program for disposing of radioactive nuclear plant waste has also hurt the nuclear power industry. In the climate of environmental quality awareness, which has been strong for the past decade, there has been much active interest in waste disposal for nuclear plants. The two major aspects of this problem are that nobody wants a storage facility in his backyard and, secondly, everybody wants a failure-proof storage system. For the nuclear power industry, this means higher operating costs for the long term and operating constraints in the near term.

The third problem overshadowing the nuclear power industry is the uncertainty of a long term fuel supply. The quantity of naturally available radioactive compounds is not sufficient to supply a large demand for many years. The fission industry would require development of the breeder reactor in order to assure a long term fuel supply. Unfortunately, there has been opposition to the breeder reactor research program and it is showing very little progress or promise.
Oil and natural gas are out of the question as fuels for the electric power industry. They are nonrenewable natural resources which are steadily being depleted. As this happens, their cost increases and their use is restricted to those activities for which they are most essential.

Finally, there is coal. Coal is the most abundant energy mineral possessed by the United States. Domestic supplies could easily furnish electric power demand for the next century and beyond. Coal has been the primary energy source for U.S. electric power generation for several decades. There are two problems associated with coal use. The first, and least serious, concerns recovering the coal. The second problem is the role played by coal plant emissions in the production of acid rain.

Coal is recovered for use via surface or underground mining operations. Surface mining (strip mining), unless followed by costly restoration operations, leaves behind a scarred landscape, disrupted surface and subsurface drainage patterns, and the problem of acid mine drainage which pollutes local watercourses. Underground mining disrupts subsurface drainage patterns, sometimes precipitates land subsidence, and also produces acid mine drainage with its water pollution consequences. Although these are serious problems, their effects are localized and can be mitigated. Control of these problems will be costly, but it will be a necessary consequence of coal fired electric generation.

The most damaging aspect of coal fired power plants is their production of $SO_2$ and $NO_x$ during the coal combustion process. These compounds are released to the atmosphere via flue gases and mix with
atmospheric moisture to form sulfuric acid and nitric acid. These acids ultimately return to the earth's surface in rain. This acid rain destroys lake ecosystems and forests. For areas dependent upon forest industry, the local economy dies with the forests. In North America, the acid rain damage has been most extensive in eastern Canada and the northeastern United States. Citizens groups and environmentalists have protested and called for action. Committees have been formed, studies have been commissioned, and reports have been rendered. The U.S. Congress seems to be on the verge of taking action. This action will most likely take the form of emissions control legislation which will markedly reduce, perhaps by as much as 50%, the permissible levels of SO₂ and NOₓ in coal plant flue gases. Such legislation would result in substantial equipment and operating cost increases for the electric utility industry. Furthermore, the flue gas clean-up equipment would reduce plant operating efficiency. While it may not be enacted this year, this new legislation will almost certainly be passed in the near future and must be considered when planning for the future of the electric power industry.

Thus the electric power industry faces a crisis. How will it generate the electric power necessary to satisfy future demand? Hydro power sources are nearly fully developed. Oil and natural gas are too precious and too costly for use in central station power plants. Nuclear power is struggling to remain viable, but is severely hampered by public distrust, high construction costs, unacceptable waste disposal alternatives, and uncertainty of a sufficient long term fuel supply.
Coal utilization generates environmental pollution problems at both the mine and smokestack; however, at least there is an abundant domestic supply of coal.

By the process of elimination, coal appears to be the best primary source for future electric power generation. Coal is selected because it is the only candidate which promises an abundant long term supply. If the emissions problems associated with coal utilization could be solved, coal would be considered a desirable fuel for central station electric power generation. Coal fired magnetohydrodynamic (MHD) electric power generation is a technology which shows substantial promise for utilizing coal, including high sulfur coal, while producing very low levels of SO₂ and NOₓ emissions. When an MHD cycle is coupled with a conventional steam cycle, the MHD/steam combination holds the potential for substantial improvement in overall generating efficiency for coal fired plants.

Although coal fired MHD power generation is presently very much in a research and development state, this document looks into the future to propose and analyze a possible plant configuration. This is accomplished by developing a computer based mathematical model of the plant processes. The second chapter of this document discusses the general configuration and system interfaces of the proposed plant. The next chapter describes the general structure and capabilities of the model. The following three chapters present the detailed algorithms which constitute the model code for each of the four major plant systems. The basis for these algorithms is also discussed. The next chapter presents
and explains a sample case execution of the complete model, and the final chapter presents the conclusions drawn from this effort.

The model presented in this document is not a completely original work. However, the pre-existing model was substantially altered and expanded by this effort. Chapters III through VI clearly identify the changes and additions made to the model. In spite of these modifications, the model, like MHD technology itself, is still in a developmental stage. Hopefully, this model will serve as a useful tool for predicting and analyzing the potential performance of future central station MHD/steam plants, and thereby contribute to the development of design criteria for future plant equipment.
CHAPTER II

PLANT DESCRIPTION

This chapter describes the general configuration and process sequence of the proposed MHD/steam combined cycle power plant. The plant is divided into the following four interrelated systems:

1. MHD topping cycle
2. Heat and seed recovery (HRSR)
3. Steam bottoming cycle
4. Seed regeneration

Figure 2-1 is a schematic portrayal of these systems and their interrelationships. The remaining paragraphs of this chapter address each of the four systems at greater length.

The primary equipment of the MHD topping cycle consists of a combustor, nozzle, MHD generator, and diffuser. The MHD generator is composed of a generating channel, a superconducting magnet, and inverters (DC to AC). Secondary equipment associated with the MHD topping cycle includes the oxidant compressor, the air separation plant, and the coal preparation equipment. The process sequence begins with the preparation of the coal and oxidant streams which are ultimately fed to the primary combustor. The air separation unit produces the oxygen which is mixed with ambient air to achieve the specified enrichment level. This mixture is then compressed to the required pressure by the oxidant compressor. After compression, the oxidant is preheated by heat.
Figure 2-1. Plant Schematic Diagram.
exchangers in the HRSR equipment and is then ready to enter the primary combustor. These heat exchangers transfer heat directly from the flue gas to the oxidant. Previous studies have identified the direct fired technique as preferable to the separately fired oxidant heating method from both economic and efficiency perspectives. Coal preparation consists of pulverizing and drying the coal. Electrically powered pulverizers accomplish the size reduction. Drying is accomplished by a nitrogen stream from the air separation unit. The nitrogen stream is heated by heat exchangers in the HRSR equipment and is then passed through the pulverized coal to dry it. The dry pulverized coal is then stored in pressurized hoppers until it is required in the primary combustor. The coal and preheated oxygen enriched air are mixed and combusted substoichiometrically in the primary combustor in order to control NO$_x$ levels. Due to the oxidant enrichment and preheat, the combustion temperature is sufficiently high to ionize the combustion gases. While the combustion is being accomplished, a recycled potassium compound is injected into the primary combustor. The potassium compound, termed seed, is added to increase the conductivity of the plasma. In this study, potassium formate is the seed compound. The resulting plasma is then accelerated through the nozzle and enters the MHD generating channel at a high velocity. The superconducting magnet which surrounds the generating channel produces a high strength stationary magnetic field. As the high velocity plasma passes through the magnetic field, a direct current is generated transverse to the direction of the moving plasma and the lines of force of the magnetic field. The direct current is passed to the inverters where it is changed to alternating current for
transmission through the power distribution grid. While the plasma is producing electrical energy, it is losing thermal energy and eventually cools to the point where it loses its electrical conductivity and becomes merely a hot flue gas. Once this happens, no more electrical energy can be recovered via the generating channel. However, the gas is still very hot, in excess of 3500°F, and is still moving at a high velocity. A diffuser receives the gas as it exits the generating channel and slows the gas while simultaneously recovering pressure. Because the combustor, nozzle, channel, and diffuser are exposed to high gas temperatures, their walls require cooling by water streams. The heat gained by these water streams is utilized by the steam cycle equipment as explained later.

The heat and seed recovery system (HRSR) performs six crucial functions. First, it provides extensive heat transfer surfaces for removing heat from the flue gas and providing that heat for use in power generation cycles and process streams. The second function of the HRSR system is to provide sufficient residence time at elevated temperatures to permit decomposition of the nitrogen oxides contained in the flue gas. Its third function is to separate coal slag from the flue gas. The fourth function is to provide a secondary combustor for completing combustion of the substoichiometric flue gas. The fifth task of the HRSR system is to recover the potassium originally contained in the seed. The final HRSR function is sulfur removal. In the flue gas, potassium combines with sulfur and oxygen to form potassium sulfate which the HRSR recovers from the flue gas.
The process sequence for the HRSR system begins with the radiant furnace which receives the flue gas flow from the MHD topping cycle diffuser. The radiant furnace encloses sufficient volume to provide the required flue gas residence time at high enough temperature to accomplish decomposition of nitrogen oxides. The walls of the radiant furnace contain water tubes which absorb heat from the flue gas and produce steam which ultimately powers the plant's steam driven equipment. The radiant furnace also accomplishes removal of most of the coal slag from the flue gas stream. As it exits the radiant furnace, the flue gas enters the secondary combustor where it is mixed with air and completes the combustion process. Like the radiant furnace, the walls of the secondary combustor will consist of water walls which contribute to steam generation. After exiting the secondary combustor, the flue gas passes over convective heat transfer surfaces which accomplish steam superheating and reheating as well as preheating of the oxidant for the MHD cycle. As the flue gas passes over these surfaces and cools, a large fraction of the potassium sulfate condenses and is separated from the flue gas. The potassium sulfate is recovered and transported to the seed regeneration plant for processing. As the flue gas exits the convective heat transfer section, it is divided into four streams. One stream passes through a heat exchanger and heats the nitrogen flow stream intended for coal drying. Another stream passes through a second heat exchanger and heats the secondary combustion air. The third flue gas stream provides the heat necessary for generating the low pressure steam required by the seed regeneration process. The remaining flue gas constitutes the fourth stream which is passed through economizers to
provide heat for feedwater heating in the steam cycle. After exiting their respective heat exchangers, the four flue gas streams are recombined and passed through an electrostatic precipitator which recovers the remaining potassium sulfate and ash from the flue gas. The recovered potassium sulfate is transported to the seed regeneration plant for processing. Upon exiting the electrostatic precipitator, the flue gas is divided into two streams. One stream is diverted to the seed regeneration plant for the purpose of drying the reprocessed potassium formate seed. The other stream proceeds directly to the stack where it is rejoined by the diverted stream with its added moisture. The flue gas is then released to the atmosphere as it exits the stack.

The steam bottoming cycle utilizes thermal energy recovered from the HRSR equipment and the MHD topping cycle to produce mechanical shaft power which is then used to generate electric power and to drive the MHD cycle oxidant compressor as well as the oxygen plant compressor. The equipment which comprises the steam cycle consists of the steam turbines which drive the electricity generator, the MHD oxidant compressor, and the oxygen plant compressor; the condenser which receives the low pressure, low temperature steam exhausted from the turbines; the feedwater heaters which use extraction steam from the turbines for heating the feedwater; the steam drum; the cooling water passages in the MHD topping cycle equipment which provide additional feedwater heating and some steam generation; and finally the heat transfer surfaces contained in the HRSR equipment which provide steam generation, superheating and reheating, as well as some feedwater heating. There are four general process steps which comprise the steam cycle. They are condense spent
steam, heat feedwater, generate steam, and expand steam. Low tempera-
ture, low pressure turbine exhaust steam is piped to the condenser.
The condensate (or feedwater) produced in the condenser is then directed
to a series of feedwater heaters which provide incremental increases in
feedwater temperature. The source of heat for the feedwater heaters is
steam extracted from different stages of the electric power turbine.
The feedwater heaters are designated as low pressure if located upstream
of the boiler feed pump, and high pressure if located downstream of the
boiler feed pump. Additional feedwater heating is accomplished in the
waterwalls of the MHD channel and in the economizers located in the HRSR
system. Steam generation is divided into the phases of initial genera-
tion, superheating, and reheating. Initial generation takes place in
the cooling passages in the walls of the MHD cycle combustor, nozzle,
and diffuser as well as the cooling passages which form the walls of the
radiant furnace and the secondary combustor which are located in the
HRSR system. The heated feedwater enters these passages and approxi-
mately twenty percent of this water turns to steam by the time it
reaches the steam drum. In the steam drum, the steam and the water are
separated. The water is recirculated through the cooling passages for
additional steam generation. The steam is directed to the superheater,
located after the secondary combustor, for additional heating. From the
superheater the steam enters the turbines and begins the expansion stage
in which the pressure and thermal energy of the steam is converted into
mechanical shaft power. After traversing the high pressure section of
the electric power turbine, the steam is returned to the HRSR system and
enters the reheater where it absorbs additional thermal energy before
returning to the electric power turbine and entering the intermediate pressure section. After the intermediate pressure section, the steam encounters the low pressure section from which it is discharged to the condenser and begins the cycle again. The compressor turbines are similar except that they have only one section each, and their steam supplies are not reheated.

Potassium seed regeneration is an absolute necessity for MHD power generation to be commercially viable. Previous studies have established that seed regeneration is preferable to scrubber technology due to economic and efficiency considerations. The initial cost of potassium compounds such as potassium carbonate and potassium formate dictates the need for potassium recycling. For this reason, a seed regeneration system is an integral part of the plant. The formate process is employed to accomplish regeneration of the potassium seed. Potassium sulfate recovered from the flue gas by the HRSR equipment is fed to the seed regeneration plant which converts it to potassium formate. There are six major steps associated with the formate regeneration process. The first step is to gasify coal in order to produce carbon monoxide for the formate reaction. This is accomplished by feeding coal, preheated compressed air, and water to a pressurized gasifier which produces a product gas which is fed to the formate reactor. The second step is to dissolve the recovered potassium sulfate in water and mix it with unslaked lime. The resulting slurry is then heated and fed to the formate reactor. Step three is accomplished in the formate reactor when the slurry and product gas react to produce potassium formate and gypsum. The fourth process step is to filter the gypsum from the formate
product stream. In the fifth step, water is removed from the formate product stream. The sixth and final step consists of reheating the potassium formate stream until the formate becomes molten. This permits filtering out any remaining potassium sulfate because it remains in the solid state. The potassium formate is then returned to the MHD cycle for use as seed.

This chapter has provided a brief overview of each of the four major plant systems. It has also provided a general description of the system interfaces. The next chapter presents an overview of the plant model. It is followed by chapters which explain the details of each system model as well as how to use the complete model code.
CHAPTER III

MODEL STRUCTURE AND CAPABILITIES

This chapter describes the general structure and capabilities of SYSTEMS III as revised in June 1984. SYSTEMS III is a special purpose program for analyzing the process performance of a potential commercial prototype central station power plant. This plant, as described in Chapter II, employs a coal fired, full slag carryover, oxygen enriched MHD topping cycle which is coupled with a conventional, regenerative, superheated steam bottoming cycle. In its present form, SYSTEMS III is a composite of the following five subordinate programs:

COAL
DESIGN3
SINGH
NASA SP-273*
PRESTO II

Program COAL is the first program executed during a plant performance analysis by SYSTEMS III. COAL is a data transformation program which prepares an input data file for the NASA SP-273 program and select input data values for the SINGH program. The program user provides the following data input to COAL.

1. Coal proximate analysis (ASTM D3172).
2. Coal ultimate analysis (ASTM D3176).
3. Coal ash analysis (ASTM D3174).

*NASA SP-273 was modified at UTSI to calculate the electric transport property per Frost\(^3\), and to provide the means for specifying combustor heat loss.
5. "As fired" coal moisture content.
6. MHD combustor heat loss.
7. Stoichiometric ratio for MHD primary combustion.
8. Enriching oxygen content of MHD primary oxidant.
10. Percent potassium in total plasma flow.

Using the above information, COAL performs a series of calculations as explained by Woodring. As a result of these calculations, COAL is able to output the chemical composition, relative proportions, and preheat temperatures of the coal, potassium seed, and oxidant which are fed to the MHD combustor. The combustor heat loss is also included in this output. The format in which COAL prints this data is precisely that required for the input data file read by the NASA SP-273 program. COAL also prints out values for the following parameters required by SINGH:

1. Higher heating value of dried coal.
2. Moisture content of "as fired" coal.
3. Percent of MHD oxidant that is air.
4. Percent of MHD oxidant that is pure oxygen.
5. Fraction of fuel input that is potassium seed.
6. MHD combustor heat loss per unit mass of dried coal flow.
7. Sulfur content of dried coal.

In its present form, COAL is run independently and the program user must prepare the input files used by NASA SP-273 and SINGH. The use of COAL as a part of SYSTEMS III is one of the additions implemented by the current revision of SYSTEMS III.
DESIGN3 is the second program executed during a plant performance analysis by SYSTEMS III. DESIGN3 is a program which designs an MHD generating channel. It provides the user with a wide range of options for specifying channel conditions, characteristics, and restraints. The following constitutes a general list of parameters addressed:

1. Channel mass flow.
2. Plasma thermodynamic and electric properties.
3. Channel geometry.
4. Magnetic field distribution and maximum strength.
5. Electrical loading.
6. Electrical operating restraints.
7. Gas dynamics considerations.

The detailed use of DESIGN3 has been documented by Wu. Normally, the design of a generating channel using DESIGN3 requires several program executions before the user has satisfactorily balanced all the significant considerations and specified a reasonably efficient channel. The final channel design serves as a reference channel for the SYSTEMS III plant analysis. The following parameters from the DESIGN3 output file are included in the input file for SINGH:

1. Plasma Mach number at channel entrance.
2. Ratio of channel exit area to entrance area.
3. Maximum magnetic field strength.
4. Channel length.
5. Channel entrance area.
6. Plasma mass flow rate.
7. Generator channel efficiency.
8. Generating channel enthalpy extraction.

9. Static pressure at channel exit.

As explained in Chapter IV, SINGH uses these reference channel parameters to extrapolate the performance of similarly designed generator channels which must accommodate different plasma mass flow rates. In its present form, DESIGN3 is executed independently and the program user must prepare the input file required by SINGH. The use of DESIGN3 in the plant performance analysis does not constitute a new development for SYSTEMS III.

The third phase of plant performance analysis by SYSTEMS III consists of the sequential execution of NASA SP-273, SINGH, and PRESTO II. The main program of NASA SP-273\(^6\) begins the sequence by reading and storing the input data generated by COAL. After this is accomplished, NASA SP-273 relinquishes program execution control to SINGH which, technologically, is a subroutine of NASA SP-273. SINGH first reads values for the variables listed in Table 4-2 (see Chapter IV). SINGH then executes its program code which models the process performance of the MHD topping cycle, the seed regeneration plant, and the heat and seed recovery system (HRSR). As it performs calculations for the MHD topping cycle and the HRSR system, SINGH calls other NASA SP-273 subroutines which provide plasma/flue gas thermodynamic properties for several state points. After HRSR model calculations are completed, SINGH calls PRESTO II which models the steam cycle based upon input data provided by SINGH. PRESTO II\(^7,8\) is a computer code for analyzing the performance of regenerative, superheated steam turbine cycles at valves-wide-open design
flow. At the conclusion of PRESTO II execution, SINGH completes the plant performance analysis by calculating the overall plant efficiency.

Before closing this chapter, a few words about energy loss considerations are in order. This model accounts for major heat and equipment efficiency losses. The MHD topping cycle and the steam cycle models estimate losses associated with fluid flow through heat exchangers and piping. The seed regeneration model and the HRSR system model do not address energy losses associated with fluid flow. The losses which are calculated by the model are described in the following three chapters or addressed in the references mentioned in those chapters.
CHAPTER IV

MHD TOPPING CYCLE

The MHD topping cycle is the first plant system modeled during execution of the SYSTEMS III program. Figure 4-1 is a diagram of the topping cycle process as modeled by SYSTEMS III. The process steps which constitute the topping cycle model consist of the following:

1. Produce oxygen from ambient air.
2. Blend the oxygen with ambient air to produce an oxygen enriched MHD oxidant.
3. Compress the MHD oxidant.
4. Preheat the MHD oxidant.
5. Pulverize coal.
6. Dry the pulverized coal.
7. Inject coal, oxidant, and potassium seed into the MHD combustor.
8. Combust the coal, oxidant, and seed mixture substoichiometrically to produce a high temperature plasma.
9. Accelerate the plasma into the MHD electric power generation channel.
10. Generate D.C. electric power and invert to A.C.
11. Decelerate the plasma in the diffuser.
12. Cool the walls of the combustor, nozzle, MHD power generation channel, and diffuser.
Figure 4.1. Process Mass Flow Diagram for MHD Topping Cycle.
Subroutine SINGH contains the algorithms which model these process steps. This chapter is devoted to a description of both the form and the basis of these algorithms. As a process model, SINGH has four distinct objectives:

1. Calculate mass flow rates for process flow-streams.
2. Calculate energy transfers, equipment energy requirements, and electrical energy production quantities.
3. Calculate select thermodynamic properties for specified process flow streams.
4. Calculate select geometric dimensions for specified cycle equipment.

The following description of the topping cycle algorithms contained in SINGH is presented in two segments. The first part addresses calculation of process mass flows while the second addresses energy calculations as well as computation of the thermodynamic properties and geometrical dimensions. This presentation format parallels the SINGH execution sequence.

Before beginning the topping cycle model description, a word about variables is in order. SINGH uses a large number of variables to model the MHD topping cycle. An attempt to fully explain each of these variables in the text would be extremely tedious and would likely confound the reader. The following presentation explains variables only to the extent necessary to clearly describe the functioning of the model as it works to achieve its four previously stated objectives. Appendix A contains a listing of subroutine SINGH which includes comment statements containing definitions of variables. For detailed explanations of
those variables whose source is the original NASA SP-273, the reader is
directed to the manual by Gordon and McBride\textsuperscript{6}.

The MHD topping cycle mass flows modeled by SINGH are depicted in
Figure 4-1 and described in Table 4-1. SINGH begins its execution by
reading input values for certain topping cycle variables. These
variables are named and defined in Table 4-2. The first mass flow
calculated by SINGH is the flow of dried coal (MCT02, lbm/hr) to the MHD
combustor. To accomplish this, SINGH first uses the desired net
electrical output (P\textsubscript{OUT}, Watts) and the estimated efficiency (EFF, %) of
the combined MHD and steam cycles to compute the thermal input (THIN,
Btu/hr) required from coal. The coal referred to here does not include
that required by the seed regeneration plant. The algorithm has the
form:

\[
\text{THIN} = \frac{\text{P\textsubscript{OUT}} \times 3.4129}{(\text{EFF}/100.)}
\]

The higher heating value (HCC, Btu/lbm) of dry coal is then used with
THIN to calculate the required flow rate of dried coal (MCT02, lbm/hr)
to the MHD combustor.

MCT02 = \frac{\text{THIN}}{\text{HCC}}

The mass flow rate of "as received" coal (MCT01, lbm/hr) is the next
quantity calculated. This calculation requires specification of the "as
received" moisture content (MOISAR, %) of the coal as well as the "as
fired" moisture content (MOISAF, %) of the coal. These two moisture
contents are used to calculate the moisture restoration factor (MOISRF,
dimensionless) as follows:

\[
\text{MOISRF} = \frac{(\text{MOISAR} \times ((100.-\text{MOISAF})/(100.-\text{MOISAR})) - \text{MOISAF}) + 100.}{100.}
\]
Table 4-1. Process Mass Flows for MHD Topping Cycle.

<table>
<thead>
<tr>
<th>Steam No.</th>
<th>Description</th>
<th>Variable Name</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Coal from stockpile to pulverizers</td>
<td>MCT01</td>
<td>MCT02*MOISRF</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T2</td>
<td>Dried coal to MHD combustor</td>
<td>MCT02</td>
<td>THIN/HCC</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T3</td>
<td>Ambient air to MHD compressor</td>
<td>MAT03</td>
<td>(PCTA/100.)*MOAT08</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T4</td>
<td>Ambient air to air separation plant</td>
<td>MAT04</td>
<td>MOTO5/0.232</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T5</td>
<td>Oxygen from air separation plant</td>
<td>MOTO5</td>
<td>(PCTO/100.)*MOAT08</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T6</td>
<td>Oxygen enriched air to MHD compressor</td>
<td>MOAT06</td>
<td>MOAT08</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T7</td>
<td>Oxygen enriched air to air heater</td>
<td>MOAT07</td>
<td>MOAT08</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T8</td>
<td>Oxygen enriched air to MHD combustor</td>
<td>MOAT08</td>
<td>OF*MCT02/(1. -SFLO)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T9</td>
<td>Nitrogen and argon from air separation</td>
<td>MNAT09</td>
<td>MAT04 - MOTO5</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T10</td>
<td>Nitrogen and argon released to atmosphere</td>
<td>MNAT10</td>
<td>MNAT09-MNAT11</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T11</td>
<td>Nitrogen and argon for coal drying</td>
<td>MNAT11</td>
<td>1.25<em>QWVT13/(250.0</em>0.244)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T12</td>
<td>Nitrogen and argon for coal drying</td>
<td>MNAT12</td>
<td>MNAT11</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>Steam No.</td>
<td>Description</td>
<td>Variable Name</td>
<td>Algorithm</td>
<td>Units</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------------------------------</td>
<td>---------------</td>
<td>------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>T13</td>
<td>Nitrogen, argon, and moisture from coal</td>
<td>MTT13</td>
<td>MNAT11 + MCT01 - MCT02</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T14</td>
<td>Potassium seed to MHD combustor</td>
<td>MKT14</td>
<td>SFLO*MCT02/(1.-SFLO)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T15</td>
<td>Plasma to MHD channel</td>
<td>MPT15</td>
<td>MCT02 + MKT14 + MOAT08</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T16</td>
<td>Plasma to MHD diffuser</td>
<td>MPT16</td>
<td>MPT15</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>T17</td>
<td>Flue gas to HRSR equipment</td>
<td>MFGT17</td>
<td>MPT15</td>
<td>lbm/hr</td>
</tr>
</tbody>
</table>
Table 4-2. Variables for which Values are Read by SINGH.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>POUT</td>
<td>Desired net electric power output from plant</td>
<td>WATTS</td>
<td>User Specified</td>
</tr>
<tr>
<td>EFF</td>
<td>Estimated net efficiency of plant</td>
<td>%</td>
<td>User Specified</td>
</tr>
<tr>
<td>HCC</td>
<td>Higher heating value of dried coal</td>
<td>Btu/lbm</td>
<td>Program COAL</td>
</tr>
<tr>
<td>MOISAR</td>
<td>Moisture content (by weight) of &quot;as received&quot; coal</td>
<td>%</td>
<td>Coal Proximate Analysis</td>
</tr>
<tr>
<td>MOISAF</td>
<td>Moisture content (by weight) of &quot;as fired&quot; coal</td>
<td>%</td>
<td>Program COAL</td>
</tr>
<tr>
<td>PCTA</td>
<td>Percent of MHD oxidant flow that is air</td>
<td>%</td>
<td>Program COAL</td>
</tr>
<tr>
<td>PCTO</td>
<td>Percent of MHD oxidant flow that is pure oxygen</td>
<td>%</td>
<td>Program COAL</td>
</tr>
<tr>
<td>SFLO</td>
<td>Fraction of fuel input that is potassium seed</td>
<td>-</td>
<td>Program COAL</td>
</tr>
<tr>
<td>PRINT</td>
<td>MHD combustor operating pressure</td>
<td>ATM</td>
<td>User Specified</td>
</tr>
<tr>
<td>TAIC</td>
<td>Temperature of oxidant enriched air at combustor inlet</td>
<td>°K</td>
<td>User Specified</td>
</tr>
<tr>
<td>QLCPUM</td>
<td>Heat loss from combustor to cooling water per unit mass of gas side combustor mass flow</td>
<td>Btu/lbm</td>
<td>Program COAL</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Description</td>
<td>Units</td>
<td>Source</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------------------------</td>
<td>-------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>EMACH</td>
<td>Plasma Mach No. at channel entrance</td>
<td>-</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>AREAR</td>
<td>Ratio of reference channel exit area to entrance area</td>
<td>-</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>BMAX</td>
<td>Maximum magnetic field strength</td>
<td>Tesla</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>CEFFI</td>
<td>Inverter efficiency</td>
<td>%</td>
<td>User Specified</td>
</tr>
<tr>
<td>CLEN</td>
<td>Length of reference channel</td>
<td>Meters</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>ENT</td>
<td>Entrance area of reference channel</td>
<td>Sq M</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>GDMF</td>
<td>Reference generating channel mass flow</td>
<td>lbm/hr</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>GEF</td>
<td>Fractional generator efficiency of reference channel</td>
<td>-</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>HF</td>
<td>Fractional enthalpy extraction of reference channel</td>
<td>-</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>PSTAT</td>
<td>Static pressure at reference channel exit</td>
<td>ATM</td>
<td>Program DESIGN3</td>
</tr>
<tr>
<td>XS</td>
<td>Weight fraction of dried coal that is sulfur</td>
<td>-</td>
<td>Program COAL</td>
</tr>
<tr>
<td>XSAR</td>
<td>Weight fraction of &quot;as received&quot; coal that is sulfur</td>
<td>-</td>
<td>Coal Ultimate Analysis</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Description</td>
<td>Units</td>
<td>Source</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------------------</td>
<td>---------</td>
<td>----------------------</td>
</tr>
<tr>
<td>XAAR</td>
<td>Weight fraction of &quot;as received&quot; coal that is ash</td>
<td>-</td>
<td>Coal Ultimate Analysis</td>
</tr>
<tr>
<td>TAH04</td>
<td>Secondary combustion air temperature at secondary combustor inlet</td>
<td>°R</td>
<td>User Specified</td>
</tr>
<tr>
<td>SR</td>
<td>Stoichiometric ratio for MHD combustor</td>
<td>-</td>
<td>Program COAL</td>
</tr>
<tr>
<td>HSTEAMA</td>
<td>Steam enthalpy at Superheater exit</td>
<td>Btu/lbm</td>
<td>User Specified</td>
</tr>
<tr>
<td>HSTEAMR</td>
<td>Steam enthalpy increase in reheater</td>
<td>Btu/lbm</td>
<td>User Specified</td>
</tr>
</tbody>
</table>
The development of the above equation begins by considering a mass of 100 pounds of "as fired" or dried coal. Of this 100 pounds, MOISAF pounds is the amount of moisture contained in the mass and (100. - MOISAF) pounds is the amount of other coal material. Similarly, a 100 pound mass of "as received" coal contains MOISAR pounds of moisture and (100. - MOISAR) pounds of other coal material. The "as received" mass will contain less coal material than the "as fired" mass. The coal material content of the "as received" coal has to be increased by a factor of

\[
\frac{(100. - \text{MOISAF})}{100. - \text{MOISAR}}
\]

to make it equal to the coal material content of the "as fired" coal. Since moisture content and coal material content of a given mass are proportional, MOISAR must also be increased by the same factor.

\[
\text{MOISAR*}\left(\frac{(100. - \text{MOISAF})}{100. - \text{MOISAR}}\right)
\]

The quantity of moisture which must be removed from the enlarged "as received" mass in order to yield a 100 pound mass of "as fired" coal is expressed as:

\[
\text{MOISAR*}\left(\frac{(100. - \text{MOISAF})}{100. - \text{MOISAR}}\right)\times\text{MOISAF}
\]

The total mass of "as received" coal necessary to yield 100 pounds of as fired coal is then expressed as the sum of the moisture removed plus 100 pounds.

\[
(\text{MOISAR*}\left(\frac{(100. - \text{MOISAF})}{100. - \text{MOISAR}}\right)\times\text{MOISAF}) + 100.
\]

Dividing the above expression by 100 yields the dimensionless value for MOISRF. Using MOISRF and MCT02, SINGH calculates the mass flow rate of "as received" coal (MCT01).

\[
\text{MCT01} = \text{MCT02*MOISRF}
\]
At this point, SINGH calls data and subroutines from the NASA SP-273 program for the purpose of specifying combustion conditions for the MHD primary combustor. The program execution details can be obtained by reviewing the reference cited for the NASA SP-273 program.

The oxidant flow rate (MOAT08, lbm/hr) is the next quantity to be computed by SINGH. This calculation requires the oxidant to fuel ratio (OF) which was calculated during the preceding call for NASA SP-273 subroutines. The fraction of the fuel input consisting of potassium seed (SFLO) is also required for calculating MOAT08.

\[
MOAT08 = OF \times MCT02 / (1. - SFLO)
\]

SINGH continues by calculating the following quantities:

- Ambient air to the MHD compressor (MAT03, lbm/hr).
- Oxygen for enriching MHD combustion air (MOT05, lbm/hr).
- Ambient air to air separation plant (MAT04, lbm/hr).
- Nitrogen and argon exhausted from air separation plant (MNAT09, lbm/hr).
- Moisture to be removed from stockpiled coal (MWVT13, lbm/hr).

The algorithms for the above quantities are straightforward and are presented in Table 4-1.

At this point, SINGH must determine how much of the air separation plant's nitrogen and argon effluent will be used for coal drying. Formulation of the algorithms necessary to make this determination required some assumptions and analysis. First, it was necessary to estimate an initial temperature of the stockpiled coal and its moisture. The ambient temperature for the plant evaluation was assumed to be 80°F (540°F, 300K). It was also necessary to specify a temperature for the
heated moisture. Based on the example of another MHD/steam plant study, 150°F (610°F, 339K) was selected as the temperature to which the moisture must be heated in order to drive it from the coal. At 80°F the moisture is assumed to be a saturated liquid. At 150°F the moisture is assumed to be a saturated vapor. These assumptions are conservative and they assure that the calculated heat requirement for coal drying will be sufficient. Using the 1967 ASME Steam Tables, the heat required to raise the temperature of one pound of moisture from the saturated liquid state at 80°F to the saturated vapor state at 150°F was found to be 1078 Btu. The heat (QWVT13, Btu/hr) required to raise the temperature of the excess moisture contained in the "as received" coal could then be expressed as:

\[ QWVT13 = 1078 \times MWFT13. \]

The above calculation is performed by SINGH. The next step in the analysis required specification of the temperature to which the drying gas must be heated. Based upon the results of a previous MHD/steam plant study conducted at UTSI, flue gas at temperatures less than 700°F (1160°F, 644K) is of negligible value to either the steam cycle or the primary oxidant heating process. Flue gas cooler than 700°F is therefore an excellent source of heat for coal drying. Allowing a temperature differential of 100°F across the heat exchanger, the flue gas can heat the drying gas to a temperature of 600°F (1060°F, 589K). A standard reference on coal fired power plants states that some commercially available pulverizers are capable of receiving drying gases as hot as 650°F (1110°F, 617K). Thus, 600°F was chosen as the temperature to which the drying gas will be heated. The nitrogen and
argon gas is assumed to cool to 150°F during the coal drying process. It is also assumed that only 80% of the heat released from cooling the drying gas will actually contribute to moisture removal. The remaining 20% of the heat is assumed to heat the coal itself. It is further assumed that the coal cools back to the ambient temperature while stored in a charging hopper. Thus, that fraction of the heat released by the drying gas is ultimately lost to the atmosphere. From Reynolds and Perkins, approximately 100 Btu are released by each pound of nitrogen as it cools from 600°F to 150°F. Because argon constitutes such a small fraction of the drying gas, the gas was idealized as pure nitrogen when calculating thermodynamic properties. Based on the preceding information, the algorithm developed to calculate the required mass flow of nitrogen and argon drying gas (MNAT11, lbm/hr) takes the form:

\[ MKT14 = SFLO \times MCT02 / (1. - SFLO) \]

The potassium formate seed is a combination of recycled seed and make-up seed. The relative amounts of recycle and make-up seed are calculated as described in Chapter V.

At this point SINGH is able to calculate the mass flow rate of plasma to the MHD channel (MPT15, lbm/hr) which is simply the sum of dry coal to the combustor (MCT02), oxidant to the combustor (MOAT08), and potassium formate seed to the combustor (MKT14). Because there are no mass losses from the plasma side of the MHD channel and diffuser during steady state operation, the values for plasma to the diffuser (MPT16, lbm/hr) and flue gas to the HRSR equipment (MFGT17, lbm/hr) are equal to MPT15 and are not separately calculated by SINGH. At this
point, the determination of topping cycle mass flows, as depicted in Figure 4-1 (page 23), is complete.

The remainder of this chapter addresses the energy requirements, energy production, and energy losses associated with the MHD topping cycle. The presentation includes description of the algorithms which calculate required thermodynamic properties and component geometry. Each major equipment component is considered individually and the order of presentation parallels the SINGH execution sequence. Table 4-3 presents a list of the key energy quantities developed in this section. The table includes definitions, algorithms, units, and variable names for the subject quantities.

The air separation plant (ASP) model was developed from information provided by Lotepro Corporation. The process model is essentially a black box which receives air at ambient temperature and pressure and discharges an oxygen product stream as well as an effluent stream composed of nitrogen and argon. Both the product stream and the effluent stream are discharged at ambient temperature and pressure. Because all incoming and outgoing mass flows are at ambient temperature and pressure, there is no net energy transfer among them. The only energy required by the ASP is that required to power the plant equipment (POWERO, MW). A process air compressor and a cold box constitute the major plant equipment and both are powered by a steam driven turbine. According to the Lotepro report, the plant energy requirement is 203.5 kilowatt hours per ton of oxygen produced. This information was used to develop the algorithm for POWERO which is presented in Table 4-3. In this model, POWERO is the power delivered by the turbine shaft. The
<table>
<thead>
<tr>
<th>Description</th>
<th>Variable</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat required to remove moisture from coal</td>
<td>QWVT13</td>
<td>1078.*MWVT13</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Shaft power required from ASP turbine</td>
<td>POWER0</td>
<td>101.75*MT05</td>
<td>Watts</td>
</tr>
<tr>
<td>Shaft power delivered to oxidant compressor</td>
<td>PCOMP</td>
<td>See text pg. 39</td>
<td>Watts</td>
</tr>
<tr>
<td>Heat gained by oxidant during compression</td>
<td>QOAT07</td>
<td>See text pg. 40</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Energy lost during compression process</td>
<td>ELOCT</td>
<td>PCOMP - 0.2931*QOAT07</td>
<td>Watts</td>
</tr>
<tr>
<td>Heat added to oxidant in HRSR heat exchanger</td>
<td>QHEOAT</td>
<td>See text pg. 41</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Energy transported into combustor by oxidant</td>
<td>QOAT08</td>
<td>QOAT07 + QHEOAT</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Electric power required by pulverizers and drying fans</td>
<td>PPFT</td>
<td>7*MCT01</td>
<td>Watts</td>
</tr>
<tr>
<td>Heat gained by N$_2$ and Ar drying gas in HRSR</td>
<td>QNAT12</td>
<td>131*MNAT11</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Drying gas heat lost to coal and atmosphere</td>
<td>QLCDT</td>
<td>0.25 QWVT13</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Heat retained by coal drying gas</td>
<td>QNAT13</td>
<td>QNAT12 - QWVT13 - QLCDT</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Energy required to decompose potassium formate</td>
<td>QKT14</td>
<td>4.*MKT14</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Heat lost from combustor to cooling water</td>
<td>QLCOMB</td>
<td>QLCPUM*MPT15</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Description</td>
<td>Variable</td>
<td>Algorithm</td>
<td>Units</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>----------</td>
<td>---------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Kinetic energy and heat transported from combustor by plasma</td>
<td>EQKT15</td>
<td>((H_{SUM}(1)-H_{SUM}(5)) \times 1.8 \times R \times MPT15)</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Unreleased chemical energy transported from combustor by plasma</td>
<td>ECT15</td>
<td>(THIN + QOAT08 - QKT14 - EQKT15)</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>DC electric power developed by the MHD channel</td>
<td>PEXM</td>
<td>((H_{SUM}(1)-H_{SUM}(5)) \times R \times 1.8 \times 2931 \times H_{FF} \times MPT15)</td>
<td>Watts</td>
</tr>
<tr>
<td>AC electric power to grid from channel</td>
<td>POUTM</td>
<td>(CEFFI \times PEXM)</td>
<td>Watts</td>
</tr>
<tr>
<td>Plasma energy lost to channel cooling water as heat</td>
<td>QLMHD</td>
<td>((PEXM \times 3.4129 \times (1.-GEFF))/GEFF)</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Kinetic energy and heat transported from channel by plasma</td>
<td>EQKT16</td>
<td>(EQKT15 - (PEXM \times 3.4129) - QLMHD)</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Total energy transported from channel by plasma</td>
<td>ETT16</td>
<td>(EQKT16 + ECT15)</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Electric power required to operate the superconducting magnet</td>
<td>PMAG</td>
<td>See Text pg. 49</td>
<td>Watts</td>
</tr>
<tr>
<td>Heat lost from plasma to diffuser cooling water</td>
<td>QLDIF</td>
<td>See Text pg. 49</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Total energy transported from diffuser by flue gas</td>
<td>ETT17</td>
<td>(ETT16 - QLDIF)</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Kinetic energy and sensible heat transported from diffuser by flue gas</td>
<td>EQKT17</td>
<td>(ETT17 - ECT15)</td>
<td>Btu/hr</td>
</tr>
</tbody>
</table>
The steam cycle model, presented in Chapter VI, calculates the steam flow required by the turbine.

The MHD oxidant compressor is assumed to be an axial, multistage, turbine driven machine without intercooling. Whether or not intercoolers should be used for this particular application is an unresolved question. On one hand, intercoolers are expensive and the oxidant will have to be reheated anyway. On the other hand, intercooling reduces the energy required for oxidant compression, and low temperature flue gas is available for oxidant preheating. A final resolution of this question requires a second law thermodynamic analysis as well as a detailed cost analysis. Both of these analyses are beyond the scope of this work, and this study assumes intercoolers will not be used.

The compressor model calculates shaft power required to drive the compressor, the temperature of the oxidant as it is discharged from the compressor, and the heat gained by the oxidant during the compression process. The oxygen enriched air enters the compressor suction side at ambient temperature and pressure, and is compressed to a specified discharge pressure (POAT07, psia). During the compression, the oxidant is assumed to behave as a perfect gas. SINGH calculates POAT07 from the following expression:

$$\text{POAT07} = 14.7 \times \text{PRINT} + 15.$$  

PRINT is the operating pressure of the MHD combustor. It is specified in atmospheres and its value is read from the input data file. The 15 psi term is added to PRINT to account for friction losses accumulated from the HRSR heat exchanger and the interconnecting piping between the
compressor exit and the combustor entrance. From Hansen\textsuperscript{15}, the compressor power requirement can be estimated by the following expression:

\[
\text{Power} = \frac{144}{33000} \frac{P_1 V_1}{\gamma - 1} \left[ \frac{(P_2/P_1)^{(\gamma - 1)}/\gamma - 1}{\gamma - 1} \right] / n
\]

where

- \( \text{Power} \) = shaft power delivered to compressor (horsepower)
- \( P_1 \) = oxidant pressure at compressor entrance (psia)
- \( P_2 \) = oxidant pressure at compressor exit (psia)
- \( V_1 \) = oxidant flow volume at compressor entrance (cfm)
- \( \gamma \) = ratio of oxidant specific heats (i.e. \( C_p/C_v \))
- \( n \) = compressor isentropic efficiency

A modified form of the above equation is used by SINGH to calculate the shaft power (\( P_{COMP} \), Watts) which must be developed by the turbine to drive the oxidant compressor. \( P_1 \) is the ambient pressure and has a value of 14.7 psia. \( P_2 \) is the previously defined POAT07. \( V_1 \) is represented in SINGH by AFLOV which is calculated from MOAT08 and the fact that one pound of air occupies 13.56 cubic feet at 80°F and 1 atmosphere.

\[ \text{AFLOV} = 13.56 \times \text{MOAT08}/60. \]

The value for \( \gamma \) is 1.4 and consequently, the value for \( \gamma/(1 - \gamma) \) is 3.5. The value for \( (\gamma - 1)/\gamma \) is 0.286. According to Chapman\textsuperscript{16}, 0.89 is a reasonable estimate for compressor efficiency. The resulting expression for \( P_{COMP} \) becomes:

\[ P_{COMP} = 3.25 \times 14.7 \times \text{AFLOV} \times 3.5 \]

\[ \times (((\text{POAT07}/14.7)^{0.286}-1))/0.89 \]
The temperature of the oxidant as it exits the compressor (TOAT07, °R) is calculated from the following expression from Hansen\textsuperscript{15}:

\[ T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{(\gamma - 1)}{\gamma}} \]

where
\[ T_1 = \text{oxidant temperature at compressor entrance (°R)} \]
\[ T_2 = \text{oxidant temperature at compressor exit (°R) for isentropic process} \]
\[ P_1, P_2 \text{ and } \gamma \text{ remain as previously defined} \]

For the oxidant compressor model, \[ T_1 \] is 540°R, \[ P_1 \] is 14.7 psia, \[ T_2 \] is TOAT07, \[ P_2 \] is POAT07, and \[ \gamma \] is 1.4. \[ T_2 \] is the outlet temperature calculated for an isentropic process, but the compressor is not an isentropic machine. Therefore, TOAT07 will actually be greater than \[ T_2 \]. To provide a better estimate for the value of TOAT07, the preceding expression for \[ T_2 \] is divided by the compressor isentropic efficiency. The resulting algorithm for TOAT07, as used in SINGH, becomes:

\[ \text{TOAT07} = \left(540. \ast \left(\frac{\text{POAT07}}{14.7}\right)^{0.286}\right) / 0.89 \]

SINGH next calculates the rate at which heat is transferred to the oxidant (QOAT07, Btu/hr) as it undergoes compression. The following algorithm is based on Van Wylen\textsuperscript{17} and the fact that the oxidant is idealized as a perfect gas:

\[ \text{QOAT07} = \text{MOAT08} \ast \left(1.1875 \times 10^{-5} \ast ((\text{TOAT07}^{2}) - (540.^{2})) + 0.224(\text{TOAT07} - 540.)\right) \]

SINGH calculates the energy lost during the compression process (ELOCT, Btu/hr) as the difference of PCOMP minus 0.2931*QOAT07.

After exiting the compressor, the oxidant passes through a heat exchanger in the HRSR section. This heat exchanger transfers heat from
the flue gas to the oxidant in order to raise the temperature of the oxidant to the value required for entering the combustor (TAIC,K).

SINGH reads the value of TAIC from the input data file. From Van Wylen, the rate at which heat is added to the oxidant flow in the heat exchanger (QHEOAT, Btu/hr) can be calculated from the following algorithm:

\[
Q_{HEOAT} = M_{OAT08} \times (1.1875 \times 10^{-5} \times ((T_{AIC} \times 1.8)^2 - (T_{OAT07}^2) + 0.224 \times (T_{AIC} \times 1.8 - T_{OAT07}))
\]

After calculating QHEOAT from the above expression, SINGH calculates the total amount of heat entering the combustor with the oxidant flow (QOAT08, Btu/hr). QOAT08 is calculated as the sum of QOAT07 and QHEOAT.

The requirements for pulverizing and drying coal include pulverizers for reducing coal particle size, a drying gas which vaporizes and transports the moisture, and fans to move the drying gas through the coal particles. This model assumes the pulverizers and fans are driven by electric power. From Babcock and Wilcox, the electric power required to operate pulverizers and fans can be estimated as 14 kilowatt hours per ton of coal input. SINGH calculates the electric power required to drive the pulverizers and fans (PPFT, watts) as follows:

\[
PPFT = 7 \times M_{C01}
\]

As previously discussed, the drying gas is a portion of the nitrogen and argon effluent (MNAT11) from the air separation plant. The nitrogen and argon effluent exits the air separation plant at ambient temperature and pressure. It is then passed through an HRSR heat exchanger where it receives heat from flue gas. During this heat transfer process the temperature of the drying gas increases from its
initial ambient value of 80°F to a final value of 600°F. From Reynolds and Perkins\textsuperscript{13}, the heat gained per pound of drying gas will be 131 Btu/lbm. Accordingly, SINGH calculates the heat transferred to the drying gas \( (QNAT12, \text{Btu/hr}) \) as:

\[
QNAT12 = 131 \times MNAT11
\]

When the drying gas mixes with the coal, its heat content is divided three ways. Part of the heat is used to vaporize the moisture and bring its temperature to 150°F. This quantity \( (QWVT13) \) was previously calculated during the mass flow analysis. The algorithm for \( QWVT13 \) is listed in Table 4-3. Some of the heat is lost to immediate coal heating and ultimately to the atmosphere. This quantity \( (QLCDT, \text{Btu/hr}) \) is calculated as equivalent to 25% of \( QWVT13 \). The remaining heat \( (QNAT13, \text{Btu/hr}) \) is never released from the drying gas and serves to maintain the gas temperature at 150°F as the gas transports the vaporized moisture to the HRSR equipment. The algorithm used by SINGH to calculate \( QNAT13 \) is as follows:

\[
QNAT13 = QNAT12 - QWVT13 - QLCDT
\]

At this point, SINGH calls upon several NASA SP-273 subroutines\textsuperscript{6} to calculate and store chemical and thermodynamic data for four plasma/flue gas states. Each individual state is identified by a different index value for the NASA SP-273 variable NPT(I). For example, the previously calculated plasma properties in the combustor are identified by NPT(1). The four states calculated at this point are numbered 2, 5, 6 and 7. They are described in Table 4-4 along with the other three states. These calculations are accomplished at this point in the SINGH execution because data for NPT(5) is required for the combustor analysis. The
Table 4-4. States for which SINGH calls NASA SP-273 to Calculate Plasma/Flue Gas Properties.

<table>
<thead>
<tr>
<th>Identification Number</th>
<th>Description of State</th>
<th>Temperature (K)</th>
<th>Pressure (Atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plasma at combustor exit</td>
<td>TAIC</td>
<td>PRINT</td>
</tr>
<tr>
<td>2</td>
<td>Flue gas at stack</td>
<td>395</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>Flue gas at MHD channel exit</td>
<td>TT(3)</td>
<td>PSTAT</td>
</tr>
<tr>
<td>4</td>
<td>Flue gas at diffuser exit</td>
<td>TT(4)</td>
<td>PDO/14.7</td>
</tr>
<tr>
<td>5</td>
<td>Reference</td>
<td>300</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>Flue gas at economizer inlet</td>
<td>644</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>Flue gas at secondary combustor inlet</td>
<td>1867</td>
<td>1.0</td>
</tr>
</tbody>
</table>
computational techniques used by the NASA SP-273 subroutines begin with properties for a given temperature and use convergence techniques to calculate values for lower temperatures. Thus it is expeditious to calculate as many points as possible during a convergence sequence.

The MHD combustor is a watercooled pressure vessel which accomplishes substoichiometric combustion at a specified pressure (PRINT, atmospheres). For this analysis, the nozzle, which accelerates the plasma flow into the MHD channel, is considered as part of the combustor assembly. The combustor receives three injected mass flows which consist of oxygen enriched air (MOAT08), dried coal (MCT02), and potassium formate seed (MKT14). The oxygen enriched air flow transports energy (QOAT08), in the form of sensible heat, into the combustor. The dried coal flow transports chemical energy (THIN) into the combustor. The potassium formate seed contributes no energy; instead, it requires an estimated 4 Btu/lbm to drive the reaction which frees potassium atoms for the work of sulfate formation and sulfur removal. SINGH calculates this energy requirement (QKT14, Btu/hr) using the required mass flow rate of potassium formate seed (MKT14):

\[ QKT14 = 4 \times MKT14 \]

There are only two paths for energy transport out of the MHD combustor. One path is the cooling water flow which cools the combustor and nozzle walls. SINGH calculates the amount of heat transferred from the combustor and nozzle walls to the cooling water (QLCOMB, Btu/hr). To accomplish this, SINGH reads a value for the amount of heat lost to combustor cooling water (QLCPUM, Btu/lbm) per pound of coal input to the
combustor. As part of its calculation sequence, program COAL calculates a value for QLCPUM. The resulting algorithm for QLCOMB becomes:

\[
QLCOMB = QLCPUM \times MCT02
\]

The other path for energy transport out of the combustor is provided by the plasma flow which exits the nozzle. There are three energy forms transported by the plasma. First there is the kinetic energy of the plasma flow. Next there is the sensible heat of the plasma. Finally, there is the chemical energy retained by the uncombusted fuel compounds. The kinetic energy and sensible heat are calculated as one quantity (EQKT15, Btu/hr) by recalling the stagnation enthalpy of the plasma (HSUM(1), J/KG) at combustor conditions. HSUM(1) was previously calculated and stored by NASA SP-273. SINGH calculates EQKT15 with the following algorithm:

\[
EQKT15 = (HSUM(1) - HSUM(5)) \times R \times 1.8 \times MPT15
\]

The unreleased chemical energy (ECT15, Btu/hr) transported by the plasma is computed by difference in SINGH.

\[
ECT15 = THIN + QOAT08 - EQKT15
\]

SINGH then calculates the total energy transported from the combustor (ETT15, Btu/hr) by the plasma flow as the sum of EQKT15 and ECT15.

The final step in the combustor analysis sequence is to calculate select thermodynamic and geometric parameters from plasma flow through the nozzle. The six values calculated are the nozzle cross sectional area at the throat (AT, Sq. Meters) and at the exit (AE, Sq. Meters), the plasma density at the nozzle throat (RHOT, KG/Cu. Meters), and at the nozzle exit (RE, KG/Cu. Meter), as well as the static pressure (PENZ, ATM) and temperature (TE, Kelvin) of the plasma flow at the
nozzle exit. SINGH calculates these quantities through the use of classical gas dynamics equations for isentropic nozzle analysis in conjunction with data values previously calculated by NASA SP-273 subroutines. The Mach number for the plasma as it enters the MHD channel (EMACH, dimensionless) is required and is read by SINGH. The calculation sequence is clearly identified in SINGH and is not elaborated upon here.

The MHD generating channel is the next topping cycle component addressed by SINGH. The channel receives the accelerated plasma flow from the nozzle exit. The energy transported, by the plasma, into the channel has been previously calculated as ETT15. As the plasma passes through the channel and its associated magnetic field, the plasma energy content is decreased by two mechanisms. First, the MHD effect transforms a portion of the kinetic and sensible heat energy (EQKT15) into electric power. Second, a portion of the plasma sensible heat is transferred to the channel cooling water.

The determination of the electric power produced by the MHD channel is a lengthy process. The first step is design of a reference generating channel by means of independent execution of the DESIGN3 program. The DESIGN3 user sizes the reference generating channel in accordance with the expected plasma flow and composition for the subsequent SINGH execution. In addition, the DESIGN3 user must specify numerous other parameters required to adequately describe the operating characteristics of the reference channel. The detailed use of DESIGN3 is addressed by Wu, and is not explained here. Several data values output by DESIGN3 are required by the channel modeling algorithms and are read
by SINGH at the beginning of its execution cycle. The variable names associated with those data outputs are listed below and are defined in Table 4-2.

<table>
<thead>
<tr>
<th>BMAX</th>
<th>CLEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEFFI</td>
<td>AREAR</td>
</tr>
<tr>
<td>GDMF</td>
<td>ENT</td>
</tr>
<tr>
<td>HF</td>
<td>PSTAT</td>
</tr>
</tbody>
</table>

The values read by SINGH are used to calculate the performance and geometry of a generating channel, similar to the reference channel, but proportioned to receive the exact plasma flow calculated for the current SINGH execution cycle. This is accomplished through the use of algorithms which modify selected reference channel parameters using coefficients expressed in terms of the ratio of plasma flows through the SINGH developed channel and the reference channel specified by DESIGN3.

The first such value calculated is the fractional enthalpy extraction (HFF, dimensionless). SINGH uses the following algorithm from Chapman\textsuperscript{16} to calculate HFF.

$$HFF = HF *((1 + (MPT15/GDMF) * 0.5)^0.35$$

The fractional MHD generator efficiency (GEFF, dimensionless) is the next quantity calculated by SINGH. The algorithm for this parameter is also from Chapman\textsuperscript{16}.

$$GEFF = GEF *((1 + (MPT15/GDMF) * 0.5)^0.5$$

The channel entrance area (ENTA, Sq. Meters) is assumed to be proportional to mass flow through the channel and is calculated as follows:

$$ENTA = (MPT15/GDMF) * ENTA$$
Using AREAR and ENTA, SINGH calculates the cross sectional area of the channel exit (EXTA, Sq. Meters).

\[ \text{EXTA} = \text{AREAR} \times \text{ENTA} \]

The length of the generating channel (CLEN, meters) is assumed equal to the length of the reference channel.

Using HFF and stagnation enthalpy data previously calculated by NASA SP-273, SINGH next calculates the direct current electric power developed by the MHD generating channel (PEXM, Watts).

\[ \text{PEXM} = (\text{HSUM}(1) - \text{HSUM}(5)) \times R \times 1.8 \times 2.931 \times \text{HFF} \times \text{MPT15} \]

To calculate the electric power output to the alternating current bus (POUTM, Watts), SINGH multiplies PEXM by the inverter efficiency (CEFFI, dimensionless).

\[ \text{POUTM} = \text{CEFFI} \times \text{PEXM} \]

Once PEXM AND GEFF have been calculated, it is possible to calculate the amount of plasma sensible heat transferred through the channel walls to the cooling water (QLMHD, Btu/hr). SINGH calculates QLMHD as follows:

\[ \text{QLMHD} = (\text{PEXM} \times 3.4129 \times (1 - \text{GEFF})) / \text{GEFF} \]

The energy content of the plasma exiting the generating channel has two components. The first component is the kinetic energy and sensible heat content (EQKT16, Btu/hr). SINGH calculates the value of EQKT16 as:

\[ \text{EQKT16} = \text{EQKT15} - (\text{PEXM} \times 3.4129) - \text{QLMHD} \]

The second plasma energy component is the unreleased chemical energy which remains unchanged at ECT15. The total plasma energy content at the generating channel exit (ETT16, Btu/hr) is calculated thus:

\[ \text{ETT16} = \text{EQKT16} + \text{ECT15} \]
The next quantity calculated is the power required to operate the superconducting magnet and its cooling system (PMAG, Watts). SINGH uses the following algorithm from Chapman\(^{16}\) to calculate PMAG.

\[
PMAG = CLEN \times 1000 \times (13.4 \times (ENTA^{0.5}) + (ENTA \times AREAR)^{0.5}) + 7. \times BMAX \times ENTA
\]

As the final step in generating channel analysis, SINGH calls upon NASA SP-273 subroutines to calculate plasma properties at the channel exit (NPT = 3). The sequence in which SINGH calls the other subroutines is clearly evident in the SINGH listing and is not explained here. Interested readers are invited to refer to Gordon and McBride\(^6\).

The last topping cycle component addressed by SINGH is the diffuser. The primary functions of the diffuser are to decelerate the plasma flow and to recover pressure. For this model, the diffuser coefficient of performance is set at 0.50. The MHD channel design procedure requires the channel exit Mach number to be between 0.9 and 0.999. The channel exit static pressure (PSTAT) is set at a value (normally about 0.7 ATM) which permits the static pressure to recover to 1.0 ATM at the diffuser exit. As the plasma passes through the diffuser, a portion of the plasma sensible heat energy passes through the diffuser walls and is transferred to the cooling water. The quantity of heat lost to the cooling water (QLDIF, Btu/hr) is calculated by SINGH in accordance with a procedure presented by Chapman\(^{16}\). The algorithm for QLDIF is as follows:

\[
QLDIF = 3.4129 \times 4 \times (TTT (3) - TWALL) \times (0.0316 \times BBB \times DLEN + 0.0316 \times 0.0349) \\
* DLEN \times DLEN - 3.53 \times 0.06 \times BBB
\]
\[ *DLEN*DLEN-(1.412E-05*0.0349) \\
\text{where} \\
\text{TTP}(3) = \text{plasma temperature at diffuser entrance. Calculated by} \\
\text{NASA SP-272 (°K)} \\
\text{BBB} = (\text{ENTA*AREAR})\text{.5*100.} \\
\text{DLEN} = \text{diffuser length (centimeters)} \\
\text{= 3.79*BBB} \\
\text{Since QLDIF is the only energy transferred from the plasma during its} \\
\text{passage through the diffuser, the energy balance for the diffuser is} \\
\text{straightforward. The total energy content of the plasma flow entering} \\
\text{the diffuser equals that of the plasma flow exiting the generating channel} \\
\text{which has already been calculated as ETT16. The total energy} \\
\text{content of the flue gas exiting the diffuser (ETT17, Btu/hr) is then} \\
\text{readily calculated as follows:} \\
\text{ETT17} = \text{ETT16-QLDIF} \\
\text{Like ETT16, ETT17 consists of two separate energy components. One} \\
\text{component is the composite of kinetic and sensible heat energy (EQKT17,} \\
\text{Btu/hr), and the other component is the unreleased chemical energy} \\
\text{(ECT17, Btu/hr). Because no additional oxidant is added to the plasma} \\
\text{flow in the diffuser, the unreleased chemical energy remains unchanged} \\
\text{at a value of ECT15. The kinetic and sensible heat energy of the flue} \\
\text{gas exiting the diffuser is then calculated as:} \\
\text{EQKT17} = \text{ETT17-ECT15} \]
Finally, SINGH calls upon NASA SP-273 subroutines to calculate and store flue gas properties at the diffuser exit (NPT = 4). This is accomplished per Gordon and McBride and is not explained here.

The description of the MHD topping cycle is now complete. The algorithms which calculate mass flows, energy transport and transfer, and power requirements for the coal processing equipment and the air separation plant are new additions to SINGH. The remaining calculations were generally unchanged.
CHAPTER V

SEED REGENERATION

One of the major changes implemented by this revision of SYSTEMS is the replacement of the Tomlinson/Tampella seed regeneration model by the Formate process model. This chapter describes both the process sequence and the algorithms which comprise the potassium formate recovery process model now contained in SYSTEMS. Figure 5-1 is a process flow diagram of the formate process. Table 5-1 defines the numbered flow streams presented in Figure 5-1. Both the figure and the table will be useful references while reading the remainder of this chapter. The primary reference for developing this model was the Conceptual Design Study of Potential Early Commercial MHD Powerplant by Finn A. Hals. Throughout this chapter, the report will be referenced simply as the Hals report or Hals model.

The seed regeneration plant receives potassium sulfate from the HRSR as well as its own gasifier. Through application of the formate process, the seed regeneration plant transforms the potassium sulfate into potassium formate seed which is routed back to the MHD combustor as well as the gasifier used by the seed regeneration plant. The six major processing steps which comprise the formate process are as follows:

1. Gasify coal to supply carbon monoxide to the reactor.
2. Dissolve the potassium sulfate.
3. Produce potassium formate product in reactor.
Figure 5-1. Seed Regeneration Process Diagram.
R34

Figure 5-1. (continued)
Table 5-1. Seed Regeneration Process Streams.

<table>
<thead>
<tr>
<th>Steam No.</th>
<th>Description</th>
<th>Variable Name</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Dry $K_2SO_4$ from HRSR equipment</td>
<td>MKSR01</td>
<td>$5.44 \times 0.98 \times XS \times MCT02$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R2</td>
<td>Service water for $K_2SO_4$ slurry</td>
<td>MSWR02</td>
<td>$0.11 \times MKSR01$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R3</td>
<td>$K_2SO_4$ slurry to dissolver</td>
<td>MKWR02</td>
<td>$MKSR01 + MSWR02$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R4</td>
<td>Gasifier coal to mixing tank</td>
<td>MCR04</td>
<td>$(0.34 \times MKSR01) / (1 - 1.85 \times XS)$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R5</td>
<td>Potassium formate to mixing tank</td>
<td>MKR05</td>
<td>$(78/32) \times XS \times MCR04$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R6</td>
<td>Service water for gasifier coal slurry</td>
<td>MSWR06</td>
<td>$0.52 \times MCR04$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R7</td>
<td>Coal and potassium formate slurry to gasifier</td>
<td>MCWR07</td>
<td>$MCR04 + MSWR06 + MKR05$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R8</td>
<td>Air to gasifier</td>
<td>MAR08</td>
<td>$4.02 \times MCR04$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R9</td>
<td>Coal slag from gasifier</td>
<td>MASR09</td>
<td>$XSAR \times MCR04$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R10</td>
<td>Dry $K_2SO_4$ from gasifier</td>
<td>MKSR10</td>
<td>$544 \times XSAR \times MCR04$</td>
<td>lbm/hr</td>
</tr>
</tbody>
</table>
### Table 5-1 (Continued)

<table>
<thead>
<tr>
<th>Steam No.</th>
<th>Description</th>
<th>Variable Name</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>R11</td>
<td>Product gas from gasifier</td>
<td>MGR011</td>
<td>MCWR07 + MAR08 - MASR09 - MKSR10</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R12</td>
<td>Service water for K₂SO₄ slurry</td>
<td>MSWR12</td>
<td>0.11*MKSR10</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R13</td>
<td>K₂SO₄ slurry to dissolver</td>
<td>MKWR13</td>
<td>MKSR10 + MSWR12</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R14</td>
<td>Lime to K₂SO₄ dissolver</td>
<td>MCAR14</td>
<td>0.32*(MKSR01 + MKSR10)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R15</td>
<td>K and Ca compound slurry from dissolver</td>
<td>MTR15</td>
<td>MKSR15 + MKFR15 + MWR15 + MCHR15</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R16</td>
<td>Steam to heat exchanger B</td>
<td>MSR16</td>
<td>QTR18/983.6</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R17</td>
<td>Condensate from heat exchanger B</td>
<td>MWR17</td>
<td>MSR16</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R18</td>
<td>K and Ca compound slurry to reactor</td>
<td>MTR18</td>
<td>MTR15</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R19</td>
<td>Product gas to scrubber</td>
<td>MGR19</td>
<td>MGR11</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R20</td>
<td>CO₂ from regenerator to atmosphere</td>
<td>MCDR20</td>
<td>0.085*MGR19</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R21</td>
<td>Product gas to reactor</td>
<td>MGR21</td>
<td>MGR19 - MCDR20</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R22</td>
<td>Product gas to heat recovery</td>
<td>MGR22</td>
<td>0.93*MGR21</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>Steam No.</td>
<td>Description</td>
<td>Variable Name</td>
<td>Algorithm</td>
<td>Units</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------------------------------</td>
<td>---------------</td>
<td>------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>R23</td>
<td>K and Ca compound slurry to flash tank</td>
<td>MTR23</td>
<td>MTR18 + MGR21 - MGR22</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R24</td>
<td>K and Ca compounds from flash tank</td>
<td>MTR24</td>
<td>MTR23 - MSR25</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R25</td>
<td>Steam from flash tank</td>
<td>MSR25</td>
<td>0.12*MTR23</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R26</td>
<td>Service water to heat exchanger A</td>
<td>MSWR26</td>
<td>1.80*MGR11</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R27</td>
<td>Service water from heat exchanger A</td>
<td>MSWR27</td>
<td>MSWR26</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R28</td>
<td>Gypsum and water to disposal</td>
<td>MYWR28</td>
<td>0.24*MTR24</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R29</td>
<td>Recycle K compound slurry from gypsum filter</td>
<td>MTR29</td>
<td>MTR31 - MSR25</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R30</td>
<td>K compound slurry from gypsum filter</td>
<td>MTR30</td>
<td>MTR24 + MSWR27 - MYWR28 - MTR29</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R31</td>
<td>Recycle K compound slurry from flash tank and gypsum filter</td>
<td>MTR31</td>
<td>MKSR31 + MKCR31 + MWR31</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R32</td>
<td>Recycle K compound slurry</td>
<td>MTR32</td>
<td>MKSR32 + MKCR3 + MWR32</td>
<td>1bm/hr</td>
</tr>
<tr>
<td>R33</td>
<td>K compound slurry to evaporator</td>
<td>MKWR33</td>
<td>MTR30 - MTR32</td>
<td>1bm/hr</td>
</tr>
</tbody>
</table>
Table 5-1 (Continued)

<table>
<thead>
<tr>
<th>Steam No.</th>
<th>Description</th>
<th>Variable Name</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>R34</td>
<td>Steam vented from K compound slurry</td>
<td>MSR34</td>
<td>0.50*MKWR33</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R35</td>
<td>K compounds to spray dryer</td>
<td>MKWR35</td>
<td>MKWR33 - MSR34</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R36</td>
<td>Gas from evaporator</td>
<td>MGR36</td>
<td>MGR22</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R37</td>
<td>Flue gas to spray dryer</td>
<td>MFGR37</td>
<td>14.12*MKWR35</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R38</td>
<td>K compounds to heat exchanger C</td>
<td>MKR38</td>
<td>0.636*MKWR35</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R39</td>
<td>Flue gas and moisture to stack</td>
<td>MFGR39</td>
<td>MFGR37 + MKWR35 + MKR38</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R40</td>
<td>K compounds to $K_2SO_4$ filter</td>
<td>MKR40</td>
<td>MKR38</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R41</td>
<td>Steam to heat exchanger C</td>
<td>MSR41</td>
<td>QKR40/983.6</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R42</td>
<td>Condensate from heat exchanger C</td>
<td>MWR42</td>
<td>MSR41</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R43</td>
<td>Recycle $K_2SO_4$ from filter</td>
<td>MKSR43</td>
<td>0.20*(MKS R01 + MKS R10)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R44</td>
<td>Potassium Formate to MHD cycle</td>
<td>MKCR44</td>
<td>MKR40 - MKSR43</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>Stream No.</td>
<td>Description</td>
<td>Variable Name</td>
<td>Algorithm</td>
<td>Units</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------</td>
<td>---------------</td>
<td>-----------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>R18</td>
<td>Heat required from heat exchanger B</td>
<td>QTR18</td>
<td>101.7*MTR13</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>R31</td>
<td>$\text{K}_2\text{SO}_4$ component of recycle stream R31</td>
<td>MKSR31</td>
<td>0.01*MKSR01 + MKSR09</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R31</td>
<td>$\text{KCO}_2\text{H}$ component of recycle stream R31</td>
<td>MKCR31</td>
<td>4.85*MKSR29</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R31</td>
<td>Water component of recycle stream R31</td>
<td>MWR31</td>
<td>324.07*MKSR29</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R32</td>
<td>$\text{K}_2\text{SO}_4$ component of recycle stream R32</td>
<td>MKSR32</td>
<td>0.008*(MKSR01 + MKSR09)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R32</td>
<td>$\text{KCO}_2\text{H}$ component of recycle stream R32</td>
<td>MKCR32</td>
<td>4.85*MKSR30</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R32</td>
<td>Water component of recycle stream R32</td>
<td>MWR32</td>
<td>12.62*MKSR30</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>R40</td>
<td>Heat required from heat exchanger C</td>
<td>QKR40</td>
<td>MKS38*40</td>
<td>Btu/hr</td>
</tr>
</tbody>
</table>
4. Filter reactor effluent to separate potassium formate product from gypsum by-product.

5. Dry the potassium formate product.

6. Reheat formate and filter sulfate.

Potassium sulfate recovered in the HRSR is mixed with service water to form a slurry. The slurry is pumped into a potassium sulfate dissolver. "As received" coal is mixed with potassium formate and service water to form a slurry which is fed to the gasifier. In the gasifier, the slurry reacts with air to produce product gas, coal slag, and potassium sulfate. The potassium sulfate is expelled from the gasifier, mixed with service water and pumped to the potassium sulfate dissolver. The coal slag is removed from the gasifier and moved to a disposal site.

The product gas is cooled after exiting the gasifier. It is then passed through a regenerator which removes carbon dioxide. From the regenerator, the product gas is moved to the reactor where the majority of its carbon monoxide is utilized in the formation of potassium formate. The remaining gas is discharged from the reactor and is passed through the evaporator where it transfers its excess heat to the potassium compound flow stream. The gas exits the evaporator at 250°F and is released to the atmosphere through the plant stack.

Back at the potassium sulfate dissolver, lime is added to the potassium sulfate slurry as are recycle streams from the flash tank, gypsum filter, and potassium sulfate filter. The resulting slurried mixture is heated by heat exchanger B and then fed to the reactor where the formate reaction takes place. After exiting the reactor, the product stream is passed through a flash tank which removes a substantial
amount of water from the product stream in the form of steam. Next the product stream passes through a gypsum filter which removes the calcium sulfate formed in the reactor. From the gypsum filter, the product stream moves on through an evaporator and a spray dryer. Both of these components remove more water from the product stream. The evaporator employs heat available from the reactor effluent gas while the spray dryer uses flue gas extracted from the HRSR. The product stream continues on through heat exchanger C which provides sufficient heat for melting the potassium formate and contained in the product stream. The molten product stream passes through a potassium sulfate filter which removes the potassium sulfate for return to the potassium sulfate dissolver. The potassium formate is returned to the stockpile for recycling through the MHD combustor or the gasifier.

The first step in modeling the seed regeneration process is to determine how much potassium sulfate \( K_2SO_4 \) will have to be processed. The HRSR model assumes a 100% sulfur removal rate from the gas stream; however, some of the potassium and sulfur compounds are removed with coal slag and thus are not available for potassium recovery processing. The precise amount of potassium and sulfur removed with the coal slag is difficult to estimate because so little is known about the chemistry of potassium, sulfur, and coal slag interaction. This study assumes that 2% of the sulfur is removed with coal slag. The remaining 98% is recovered in the form of potassium sulfate provided that the amount of available potassium is sufficient. The model assumes the flue gas mixes thoroughly and that the \( K_2/S \) ratio of 1 will accomplish complete sulfur removal. Any excess potassium is assumed to form potassium carbonate.
SINGH calculates the amount of potassium sulfate recovered from the HRSR (MKSRO1, lbm/hr) as follows:

\[
MKSRO1 = 5.44 \times MCT02 \times 0.98 \times XS
\]

where 5.44 = reciprocal of weight fraction of S per unit weight of potassium sulfate. (dimensionless)

\[
MCT02 = \text{previously calculated mass flow rate of dry coal to the MHD combustor (lbm/hr)}
\]

0.98 = fraction of sulfur content recovered (dimensionless)

\[
XS = \text{weight fraction of sulfur in dried coal (dimensionless)}
\]

The value of XS is read by SINGH at the beginning of its execution cycle.

SINGH next calculates the amount of potassium lost with the ash and slag (KLHRSR, lbm/hr):

\[
KLHRSR = \frac{39}{84} \times MKT14 - \frac{78}{174} \times MKSRO1
\]

where 39/84 = weight fraction of potassium per unit weight of potassium formate (dimensionless).

\[
MKT14 = \text{previously calculated mass flow rate of potassium formate to the MHD combustor (lbm/hr)}
\]

78/174 = weight fraction of potassium per unit weight of potassium sulfate (dimensionless).

If KLHRSR is less than zero, SINGH prints a warning that insufficient potassium is present for complete sulfur recovery. SINGH then recalculates MKSRO1 based on the available potassium as shown below.

\[
MKSRO1 = \frac{174}{78} \times \frac{39}{84} \times MKT14 \times 0.98
\]

Once the amount of potassium sulfate recovered from the HRSR equipment has been determined, the amount of service water (MSWRO2, lbm/hr)
necessary to create the slurry is computed by proportion from the Hals model:

\[ \text{MSWR02} = 0.1111 \times \text{MKSR01} \]

The potassium sulfate slurry (MKWR03, lbm/hr) entering the potassium sulfate dissolver is then computed as the sum of MKSR01 and MSWR02.

The next quantity calculated by SINGH is the amount of coal (MCR04, lbm/hr) required by the seed regeneration gasifier. In the Hals report, the quantity of potassium sulfate entering the potassium sulfate dissolver included a contribution from the gasifier coal. The Hals model required 13048 lbm/hr of gasifier coal for reprocessing 38421 lbm/hr of potassium sulfate. That quantity of potassium sulfate included a contribution from gasifier coal as well as that recovered from the HRSR equipment. The gasifier coal requirement is 0.34 lbm of coal per pound of potassium sulfate. Assuming 100% sulfur removal from the gasifier coal, and having previously calculated the amount of potassium sulfate recovered from the HRSR equipment, the algorithm for calculating the gasifier coal requirement is developed as follows:

\[ \text{MCR04} = 0.34 \times (\text{MKSR01} + (544 \times \text{XS} \times \text{MCR04})) \]
\[ \text{MCR04} - 1.85 \times (\text{XS} \times \text{MCR04}) = 0.34 \times \text{MKSR01} \]
\[ \text{MCR04} \times (1 - 1.85 \times \text{XS}) = 0.34 \times \text{MKSR01} \]
\[ \text{MCR04} = 0.34 \times \text{MKSR01} / (1 - 1.85 \times \text{XS}) \]

The last of the four expressions for MCR04 is the one which appears in SINGH. After MCR04 has been calculated, SINGH determines the quantity of potassium formate (MKR05, lbm/hr) required for recovery of the sulfur contained in the gasifier coal.
MKR05 = (78/32) * XSAR * MCR04

The gasifier coal and potassium formate are mixed with service water (MSWR06, lbm/hr) to form a slurry (MCWR07, lbm/hr) which is then fed to the gasifier. MSWR06 is calculated as follows:

MSWR06 = 0.52 * MCR04

The value of MCWR07 is calculated as the sum of MCR04, MCR05, and MCWR06. The mass flow of air to the gasifier (MAR08, lbm/hr) is computed by proportion from the Hals model as follows:

MAR08 = 4.02 * MCR04

The coal slag (MASR09, lbm/hr) is calculated by the following algorithm:

MASR09 = XAAR * MCR04

XAAR is the "as received" ash content of the gasifier coal. The value of XAAR is read by SINGH. The dry potassium sulfate discharged from the gasifier (MKSR10, lbm/hr) is calculated as follows:

MKSR10 = 5.44 * XAAR * MCR04

The product gas produced in the gasifier (MGR11, lbm/hr) is then calculated by difference.

MGR11 = MCWR07 + MAR08 - MASR09 - MKSR10

Most of the remaining mass flow streams are calculated by proportion from factors based on the Hals model. The flow stream descriptions, variable names, and algorithms are presented in Table 5-1. The flow streams whose algorithms require additional explanation are addressed in the following paragraphs.

One of the flow streams not readily determined from the Hals report is R16 which is steam supplied to heat exchanger B. The purpose of this steam is to heat process stream R15 from 200°F to 392°F. From data
contained in the Hals report, one can determine that 101.7 Btu are required for heating each pound of the potassium sulfate/lime slurry which passes through heat exchanger B. The Hals report gives no information regarding the required steam flow or steam conditions. This paragraph develops the necessary algorithms for modeling the steam flow to and from heat exchanger B. This analysis assumes the use of the counterflow heat exchanger with a minimum temperature difference (ΔT) of 50°F between flow streams. The slurry entering the heat exchanger has a temperature of 200°F. Therefore, the minimum temperature of the process steam will be 250°F. The slurry exiting heat exchanger B will have a temperature of 392°F. Accordingly the steam entering heat exchanger B will have a minimum temperature of 442°F. However, a higher temperature difference will permit construction of a smaller less expensive heat exchanger. For this reason, the temperature of the steam entering heat exchanger B will be set at 500°F. To ensure the steam condenses at 250°F the system will be designed with a pressure of 28 psia at the condensate outlet from heat exchanger B. From the ASME steam tables\(^{10}\), the enthalpy of the entering steam at 500°F is 1202.2 Btu/lbm. The enthalpy of the condensed water, exiting heat exchanger B, is 218.6 Btu/lbm. This means that each pound of steam will yield 983.6 Btu for heating the slurry. Thus, the required mass flow rate of process steam to heat exchanger B (MSR15) can be determined once the mass flow rate of potassium sulfate/lime slurry from the \( \mathrm{K}_2\mathrm{SO}_4 \) dissolver (MTR15, lbm/hr) has been calculated. Determination of the mass flow rate of the potassium sulfate/lime slurry from the potassium sulfate dissolver is an involved process because there are three recycle steams (i.e. R31, R32,
and R44) whose precise values have not yet been determined and which enter the potassium sulfate dissolver. Two of these streams are multi-compound streams. Using proportional relations from the Hals report it is possible to calculate the mass flows of these recycle streams before calculating the mass flows of all of the streams which precede them. Four distinct compounds comprise flow stream R15. The compounds and their variable names are listed below:

- Potassium sulfate: MKSR15
- Potassium formate: MKFR15
- Water: MWR15
- Calcium Hydroxide: MCHR15

The units for each of the above mass flows are pounds per hour. Mass flows for the above compounds cannot be specified until mass flows have been estimated for each of three recycle streams. Two of the recycle streams are also multi-compound flow streams. The three recycle streams, their component compounds, and variable names are shown in Table 5-2. Each variable is calculated in terms of pounds per hour.

The Hals model provides the data for determining proportion factors which serve as the basis for the algorithms used in SINGH to calculate the mass flows. The potassium sulfate portion of each of the three recycle flows is calculated in relation to the quantity of potassium sulfate received by the potassium sulfate dissolver. The three algorithms are as follows:

- \[ MKSR31 = \left( \frac{442}{38421} \right) \ast (MKSR01+MKSR10) \]
- \[ MKSR32 = \left( \frac{323}{38421} \right) \ast (MKSR01+MKSR10) \]
- \[ MKSR43 = \left( \frac{7649}{38421} \right) \ast (MKSR01+MKSR10) \]
Table 5-2. Recycle Streams to Potassium Sulfate Dissolver.

<table>
<thead>
<tr>
<th>Flow Stream</th>
<th>Compound</th>
<th>Variable Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>R31</td>
<td>Potassium Sulfate</td>
<td>MKSR31</td>
</tr>
<tr>
<td>R31</td>
<td>Potassium Formate</td>
<td>MKFR31</td>
</tr>
<tr>
<td>R31</td>
<td>Water</td>
<td>MWR31</td>
</tr>
<tr>
<td>R32</td>
<td>Potassium Sulfate</td>
<td>MKSR32</td>
</tr>
<tr>
<td>R32</td>
<td>Potassium Formate</td>
<td>MKFR32</td>
</tr>
<tr>
<td>R32</td>
<td>Water</td>
<td>MWR32</td>
</tr>
<tr>
<td>R43</td>
<td>Potassium Sulfate</td>
<td>MKSR43</td>
</tr>
</tbody>
</table>
The remaining compound mass flows which comprise recycle streams R31 and R32 are calculated from the Hals model using proportion factors relating the potassium sulfate mass flow for the particular recycle stream to the mass flow of the compound of interest. The remaining four algorithms are as follows:

\[\text{MKFR31} = \left(\frac{2143}{442}\right) \times \text{MKSR31}\]
\[\text{MWR31} = \left(\frac{143240}{442}\right) \times \text{MKSR31}\]
\[\text{MKFR32} = \left(\frac{1566}{323}\right) \times \text{MKSR32}\]
\[\text{MWR32} = \left(\frac{4076}{323}\right) \times \text{MKSR32}\]

At this point it is possible for SINGH to calculate the quantity of each compound contained in the mass flow exiting the potassium sulfate dissolver. The algorithms are as follows:

\[\text{MKSR15} = \text{MKSR01} + \text{MKSR13} + \text{MKSR31} + \text{MKSR32} + \text{MKSR43}\]
\[\text{MKFR15} = \text{MKFR31} + \text{MKFR32}\]
\[\text{MWR15} = \text{MWR02} + \text{MWR12} + \text{MWR31} + \text{MWR32}\]
\[\text{MCHR15} = \left(\frac{16335}{12364}\right) \times \text{MCAR14}\]

MCAR14 is the lime added to the potassium sulfate dissolver in pounds per hour. The algorithm for MCHR15 is based upon the Hals report. The total flow from the potassium sulfate dissolver (MTR15, lbm/hr) is then calculated as the sum of the constituent compound flows.

\[\text{MTR15} = \text{MKSR15} + \text{MKFR15} + \text{MWR15} + \text{MCHR15}\]

Once MTR15 has been calculated, it is possible to compute the required steam flow to heat exchanger B (MSR16, lbm/hr). Each pound of MTR15 requires 101.7 Btu as previously explained. Thus the total heat to be added to MTR15 (QTR18, Btu/hr) is calculated as follows:

\[\text{QTR18} = 101.7 \times \text{MTR15}\]
Recalling that each pound of steam in MSR16 yields 983.6 Btu, MSR18 is calculated by the following

\[ MSR16 = QTR18/983.6 \]

The condensate flow from heat exchanger B (MWR17) equals MSR16.

The steam flow to heat exchanger C is another quantity whose calculation requires some explanation. According to the Hals report, each pound of the potassium formate and potassium sulfate mixture which passes through heat exchanger C requires 40 Btu of heat addition. The steam used to supply this heat will be at the same temperature and pressure as that supplied to heat exchanger B. Thus, each pound of steam will be able to supply 983.6 Btu. Using this information, the amount of heat required by MK38 (QKR40, Btu/hr) can be calculated as follows:

\[ QKR40 = MK38*40. \]

The required steam flow to heat exchanger C (MSR41) then becomes:

\[ MSR41 = QKR40/983.6 \]

The condensate flow from heat exchanger C (MWR42, lbm/hr) equals MSR42.

The potassium formate processed for recycling (MKFR44, lbm/hr) is subtracted from the sum of MKT14 and MKR05 to determine the required make-up mass flow of potassium formate (MKMTR, lbm/hr). At this point, SINGH has completed its calculations for modeling seed regeneration by the formate process.
CHAPTER VI

HRSR SYSTEM AND STEAM CYCLE

This chapter presents the models for the heat recovery and seed recovery (HRSR) system and the steam cycle. It also contains a description of the calculations for overall plant efficiency which are performed at the end of a SINGH execution cycle. The chapter begins with a description of the objectives and configuration of the HRSR system. This is followed by a similar description for the steam cycle. Next, the algorithms which comprise the models of these two major subsystems are addressed. The final paragraph of this chapter describes the overall plant efficiency calculations performed by SINGH. With the exception of plant efficiency and coal slag rejection calculations, the model relationships presented in this chapter are new additions to SYSTEMS.

The process objectives of the HRSR are as follows:

1. Heat recovery from flue gas for the following purposes:
   a. steam generation for electric power production.
   b. primary oxidant heating.
   c. coal drying.
   d. secondary combustion air heating.
   e. steam generation for seed regeneration heat exchangers.

2. Removal of sulfur from flue gas stream.

3. Recovery of potassium seed from flue gas stream.
4. Provide sufficient residence time at elevated temperature (≥ 2900°F) for decomposition of flue gas NO\textsubscript{x} content.

5. Removal of coal slag and ash from the flue gas stream.

6. Combustion of remaining flue gas fuel content.

To accomplish the above objectives, the HRSR is configured as shown in Figure 6-1. Flue gas enters the radiant furnace from the MHD diffuser. Inside the radiant furnace, the flue gas first encounters a slag screen which is assumed to remove 80 percent of the coal slag contained in the flue gas. As explained in Chapter V, some potassium and sulfur are also removed from the flue gas stream with the coal slag. After passing the slag screen the flue gas stream is directed vertically upward into the main chamber of the radiant furnace. The main chamber contains sufficient volume to provide the necessary residence time for decomposition of the NO\textsubscript{x} contained in the flue gas. The radiant furnace shell consists of water walls which constitute boiler surface for steam generation. As it passes through the radiant furnace, the flue gas surrenders the heat required for steam generation. Simultaneously, the NO\textsubscript{x} content in the flue gas decomposes to a negligible amount. By the time it exits the radiant furnace, the flue gas has been cooled to 2900°F (1867K). Below 2900°F, the NO\textsubscript{x} formation and decomposition reactions cease functioning. Thus, the flue gas will remain essentially NO\textsubscript{x} free provided its temperature is not increased above 2900°F during the remaining process steps.

Before considering the remaining HRSR components, it is necessary to address two major obstacles to detailed modeling of the HRSR system.
Figure 6-1. HRSR System Diagram.
The first obstacle is the limited information addressing the behavior and interaction of coal slag/ash and potassium sulfate in the HRSR environment. To reduce this obstacle, this model assumes that 80 percent of the coal slag, 2 percent of the potassium sulfate, and any additional potassium in the flue gas are removed from the flue gas in the radiant furnace. The model also assumes that the remaining coal slag/ash and potassium sulfate is removed from the flue gas stream by the time it exits the electrostatic precipitator. The final assumption is that some unspecified mechanism permits the recovered potassium sulfate to be conveniently separated from the coal slag/ash.

The second major obstacle to HRSR modeling concerns heat recovery and NO\textsubscript{x} formation. One approach would cool the flue gas well below the NO\textsubscript{x} formation temperature zone in the radiant furnace. This would permit secondary combustion to be accomplished without raising the flue gas temperature to the NO\textsubscript{x} formation zone. According to an earlier study\textsuperscript{11}, this approach requires co-location of a superheater, reheater, or primary oxidant heater with the radiant furnace. This is necessary to balance the relative requirements for boiler steam, superheat, reheat, and primary oxidant preheat against the available flue gas heat at temperatures permitting economical heat transfer. Unfortunately, material constraints prohibit placement of a convective heat transfer surface in the chemically reducing environment of the radiant furnace. The alternative is to introduce the flue gas into the secondary combustor at the highest possible temperature (i.e. 2900°F), to accomplish secondary combustion, and then cool the flue gas below 2900°F as quickly as possible. The basis for this alternative is the fact that the
$NO_x$ formation rate is much slower than the combustion reactions. Thus, secondary combustion and subsequent cooling can be accomplished before any appreciable amount of $NO_x$ has formed. At present, there is no prescribed method for executing this process. This model assumes the secondary combustor water walls absorb sufficient combustion generated heat to maintain the flue gas at $2900^\circ F$ during its passage through the secondary combustor. This assumption resolves the second obstacle for modeling purposes, and the description of the remaining HRSR components follows.

As it exits the radiant furnace, the flue gas flow is redirected horizontally and enters the secondary combustor. Like the radiant furnace, the shell of the secondary combustor is composed of water walls which provide boiler surface area for steam generation. Preheated secondary combustion air is added to the flue gas to complete combustion of the remaining fuel content of the flue gas. For the reasons previously discussed, the secondary combustor is sized in such a manner as to remove sufficient heat to keep the flue gas temperature from rising above $2900^\circ F$ during the combustion process.

After exiting the secondary combustor, the flue gas passes through the convective heat transfer surfaces of the superheater, reheater, and primary oxidant heater. As the flue gas cools below $2400^\circ F$, the potassium sulfate begins to condense, form droplets, and fall from the gas stream. The potassium sulfate is recovered from the HRSR and routed to the seed regeneration plant for processing. As the flue gas exits the primary oxidant heater, its temperature has been reduced to $700^\circ F$. At this point flue gas flow is split into four parallel streams. One
stream provides heat to the nitrogen stream to be used for coal drying. The second stream heats the secondary combustion air. The third stream generates the low pressure steam required by the seed regeneration plant heat exchangers. The last stream transfers heat to boiler feedwater via the economizer. The four streams are recombined as they enter the electrostatic precipitator (ESP) at 250°F. The remaining potassium sulfate and coal ash is recovered in the ESP. After exiting the ESP, most of the flue gas passes through the induced draft fan and is released through the plant stack at 250°F. The remaining flue gas first passes through the spray dryer of the seed regeneration plant and then continues through the induced draft fan to the stack where it too is released to the atmosphere at a temperature of approximately 250°F.

The process objective of the steam cycle is to convert thermal energy recovered by the HRSR system and the MHD cycle into mechanical shaft power which is used to generate electric power and to drive both the MHD cycle oxidant compressor and the oxygen plant compressor. Figure 6-2 presents the steam cycle configuration. With two exceptions, this configuration is very similar to the steam cycle arrangement which is characteristic of conventional coal fired plants. The first exception is the addition of two single stage turbines for this plant. One turbine drives the MHD oxidant compressor and the other powers the oxygen plant compressor. The second exception is the large amount of relatively low temperature heat available from the HRSR economizer and the MHD generator cooling water. In conventional coal fired plants, low temperature flue gas heat is used to preheat combustion air at atmospheric pressure. This is not possible in the MHD plant because the MHD
Figure 6-2. Steam Cycle Diagram.
oxidant is compressed and receives a large portion of its preheat during that process. For the MHD plant, the consequence of this large amount of economizer heat is normally one or two fewer feedwater heaters in the steam cycle.

The remaining paragraphs of this chapter address the algorithms developed for the HRSR system model, the steam cycle model, and for calculating the overall plant efficiency. Table 6-1 presents variable names, descriptions, units, and algorithms for HRSR variables. Table 6-2 contains like information for steam cycle variables.

The mass flow rate of flue gas entering the radiant furnace has been previously calculated as MFGT17. Likewise, the total energy transported into the radiant furnace (ETT17) has also been previously calculated by SINGH. ETT17 consists of the thermal and kinetic energy possessed by the flue gas (EQKT17) and the unreleased chemical energy contained in the flue gas (ECT15). The mass flow rate of coal slag, potassium, and sulfur ejected through the radiant furnace slag tap (MSKHO1, lbm/hr) is calculated by the following algorithm:

\[
MSKHO1 = \left(0.80 \times MCTO2 \times XAAR \times (100.-\text{MOISAF})/100.-\text{MOISAR}\right) + KLHRSR + (0.02 \times MCTO2 \times XS)
\]

XAAR is the mass fraction of ash in the "as received" coal. The expression containing MOISAF and MOISAR correct XAAR to a dried coal basis. KLHRSR is the previously calculated mass flow rate of potassium lost from the flue gas stream. SINGH next calculates the heat lost with the material rejected at the slag tap (EQHO1, Btu/hr). The model assumes this material is rejected at a temperature of 2420°F (1600K). The model further assumes the heat content of the rejected material is
Table 6-1. HRSR System Model Variables.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>Algorithm</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSKH01</td>
<td>Mass flow of coal slag, potassium, and sulfur removed at radiant furnace slag tap</td>
<td>((0.80*\text{MCT02}<em>\text{XAAR}</em>(100.\text{MOISAF})/100.\text{MOISAR})) + \text{KLHRSR}+(0.02*\text{MCT02}*\text{XS}))</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>EQH01</td>
<td>Heat lost with mass ejected at radiant furnace slag tap</td>
<td>431.*\text{MSKH01}</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>MFGH02</td>
<td>Mass flow of flue gas exiting radiant furnace</td>
<td>\text{MFGT17}-\text{MSKH01}</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>EQH02</td>
<td>Flue gas thermal energy exiting radiant furnace</td>
<td>\text{MFGH02}*(\text{HSUM}(7)-\text{HSUM}(5)) <em>R</em>1.8</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>ETH02</td>
<td>Total energy transported with flue gas</td>
<td>\text{EQH02}+\text{ECT15}</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>EQSRLF</td>
<td>Heat for steam generation transferred in radiant furnace</td>
<td>\text{EQKT17}-\text{EQH01}-\text{EQH02}</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>MAH04</td>
<td>Mass flow of secondary combustion air</td>
<td>((1.05-\text{SR})/\text{SR}*(\text{MAT03}+\text{MAT04}))</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>MFGH05</td>
<td>Flue gas mass flow from secondary combustor</td>
<td>\text{MFGH02}+\text{MAH04}</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Description</td>
<td>Algorithm</td>
<td>UNITS</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>EQH04</td>
<td>Heat transported to secondary combustor by combustion air</td>
<td>((1.1875\times10^{-5} (T_AH04)^2 -540.**2) + .224 (T_AH04-540.) )*MAH04</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>QAFG05</td>
<td>Heat gained by secondary air mass in combustor</td>
<td>((1.1875\times10^{-5} (3360.<strong>2 -TAH04</strong>2)+ .224(3360.-TAH04) )</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>EQSSC</td>
<td>Heat for steam generation transferred in secondary combustor</td>
<td>ECT15-QAFGH5</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>QFRG56</td>
<td>Heat removed from flue gas in superheater/reheater/oxidant heating section</td>
<td>MFGHO5*(HSUM(7)-HSUM(6))<em>R</em>1.8</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>EQSSR</td>
<td>Heat available for superheating, reheating, and steam generation in first convective section</td>
<td>QRFRG56-QHEOAT</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>QRFG67</td>
<td>Heat recovered from flue gas in second convective heat transfer section</td>
<td>MFGHO5*(HSUM(6)-HSUM(2))<em>R</em>1.8</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>EQSE</td>
<td>Heat transferred to economizer water</td>
<td>QRFG67-QTR18-QKR40-QNat12-EQH04</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>Variable Name</td>
<td>Description</td>
<td>Algorithm</td>
<td>UNITS</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>MSH08</td>
<td>Mass flow of coal ash recovered in ESP</td>
<td>0.20*MCT02*XAAR* (100.-MOISAF) / (100.-MOISAR)</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>MTH08</td>
<td>Mass flow of coal ash and potassium sulfate recovered in EXP</td>
<td>MKSR01+MSH08</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>MFGH09</td>
<td>Flue gas mass flow from ESP to ID fan</td>
<td>MFG07-MSH08-MFGR37</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>MFGH10</td>
<td>Flue gas mass flow to stack</td>
<td>MFGH09+MFGR39</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>PFAN</td>
<td>Electric power required by ID fan</td>
<td>0.4*MFGH10</td>
<td>Watts</td>
</tr>
</tbody>
</table>
Table 6-2. Steam Cycle Model Variables (SINGH).

<table>
<thead>
<tr>
<th>PRESTO II Run No.</th>
<th>Variable Name</th>
<th>Description</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QT</td>
<td>Estimated steam flow to MHD and oxygen plant compressors</td>
<td>$3.413 \times \frac{(PCOMP+POWER0)}{(HSTEAMA\times 0.35)}$</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>1</td>
<td>WSHAFT</td>
<td>Shaft power required by MHD and oxygen plant compressors</td>
<td>$(PCOMP+POWER0)/1,000,000$</td>
<td>MW</td>
</tr>
<tr>
<td>2</td>
<td>QHPE</td>
<td>Heat recovered in high pressure economizer</td>
<td>$0.55EQSE$</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>2</td>
<td>QLPE</td>
<td>Heat recovered in low pressure economizer</td>
<td>$0.45EQSE$</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>2</td>
<td>EXTSER(7)</td>
<td>Heat added to feedwater between heaters 6 and 7</td>
<td>$QLMHD+QLPE$</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>2</td>
<td>EXTSER(3)</td>
<td>Heat added to feedwater between heaters 2 and 3</td>
<td>$QHPE$</td>
<td>Btu/hr</td>
</tr>
<tr>
<td>2</td>
<td>EXTRNL</td>
<td>Total heat available to steam cycle</td>
<td>$QLCOMB+QLMHD+QLDIF+EQSRE+EQSSC+EQSSR+EQSE$</td>
<td>MW</td>
</tr>
<tr>
<td>2</td>
<td>QTB</td>
<td>Steam flow to MHD and oxygen plant compressors</td>
<td>$-QT$ (from Run 1)</td>
<td>lbm/hr</td>
</tr>
</tbody>
</table>
### Table 6-2 (Continued)

<table>
<thead>
<tr>
<th>PRESTO II Run No.</th>
<th>Variable Name</th>
<th>Description</th>
<th>Algorithm</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>QT</td>
<td>Estimated total steam flow</td>
<td>((\text{EXTRNL} \times 3.413 \times 1.0E+06) / (\text{HSTEAMA} + \text{HSTEAMR}))</td>
<td>lbm/hr</td>
</tr>
<tr>
<td>2</td>
<td>WRATE</td>
<td>Estimated electrical output</td>
<td>(0.35 \times \text{EXTRNL})</td>
<td>MW_e</td>
</tr>
</tbody>
</table>
431 Btu/lb at 2400°F. Thus, SINGH uses the following expression for calculating EQH01:

\[ EQH01 = 431 \times MSKH01. \]

SINGH next calculates the mass flow rate of flue gas exiting the radiant furnace (MFGH02, lbm/hr) as the difference MFGT17 and MSKH01.

The energy transported from the radiant furnace by the flue gas (ETH02) has two components. One component is unreleased chemical energy whose value has been previously calculated as ECT15. The other component is the thermal energy of the flue gas (EQH02, lbm/hr). To calculate EQH02, SINGH recalls data previously calculated and stored by NASA SP-273 subroutines EQLBRM and SAVE. During execution of the MHD topping cycle code, SINGH directed other NASA SP-273 subroutines to compute and store flue gas thermodynamic properties for several states defined by specific temperatures and pressures. The state specified for the radiant furnace exit required a temperature of 2900°F (1867K) and a pressure of 1 ATM. This state point for this condition is identified as point 7 in the program code. Another state, identified as point 5, was specified with a temperature of 80°F (300K) and a pressure of 1 ATM. Point 5 represents the zero enthalpy reference condition established for the plant analysis. SINGH uses the recalled data in the following algorithm for EQH02:

\[ EQH02 = MFGH02 \times (HSUM(7) - HSUM(5)) \times R \times 1.8 \]

where \( R = \) Universal gas constant = 8314.3 J/((KG-MOLE)(K))

\[ HSUM(7) = h/R \text{ at point 7} \]
\[ HSUM(5) = h/R \text{ at point 5} \]
\[ h = \text{enthalpy (Joules/Kg)} \]
After EQH02 has been calculated, SINGH calculates ETH02 as the sum of EQH02 and ECT15. The next quantity of interest is the amount of heat transferred from the flue gas to the water walls for steam generation (EQRSF, Btu/hr). EQRSF is calculated by the following expression:

$$EQRSF = EQKT17 - EQH01 - EQH02$$

As the flue gas exits the radiant furnace, it simultaneously enters the secondary combustor where it mixes with secondary combustion air and spontaneously completes combustion. SINGH calculates the mass flow rate of secondary combustion air (MAH04, lbm/hr) as follows:

$$MAH04 = (\frac{1.05-SR}{SR}) \times (MAT03+MAT04)$$

SR is the stoichiometric ratio for primary MHD combustion. The value of SR is read by SINGH. The desired mass flow rate of secondary air should be 5 percent in excess of the minimum required for complete combustion. This is the significance of the 1.05 term in the expression for MAH04. The sum MAT03 and MAT04 represents the oxidant mass flow to the MHD combustor for the case of no oxygen enrichment. The mass flow rate of flue gas from the secondary combustor (MFGH05, lbm/hr) is calculated as the sum of MFGH02 and MAH04.

The heat released by secondary combustion has been previously calculated as ECT15. This heat performs two functions. Because this model assumes that all flue gas exits the secondary combustor at 2900°F, some of the heat released during combustion must be used to heat the mass that entered the secondary combustor as secondary combustion air. The remaining heat released during combustion is allocated to steam generation in the secondary combustor water walls.
The secondary combustion air enters the secondary combustor at TAH04 degrees Rankine. The value of TAH04 is specified by the program user and read by SINGH. The heat required to raise the temperature of the secondary air (QAFGH5, Btu/hr) from TAH04 to 2900°F (3360°F) is calculated by SINGH according to Chapman

\[ QAFGH5 = (1.1875E-05 \times (3360. **2 - TAH04) **2) + 224 \times (3360. - TAH04)) \times MAH04 \]

Once QAFGH5 has been determined, SINGH calculates the heat available for steam generation in the secondary combustor water walls (EQSSC, Btu/hr) by the following:

\[ EQSSC = ECT15 - QAFGH5 \]

The amount of thermal energy transported into the secondary combustor by the secondary combustion air (EQH04, Btu/hr) is also calculated according to Chapman

\[ EQH04 = (1.1875E-05 \times (TAH04 **2 - 540. **2) + 224 \times (TAH04 - 540.)) \times MAH04 \]

The total energy transported from the secondary combustor by the flue gas (EQH05, Btu/hr) is in the form of thermal energy and is calculated by SINGH as the sum of EQH02, EQH04, and QAFGH5.

From the secondary combustor, the flue gas enters a convective heat transfer section consisting of the superheater, the reheater, and the MHD primary oxidant heater. These heat exchangers reduce the temperature of the flue gas from 2900°F (1867K) to 700°F (644K). SINGH calculates the quantity of heat removed from the flue gas (QRFG56, Btu/hr) as follows:

\[ QRFG56 = MFGH05 \times (HSUM(7) - HSUM(6)) \times R1.8 \]

HSUM(6) is calculated for a temperature of 700°F and a pressure of 1
ATM. The amount of thermal energy transported from this section by the flue gas (E\text{QH06}, \text{Btu/hr}) is calculated as the difference of E\text{QH05} and QRFG56. The quantity of heat required for MHD primary oxidant heating has been previously calculated as Q\text{HEOAT}. Thus, the quantity of heat available for steam superheating and reheating (E\text{QSSR}, \text{Btu/hr}) is readily calculated by SINGH as the difference of QRFG56 and Q\text{HEOAT}. At this point it is not possible to divide E\text{QSSR} between superheating and reheating requirements. The precise superheat and reheat demands will not be calculated until the PRESTO II program is executed. To execute, the PRESTO II program must be provided with only the gross quantity of heat available for steam generation. PRESTO II then determines the boiler, superheating, and reheating requirements. It is possible that PRESTO II results will not require all of E\text{QSSR} for superheat and reheat. In this case, the excess heat will be allocated for initial steam generation. For this reason, the model is very general in its treatment of E\text{QSSR}.

The flue gas exits the first convective heat transfer section at 700°F (394K). The second heat transfer section uses the recovered flue gas heat to generate steam for the seed regeneration plant, to heat a nitrogen stream for coal drying, to heat secondary combustion air, and to heat economizer water for the steam cycle. SINGH calculates the heat recovered from the flue gas by this second heat transfer section (QRFG67, \text{Btu/hr}) as follows:

\[ \text{QRFG67} = \text{MFGHO5} \times (\text{HSUM(6)} - \text{HSUM(2)}) \times \text{R} \times 1.8 \]

HSUM(2) is calculated for a temperature of 250°F and a pressure of 1 ATM. With the exception of economizer heat, all of the heat demands for
this heat exchanger section have been previously calculated. The seed regeneration plant demand is the sum of QTR18 and QKR40. The coal drying demand is QNAT12, and the secondary combustion air demand is EQH04. The amount of economizer heat available (EQSE, Btu/hr) is then calculated by SINGH as follows:

\[
EQSE = QRFG67 - QTR18 - QKR40 - QNAT12 - EQH04
\]

The amount of thermal energy transported by the flue gas from the second convective heat transfer section (EQH07, Btu/hr) is calculated as the difference of EQH06 and QFRG67.

From the exit of the second convective heat transfer section, the flue gas enters the electrostatic precipitator (ESP) where the model assumes all potassium sulfate and the remaining coal ash are recovered. The author recognizes that this assumption will be proven inaccurate, however, there is no available data to indicate how the potassium sulfate and ash will ultimately be removed. Therefore, this assumption will have to serve for the present. The amount of potassium sulfate collected has been previously calculated as MKSRO1. The mass flow rate of the remaining coal ash (MSH08, lbm/hr) is calculated by SINGH as follows:

\[
MSH08 = 0.20\times MCT02\times XAAR\times (100.- MOISAF)/100.- MOISAR)
\]

SINGH then calculates the total potassium sulfate and coal ash recovered (MTH08, lbm/hr) as the sum of MKSRO1 and MSH08. As it exits the electrostatic precipitator, the flue gas flow is split into two streams. One stream flows to the seed regeneration plant where it removes moisture from the potassium formate flow in the spray dryer. The mass flow rate of this flue gas stream has been previously calculated as
MFGR37. The other flue gas stream (MFGH09, lbm/hr) proceeds directly to the induced draft fan after exiting the electrostatic precipitator. SINGH calculates MFGH09 by the following algorithm:

\[ MFGH09 = MFGH07 - MSH08 - MFGR37 \]

At the induced draft fan, the flue gas stream returning from the seed regeneration plant's spray dryer rejoins the main flue gas flow. The mass flow rate of the flue gas plus its added moisture has been previously calculated as MFGR39. The total flue gas mass flow rate through the stack (MFGH10, lbm/hr) is calculated as the sum of MFGH09 and MFGR39. The heat load transported from the plant by the flue gas was previously calculated as EQH07. The power required to drive the induced draft fan (PFAN, Watts) is calculated by the following algorithm from Chapman

\[ PFAN = MFGH10 \times 0.4 \]

This calculation concludes the HRSR system calculation sequence.

The steam cycle is the last major plant system modeled by SYSTEMS III. PRESTO II is the program used to model the steam cycle. The original version of this program, titled "PRESTO", was developed at the Oak Ridge National Laboratory, Oak Ridge, Tennessee and was documented by Fuller and Stovall. PRESTO was later modified by Choo and Steiger. The modified program was named "PRESTO II". For a complete understanding of how to use PRESTO II, both reference 7 and reference 8 must be consulted. This chapter does not attempt to fully explain the program code which constitutes PRESTO II. Instead, it describes the steam cycle configuration modeled by PRESTO II and presents a summary of the technique by which PRESTO II is used to model this steam bottoming
cycle. This chapter also describes the calculations performed by SINGH in preparation for executing PRESTO II.

PRESTO II is a program for predicting regenerative superheated steam cycle performance at the cycle design steam flow condition (i.e. valves wide open). PRESTO II is capable of performing these predictive calculations for a variety of cycle configurations. The cycle configuration modeled for the SYSTEMS III program is diagrammed in Figure 6-2. Heat from the MHD topping cycle components and the HRSR system produces superheated steam which drives the oxidant compressor turbine, the air separation plant compressor, and the high pressure stage of the generator turbine. Spent steam from the oxidant and air separation compressors is routed directly to the condenser. Steam exhausted from the high pressure stage is passed through a reheater and then enters the intermediate pressure stage. The steam exhausted from the intermediate pressure stage is split into two streams. One stream drives the boiler feed pump and is then routed to the condenser as spent stream. The other stream enters the low pressure stage of the generator turbine and is exhausted as spent steam which is routed to the condenser. The condensate leaving the condenser is passed through a series of feedwater heaters whose heat source is steam extracted from the three stages of the generator turbine. After exiting feedwater heater 7 (i.e. the heater immediately downstream from the condensate pump), the condensate is passed through the MHD channel cooling water passages as well as the low temperature segment of the economizer where it receives the available heat. The condensate is then returned to feedwater heater 6 and continues through the heater series until it exits feedwater heater 3.
From feedwater heater 3, the condensate passes through the high temperature side of the economizer and then returns to complete its passage through the remaining feedwater heaters. From feedwater heater 1, the feedwater begins the steam generation phase and the cycle repeats itself.

To model this steam cycle, SINGH calls PRESTO II twice. The first PRESTO II execution calculates the steam flow required by the oxidant and air separation compressors. To accomplish this calculation, SINGH must provide an estimate of the steam flow required by the two compressors (QT, lbm/hr). SINGH calculates QT as follows:

\[ QT = 3.413 \times \frac{(P_{COMP}+POWO)}{HSTEAMA^{.35}} \]

HSTEAMA is the enthalpy of the steam in its superheated state in Btu/lbm. HSTEAMA is read by SINGH. SINGH must also calculate the required value for the shaft power required by the compressors (WSHAFT, Megawatts). This is accomplished by the following algorithm:

\[ WSHAFT = \frac{(P_{COMP}+POWO)}{1,000,000}. \]

The remaining values required by PRESTO II have already been assigned values within the adapted PRESTO II code. At this point SINGH calls PRESTO II.

After the first PRESTO II execution is completed, SINGH prepares for the second PRESTO II execution which models the entire steam cycle. In preparation for this execution, SINGH calculates values for eight variables. These variables are listed and defined in Table 6-2. Table 6-2 also contains the algorithms used to calculate the variables and the units in which the results are expressed. SINGH calls PRESTO II for the second time and the steam cycle is modeled.
Upon completion of the second PRESTO II execution, SINGH performs some final calculations with the objective of determining overall plant efficiency. First SINGH calculates the electric power produced by the steam cycle (PEXS, Watts) as follows:

\[ PEXS = WWGEN \times 1,000,000. \]

WWGEN is the PRESTO II variable which reports electric power generated in Megawatts. SINGH next calculates the auxiliary power required to operate plant equipment such as pumps, HVAC equipment, lighting, motor operated valves, etc. Also included in the category of auxiliary power is the power required by the superconducting magnet, the pulverizers, the drying fans, and the induced draft fan. The auxiliary power (PAUX, Watts) is calculated by the following:

\[ PAUX = PMAG + PPFT + 0.026 \times (PEXS + POUTM) + PFAN \]

The term \(0.026 \times (PEXS + POUTM)\) accounts for the plant equipment demand as discussed by Chapman.\(^{16}\)

The next quantity calculated by SINGH is the total electric power furnished to the distribution grid by the plant (TPOWER, Watts):

\[ TPOWER = POUTM + PEXS - PAUX \]

SINGH then calculates the plant efficiency neglecting the seed regeneration coal requirement (EFFMS):

\[ EFFMS = TPOWER / (THIN \times 0.2931) \]

SINGH next recalculates THIN to include seed regeneration coal:

\[ THIN = THIN + (MCRO4 \times HCC / MOISRF) \]

Finally, SINGH calculates the overall plant efficiency (EFFC):

\[ EFFC = TPOWER / (THIN \times 0.2931) \]

At this point, execution of the SYSEMS III model is complete.
CHAPTER VII

MODEL RESULTS

This chapter reports the results of a plant analysis performed by the model described in the preceding chapters. The major characteristics of the modeled plant are presented in Table 7-1.

As discussed in Chapter III, COAL is the first program used in the model execution. Table 7-2 presents the coal analyses and HHV data required for the COAL input data file. The stoichiometric ratio, oxidant preheat temperature, and oxygen enrichment are also required as input for COAL. Their values have already been specified in Table 7-1. Three remaining input requirements for COAL are the percent potassium in the total plasma flow, the MHD combustor heat loss, and the "as fired" moisture content of the coal. For this analysis, the percent potassium is set at 1.3%, the combustor heat loss is specified as 1% of coal thermal input, and the "as fired" moisture content of the coal is set at 2%. The potassium percent is based upon sulfur removal requirements rather than plasma conductivity considerations.

DESIGN3 is the second program to be executed. The design constraints specified for the MHD generator channel are as follows:

- Magnetic Field Strength: 6.0 Tesla
- Electrical Load Parameter: 0.7
- Channel Inlet Mach Number: 0.9
- Maximum Axial Field ($E_x$): 2500 volts/meter
- Maximum Transverse Field ($E_y$): 4100 volts/meter
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate Power Output (Net)</td>
<td>1000 MW(_e)</td>
</tr>
<tr>
<td>Coal Type</td>
<td>Illinois #6</td>
</tr>
<tr>
<td>MHD Topping Cycle</td>
<td></td>
</tr>
<tr>
<td>Combustor Pressure</td>
<td>9 ATM</td>
</tr>
<tr>
<td>Oxidant Preheat Temperature</td>
<td>1100K</td>
</tr>
<tr>
<td>Oxygen Enrichment</td>
<td>20%</td>
</tr>
<tr>
<td>Stoichiometric Ratio</td>
<td>0.85</td>
</tr>
<tr>
<td>MHD Generating Channel</td>
<td>DCW</td>
</tr>
<tr>
<td>HRSR</td>
<td></td>
</tr>
<tr>
<td>Secondary Combustion Air Preheat Temperature</td>
<td>600°F</td>
</tr>
<tr>
<td>Flue Gas Temperature</td>
<td>250°F</td>
</tr>
<tr>
<td>Steam Cycle</td>
<td></td>
</tr>
<tr>
<td>Throttle Pressure</td>
<td>2400 PSIA</td>
</tr>
<tr>
<td>Throttle Temperature</td>
<td>1000°F</td>
</tr>
<tr>
<td>Reheat Temperature</td>
<td>1000°F</td>
</tr>
<tr>
<td>Condenser Pressure</td>
<td>2.00 IN.HG</td>
</tr>
<tr>
<td>Number of Feedwater Heaters</td>
<td>7</td>
</tr>
<tr>
<td>Ultimate Analysis, (%)</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.4</td>
</tr>
<tr>
<td>Carbon</td>
<td>62.4</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>16.3</td>
</tr>
<tr>
<td>Sulfur</td>
<td>3.3</td>
</tr>
<tr>
<td>Heating Value, Wet, Btu/lb</td>
<td>11265</td>
</tr>
<tr>
<td>Heating Value, Dry, Btu/lb</td>
<td>12370</td>
</tr>
<tr>
<td>Coal Rank</td>
<td>BVCB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proximate Analysis, Coal, as Received (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>8.9</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>38.0</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>41.7</td>
</tr>
<tr>
<td>Ash</td>
<td>11.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ash Analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>41.4 ± 5.4</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>19.3 ± 6.8</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>22.3 ± 6.8</td>
</tr>
<tr>
<td>T₁₀₂</td>
<td>0.9</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.12</td>
</tr>
<tr>
<td>CaO</td>
<td>5.4 ± 3.3</td>
</tr>
<tr>
<td>MgO</td>
<td>1.7 ± 1.3</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.1</td>
</tr>
<tr>
<td>S₀₃</td>
<td>7.5</td>
</tr>
<tr>
<td>Initial Deformation Temperature °F</td>
<td>1960 ± 70</td>
</tr>
<tr>
<td>Softening Temperature °F</td>
<td>2030 ± 70</td>
</tr>
<tr>
<td>Fluid Temperature °F</td>
<td>2260 ± 200</td>
</tr>
</tbody>
</table>
Maximum Transverse Current \( (J_j) \) 1 amp/meter\(^2\)
Design Mass flow 550 Kg/sec
Stagnation Pressure at Channel Inlet 9 ATM

The results of DESIGN3 and COAL executions are used to specify some of the values required by the SINGH input data file. The remaining values are user specified. The variables required by SINGH and their values as specified for this analysis are presented in Table 7-3.

The reactant data from COAL as well as the SINGH input data file are provided to NASA SP-273 and SINGH which they execute. SINGH calls PRESTO II which models the steam cycle. The results of the model execution are presented in Table 7-4. The model results were compared to a similar case analyzed by a previous study\(^{11}\), and provided agreement within reasonable limits.
### TABLE 7-3. SINGH Input Data for Modeled Plant.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>POUT</td>
<td>1,000,000,000</td>
<td>Watts</td>
</tr>
<tr>
<td>HCC</td>
<td>12370.</td>
<td>Btu/lbm</td>
</tr>
<tr>
<td>EFF</td>
<td>43.</td>
<td>%</td>
</tr>
<tr>
<td>MOISAR</td>
<td>8.9</td>
<td>%</td>
</tr>
<tr>
<td>MOISAF</td>
<td>2.0</td>
<td>%</td>
</tr>
<tr>
<td>PCTA</td>
<td>80</td>
<td>%</td>
</tr>
<tr>
<td>PCTO</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td>SFLO</td>
<td>0.139</td>
<td>Atm</td>
</tr>
<tr>
<td>PRINT</td>
<td>9.</td>
<td>°K</td>
</tr>
<tr>
<td>TAIC</td>
<td>1100.</td>
<td>Btu/lbm</td>
</tr>
<tr>
<td>QLCPUM</td>
<td>121.2</td>
<td>–</td>
</tr>
<tr>
<td>EMACH</td>
<td>0.9</td>
<td>Btu/lbm</td>
</tr>
<tr>
<td>AREAR</td>
<td>6.31</td>
<td>–</td>
</tr>
<tr>
<td>BMAX</td>
<td>6.0</td>
<td>Tesla</td>
</tr>
<tr>
<td>CEFFI</td>
<td>0.97</td>
<td>–</td>
</tr>
<tr>
<td>ENT</td>
<td>0.935</td>
<td>m²</td>
</tr>
<tr>
<td>GDMF</td>
<td>548</td>
<td>Kg/sec</td>
</tr>
<tr>
<td>GEF</td>
<td>.882</td>
<td>–</td>
</tr>
<tr>
<td>HF</td>
<td>.212</td>
<td>–</td>
</tr>
<tr>
<td>CLEN</td>
<td>9.8</td>
<td>meters</td>
</tr>
<tr>
<td>PSTAT</td>
<td>0.736</td>
<td>Atm</td>
</tr>
<tr>
<td>XS</td>
<td>0.030</td>
<td>–</td>
</tr>
<tr>
<td>XSAR</td>
<td>0.033</td>
<td>–</td>
</tr>
<tr>
<td>XAAR</td>
<td>0.114</td>
<td>–</td>
</tr>
<tr>
<td>TAH04</td>
<td>1060</td>
<td>°R</td>
</tr>
<tr>
<td>SR</td>
<td>0.85</td>
<td>–</td>
</tr>
<tr>
<td>HSTEAMA</td>
<td>1463.5</td>
<td>Btu/lbm</td>
</tr>
<tr>
<td>HSTEAMR</td>
<td>218.8</td>
<td>Btu/lbm</td>
</tr>
</tbody>
</table>
Table 7-4. Model Execution Results.

<table>
<thead>
<tr>
<th>Mass Flows (lbm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MHD Topping Cycle</strong></td>
</tr>
<tr>
<td>Raw coal to pulverizers</td>
</tr>
<tr>
<td>Dried coal to MHD combustor</td>
</tr>
<tr>
<td>Potassium formate seed to MHD combustor</td>
</tr>
<tr>
<td>Air to air separation plant</td>
</tr>
<tr>
<td>Oxygen to MHD compressor</td>
</tr>
<tr>
<td>Waste stream for coal drying</td>
</tr>
<tr>
<td>Waste stream to atmosphere</td>
</tr>
<tr>
<td>Air to MHD compressor</td>
</tr>
<tr>
<td>Oxidant to MHD compressor</td>
</tr>
<tr>
<td>Plasma to channel and diffuser</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>HRSR System</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas from topping cycle</td>
</tr>
<tr>
<td>Slag, seed, and sulfur rejected at radiant furnace</td>
</tr>
<tr>
<td>Flue gas to secondary combustor</td>
</tr>
<tr>
<td>Secondary combustion air</td>
</tr>
<tr>
<td>Flue gas to convective heat transfer sections</td>
</tr>
<tr>
<td>Potassium sulfate and ash recovered</td>
</tr>
<tr>
<td>Flue gas direct to ID fan</td>
</tr>
<tr>
<td>Flue gas to seed regeneration then to ID fan</td>
</tr>
<tr>
<td>Flue gas to stack</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Seed Regeneration Plant</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium sulfate from HRSR</td>
</tr>
<tr>
<td>Service water</td>
</tr>
<tr>
<td>Gasifier coal</td>
</tr>
<tr>
<td>Gasifier air</td>
</tr>
<tr>
<td>Lime</td>
</tr>
<tr>
<td>Flue gas to spray dryer</td>
</tr>
<tr>
<td>Carbon dioxide from regenerator</td>
</tr>
<tr>
<td>Product gas (combusted)</td>
</tr>
<tr>
<td>Gypsum and water for disposal</td>
</tr>
<tr>
<td>Vented steam</td>
</tr>
<tr>
<td>Flue gas and moisture to stack</td>
</tr>
<tr>
<td>Gasifier slag</td>
</tr>
<tr>
<td>Potassium formate for recycle</td>
</tr>
</tbody>
</table>
Table 7-4 (Continued)

<table>
<thead>
<tr>
<th>Mass Flows (lbm/hr)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam Cycle</strong></td>
<td></td>
</tr>
<tr>
<td>Steam flow to ASU compressor</td>
<td>411709.</td>
</tr>
<tr>
<td>Steam flow to MHD compressor</td>
<td>799199.</td>
</tr>
<tr>
<td>Steam flow to HP turbine</td>
<td>5198908.</td>
</tr>
<tr>
<td>Steam flow to reheater</td>
<td>4057515.</td>
</tr>
<tr>
<td>Steam flow to IP turbine</td>
<td>4043608.</td>
</tr>
<tr>
<td>Steam flow to LP turbine</td>
<td>3319409.</td>
</tr>
<tr>
<td>Condenser flow</td>
<td>6380885.</td>
</tr>
<tr>
<td>Feedwater flow</td>
<td>6380885.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy Quantities (MW)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MHD Topping Cycle</strong></td>
<td></td>
</tr>
<tr>
<td>Coal Chemical Energy</td>
<td>2326.</td>
</tr>
<tr>
<td>Oxidant Thermal Content</td>
<td>233.</td>
</tr>
<tr>
<td>Seed Decomposition</td>
<td>0.12</td>
</tr>
<tr>
<td>Combustor heat loss</td>
<td>23.</td>
</tr>
<tr>
<td>Inverter loss</td>
<td>13.</td>
</tr>
<tr>
<td>MHD electric power</td>
<td>419.</td>
</tr>
<tr>
<td>MHD channel heat loss</td>
<td>103.</td>
</tr>
<tr>
<td>Superconducting magnet power</td>
<td>0.6</td>
</tr>
<tr>
<td>Diffuser heat loss</td>
<td>25.</td>
</tr>
<tr>
<td>Flue gas thermal energy at diffuser exit</td>
<td>1610.</td>
</tr>
<tr>
<td>Flue gas unreleased chemical energy at diffuser exit</td>
<td>367.</td>
</tr>
<tr>
<td><strong>HRSR System</strong></td>
<td></td>
</tr>
<tr>
<td>Flue gas thermal energy at radiant furnace entrance</td>
<td>1610.</td>
</tr>
<tr>
<td>Steam generation in radiant furnace</td>
<td>533.</td>
</tr>
<tr>
<td>Slag, potassium, and sulfur heat loss</td>
<td>10.</td>
</tr>
<tr>
<td>Secondary air thermal content at secondary combustor entrance</td>
<td>43.</td>
</tr>
<tr>
<td>Steam generation in secondary combustor</td>
<td>152.</td>
</tr>
<tr>
<td>Superheating</td>
<td>694.</td>
</tr>
<tr>
<td>Reheating</td>
<td>257.</td>
</tr>
<tr>
<td>Steam generation in first convective section</td>
<td>33.</td>
</tr>
</tbody>
</table>
Table 7-4 (Continued)

<table>
<thead>
<tr>
<th>Energy Quantities (MW)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transferred to secondary combustion air</td>
<td>43.</td>
</tr>
<tr>
<td>Heat for coal drying</td>
<td>25.</td>
</tr>
<tr>
<td>Heat for seed regeneration steam</td>
<td>20.</td>
</tr>
<tr>
<td>Economizer</td>
<td>77.</td>
</tr>
<tr>
<td>Heat lost to stack</td>
<td>48.</td>
</tr>
</tbody>
</table>

Seed Regeneration

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>122.</td>
</tr>
<tr>
<td>Steam</td>
<td>20.</td>
</tr>
<tr>
<td>Steam Cycle Generation</td>
<td>664.</td>
</tr>
<tr>
<td>Net Power to Grid</td>
<td>1050.</td>
</tr>
<tr>
<td>Overall Plant Efficiency</td>
<td>42.7%</td>
</tr>
</tbody>
</table>

CHAPTER VIII

CONCLUSIONS

The objective of this effort has been to develop a more detailed model for analyzing prototype MHD/steam central station power plants. This has been accomplished. When the author began this work, the existing model was primarily an MHD topping cycle model. It did not address the seed regeneration process. It modeled the HRSR system and the steam cycle with one algorithm which expressed electric power produced by the turbine generator as the product of an average steam plant efficiency and the available heat. The available heat was expressed as the product of flue gas mass flow and its enthalpy difference between the MHD diffuser exit and the stack, less the heat required for oxidant heating. The plant model proposed in the preceding chapters implements a potassium formate seed regeneration model, an HRSR model, and a steam cycle model based upon PRESTO II. These new models define process streams and calculate mass flows. They calculate energy transfers and equipment power requirements. For some streams they also calculate thermodynamic property data. The new plant model also implements a modified MHD topping cycle model which contains additional process streams and required power calculations associated with the air separation plant and the coal drying and pulverizing equipment.

At this time in the development history of MHD/steam power plant technology, the model results reported in the preceding chapter are a statement of what could be as opposed to a statement of what will be.
While many of the model algorithms are well substantiated, others are only good estimates, and a very few are just estimates. As the development program continues, empirical data will either validate or alter the estimates. When this happens the validity of the model will increase. The model will then prove more useful in assessing the plant-wide impact of operating condition or performance alterations.
BIBLIOGRAPHY
BIBLIOGRAPHY


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APPENDIX
SR IS THE STOICHIOMETRIC AIR RATIO
EMAX IS THE MAGNETIC FIELD STRENGTH, TESLA
EMACH IS THE MACH # AT THE ENTRANCE OF THE MHD GENERATOR
READ (5,100C) POUT, MHC, PRINT, TAIIC, BMAX, SFLC
1,EFF,OLCPW,SP,TAH04,CEFF,HETEM,HSTEAH,EMACH,GMWF
2,HP,CEF,CEM,AREAR,ENT,PTAT,PCIA,PCTO,
3,MCSIAR,MCSIAR,AX,AXAR,XXAR
WRITE (6,1012) PCUT,MHC,PRINT,TAIIC,BMAX, SFLC
1,EFF,OLCPW,SP,TAH04,CEFF,HETEM,HSTEAH,EMACH,GMWF
2,HP,CEF,CEM,AREAR,ENT,PTAT,PCIA,PCTO
3,MCSIAR,MCSIAR,AX,AXAR,XXAR

************ FOR ED KIESLING'S DESIGN PLANT ************
THIN IS THERMAL INPUT FROM COAL INJECTED INTO THE PRIMARY
MHC COMBUSTOR (BTU/HR)
THIN=POUT*3.4129/(EFF/100.)

***** SINGH CALCULATES THE MASS FLOW RATES FOR THE MHC ICPPING CYCLE ****
(SEE FIGURE 3-1 OF REFERENCE 1)

MCT02 IS THE MASS FLOW RATE OF DRIED COAL TO THE MHC PRIMARY
COMBUSTOR (LBM/HR)
MCT02=THIN/MHC
MCISRPF IS THE MOISTURE RESTORATION FACTOR
MCISRF=((MCISRPF-(100.-MCSIAR)/(100.-MOSIF))MCSIAR+100.)/100.
MCT01 IS THE MASS FLOW RATE OF DRIED COAL FROM THE STOCKPILE (LB/M/HR)
MCT01=MCT02*MCISRPF

*** SINGH CALL DATA AND SUBROUTINES FROM NASA SF=273 IC DEFINE ***
*** MHD PRIMARY COMBUSTOR CONDITIONS ***
HP=TRUE.
PP=PRINT
TT=3000.
GA=0.007
CALL I101
CALL BOLBRM
HP_FALSE.
ICOMBSTI

*** SINGH NOW RESUMES MASS FLOW RATE CALCULATIONS ***

MCAT08 IS THE MASS FLOW RATE OF O2 ENRICHED AIR TO THE MHC COMBUSTOR (LB/M/HR)
MCAT08=O2*MCT02*(1.-SFLC)
PICIA=PCTA
#AT03 IS THE MASS FLOW RATE OF AMBIENT AIR TO THE MHC OXIDANT
CCOMPRESSOR (LB/M/HR)
#AT03=(PCTA/100.)MCAT08
PICIO IS THE PERCENT OF OXYGEN IN THE FLOW
PCTO=PCTA
#AT05 IS THE MASS FLOW RATE OF FURE C2 FROM THE AIR SEPARATION
PLANT (LB/M/HR)
#AT05=MCAT08*PICIO/100.)*MCAT08
#AT04 IS THE MASS FLOW RATE OF AMBIENT AIC TO THE AIR SEPARATION
UNIT (LB/M/HR)
#AT04=AT04=MCAT08
#AT04=AT04=MCAT08
#AT04=AT04=MCAT08
#AT04=AT04=MCAT08
#WVT13 IS THE MASS FLOW RATE OF MOISTURE REMOVED FROM THE COAL (LB/M/HR)
C MVT13 = NCT01 + NCT02
C GWVT13 is the mass flow rate of N2, AR, and moisture to the CCAL (lb/m3)
C NVT13 = 1.078 * MVT13
C NMA11 is the mass flow rate of N2 and AR, rec. for the CCAL drying (lb/m3)
C MVT11 = MVT01 + MVT02
C NMA10 is the mass flow rate of N2 and AR released to the atmosphere (lb/m3)
C MVT10 = NMA05 + NMA11
C MVT14 is the mass flow rate of FCTASSU to the seed supply to the CCAL (lb/m3)
C MVT13 = NMA10 + MVT14 + MCT14
C MVT13 is the mass flow rate of flue gas from the CCAL (lb/m3)
C MVT17 is the mass flow rate of flue gas from the diffuser (lb/m3)
C

WRITE(6,5209)NCT02, MCA01, MCA08, MCT13, MCT09, MCT14, NMA10, NMA11, NMA12, NMA13, MVT13, MVT14, MVT15
MVT13, MVT03

5209 FORMAT(*!! *** MASS FLOW SUMMARY AND OVERALL MASS BALANCE *****, /,
1X. 'MCT02: ',E10.5,'X. 'MCA01: ',E10.5,'X. 'MCA08: ',E10.5,'X. ', 'MCT13: ',E10.5,'X. ', 'MCT09: ',E10.5,'X. '
MCT14: ',E10.5,'X. 'NMA10: ',E10.5,'X. 'NMA11: ',E10.5,'X. ', 'NMA12: ',E10.5,'X. '
MVT13: ',E10.5,'X. ', 'MVT14: ',E10.5,'X. ', 'MVT15: ',E10.5,'X. '
MVT13: ',E10.5,'X. ', 'MVT03: ',E10.5,'X. '

5210 FORMAT(*!! *** MASS FLOW SUMMARY AND OVERALL MASS BALANCE *****, /,
1X. 'MCT02: ',E10.5,'X. 'MCA01: ',E10.5,'X. 'MCA08: ',E10.5,'X. ', 'MCT13: ',E10.5,'X. '
MCT09: ',E10.5,'X. ', 'MCT14: ',E10.5,'X. ', 'MVT13: ',E10.5,'X. '
MVT03: ',E10.5,'X. '

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**WARNING - MASS IS CREATED IN TOPPING CYCLE**

If unbalanced, continue.

---

**SINGH CALCULATES ENERGY QUANTITIES, THERMODYNAMIC PROPERTIES, AND GEOMETRY FOR THE MHC TOPPING CYCLE**

---

**PCWERC** is the shaft power required from the ASG turbine (Watts)

**PCWERC** = 0.175 * **POAT07**

**POAT07** is the pressure required from the oxidant

**POAT07** = 10.5 * **AFLOV**

**AFLOV** is the oxidant flow volume to the oxidant compressor (CFM)

**AFLOV** = 1.35 * **POAT06**

**PCCMP** is the shaft power delivered to the oxidant compressor (Watts)

**PCCMP** = 3.25 * **AFLOV**

**EPCMP** is the temperature of the oxidant at the compressor

**EPCMP** = 14.7 * **PCCMP**

**ECAT07** is the rate at which heat is gained by the oxidant during compression

**ECAT07** = 0.06 * **PCCMP**

**ECAT07** = 0.06 * **ECAT07**

**ELCC1** is the energy lost during the oxidant compression

**ELCC1** = **ECAT07**

**ELECC1** is the electric power required to drive the oxidant compressors

**ELECC1** = **ECAT07**

**ELECC1** = **ECAT07**

**ECAT07** is the heat transferred to the MHC feed air and argon
CRYING GAS FROM FLUE GAS (BTU/HR)
GNAT12=101.*MNAT11
GLCDT IS THE DRYING HEAT LCST TC COAL HEATING AND THEN TC
THE ATMOSPHERE (BTU/HR)
GLCDT=0.25*DMVT13
GNAT13 IS THE HEAT RETAINED BY THE COAL CRYING GAS (BTU/HR)
GNAT13=GNAT12-DMVT13-GLCDT

**** SINGH CALLS NASA SF-273 TC CALCULATE AND STORE FLUE
GAS PROPERTY DATA AT FOUR DIFFERENT STATES. THEY ARE
STATE POINTS FOR SECONDARY COMBUSTOR INLET,
ECONOMIZER INLET, STACK AND REFERENCE CONDITION ****

CTP=TRUE.
NPT=2 IDENTIFIES PROPERTIES AT THE EXIT OF THE STEAM PLANT
ISV=-NPT
NPT=7 IDENTIFIES PROPERTIES AT THE SECONDARY COMBUSTOR INLET
CALL SAVE
ISV=1
CALL SAVE
P=1.00
IT=1666.7
CALL EQLBRM
ISV=-7
CALL SAVE
AMIX=EGRAT
EGRAT=.9524
CF=(-EGRAT*VMIN(2)+VPLS(2))/(VPLS(1)+EGRAT*VMIN(1))
call newof
CTP=TRUE.
NPT=6 IDENTIFIES PROPERTIES AT THE ECONOMIZER INLET
ISV=-NPT
NPT=6
CALL SAVE
TTLCD=2000.
TT=TTGLD
PP=1.00
IT=2000
CALL EQLBRM
ISV=6
CALL SAVE
CALL CUTF2
NPT=6
ISV=6
CALL SAVE
IT=1600.
PP=1.00
CALL EQLBRM
ISV=6
CALL SAVE
CALL CUTF2
IF(IT.NE.0.0) GO TO 4001
TTLCD=TTGLD+100.
NPT=2
GO TO 4002
CONTINUE
NPT=6
ISV=6
CALL SAVE
IT=1200.
PP=1.00
CALL EQLBRM
ISV=-6
CONTINUE
NPT=6
ISV=6
CALL SAVE
IT=1200.
PP=1.00
CALL EQLBRM
ISV=-6
CALL SAVE
CALL OUT2
NPT=6
ISV=6
CALL SAVE
TT=900
PP=1.00
CALL EOLBR
ISV=6
CALL SAVE
CALL OUT2
NPT=6
ISV=6
CALL SAVE
TT=644.4
PP=1.00
CALL EOLBR
ISV=6
CALL SAVE
CALL OUT2
NPT=2
ISV=6
CALL SAVE
PP=1.00
CALL EOLBR
ISV=2
CALL SAVE
CALL OUT2
NPT=5
ISV=6
CALL SAVE
TT=298 DEG K., AND P=1.0 ATM.
NPT=5
ISV=2
CALL SAVE
PP=1
TT=300
CALL EOLBR
CALL OUT2
IF(TT.LE.0.0) GO TO 5003
NPT=2
ISV=6
CALL SAVE
PP=1.00
TT=200
CALL EOLBR
CALL OUT2
STOP

5003 EGRAT=AMIX
FF=(EGRAT*VMIN(2)-VPLS(2))/(VFLS(1)+EGRAT*VMIN(1))
CALL NEMOF
C TP=.FALSE.
**** SINGLE RESUMES CALCULATION OF ENERGY QUANTITIES,
THE THERMOCYCLIC PROPERTIES, & GEOMETRY FOR THE TOPPING
CYCLE. ****
C CMT14 IS THE ENERGY REQUIRED TO FREE POTASSIUM FROM FORMATE
(C2H2O2)2
C CMT14=4.9MT14
C C MCB IS THE HEAT FROM THE COMBUSTION LOST IN THE COOLING
C WATER (BTU/HR)
C CMCB=OLCFI#
C C EKG15 IS THE KINETIC ENERGY AND HEAT TRANSFERRED FROM THE
CCM很多事情 BY THE PLASMA (BTU/HR)
EQR15=(HSUM(1)-HSUM(4))*G*MPT15*E
EQR15 IS THE UNRELEASED CHEMICAL ENERGY TRANSPORTED FROM THE
COMBUSTOR BY THE PLASMA (BTU/HR)
EC115=TH15*GQAO16-EQR15-GCQOMB

**** SINGH CALCULATES NOZZLE GEOMETRY AND PLASMA THERMODYNAMIC
PROPERTIES ****
SCONVEL(1) IS THE VELOCITY CF SOUND THROUGH THE PLASMA AT
COMBUSTOR CONDITIONS (FTERS/SEC)
SCONVEL(1)=(RR*GAMMAS(1)*TMY(1)/MM(1))*S
RHQC IS THE PLASMA DENSITY IN THE COMBUSTOR (KG/CUBIC METER)
RHQC=1./(VLM(1)*0.001)
RHCT IS THE PLASMA DENSITY AT THE NOZZLE THRUST (KG/CUBIC METER)
RHCT=RHQC/((1./GAMMAS(1)-1./2.)*((1./GAMMAS(1)-1.)))
AT IS THE CROSS SECTIONAL AREA OF THE NOZZLE THRUST (SQUARE METERS)
AT=(MPT15*45359)/(SCONVEL(1)*RHCT*3600.)
BN=1./(GAMMAS(1)-1.)
CN=1./(BN*GAMMAS(1)-1.)
AK IS THE CROSS SECTIONAL AREA OF THE NOZZLE EXIT (SQUARE METERS)
AK=1.78/AT/GAMMAS(1)*CN
RE IS THE PLASMA DENSITY AT THE NOZZLE EXIT (KG/CUBIC METER)
RE=RHQC/(1./(GAMMAS(1)-1.)))
TE IS THE STATIC TEMPERATURE AT THE NOZZLE EXIT (DEGREES KELVIN)
TE=TCOMB/AN
PENZ IS THE STATIC PRESSURE AT THE NOZZLE EXIT (ATM)
PENZ=PRINT/((GAMMAS(1))/GAMMAS(1)-1.)))

**** MHD GENERATOR CHANNEL ANALYSIS ****
CCMP IS THE GENERATOR DESIGN Mass FLOW IN LB/HR
HFF IS THE UNAPPROPRIATE ELECTRICAL ENERGY EXTRACTED BY GENERATOR CHANNEL
HFF=HFF*G0**G**0.05**0.35
GEFF IS THE ELECTRICAL MHD GENERATOR EFFICIENCY
GEFF=GEFF/(1.+G0**G**0.05**0.35
ENTA IS THE ENTRANCE AREA OF THE CHANNEL IN (SQUARE METERS)
ENTA=MP15*G0**G
AREA IS THE AREA RATIO OF THE CHANNEL=EXIT AREA OVER ENTRANCE
AREA=ENTRA/ENTA
PEXM IS THE D.C. ELECTRIC POWER DEVELOPED BY MHD CHANNEL (WATTS)
PPEXM=PRINT/((GAMMAS(1))/GAMMAS(1)-1.)))**7931HFF**PPI15
CROSS IS THE INVERTER EFFICIENCY
CROSS IS THE A.C. ELECTRIC POWER AVAILABLE TO GRID (WATTS)
CROSS=CROSS**PPEXM
GLMHC IS THE PLASMA ENERGY TRANSFERRED TO CHANNEL COOLING
WATER AS HEAT (BTU/HR)
GLMHC=PEXM**3.4129-1.**G**0.0**0.35
EQT16 IS THE KINETIC ENERGY AND HEAT TRANSPORTED FROM CHANNEL
BY PLASMA (BTU/HR)
EQT16=EQT16-(PEXM**3.4129)-GLMHC
ETT16 IS THE TOTAL ENERGY TRANSPORTED FROM CHANNEL BY PLASMA
ETT16=EQT16+EC115
CLEN IS THE CHANNEL LENGTH IN METERS
PEAC IS THE ELECTRIC POWER REQUIRED TO OPERATE THE SUPER-
CONDUCTING MAGNET (WATTS)
PEAC=CLEN**1000.*(13.*((ENTA**0.5)+(ENTA*AREA)**0.5))
1+**G**0.0**0.35
WRITE (6,3014) CLEN,ENTA,AREA,HFF,GEFF,FSTAT,FRECM

THE NEXT STEPS UTILIZE SP-273 TO FIND THE OTHER THERMODYNAMIC
PROPERTIES FOR THE ENTRANCE AND PRESSURE AT THE EXIT OF THE MHD
**SING CALLS NASA SP-273 SUBROUTINES FOR CHANNEL EXIT PROPERTIES (NPT=3)**

NPT=3 identifies properties at the exit of the duct (entrance of the diffuser).

ISV=1
CALL SAVE
MP=TRUE
PSTAT is the static pressure at the output of the duct.
PP=PSTAT
TT=2400.
HSUBO=HSUB-PECN(3.1413/(NPT15*1.8*GEFF))
CALL EBLKSM

**DIFFUSER ANALYSIS**

BBB=(ENT#AREAR)**.5*100
LEN is the diffuser length (CM)
LEN=(3.79*BBB)

DWT is the wall temperature
DWT=1200.

GLCIF is the heat transferred from the plasma to the diffuser.
GLCIF=6.4*(TTT(3)**2)*CLEN(1.0316*BBB*LEN+0.016*0.016*CLEN(1.0)
1.025E-06*BBB*LEN*VAL-1.6125E-05*(CLEN(3)))/2.)**3.129

ETT17 is the total energy transferred from the diffuser by the fluid gas (BTU/HR)
ETT17=(ETT17-GLCIF)

ETT17 is the kinetic energy and sensible energy transferred from the diffuser.

ETT17=ETT17-ETT15

**SING CALLS NASA SP-273 SUBROUTINES TO DETERMINE FLUE GAS PROPERTIES AT DIFFUSER EXIT (NPT=4)**

PDC is the stagnation pressure at the output of the diffuser in FSA.
PDC=(.25*1.40*3/(SONVEL(3)**2))/(VLM(3)**101385.1)*PSTAT)*14.7

ISV=1
CALL SAVE
MP=TRUE
HSUBO=(HSMU(3)-GLCIF)/(R*1.8*NPT15)-((N.COMVEL(3)**2)/(5.39
1E05*R*1.8))
TT=2000.
PP=PDC/14.7
CALL EBLKSM

**MC TCPING CYCLE ENERGY BALANCE**

1210 FORMAT(1X,'MC TCPING CYCLE - ENERGY QUANTITIES'

1.0D-120,'ENERGY IN',T30,'ENERGY CUT',T30',AIR SEPARATION PLANT'

T30,'DESCRIPTION',T42,'QUANTITY(BTU/HR OR WATTS)',10X'

5.95,'QUANTITY(FTU/HX CR WATTS)',T42,
6.5SHAFT POWER REQUIRED BY TURBINE',T42,
7F12.1,'WATTS',12)

WRITE(6,1211)PCOMP,00AT07
1211 FORMAT(T3), * ** PRIMARY OXICANT COMPRESSION ***, //T5,
1 ' DESCRIPTION', T42,
2 ' QUANTITY(BTU/HR)', 10X, ' DESCRIPTION', T95,
3 ' QUANTITY(BTU/HR]', //,
4 'SHAFT POWER REQUIRED BY TURBINE', T42,F12.1, 'WATTS', 5X,
5 'OXICANT THERMAL ENERGY', T95,F12.1, //)
WRITE(6,1211)PPFT,GCDC,GMAT12,GMAT13

1212 FORMAT(T30)
1 ' ' COAL PULVERIZERS & DRYERS **** , //T5,
2 ' DESCRIPTION', T42,
3 ' QUANTITY(BTU/HR CR WATTS)', 10X, ' DESCRIPTION', T95,
4 ' QUANTITY(BTU/HR CR WATTS)', //,
5 ' ELECTRIC POWER FOR PULVERIZERS & FANS', T42,F12.1,
6 ' WATTS', 5X, ' HEAT LCST TC CCAE', T95,F12.1, //T5,
7 ' THERMAL ENERGY OF NITROCELL DRYING STREAM', T42,F12.1,10X,
8 ' THERMAL ENERGY IN EXITING GAS', T95,F12.1, //)
C
WRITE(6,1213)THIN,OKT14,OCAT08,GLC02,EOKT15,ECT15

1213 FORMAT(T25), * **** MHD COMBUSTOR ***** , //T5,
1 ' DESCRIPTION', T42,' QUANTITY(BTU/HR CR WATTS)', 10X,
2 ' DESCRIPTION', T95,
3 ' QUANTITY(BTU/HR CR WATTS)', //,
4 ' THERMAL ENERGY', T95,F12.1,10X,
5 ' MHD HEAT LOSS', T95,F12.1, //
6 ' PLASMA THERMAL & KINETIC ENERGY', T95,F12.1, //
7 ' PLASMA CHEMICAL ENERGY', T95,F12.1, //)
C
WRITE(6,1214)EOKT15,POUTM,CLMHD,ECT15,EOKT16,PMAG,ECT15

1214 FORMAT(T25), * **** GENERATOR CHANNEL ***** , //T5,
1 ' DESCRIPTION', T42,' QUANTITY(BTU/HR CR WATTS)', 10X,
2 ' DESCRIPTION', T95,
3 ' QUANTITY(BTU/HR CR WATTS)', //,
4 ' THERMAL & KINETIC ENERGY', T95,F12.1,10X,
5 ' ELECTRIC POWER TO GRID', T95,F12.1,
6 ' MHD HEAT LOSS TC COOLING WATER', T95,F12.1, //
7 ' PLASMA CHEMICAL ENERGY', T42,F12.1,10X,
8 ' PLASMA THERMAL & KINETIC ENERGY', T95,F12.1, //
9 ' MAGNET POWER', T42,F12.1,10X, ' PLASMA CHEMICAL ENERGY', T95,F12.1, //)
C
WRITE(6,1215)EOKT16,QLCIF,ECT15,EOKT17,ECT15

1215 FORMAT(T25)
1 ' **** MHD DIFFUSER ***** , //T5,
2 ' DESCRIPTION', T42,' QUANTITY(BTU/HR CR WATTS)', 10X,
3 ' DESCRIPTION', T95,
4 ' QUANTITY(BTU/HR CR WATTS)', //,
5 ' THERMAL & KINETIC ENERGY', T95,F12.1,10X,
6 ' HEAT LOSS TC COOLING WATER', T95,F12.1, //
7 ' FLUE GAS CHEMICAL ENERGY', T42,F12.1,10X,
8 ' THERMAL ENERGY & KINETIC ENERGY', T95,F12.1, //
9 ' PLASMA CHEMICAL ENERGY', T95,F12.1, //)

**** SEED REGENERATION VIA THE FCRMATE PROCESS *****

WKSR01 IS CRY M2SCA FROM M2S EQUIPMENT LPM/HR
WKSR01=5.44*MT02*KS9.98
KLHRSP IS THE POTASSIUM LCST IN THE RADIANT SURFACE (LPM/HR)
KLHRSP=30./84.)*MT14=78.174,)*WKSR01
IF(KLHRSP,QG.03 GC TO 9998
WRITE(6,*) INSUFFICIENT POTASSIUM FOR SULFUR RECYCLE.
C MCR20 IS CC2 FRCA REGENERATOR TC ATMOSPHERE LEM/HR
C MCR200 IS CC2 MCR20
C MCR21 IS PRODUCT GAS TC RFACTOR LEM/HR
C MCR21=MCR21=MCR20
C MCR22 IS PRODUCT GAS TC HEAT RECOVERY LEM/HR
C MCR22=0.93*MCR21
C MTR23 IS K AND CA COMPCUN SLURRY TO FLASH TANK LBM/HR
C MTR23=MTR23+MGR22
C MCR25 IS STEAM FRCA FLASH TANK LBM/HR
C MCR25=MTR23+MTR23
C MTR24 IS K AND CA COMPCUN SLURRY FROM FLASH TANK LBM/HR
C MTR24=MTR24+MGR25
C MCR26 IS SERVICE WATER TC HEAT EXCHANGER A LEM/HR
C MCR26=0.08*MCW11
C MCR27 IS SERVICE WATER FRCA HEAT EXCHANGER A LEM/HR
C MCR27=MCR27+MGR26
C MTR28 IS Gypsum AND WATER TO DISPOSAL LEM/HR
C MTR28=MTR28+MTR24
C MTR29 IS RECYCLE K COMPCUN SLURRY FROM GYPSUM FILTER LBM/HR
C MTR29=MTR29+MGR29
C MCR30 IS K COMPOUNDS SLURRY FROM GYPSUM FILTER LBM/HR
C MCR30=MTR29+MCW27+MTR28+MTR29
C MCR33=MTR30+MTR30
C MCR34 IS STEAM VENTED FROM K COMPCUN SLURRY LEM/HR
C MCR34=0.50*MCW22
C MCR35 IS K COMPCUNDS TO SEAFAY DRYER LEM/HR
C MCR35=MCR35+MCW33+MCW34
C MGR36 IS GAS FROM EVAPRATOR LEM/HR
C MGR36=MCR22
C MGR37 IS FLUE GAS TC SPRAY DRYER LBM/HR
C MGR37=14.12*MKM35
C MCR38 IS K COMPOUNDS TC HEAT EXCHANGER C LEM/HR
C MCR38=0.636*MCW35
C MCR39 IS FLUE GAS AND MOISTURE TC STACK LBM/HR
C MCR39=MGR37+MCW35+MCR38
C MCR40 IS K COMPOUNDS TC K2CO3 FILTER LBM/HR
C MCR40=MCR38+MCW38
C MCR40 IS THE HEAT REQUIRED FROM HEAT EXCHANGER C (BTU/HR)
C MCR40=MCR38+MCW38
C MGR40 IS STEAM TC HEAT EXCHANGER C LEM/HR
C MGR40=MCR40+MCW36
C MGR41 IS CONDENSATE FROM HEAT EXCHANGER C LEM/HR
C MGR41=MGR41+MCW42
C MCR44 IS PENTASIUM FCRMATE TO MHC CYCLE LEM/HR
C MCR44=MCR40+MCW43
C SGFM IS MASS FLC RATE OF STACK GASES (LB/HR)
C SGFM=CFLOM+SFLON+FLCH3+SAFL01
C 1=SRRF+MGR37+MGR39+MGR22
C S020524 IS SUM OF MWSR02+MWSR06+MWSR26
C S020524=MWSR02+MWSR06+MWSR26
C TOTALL IS SUM OF ALL ABOVE INPUT FLOW STREAMS
C TOTALL=MSR01+S020524+MCR04+MCR14+MFGR37
C TOTALL IS SUM OF ALL ABOVE OUTPUT FLOW STREAMS
C TOTALLC=MCR20+MGR22+MTR28+MSR34+MGR39+MKCR44+MSR09
C WRITE(6,719)XG,MCCT02,MSK01,MSW02,MSW03,MCR04,MSW06,
C MCR07,MCR12,MCW11,KM01,LMR12,MCW13,MCR14,
C MCR15,MCR20,MGR22,MCR30,MCW31,MCW32,MCW33,MSR32,
C 719 FCRA2 IS MCR20=MCR20
C **** FCRA2 SEED REGENERATION MODEL ****
C MCR20=MCR20
\[ \text{MAH04 IS THE MASS FLOW RATE OF SECONDARY COMBUSTION AIR (LPM/HR)} \]
\[ \text{MAH04 = \{1.05 \times \text{SP}\} \times (\text{PA04} + \text{MAH04})} \]
\[ \text{MFGH05 IS THE MASS FLOW RATE OF FLUE GAS FROM THE SECONDARY COMBUSTION (LPM/HR)} \]
\[ \text{MFGH05 = \text{MFGH02} + \text{MAH04}} \]
\[ \text{QFGH05 IS THE HEAT REQUIRED TO RAISE SECONDARY AIR TEMPERATURE FROM TA04 TO 2900 DEG F (BTU/HR)} \]
\[ \text{QFGH05} = (1.175 \times \text{SP}) \times (\text{TA04 + \text{MAH04}}) \times \text{MAH04} \]
\[ \text{EGSSC IS THE HEAT AVAILABLE FOR STEAM GENERATION IN THE SECONDARY COMBUSTION WATER WALLS (BTU/HR)} \]
\[ \text{EGSSC = 675 \times \text{QFGH05}} \]
\[ \text{ECH04 IS THE HEAT TRANSFERRED INTO SECONDARY COMBUSTION BY SECONDARY COMBUSTION AIR (BTU/HR)} \]
\[ \text{ECH04 = (1.175 \times \text{SP}) \times (\text{TA04 + \text{MAH04}}) \times \text{MAH04}} \]
\[ \text{ECH05 IS ENERGY TRANSFERRED FROM THE SECONDARY COMBUSTION BY THE FLUE GAS (BTU/HR)} \]
\[ \text{ECH05 = ECH02 + QFGH05} \]
\[ \text{ECH06 IS THE HEAT AVAILABLE FORheaRTING AND HEATING STEAM (BTU/HR)} \]
\[ \text{ECH06 = 60 \times \text{ECH05} \times \text{ECH05}} \]
\[ \text{MSH05 IS THE QUANTITY OF C\text{AL ASH REMOVED IN THE ESP (LPM/HR)} \]
\[ \text{MSH05 = 0.2 \times (\text{MCT02} \times \text{XAH0}) / (100 + \text{MCISAF})} \]
\[ \text{MFGH09 IS THE MASS FLOW RATE OF FLUE GAS FROM THE ESP TO THE INDUCED DRAFT FAN (LPM/HR)} \]
\[ \text{MFGH09 = \text{MFGH05} - \text{MSH05} - \text{ECH05}} \]
\[ \text{MFGH10 IS THE TOTAL FLUE GAS MASS FLOW RATE TO THE STACK} \]
\[ \text{MFGH10 = \text{MFGH09} + \text{MFGR39}} \]
\[ \text{FFAN IS THE ELECTRIC POWER REQUIRED BY I.D. FAN (WATTS)} \]
\[ \text{FFAN = MFGH10 \times 0.4} \]

**OUTPUT HSRS VARIABLES**

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WRITE(6, 7203) MSKH01, ECH01, MFGH02, EH02, ECG02, EC55F, XAH04, 1MFGH05, QFGH05, ECSSC, ECHO4, ECHO5, ORFG5, ECH06, ECSSR, ORFG67, 2ECHO7, ECHO8, MFGH09, MFGH10, EFGH09, EFGH10, T209
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**7209**

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**7210**

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**7211**

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8212 FORMAT(T30,
1'*** SUPERHEATER, REHEATER & OXIDANT HEATER ***',//,T5,
6'SUPERHEATER',T5,
5'QUANTITY(ETU/HR)',10X,'DESCRIPTION',T95,
4'QUANTITY(PFU/HR)',//,
5'T5,'FLUE GAS THERMAL',T42,F12.1,10X,
6'FLUE GAS THERMAL',T95,F12.1,//,T42,
7'OXIDANT HEATER',T42,F12.1,10X,
8'T5,'SUPERHEAT, REHEAT & EILER',
9'T95,F12.1,//)
C
WRITE(6,8213)ECOH6,ECOH7,ECOH4,CNAT12,CGRP,
1ECSE,ECOH7,
8213 FORMAT(T25,
1'*** 2ND CONVECTIVE HEAT TRANSFER SECTION ***',//,
2'T5,'DESCRIPTION',T42,'QUANTITY(ETU/HR)',10X,
3'DESCRIPITION',T5,
4'QUANTITY(ETU/HR)',//,T5,'FLUE GAS THERMAL',
5'T42,F12.1,10X,'FLUE GAS THERMAL',T95,F12.1,//,
6'T64,'SECONDARY COMBUSTION AIR',T95,F12.1,//,
7'T64,'COAL DRIING NITRICN',T95,F12.1,//,
8'T64,'SEED REGENREATION STEAM',T95,F12.1,//,
9'T64,'ECONOMIZER',T95,F12.1,//,
IT64,'ENERGY LOST THROUGH STACK=',T95,F12.1,//)
C
*************** STEAM PLANT CALCULATIONS (PRESTC) ***************
DO 540 I=1,12
PE(I)=0.00
PP(I)=DBLE(PE(I))
ELSE(I)=0.0
EPES(I)=DBLE(ELSE(I))
C
540 CONTINUE
C
CT IS THE STEAM FLOW RATE TO THE AIR COMPRESSOR TURBINE AND
C OXYGEN PLANT. UNITS ARE LP/HR STEAM.
C X=3.413*(PCOMP+FCWERC)/(KSTEAM*0.35)
QOT=DBLE(QT)
QOTD=QT
QOTD=DBLE(QTD)
PT=DBLE(PT)
PP=DBLE(PP)
WSHT=DBLE(PCOMP+FCWERC)*1.0E-C6
WSHT=DBLE(WSHT)
WRATE=0.97*WSHT
WRATE=DBLE(WRATE)
WRITE(6,3130)
C
3130 FORMAT(1X)
C
WRITE(6,3939)QOT,WSHT,WRATE
3939 FORMAT(1X,'QOT=',E8.3,1X,'WSHT=',E9.3,1X,'WRATE=',E9.3,1X)
C
ITEST=0
C
C ITEST=0
C
CALL PRESTC
C
C MCSR IS FRACTIONAL CCAI WALLTURE, AS RECEIVED
C MCSR=0.001
C
C CCSR IS FRACTIONAL CCAI WALLTURE, AS FIRED
C CCSR=0.002
C
THE FOLLOWING CALCULATION ESTIMATES THE THERMAL INPUT.
C COAL BY CALCULATING THE WATER TO BE EVAPORATED AND
C ASSIGNING AN EFFICIENCY (60%) TO ACCOUNT FOR LOSSES AND
ENTHALPY EXHAUSTED FROM THE COAL/GAS SEPARATOR.

QLCD IS THE ENTHALPY REMOVED FROM THE FLUE GASES FOR COAL DRYING
QLCD = (CMOISR-CMOISF)*CFLCHF=1123.3/60

GLFE IS THE ENTHALPY ACCESSED TO THE FEEDWATER IN THE
LOW PRESSURE ECONOMIZER SECTION.

GHFE IS THE ENTHALPY ACCESSED TO THE FEEDWATER IN THE
HIGH PRESSURE ECONOMIZER.

THE FOLLOWING CALCULATION ASSUMES AN ARBITRARY DIVISION
BETWEEN HIGH AND LOW PRESSURE ECONOMIZER OF 55% TO HPE (JNC)

GHFE= 0.55*EGSE
GMEFE = DBLE (GHFE)
GLFE = 0.45*EGSE
GCLFE = DBLE (GLFE)

EXTSER(7) = GLMHD-GLFE
EXTSER(7) = DBLE (EXTSER(7))

EXTRNL = (LCC + LUMF + ECSS + EQSSR + C1MH + GSE) * 2931 / 1.0E-6

DO 541 I=1,12

541 CONTINUE

RGT = GT

QTR = DBLE (QTR)

NRH = 1

MNRH = NRH

PE(1) = 1497.6

PPE(1) = DBLE (PE(1))

PE(2) = 883.6

PPE(2) = DBLE (PE(2))

PE(3) = 484.5

PPE(3) = DBLE (PE(3))

PE(4) = 355.3

PPE(4) = DBLE (PE(4))

PE(5) = 167.2

PPE(5) = DBLE (PE(5))

PE(6) = 103.6

PPE(6) = DBLE (PE(6))

PE(7) = 55.5

PPE(7) = DBLE (PE(7))

CC 542 IE=1,12

542 CONTINUE

NSHAF = 3

NSHAF = NSHAF

NF = 7

NNF = NF

NFH = NF

NFH = NF

NFH = NF

NFH = NF

NFH = NF

NFH = NF

NFH = NF

NFH = NF

NFH = NF
C THE FOLLOWING ESTIMATES THE ELECTRICAL POWER OUTPUT, WRATF, 
BASED ON ASSUMING 35% CONVERSION EFFICIENCY. (ADDED BY JKM)

WRATF = 35*EXTERNAL

WRITE(6,2929)EXTERNAL,OTF,GT

2929 FORMAT(2I4,'EXTRNL: ',I4,'E8.3,1X,'GIR= ',E12.5,1X,'GT= ',E8.3,1X,9E12.5,1X)

C WSHFT=0.

WRITE(6,4197)EXTERNAL,WWGEN

4197 FORMAT(1X,['EXTRNL: ',I4,'E8.3,1X,'WWGEN= ',1E12.5,1X,9E12.5,1X)

C HP=TRUE.

EORAT=5524

DF=(-EORAT*VMIN(2)-VPLS(2))/(VPLS(1)+EORAT*VMIN(1))

CALL TRUE.

CALL NEWMOF

ISV=7

CALL SAVE

C EFFMS IS THE TOPPING AND BOTTOMING CYCLE EFFICIENCY

EFFMS=TPWR/THIN*2931

WRITE (6,3013) EFF,TIN,EFFMS

HFF=100.*EFF

GEFF=100.*EFF

TWN=TPWR*PCD+FF

WRITE (6,1002) HFF,GEFF, TIN, EFFMS, PC, EFFM, TPCW, PCW

1000 FORMAT(2F15.6,4F8.3,1/4F8.3,1/4F8.3,E15.6)

1012 FORMAT(2X,2F15.6,4F8.3,1/4F8.3,1/4F8.3,E15.6)

1101 FORMAT(1H5)
VITA

Edward H. Kiessling III was born on October 5, 1950 in Port Jefferson, New York. In May 1973, he received his Bachelor of Science from Rutgers—the State University of New Jersey.

Upon graduation he was commissioned in the U.S. Army Corps of Engineers and served with the 1st Engineer Battalion for three years. Following his release from active duty, the author held engineering positions with the Corps of Engineers, Mobil Oil Corporation, and The University of Tennessee Space Institute. At present the author is employed by the Nuclear Power Division of the Tennessee Valley Authority. He is a mechanical engineer assigned to the Preoperational Test Staff at the Bellefonte Nuclear Power Plant near Scottsboro, Alabama.

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