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 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.

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MODELING OF A COMBINED CYCLE MHD/STEAM POWER PLANT

A Thesis

Presented for the

Master of Science

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Edward H. Kiessling III

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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.

TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION.	1
II.	PLANT DESCRIPTION	8
III.	MODEL STRUCTURE AND CAPABILITIES.	17
IV.	MHD TOPPING CYCLE	22
V.	SEED REGENERATION	52
VI.	HRSR SYSTEM AND STEAM CYCLE	70
VII.	MODEL RESULTS	92
VIII.	CONCLUSIONS	100
BIBLIOGRAPHY		102
APPENDIX		105
VITA		124

LIST OF TABLES

TABLE		PAGE
4-1.	Process Mass Flows for MHD Topping Cycle	26
4-2.	Variables for which Values are Read by SINGH	28
4-3.	Energy Quantities for MHD Topping Cycle	36
4-4.	States for which SINGH calls NASA SP-273 to Calculate Plasma/Flue Gas Properties	43
5-1.	Seed Regeneration Process Streams	55
5-2.	Recycle Streams to Potassium Sulfate Dissolver	67
6-1.	HRSR System Model Variables	78
6-2.	Steam Cycle Model Variables (SINGH)	81
7-1.	Major Characteristics of Modeled Plant	93
7-2.	Coal Analyses and HHV	94
7-3.	SINGH Input Data for Modeled Plant	96
7-4.	Model Execution Results	97

LIST OF FIGURES

FIGURE		PAGE
2-1.	Plant Schematic Diagram.	9
4-1.	Process Mass Flow Diagram for MHD Topping Cycle.	23
5-1.	Seed Regeneration Process Diagram.	53
6-1.	HRSR System Diagram.	72
6-2.	Steam Cycle Diagram.	76

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[1]. 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[2].

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 SO_2 and NO_x 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 SO_2 and NO_x 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

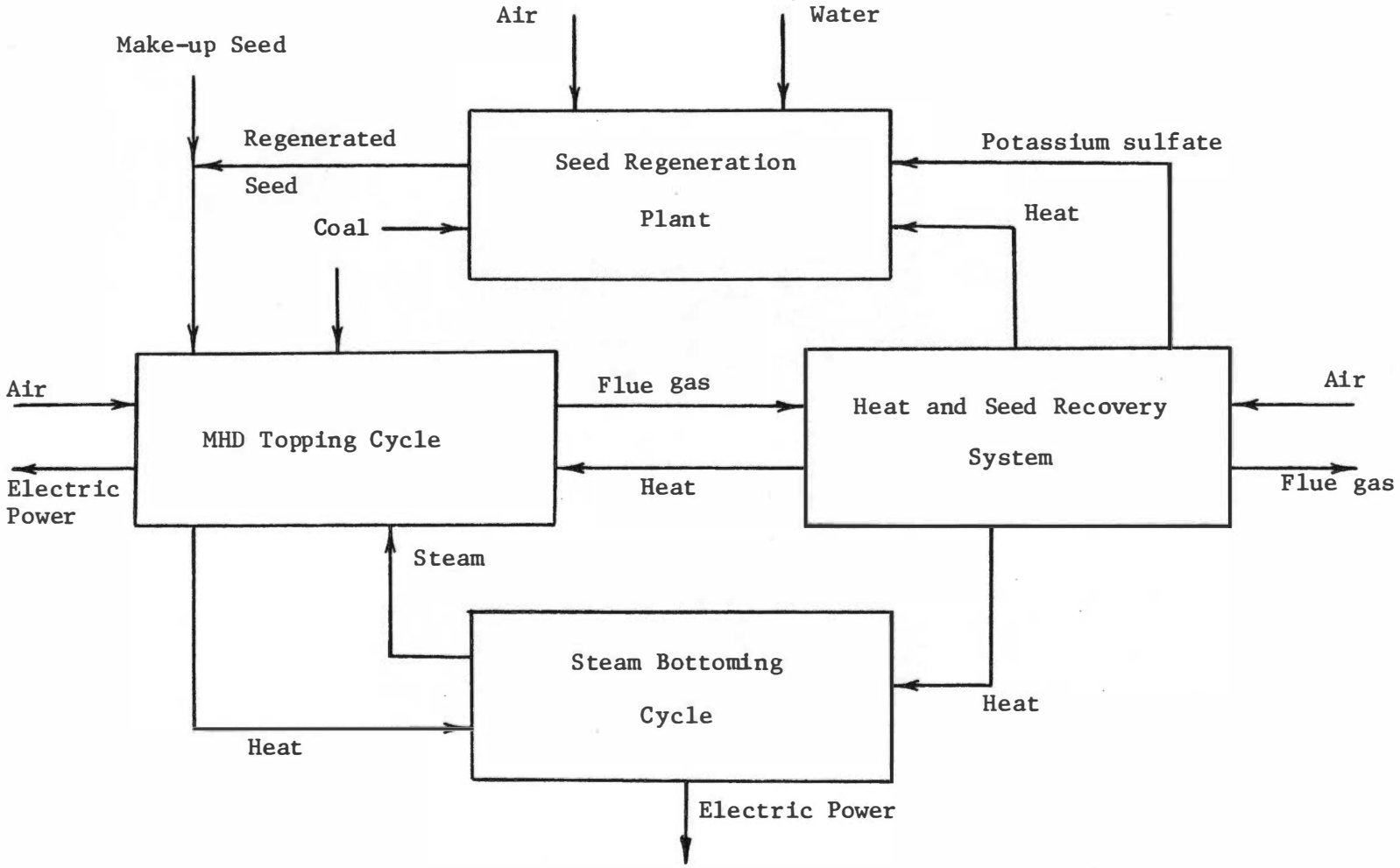


Figure 2-1. Plant Schematic Diagram.

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 temperature, 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 generation, 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 approximately 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[4] 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).
4. Higher heating value of dry coal (ASTM D3286).

---

*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.
9. Preheat temperature 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[4]. 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[5] 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[5]. 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, technically, 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.

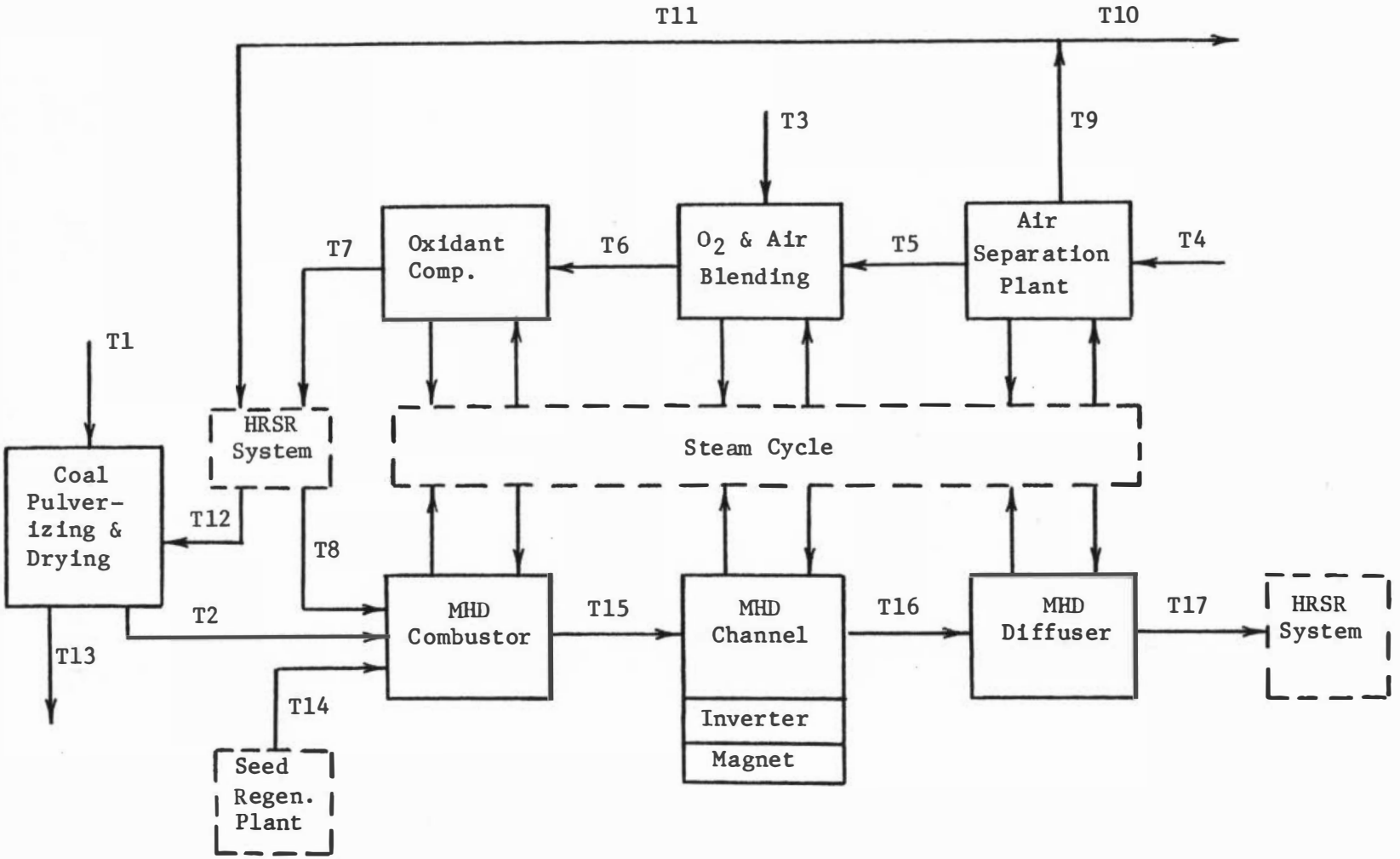


Figure 4.1. Process Mass Flow Diagram for MHD Topping Cycle.

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[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 (POUT, 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:

```
THIN = POUT*3.4129/(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 = THIN/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:

```
MIOSRF = ((MOISAR*((100.-MOISAF)/(100.-MOISAR))-MOISAF)
       +100.)/100.
```

Table 4-1. Process Mass Flows for MHD Topping Cycle.

Steam No.	Description	Variable Name	Algorithm	Units
T1	Coal from stockpile to pulverizers	MCT01	MCT02*MOISRF	lbm/hr
T2	Dried coal to MHD combustor	MCT02	THIN/HCC	lbm/hr
T3	Ambient air to MHD compressor	MAT03	(PCTA/100.)*MOAT08	lbm/hr
T4	Ambient air to air separation plant	MAT04	MOT05/0.232	lbm/hr
T5	Oxygen from air separation plant	MOT05	(PCTO/100.)*MOAT08	lbm/hr
T6	Oxygen enriched air to MHD compressor	MOAT06	MOAT08	lbm/hr
T7	Oxygen enriched air to air heater	MOAT07	MOAT08	lbm/hr
T8	Oxygen enriched air to MHD combustor	MOAT08	OF*MCT02/(1.-SFLO)	lbm/hr
T9	Nitrogen and argon from air separation	MNAT09	MAT04 - MOT05	lbm/hr
T10	Nitrogen and argon released to atmosphere	MNAT10	MNAT09-MNAT11	lbm/hr
T11	Nitrogen and argon for coal drying	MNAT11	1.25*QWVT13/(250.0*0.244)	lbm/hr
T12	Nitrogen and argon for coal drying	MNAT12	MNAT11	lbm/hr

Table 4-1 (Continued)

Steam No.	Description	Variable Name	Algorithm	Units
T13	Nitrogen, argon, and moisture from coal	MTT13	MNAT11 + MCT01 - MCT02	lbm/hr
T14	Potassium seed to MHD combustor	MKT14	SFLO*MCT02/(1.-SFLO)	lbm/hr
T15	Plasma to MHD channel	MPT15	MCT02 + MKT14 + MOAT08	lbm/hr
T16	Plasma to MHD diffuser	MPT16	MPT15	lbm/hr
T17	Flue gas to HRSR equipment	MFGT17	MPT15	lbm/hr

Table 4-2. Variables for which Values are Read by SINGH.

Variable Name	Description	Units	Source
POUT	Desired net electric power output from plant	WATTS	User Specified
EFF	Estimated net efficiency of plant	%	User Specified
HCC	Higher heating value of dried coal	Btu/lbm	Program COAL
MOISAR	Moisture content (by weight) of "as received" coal	%	Coal Proximate Analysis
MOISAF	Moisture content (by weight) of "as fired" coal	%	Program COAL
PCTA	Percent of MHD oxidant flow that is air	%	Program COAL
PCTO	Percent of MHD oxidant flow that is pure oxygen	%	Program COAL
SFLO	Fraction of fuel input that is potassium seed	-	Program COAL
PRINT	MHD combustor operating pressure	ATM	User Specified
TAIC	Temperature of oxidant enriched air at combustor inlet	°K	User Specified
QLCPUM	Heat loss from combustor to cooling water per unit mass of gas side combustor mass flow	Btu/lbm	Program COAL

Table 4-2 (Continued)

Variable Name	Description	Units	Source
EMACH	Plasma Mach No. at channel entrance	-	Program DESIGN3
AREAR	Ratio of reference channel exit area to entrance area	-	Program DESIGN3
BMAX	Maximum magnetic field strength	Tesla	Program DESIGN3
CEFFI	Inverter efficiency	%	User Specified
CLEN	Length of reference channel	Meters	Program DESIGN3
ENT	Entrance area of reference channel	Sq M	Program DESIGN3
GDMF	Reference generating channel mass flow	lbm/hr	Program DESIGN3
GEF	Fractional generator efficiency of reference channel	-	Program DESIGN3
HF	Fractional enthalpy extraction of reference channel	-	Program DESIGN3
PSTAT	Static pressure at reference channel exit	ATM	Program DESIGN3
XS	Weight fraction of dried coal that is sulfur	-	Program COAL
XSAR	Weight fraction of "as received" coal that is sulfur	-	Coal Ultimate Analysis

Table 4-2 (Continued)

Variable Name	Description	Units	Source
XAAR	Weight fraction of "as received" coal that is ash	-	Coal Ultimate Analysis
TAH04	Secondary combustion air temperature at secondary combustor inlet	°R	User Specified
SR	Stoichiometric ratio for MHD combustor	-	Program COAL
HSTEAMA	Steam enthalpy at Superheater exit	Btu/lbm	User Specified
HSTEAMR	Steam enthalpy increase in reheater	Btu/lbm	User Specified

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

(100.-MOISAF)/100.-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.

MOISAR*((100.-MOISAF)/(100.-MOISAR))

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:

MOISAR*((100.-MOISAF)/(100.-MOISAR))-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.

(MOISAR*(100.-MOISAF)/(100.-MOISAR))-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).

MCT01 = MCT02*MOISRF

At this point, SINGH calls data and subroutines from the NASA SP-273[6] 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*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°R, 300K). It was also necessary to specify a temperature for the

heated moisture. Based on the example of another MHD/steam plant study[9], 150°F (610°R, 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 insure that the calculated heat requirement for coal drying will be sufficient. Using the 1967 ASME Steam Tables[10], 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.*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[11] conducted at UTSI, flue gas at temperatures less than 700°F (1160°R, 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°R, 589K). A standard reference on coal fired power plants[12] states that some commercially available pulverizers are capable of receiving drying gases as hot as 650°F (1110°R, 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[13], 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*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[14]. 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 4-3. Energy Quantities for MHD Topping Cycle.

Description	Variable	Algorithm	Units
Heat required to remove moisture from coal	QWVT13	1078.*MWVT13	Btu/hr
Shaft power required from ASP turbine	POWERO	101.75*MOT05	Watts
Shaft power delivered to oxidant compressor	PCOMP	See text pg. 39	Watts
Heat gained by oxidant during compression	QOAT07	See text pg. 40	Btu/hr
Energy lost during compression process	ELOCT	PCOMP - 0.2931*QOAT07	Watts
Heat added to oxidant in HRSR heat exchanger	QHEOAT	See text pg. 41	Btu/hr
Energy transported into combustor by oxidant	QOAT08	QOAT07 + QHEOAT	Btu/hr
Electric power required by pulverizers and drying fans	PPFT	7*MCT01	Watts
Heat gained by N_2 and Ar drying gas in HRSR	QNAT12	131*MNAT11	Btu/hr
Drying gas heat lost to coal and atmosphere	QLCDT	0.25 QWVT13	Btu/hr
Heat retained by coal drying gas	QNAT13	QNAT12 - QWVT13 - QLCDT	Btu/hr
Energy required to decompose potassium formate	QKT14	4.*MKT14	Btu/hr
Heat lost from combustor to cooling water	QLCOMB	QLCPUM*MPT15	Btu/hr

Table 4-3 (Continued)

Description	Variable	Algorithm	Units
Kinetic energy and heat transported from combustor by plasma	EQKT15	(HSUM(1)-HSUM(5)) *1.8*R*MPT15	Btu/hr
Unreleased chemical energy transported from combustor by plasma	ECT15	THIN + QOAT08 -QKT14-EQKT15	Btu/hr
DC electric power developed by the MHD channel	PEXM	(HSUM(1)-HSUM(5))*R *1.8*.2931*HFF*MPT15	Watts
AC electric power to grid from channel	POUTM	CEFFI*PEXM	Watts
Plasma energy lost to channel cooling water as heat	QLMHD	(PEXM*3.4129* (1.-GEFF))/GEFF	Btu/hr
Kinetic energy and heat transported from channel by plasma	EQKT16	EQKT15-(PEXM*3.4129) - QLMHD	Btu/Hr
Total energy transported from channel by plasma	ETT16	EQKT16+ECT15	Btu/hr
Electric power required to operate the superconducting magnet	PMAG	See Text pg. 49	Watts
Heat lost from plasma to diffuser cooling water	QLDIF	See Text pg. 49	Btu/hr
Total energy transported from diffuser by flue gas	ETT17	ETT16 - QLDIF	Btu/hr
Kinetic energy and sensible heat transported from diffuser by flue gas	EQKT17	ETT17 - ECT15	Btu/hr

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:

POAT07 = 14.7*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[15], the compressor power requirement can be estimated by the following expression:

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

where 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)

γ = 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 (PCOMP, 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 feed at 80°F and 1 atmosphere.

```
AFLOV = 13.56*MOAT08/60.
```

The value for γ 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[16], 0.89 is a reasonable estimate for compressor efficiency. The resulting expression for PCOMP becomes:

```
PCOMP = 3.25*14.7*AFLOV*3.5
      *(((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[15]:

$$T_2 = T_1 \, (P_2/P_1)^{\frac{(\gamma - 1)}{\gamma}}$$

where T_1 = oxidant temperature at compressor entrance (°R)

T_2 = oxidant temperature at compressor exit (°R) for isentropic process

P_1, P_2 and γ 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 γ 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:

```
TOAT07 = (540.*(POAT07/14.7)**0.286)/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[17] and the fact that the oxidant is idealized as a perfect gas:

```
QOAT07 = MOAT08*(1.1875E-05*((TOAT07**2)-(540.**2))
       + 0.224(TOAT07-540.))
```

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[17], 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:

```
QHEOAT = MOAT08*(1.1875E-05*(((TAIC(1.8)**2)
 - (TOAT07**2))+.224*((TAIC*1.8)-TOAT07))
```

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[12], 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.*MCT01
```

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[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, Btu/hr) as:

```
QNAT12 = 131.*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, Btu/hr) is calculated as equivalent to 25% of QWVT13. The remaining heat (QNAT13, 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[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.

Identification Number	Description of State	Temperature (K)	Pressure (Atm)
1	Plasma at combustor exit	TAIC	PRINT
2	Flue gas at stack	395	1.0
3	Flue gas at MHD channel exit	TT(3)	PSTAT
4	Flue gas at diffuser exit	TT(4)	PDO/14.7
5	Reference	300	1.0
6	Flue gas at economizer inlet	644	1.0
7	Flue gas at secondary combustor inlet	1867	1.0

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.*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*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))*R*1.8*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[5]. 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 characeristics of the reference channel. The detailed use of DESIGN3 is addressed by Wu[5], 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.

BMAX	CLEN
CEFFI	AREAR
GDMF	ENT
HF	PSTAT
GEF	

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 expresed 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[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[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).

```
EXTA = AREAR*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).

```
PEXM = (HSUM(1)-HSUM(5))*R*1.8*.2931*HFF*MPT15
```

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

```
POUTM = CEFFI*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:

```
QLMHD = (PEXM*3.4129*(1.-GEFF))/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:

```
EQKT16 = EQKT15-(PEXM*3.4129)-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:

```
ETT16 = EQKT16+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* 1000.*(13.4*((ENTA**.5)
       +((ENTA*AREAR)**.5))+7.*BMAX*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*4.*(TTT (3)-TWALL)*
        (0.0316*BBB*DLEN+0.0316*0.0349
        *DLEN*DLEN - 3.53E-06*BBB*
```

*DLEN*DLEN-(1.412E-05*0.0349

*(DLEN**3))/3.

where

TTT(3) = plasma temperature at diffuser entrance. Calculated by NASA SP-272 (°K)

BBB = (ENTA*AREAR)**.5*100.

DLEN = diffuser length (centimeters)

= 3.79*BBB

Since QLDIF is the only energy transferred from the plasma during its passage through the diffuser, the energy balance for the diffuser is straightforward. The total energy content of the plasma flow entering the diffuser equals that of the plasma flow exiting the generating channel which has already been calculated as ETT16. The total energy content of the flue gas exiting the diffuser (ETT17, Btu/hr) is then readily calculated as follows:

ETT17 = ETT16-QLDIF

Like ETT16, ETT17 consists of two separate energy components. One component is the composite of kinetic and sensible heat energy (EQKT17, Btu/hr), and the other component is the unreleased chemical energy (ECT17, Btu/hr). Because no additional oxidant is added to the plasma flow in the diffuser, the unreleased chemical energy remains unchanged at a value of ECT15. The kinetic and sensible heat energy of the flue gas exiting the diffuser is then calculated as:

EQKT17 = 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[6] 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[9] 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.

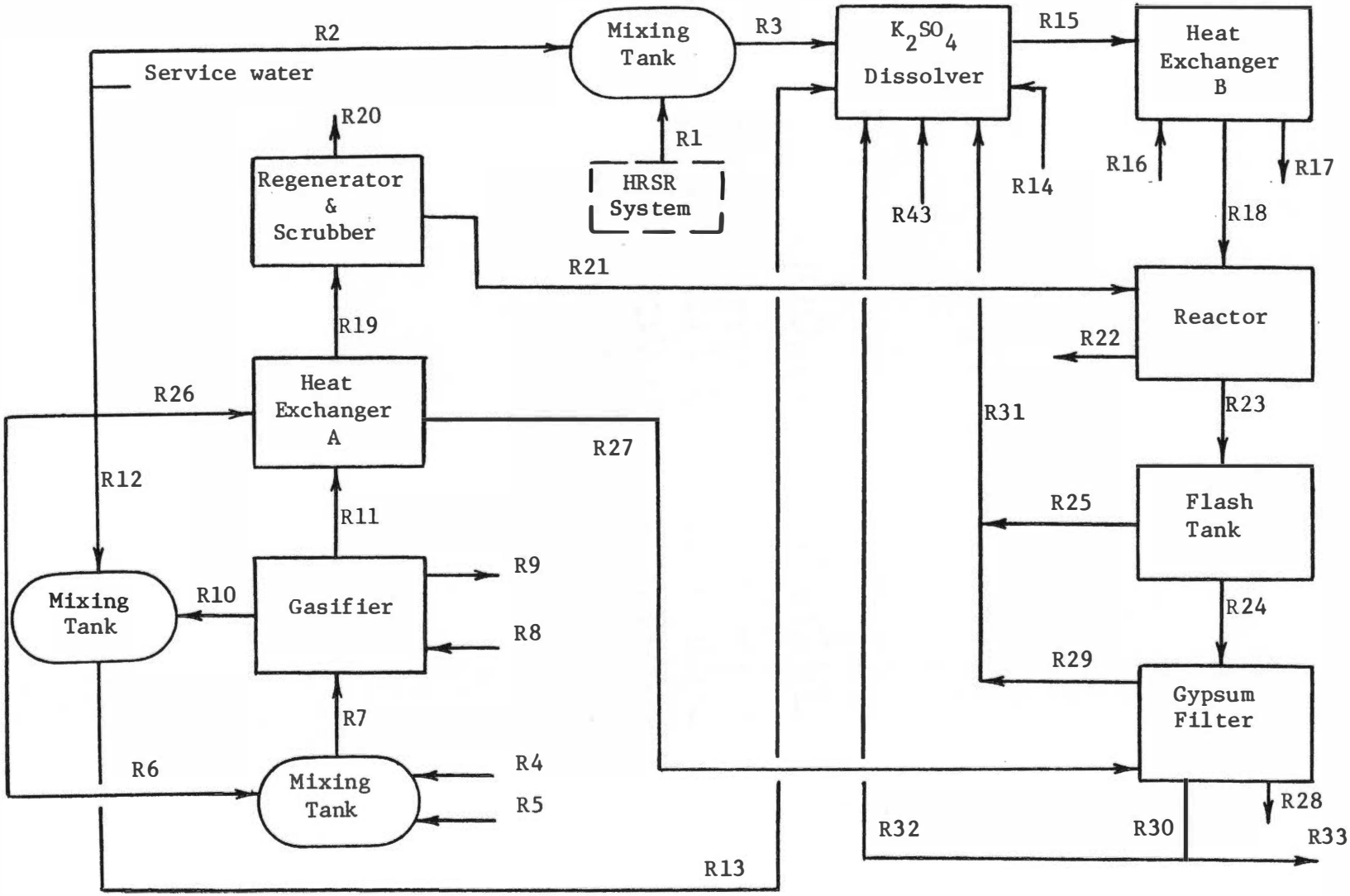


Figure 5-1. Seed Regeneration Process Diagram.

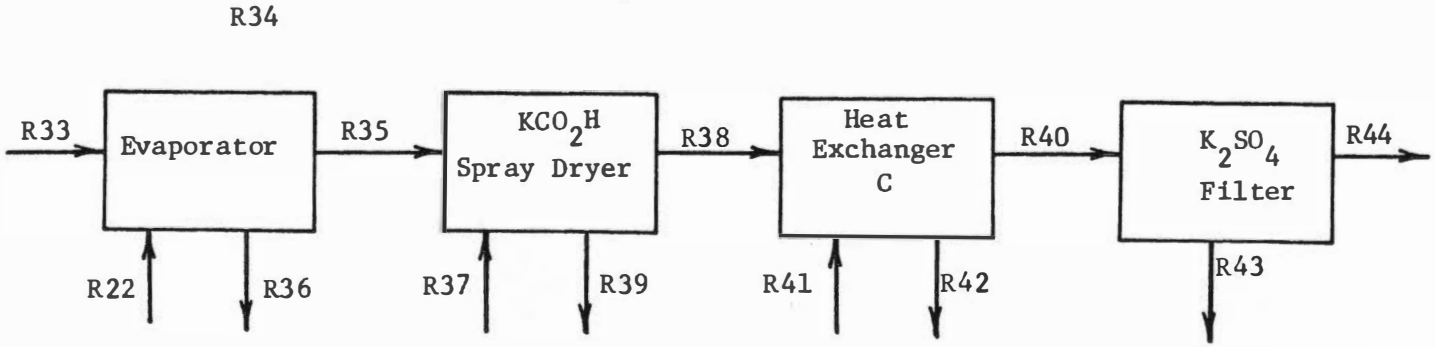


Figure 5-1. (continued)

Table 5-1. Seed Regeneration Process Streams.

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

Table 5-1 (Continued)

Steam No.	Description	Variable Name	Algorithm	Units
R11	Product gas from gasifier	MGR011	MCWR07 + MAR08 - MASR09 - MKSR10.	lbm/hr
R12	Service water for K_2SO_4 slurry	MSWR12	0.11*MKSR10	lbm/hr
R13	K_2SO_4 slurry to dissolver	MKWR13	MKSR10 + MSWR12	lbm/hr
R14	Lime to K_2SO_4 dissolver	MCAR14	0.32*(MKSR01 + MKSR10)	lbm/hr
R15	K and Ca compound slurry from dissolver	MTR15	MKSR15 + MKFR15 + MWR15 + MCHR15	lbm/hr
R16	Steam to heat exchanger B	MSR16	QTR18/983.6	lbm/hr
R17	Condensate from heat exchanger B	MWR17	MSR16	lbm/hr
R18	K and Ca compound slurry to reactor	MTR18	MTR15	lbm/hr
R19	Product gas to scrubber	MGR19	MGR11	lbm/hr
R20	CO_2 from regenerator to atmosphere	MCDR20	0.085*MGR19	lbm/hr
R21	Product gas to reactor	MGR21	MGR19 - MCDR20	lbm/hr
R22	Product gas to heat recovery	MGR22	0.93*MGR21	lbm/hr

Table 5-1 (Continued)

Steam No.	Description	Variable Name	Algorithm	Units
R23	K and Ca compound slurry to flash tank	MTR23	MTR18 + MGR21 - MGR22	lbm/hr
R24	K and Ca compounds from flash tank	MTR24	MTR23 - MSR25	lbm/hr
R25	Steam from flash tank	MSR25	0.12*MTR23	lbm/hr
R26	Service water to heat exchanger A	MSWR26	1.80*MGR11	lbm/hr
R27	Service water from heat exchanger A	MSWR27	MSWR26	lbm/hr
R28	Gypsum and water to disposal	MYWR28	0.24*MTR24	lbm/hr
R29	Recycle K compound slurry from gypsum filter	MTR29	MTR31 - MSR25	lbm/hr
R30	K compound slurry from gypsum filter	MTR30	MTR24 + MSWR27 - MYWR28 - MTR29	lbm/hr
R31	Recycle K compound slurry from flash tank and gypsum filter	MTR31	MKSR31 + MKCR31 + MWR31	lbm/hr
R32	Recycle K compound slurry	MTR32	MKSR32 + MKCR3 + MWR32	lbm/hr
R33	K compound slurry to evaporator	MKWR33	MTR30 - MTR32	lbm/hr

Table 5-1 (Continued)

Steam No.	Description	Variable Name	Algorithm	Units
R34	Steam vented from K compound slurry	MSR34	0.50*MKWR33	lbm/hr
R35	K compounds to spray dryer	MKWR35	MKWR33 - MSR34	lbm/hr
R36	Gas from evaporator	MGR36	MGR22	lbm/hr
R37	Flue gas to spray dryer	MFGR37	14.12*MKWR35	lbm/hr
R38	K compounds to heat exchanger C	MKR38	0.636*MKWR35	lbm/hr
R39	Flue gas and moisture to stack	MFGR39	MFGR37 + MKWR35 + MKR38	lbm/hr
R40	K compounds to K_2SO_4 filter	MKR40	MKR38	lbm/hr
R41	Steam to heat exchanger C	MSR41	QKR40/983.6	lbm/hr
R42	Condensate from heat exchanger C	MWR42	MSR41	lbm/hr
R43	Recycle K_2SO_4 from filter	MKSR43	0.20*(MKS R01 + MKS R10	lbm/hr
R44	Potassium Formate to MHD cycle	MKCR44	MKR40 - MKSR43	lbm/hr

Table 5-1 (Continued)

Stream No.	Description	Variable Name	Algorithm	Units
R18	Heat required from heat exchanger B	QTR18	101.7*MTR13	Btu/hr
R31	K_2SO_4 component of recycle stream R31	MKSR31	0.01*MKSR01 + MKS R09	lbm/hr
R31	KCO_2H component of recycle stream R31	MKCR31	4.85*MKSR29	lbm/hr
R31	Water component of recycle stream R31	MWR31	324.07*MKSR29	lbm/hr
R32	K_2SO_4 component of recycle stream R32	MKSR32	0.008*(MKSR01 + MKS R09)	lbm/hr
R32	KCO_2H component of recycle stream R32	MKCR32	4.85*MKSR30	lbm/hr
R32	Water component of recycle stream R32	MWR32	12.62*MKSR30	lbm/hr
R40	Heat required from heat exchanger C	QKR40	MKS38*40	Btu/hr

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 (MKSR01, lbm/hr) as follows:

MKSR01 = 5.44*MCT02*0.98*X5

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

MCT02 = previously calculated mass flow rate of dry coal to the MHD combustor (lbm/hr)

0.98 = fraction of sulfur content recovered (dimensionless)

XS = 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 = (39/84)*MKT14-(78/174)*MKSR01

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

MKT14 = 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 MKRS01 based on the available potassium as shown below.

MKSR01 = (174/78)*(39/84)*MKT14*0.98

Once the amount of potassium sulfate recovered from the HRSR equipment has been determined, the amount of service water (MSWR02, lbm/hr)

necessary to create the slurry is computed by proportion from the Hals model:

MSWR02 = 0.1111*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:

MCR04 = 0.34*(MKSR01+(544*XS*MCR04)

MCR04-1.85*(XS*MCR04) = 0.34*MKSR01

MCR04*(1-1.85*XS) = 0.34*MKSR01

MCR04 = 0.34*MKSR01/(1-1.85*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 potasisum 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 K_2SO_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 recyle flows is calculated in relation to the quantity of potassium sulfate received by the potassium sulfate dissolver. The three algorithms are as follows:

```
MKSR31 = (442/38421)*(MKSR01+MKSR10)

MKSR32 = (323/38421)*(MKSR01+MKSR10)

MKSR43 = (7649/38421)*(MKSR01+MKSR10)
```

Table 5-2. Recycle Streams to Potassium Sulfate Dissolver.

Flow Stream	Compound	Variable Name
R31	Potassium Sulfate	MKSR31
R31	Potassium Formate	MKFR31
R31	Water	MWR31
R32	Potassium Sulfate	MKSR32
R32	Potassium Formate	MKFR32
R32	Water	MWR32
R43	Potassium Sulfate	MKSR43

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:

```
MKFR31 = (2143/442)*MKSR31
MWR31  = (143240/442)*MKSR31
MKFR32 = (1566/323)*MKSR32
MWR32  = (4076/323)*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:

```
MKSR15 = MKSR01+MKSR13+MKSR31+MKSR32+MKSR43
MKFR15 = MKFR31+MKFR32
MWR15  = MWR02+MWR12+MWR31+MWR32
MCHR15 = (16335/12364)*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.

```
MTR15 = MKSR15+MKFR15+MWR15+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:

```
QTR18 = 101.7*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 ($\geq$ 2900°F) for decomposition of flue gas NO_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_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_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_x formation and decomposition reactions cease functioning. Thus, the flue gas will remain essentially NO_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.

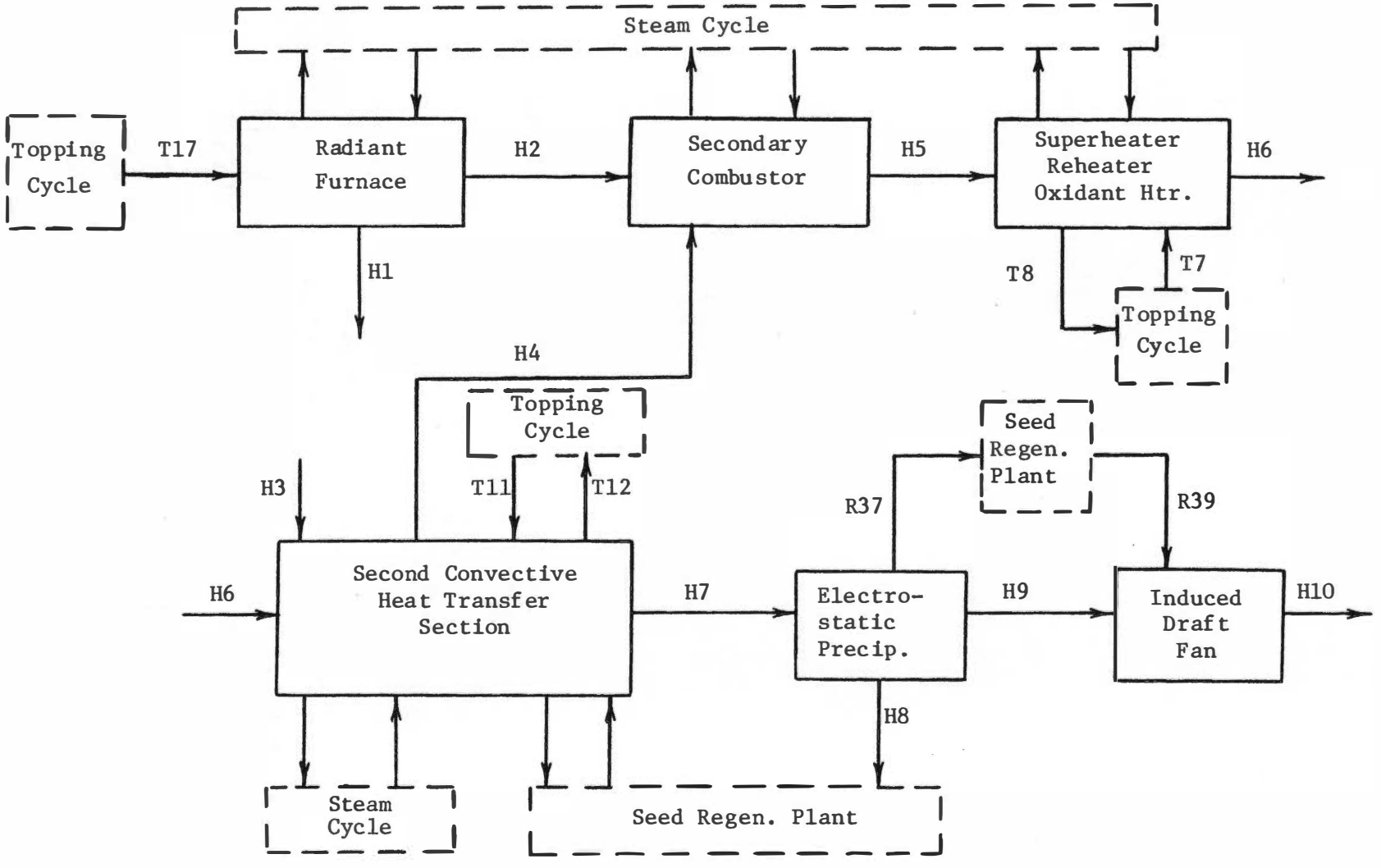


Figure 6-1. HRSR System Diagram.

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_x formation. One approach would cool the flue gas well below the NO_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_x formation zone. According to an earlier study[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°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°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°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°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

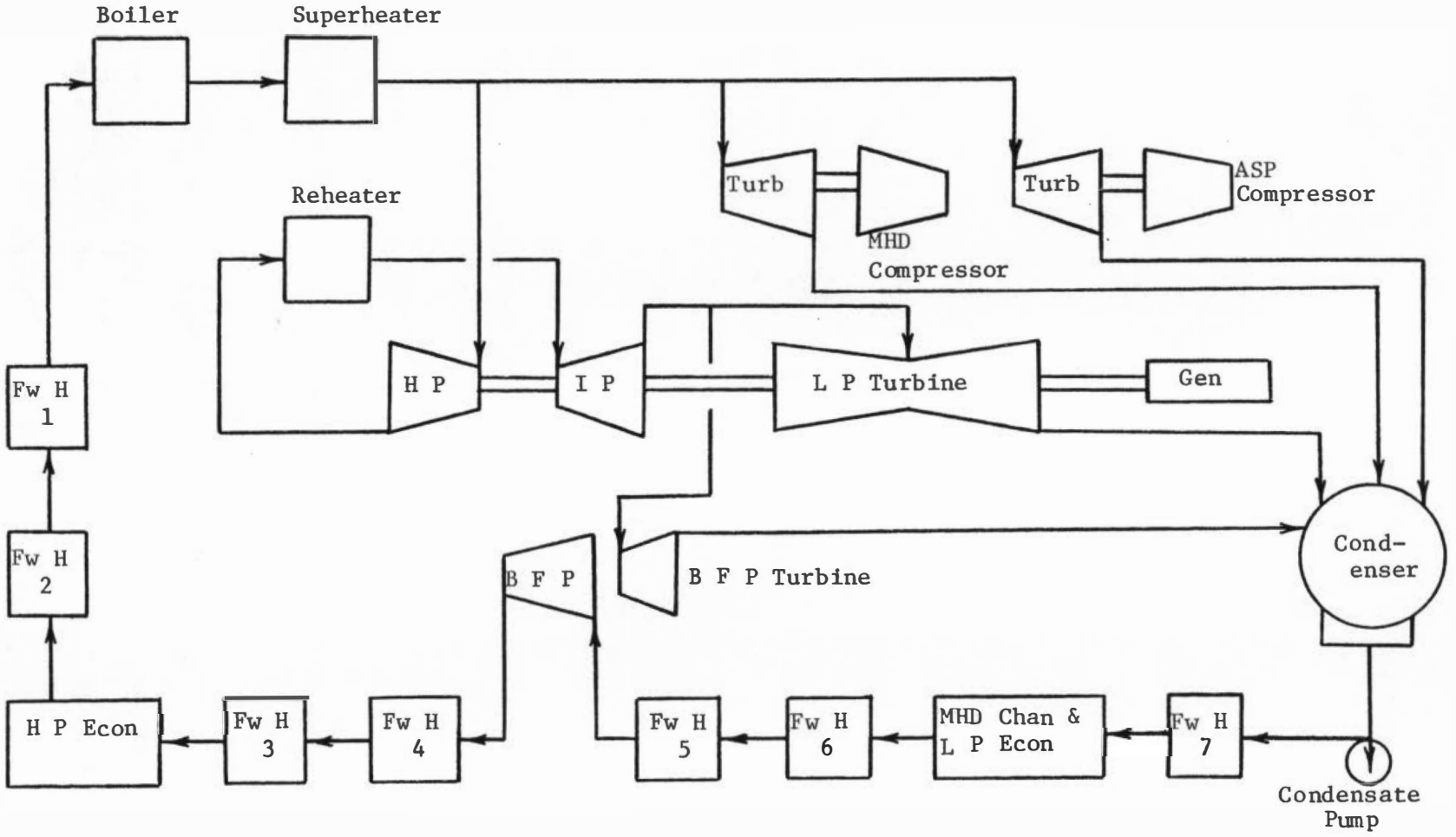


Figure 6-2. Steam Cycle Diagram.

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 (MSKH01, lbm/hr) is calculated by the following algorithm:

```
MSKH01 = (0.80*MCT02*XAAR*(100.-MOISAF)/100.-MOISAR))
       + KLHRSR+(0.02*MCT02*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 (EQH01, 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.

Variable Name	Description	Algorithm	UNITS
MSKH01	Mass flow of coal slag, potassium, and sulfur removed at radiant furnace slag tap	(0.80*MCT02*XAAR* (100.MOISAF)/100.MOISAR)) +KLHRSR+(0.02*MCT02*XS)	lbm/hr
EQH01	Heat lost with mass ejected at radiant furnace slag tap	431.*MSKH01	Btu/hr
MFGH02	Mass flow of flue gas exiting radiant furnace	MFGT17-MSKH01	lbm/hr
EQH02	Flue gas thermal energy exiting radiant furnace	MFGH02*(HSUM(7)-HSUM(5)) *R*1.8	Btu/hr
ETH02	Total energy transported with flue gas	EQH02+ECT15	Btu/hr
EQSRF	Heat for steam generation transferred in radiant furnace	EQKT17-EQH01-EQH02	Btu/hr
MAH04	Mass flow of secondary combustion air	((1.05-SR)/SR)*(MAT03 +MAT04))	lbm/hr
MFGH05	Flue gas mass flow from secondary combustor	MFGH02+MAH04	lbm/hr

Table 6-1 (Continued)

Variable Name	Description	Algorithm	UNITS
EQH04	Heat transported to secondary combustor by combustion air	(1.1875E-05*(TAH04**2 -540.**2)+.224* (TAH04-540.))*MAH04	Btu/hr
QAFG05	Heat gained by secondary air mass in combustor	(1.1875E-05*(3360.**2- TAH04**2)+.224(3360.- TAH04)	Btu/hr
EQSSC	Heat for steam generation transferred in secondary combustor	ECT15-QAFGH5	Btu/hr
QFRG56	Heat removed from flue gas in superheater/ reheater/oxidant heating section	MFGH05*(HSUM(7)- HSUM(6))*R*1.8	Btu/hr
EQSSR	Heat available for superheating, reheating, and steam generation in first convective section	QRFRG56-QHEOAT	Btu/hr
QRFG67	Heat recovered from flue gas in second convective heat transfer section	MFGH05*(HSUM(6)- HSUM(2))*R*1.8	Btu/hr
EQSE	Heat transferred to economizer water	QRFG67-QTR18-QKR40 -QNAT12-EQH04	Btu/hr

Table 6-1 (Continued)

Variable Name	Description	Algorithm	UNITS
MSH08	Mass flow of coal ash recovered in ESP	0.20*MCT02*XAAR* (100.-MOISAF)/ (100.-MOISAR)	lbm/hr
MTH08	Mass flow of coal ash and potassium sulfate recovered in EXP	MKSR01+MSH08	lbm/hr
MFGH09	Flue gas mass flow from ESP to ID fan	MFG07-MSH08-MFGR37	lbm/hr
MFGH10	Flue gas mass flow to stack	MFGH09+MFGR39	lbm/hr
PFAN	Electric power required by ID fan	0.4*MFGH10	Watts

Table 6-2. Steam Cycle Model Variables (SINGH).

PRESTO II Run No.	Variable Name	Description	Algorithm	Units
1	QT	Estimated steam flow to MHD and oxygen plant compressors	3.413*(PCOMP+POWERO)/ (HSTEAMA*.35)	lbm/hr
1	WSHAFT	Shaft power required by MHD and oxygen plant compressors	(PCOMP+POWERO)/1,000,000	MW
2	QHPE	Heat recovered in high pressure economizer	0.55EQSE	Btu/hr
2	QLPE	Heat recovered in low pressure economizer	0.45 EQSE	
2	EXTSER(7)	Heat added to feedwater between heaters 6 and 7	QLMHD+QLPE	Btu/hr
2	EXTSER(3)	Heat added to feedwater between heaters 2 and 3	QHPE	Btu/hr
2	EXTRNL	Total heat available to steam cycle	QLCOMB+QLMHD+QLDIF +EQSRF+QESSC+EQSSR +EQSE	MW
2	QTB	Steam flow to MHD and oxygen plant compressors	-QT (from Run 1)	lbm/hr

Table 6-2 (Continued)

PRESTO II Run No.	Variable Name	Description	Algorithm	Units
2	QT	Estimated total steam flow	(EXTRNL*3.413 * 1.0E +06)/ (HSTEAMA + HSTEAMR)	lbm/hr
2	WRATE	Estimated electrical output	0.35*EXTRNL	MW_e

431 Btu/lb at 2400°F. Thus, SINGH uses the following expression for calculating EQH01:

EQH01 = 431.*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*(HSUM(7)-HSUM(5))*R*1.8

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

HSUM(7) = h/R at point 7

HSUM(5) = h/R at point 5

h = 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 (EQSRF, Btu/hr). EQSRF is calculated by the following expression:

EQSRF = 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 = ((1.05-SR)/SR)*(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°R) is calculated by SINGH according to Chapman[16]:

```
QAFGH5 = (1.1875E-05*(3360.**2-TAH04)**2)+.224*(3360.-TAH04))
        *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[16]:

```
EQH04 = (1.1875E-05*(TAH04**2-540.**2)+.224*(TAH04-540.))*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*(HSUM(7)-HSUM(6))*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 (EQH06, Btu/hr) is calculated as the difference of EQH05 and QRFG56. The quantity of heat required for MHD primary oxidant heating has been previously calculated as QHEOAT. Thus, the quantity of heat available for steam superheating and reheating (EQSSR, Btu/hr) is readily calculated by SINGH as the difference of QRFG56 and QHEOAT. At this point it is not possible to divide EQSSR 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 EQSSR 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 EQSSR.

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, Btu/hr) as follows:

```
QRFG67 = MFGH05*(HSUM(6)-HSUM(2))*R*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 MKSR01. The mass flow rate of the remaining coal ash (MSH08, lbm/hr) is calculated by SINGH as follows:

MSH08 = 0.20*MCT02*XAAR*(100.-MOISAF)/100.-MOISAR)

SINGH then calculates the total potassium sulfate and coal ash recovered (MTH08, lbm/hr) as the sum of MKSR01 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[16]:

PFAN = MFGH10*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[7]. PRESTO was later modified by Choo and Steiger[8]. 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*(PCOMP+POWERO)/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 = (PCOMP+POWERO)/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*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*(PEXS+POUTM)+PFAN
```

The term 0.026*(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 (TPOWR, Watts):

```
TPOWR = POUTM+PEXS-PAUX
```

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

```
EFFMS = TPOWR/(THIN*.2931)
```

SINGH next recalculates THIN to include seed regeneration coal:

```
THIN = THIN+(MCR04*HCC/MOISRF)
```

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

```
EFFC = TPOWR/(THIN*.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 7-1. Major Characteristics of Modeled Plant.

Approximate Power Output (Net)	1000 MW_e
Coal Type	Illinois #6
MHD Topping Cycle	
Combustor Pressure	9 ATM
Oxidant Preheat Temperature	1100K
Oxygen Enrichment	20%
Stoichiometric Ratio	0.85
MHD Generating Channel	DCW
HRSR	
Secondary Combustion Air Preheat Temperature	600°F
Flue Gas Temperature	250°F
Steam Cycle	
Throttle Pressure	2400 PSIA
Throttle Temperature	1000°F
Reheat Temperature	1000°F
Condenser Pressure	2.00 IN.HG
Number of Feedwater Heaters	7

Table 7-2. Coal Analyses and HHV.

Ultimate Analysis, (%)	
Hydrogen	5.4
Carbon	62.4
Nitrogen	1.2
Oxygen	16.3
Sulfur	3.3
Heating Value, Wet, Btu/lb	11265
Heating Value, Dry, Btu/lb	12370
Coal Rank	BVCB
Proximate Analysis, Coal, as Received (%)	
Moisture	8.9
Volatile Matter	38.0
Fixed Carbon	41.7
Ash	11.4
Ash Analysis	
SiO_2	41.4 ± 5.4
Al_2O_3	19.3 ± 6.8
Fe_2O_3	22.3 ± 6.8
T_1O_2	0.9
P_2O_5	0.12
CaO	5.4 ± 3.3
MgO	1.7 ± 1.3
Na_2O	0.6 ± .2
K_2O	2.1 .4
SO_3	7.5 .6
Initial Deformation Temperature °F	1960 ± 70
Softening Temperature °F	2030 ± 70
Fluid Temperature °F	2260 ± 200

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.

Variable	Value	Units
POUT	1,000,000,000	Watts
HCC	12370.	Btu/lbm
EFF	43.	%
MOISAR	8.9	%
MOISAF	2.0	%
PCTA	80	%
PCTO	20	%
SFLO	0.139	-
PRINT	9.	Atm
TAIC	1100.	°K
QLCPUM	121.2	Btu/lbm
EMACH	0.9	-
AREAR	6.31	-
BMAX	6.0	Tesla
CEFFI	0.97	-
ENT	0.935	M^2
GDMF	548	Kg/sec
GEF	.882	-
HF	.212	-
CLEN	9.8	meters
PSTAT	0.736	Atm
XS	0.030	-
XSAR	0.033	-
XAAR	0.114	-
TAH04	1060	°R
SR	0.85	-
HSTEAMA	1463.5	Btu/lbm
HSTEAMR	218.8	Btu/lbm

Table 7-4. Model Execution Results.

Mass Flows (lbm/hr)	
MHD Topping Cycle	
Raw coal to pulverizers	690229.
Dried coal to MHD combustor	641631.
Potassium formate seed to MHD combustor	10355.
Air to air separation plant	2550013.
Oxygen to MHD compressor	591603.
Waste stream for coal drying	654855.
Waste stream to atmosphere	13035555.
Air to MHD compressor	2366412.
Oxidant to MHD compressor	2958015.
Plasma to channel and diffuser	3703231.
HRSR System	
Flue gas from topping cycle	3703231.
Slag, seed, and sulfur rejected at radiant furnace	81163.
Flue gas to secondary combustor	3622068.
Secondary combustion air	1156805.
Flue gas to convective heat transfer sections	4778874.
Potassium sulfate and ash recovered	118057.
Flue gas direct to ID fan	2174944.
Flue gas to seed regeneration then to ID fan	2485573.
Flue gas to stack	4827212.
Seed Regeneration Plant	
Potassium sulfate from HRSR	102620.
Service water	385303.
Gasifier coal	36941.
Gasifier air	148503.
Lime	34768.
Flue gas to spray dryer	2485573.
Carbon dioxide from regenerator	16755.
Product gas (combusted)	167734.
Gypsum and water for disposal	138225.
Vented steam	176032.
Flue gas and moisture to stack	2549649.
Gasifier slag	4211.
Potassium formate for recycle	90227.

Table 7-4 (Continued)

Mass Flows (lbm/hr)	
Steam Cycle	
Steam flow to ASU compresser	411709.
Steam flow to MHD compresser	799199.
Steam flow to HP turbine	5198908.
Steam flow to reheater	4057515.
Steam flow to IP turbine	4043608.
Steam flow to LP turbine	3319409.
Condenser flow	6380885.
Feedwater flow	6380885.

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

Table 7-4 (Continued)

Energy Quantities (MW)	
Heat transferred to secondary combustion air	43.
Heat for coal drying	25.
Heat for seed regeneration steam	20.
Economizer	77.
Heat lost to stack	48.
Seed Regeneration	
Coal	122.
Steam	20.
Steam Cycle Generation	664.
Net Power to Grid	1050.
Overall Plant Efficiency	42.7%

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.

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APPENDIX

```
      SUBROUTINE SINGH
C       VERSION: MARCH 26,1984 FORMATE SEED REGENERATION (BY EHK)
C
      DOUBLE PRECISION DEXP
      DOUBLE PRECISION DLOG
      DOUBLE PRECISION X,G,SUM
      DOUBLE PRECISION HSUM,SSUM,CPR,DLVTP,DLVPT,GAMMAS
      DOUBLE PRECISION COEF,S,EN,ENLN,HO,DELN
      DOUBLE PRECISION ENL,FRCW,CLNT,AA
C
      DOUBLE PRECISION BBLS,CCP1,CCP2
      DOUBLE PRECISION PPBIP
      DOUBLE PRECISION PPBLP,PPDLS,PPT,PPXLPI,TTEMPTE,QQLPE
      DOUBLE PRECISION QQHPE,HHSTEMA
      DOUBLE PRECISION HHSTEMR,PPE,EEXTSER,QQTD,QQT,QQTB,EEXTRNL
      DOUBLE PRECISION WWSHFT,QQGEN
      DOUBLE PRECISION WWRATE
C
      LOGICAL HP,SP,TP,CONVG,IONS,SINGC,LOGV,ISING,IC,VCL,SHOCK,RITE,JIM
     1,CALCH
C
      COMMON/COST/TFLO,FEXM,FEXS,ENTA,AREAR,CLEN,BMAX,CFLC,TAIC,FCCMP
     1,TCOMB,PRINT,HFF,GEFF,PMAG,AFLCV,POUT,THIN,DLEN,BBB,GLDIF,FDC,
     2PCUTM,TPOWR,PAUX,EFFC,SFLC,TACLH,TFG,HCC,QLM,QCHH,QSLAG,
     3QLCOMB,TAIP,TAIPK,MFRKS,MFRKC,SRRF,WSO,ASCEP,QLSR,
     4FFAN,SAFLO,AFLC,MFRAST,SGMFR,OFFGA,SR,CFLOH,SFLOH,AFLCH,ENGDE
     5,PECTO2,NOP,AFCPI,WGXY,POWERA,PCWERC,PECT
C
      COMMON/COSTT/BCAS,QHPAH,SCRUB,QLMHD,QCVAL
C
      COMMON/MODEL/FUNCT(9),TCI,PCI,BCI
      COMMON/POINTS/HSUM(13),SSUM(13),CPR(13),DLVTP(13),DLVPT(13)
     1 ,GAMMAS(13),P(26),T(26),V(13),PPP(13),WM(13)
     2 ,SONVEL(13),TTT(13),VLM(13),TOTN(13)
C
      COMMON/SPECES/COEF(2,7,300),S(300),EN(300,13),ENLN(300),
     1HO(300),DELN(300),A(15,300),SUB(300,3),IUSE(300),TEMP(120,2)
     2,SLN(300)
C
      COMMON/MISC/ENN,SUMN,TT,SC,ATOM(3,101),LLMT(15),PO(15),BOP(15,2)
     1 ,TM,TLOW,TWID,THIGH,PP,CPSUM,OF,EQRAT,FPCT,R,RR,HSUBO,AC(2),AM(2)
     2 ,HPP(2),RH(2), VMIN(2),VPLS(2),WP(2),DATA(22),NAME(15,5)
     3 ,ANUM(15,5),PECWT(15),ENTP(15),FAZ(15),RTEMP(15),FCX(15),DENS(15)
     4 ,RHOP,RMW(15),TLN,CR,CXF(15),ENNL,ENSAVE,ENLSAV ,TRACE
C
      COMMON /DOUBLE/ G(25,26), X(25)
      COMMON/INDX/ IDEBUG,CONVG,TP,HP,SP,ISV, NPF, MOLES,NP,NT,NFT,NLM
     1  ,NS,KMAT,IMAT,IG1,NCF,NCVIT,IFI,NEWR,NSUB,NSUP,ITM,CPCVFR,CPCVEG
     2 ,IONS,NC,NSERT,JSOL,JLIQ,KASE,NREAC,IC,JS1,VOL,SHOCK,IT,NFZ,CALCH
     3 ,IQSAVE,LSAVE,ISUP,ISUB,ITNUM
C
      COMMON/CALVIN/BBLS,CCP1,CCP2,IICC,IIFPT,IIP,NNCASE,NNEXTRN,
     1NNF,NNFH,NNFI,NNFL,NNHP,NNTP,NNLP,NNCSPE,NNRP,NNSHAFT,PPBIP,
     2PPBLP,PPDLS,PPT,PPXLPI,TTEMPTE,IITEST,QQLPE,QQHPE,HHSTEMA,
     3HHSTEMR,PPE(12),EEXTSER(12),QQTD,QQT,QQTB,EEXTRNL,WWSHFT,
     4NNDSGN,WWRATE,NNC(12),ITEST,QQGEN
C
      COMMON/CAL1/WWGEN,QQTT
C
      COMMON/ADATBLK/QGEN,IMETER
      COMMON/ADATA/PCMU,PDLS,PLS, QTD, PDGS, PF,VERS,NHP,IRHP,
     * NIP,IRIP,NLP,IRLP,      NFF,NFI,NFL,ICC,      NRGS,NCSPE
     *,IPEAK,IPLACE
      COMMON /AEXTHI/ EXTPAR(12), EXTSER(12),GPROSS(2),HPROSS(2),
     * GEXT(12), HEXT(12), GECONC(13),GFWEXT(12),HFWEXT(12), HECONC(13),
```

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      * INAME2
       COMMON /AFEED/ EFF, EFM, EFT, CP1, CP2
       COMMON /AFPT/QFPT,PBFPT,HPFPT,PXFPT,HXFPT,IFPT
       COMMON /AFWH/HAEI,HAEC,GR,
      * QEF(12), HEF(12)
      *       QD(12),QF(12),QE(12),QCR,HCR,GRO,GC,I1LP,I
       COMMON /AGS/QGS,HBGS,PBGS,AMBGS,SBGS,VBGS,TBGS,PXGS,AMXGS,SXGS,
      *VXGS,TXGS,HXGS,          MBGS,MXGS,     IRGS,NGS
       COMMON/AHEAT/PE(12),HE(12)
       COMMON /AIP2/ PBIP
       COMMON /ALEAK/QLK(21),HLK(21),QSPE,QMC,QSSR,HSSR,PSSR,QFWH,QSSRMU,
      *HSSRMU,QSSRM1,NCLK(21),NCHEAT(3),LK,NCOL,NCASE
       COMMON /ALP/QBLP,PBLP,TBLP,AMBLP,HBLP,SBLP,GXLP,PXLP,TXLP,AMXLP,
      *PXLPIO,
      1HXLP,SXLP,UEEPLP,PXLPI
       COMMON /AMIS/CMTS(18),     TC,TFP,TR,HR,WRATE,GC,WML,WGL,QMU,QFP,
      1DP,WGEN,WFWP,HTRTN,HTRTG,CEFFN,CEFFG,PXDROP(2)
       COMMON /APAR1/HO(12),HI(12),QAE,HC,HFP,DHP,TI(12),TD(12),TDCA(12),
      * TID(12),
      1HD(12),PLA,PLB,ND(12),NDC(12),XX,NF,NSHAFT
       COMMON /APAR2/PSH(12),TSH(12),TC(12),          PXHP,PXIP
       COMMON/ARH1/TRH1,TRH2,NRH
       COMMON/ARH2/PXRH1,PIRH1,PFFT,TXRH1,HXRH1,HIRH1,GRH
      *  ,PXRH2,PIRH2,HXRH2,HIRH2,GRH2,TXRH2,WSHAF1,WSHAF2,WSHAFT,CONREJ,
      *EXTERN
       COMMON /AT/GT,PT,TEMPTE,AMT,HT
       COMMON /AADCOP/QIE,EXTRNL,EXTRN,EXTHTT,WSHFT,NDSGN,NCON,NEXTRN
      *  ,NPARA
       COMMON /APROSS/PPEXT(12),HPEXT(12),QPEXT(12),NPE,NPEH,NPEI,NPEL
       COMMON/AENTHM/HTM,HBGSM,HXGSM,HBHPM,HXHPM,HIRH1M,HXRH1M,PBFPM,HXFPM
      *,HBIPM,HXIPM,HIRH2M,HXRH2M,HBLPM,HXLPM,UEEPM,HAEIM,HAEOM,HCM(12),H
      *IM(12),HEM(12),HDM(12),HCRM,HFPM,HRM,DHPM,HBFPIM,HXFPIM,HSSRM,
      *HSSRMM,HLKM(21)
       COMMON/AEXTM/EXTSEM(12),EXTFAM(12),QEXTM(12),HEXTM(12),QECONM(13),H
      *ECONM(13),QPROSM(2),HPRCSM(2),QEFM(12),HEFM(12),HIRDUM(12),CONPEM
      *,EXTERM,QFWEXM(12),HFWEXM(12)
       COMMON/APRESSM/PTM,PBGSM,PXGSM,PBHPM,PXHPM,PIRH1M,PXRH1M,PBIPM,PXIP
      *M,PIRH2M,PXRH2M,PBLPM,PXLPM,PEM(12),PSHM(12),DPM,PBFPTM,PXFPTM

C
C      REAL VARIABLES FOR THE SEED REGERATION SYSTEM
       REAL MCT03,MKSR01,MSWR02,MKWR03,MCR04,MSWR06,MCWR07,
      1MAR08,MGR11,MKSR10,MSWR12,MKWR13,MCAR14,MKSR31,MKCR31,
      2MWR31,MTR31,MKSR32,MKCR32,MWR32,MTR32,MTR15,MSR16,MWR15,
      3MTR18,MCDR20,MGR21,MGR22,MTR23,MSR25,MTR24,MSWR26,MSWR27,
      4MYWR28,MTR29,MTR30,MKWR33,MKWR35,MSR34,MGR36,MFGR37,
      5MKR38,MFGR39,MKR40,MSR41,MWR42,MKSR43,MKCR44,KLHRSR,MKR05,
      6MASR09,MKSR15,MKFR15,MCHR15,MWR17
C
C      REAL VARIABLES FOR MHD TOPPING CYCLE
       REAL MCT02,MCISAR,MCISAF,MCT01,MCAT08,MAT03,MCT05,MAT04,
      1MNAT09,MWVT13,MNAT11,MNAT10,MTT13,MKT14,MPT15,MTT1,MTC1,
      2MFGT17
C
C      REAL VARIABLES FOR THE HRSR SECTION
       REAL MSKH01,MFGH02,MAH04,MFGH05,MSH08,MTH08,MFGH09,MFGH10
C
C      REAL VARIABLES FOR SINGH
       REAL K,MFRKS,MFRKC,MFRAST,MCISRF
C
C      PCUT IS DESIRED ELECTRICAL CUTPUT OF PLANT IN WATTS
C      HCC IS THE HEAT CONTENT OF COAL IN BTU PER LB
C      PRINT IS THE AIR PRESSURE TO COMBUSTOR IN ATM
C      PRESA IS THE AIR PRESSURE TO COMPRESSOR IN PSIA
C      TAIC IS THE AIR TEMPERATURE TO THE COMBUSTOR IN DEG K
C      SFLO IS THE FRACTION OF SEED IN THE FUEL PORTION OF THE INPUT
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C      SR IS THE STOICHIOMETRIC AIR RATIO
C      BMAX IS THE MAGNETIC FIELD STRENGTH.   TESLA
C      EMACH IS THE MACH # AT THE ENTRANCE OF THE MHD  GENERATOR
C
       READ (5,1000) POUT, HCC, PRINT, TAIC,BMAX,SFLC
      1,EFF,QLCPUM,SR,TAH04,CEFFI,HSTEAMA,HSTEAMR,EMACH,GDMF
      2,HF,GEF,CLEN,AREAR,ENT,PSTAT,PCTA,PCTO,
      3MOISAR,MOISAF,XS,XSAR,XAAR
C
       WRITE (6,1012) POUT,HCC,PRINT,TAIC,BMAX,SFLC
      1,EFF,QLCPUM,SR,TAH04,CEFFI,HSTEAMA,HSTEAMR,EMACH,GDMF
      2,HF,GEF,CLEN,AREAR,ENT,PSTAT,PCTA,PCTO
      3,MOISAR,MOISAF,XS,XSAR,XAAR
C
C      ************  FOR ED KIESSLING'S DESIGN PLANT  ****************
C      THIN IS THERMAL INPUT FROM COAL INJECTED INTO THE PRIMARY
C      MHD COMBUSTOR (BTU/HR)
C
       THIN=POUT*3.4129/(EFF/100.)
C
C***** SINGH CALCULATES THE MASS FLOW RATES FOR THE MHD TOPPING CYCLE ****
C            ( SEE FIGURE 3-1 OF REFERENCE 1)
C
C      MCI02 IS THE MASS FLOW RATE OF DRIED COAL TO THE MHD PRIMARY
C      COMBUSTOR (LBM/HR)
       MCI02=THIN/HCC
C      MOISRF IS THE MOISTURE RESTORATION FACTOR
       MOISRF=((MOISAR*((100.-MOISAF)/(100.-MOISAR))-MOISAF)+100.)/100.
C      MCI01 IS THE MASS FLOW RATE OF DRIED COAL FROM THE STOCK PILE (LBM/HR)
       MCI01=MCI02*MOISRF
C
C   *** SINGH CALL DATA AND SUBROUTINES FROM NASA SP-273 TO DEFINE ***
C   *** MHD PRIMARY COMBUSTOR CONDITIONS                          ***
C
       HP=.TRUE.
       PP=PRINT
       TT=3000.
       OF=OXF(1)
       CALL NEWOF
       CALL EQLBRM
       HP=.FALSE.
       TCOMB=TT
C
C *** SINGH NOW RESUMES MASS FLOW RATE CALCULATIONS  ***
C
C      MOAT08 IS THE MASS FLOW RATE OF O2 ENRICHED AIR TO THE MHD COMB (LBM/HR)
       MOAT08=OF*MCI02/(1.-SFLC)
C      PCTA IS THE PERCENT OF AIR IN THE FLOW
       PCTA=PCTA
C      MAI03 IS THE MASS FLOW RATE OF AMBIENT AIR TO THE MHD OXIDANT
C      COMPRESSOR (LBM/HR)
       MAI03=(PCTA/100.)*MOAT08
C      PCTO IS THE PERCENT OF OXYGEN IN THE FLOW
       PCTO=PCTO
C      MCI05 IS THE MASS FLOW RATE OF PURE O2 FROM THE AIR SEPARATION
C      PLANT (LBM/HR)
       MCT05=(PCTO/100.)*MOAT08
C      MAI04 IS THE MASS FLOW RATE OF AMBIENT AIR TO THE AIR SEPARATION
C      UNIT (LBM/HR)
       MAI04=MOT05/0.232
C      MNAI09 IS THE MASS FLOW RATE OF N2 AND AR FROM THE AIR SEPARATION
C      UNIT (LBM/HR)
       MNAI09=MAI04-MCI05
C      MWVI13 IS THE MASS FLOW RATE OF MOISTURE REMOVED FROM THE COAL (LBM/HR)
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```
      MWVT13=MCT01-MCT02
C     GWVT13 IS THE HEAT REQUIRED TO REMOVE MOISTURE FROM THE COAL (BTU/HR)
      GWVT13=1078.*MWVT13
C     MNAT11 IS THE MASS FLOW RATE OF N2 AND AR REQ. FOR COAL DRYING (LBM/HR)
      MNAT11=1.25*GWVT13/100.
C     MNAT10 IS THE MASS FLOW RATE OF N2 AND AR RELEASED TO THE
C     ATMOSPHERE (LBM/HR)
      MNAT10=MNAT09-MNAT11
C     MTT13 IS THE MASS FLOW RATE OF N2,AR, AND MOISTURE RELEASED TO THE
C     PLANT STACK (LBM/HR)
      MTT13=MNAT11+MWVT13
C     MKT14 IS THE MASS FLOW RATE OF POTASSIUM FORMATE SEED SUPPLIED TO
C     THE MHD COMBUSTOR (LBM/HR)
      MKT14=SFLO*MCT02/(1.-SFLO)
C     MPT15 IS THE MASS FLOW RATE OF PLASMA TO THE MHD CHANNEL (LBM/HR)
      MPT15=MCT02+MKT14+MOAT08
C     MTIT IS THE TOTAL MASS INFLOW TO THE MHD TOPPING CYCLE (LBM/HR)
      MTIT=MAT03+MAT04+MCT01+MKT14
C     MTCT IS THE TOTAL MASS OUTFLOW FROM THE MHD TOPPING CYCLE (LBM/HR)
      MTCT=MNAT10+MTT13+MPT15
C     MFGT17 IS THE MASS FLOW RATE OF FLUE GAS FROM THE DIFFUSER (LBM/HR)
      MFGT17=MPT15
C
C     ******  MASS FLOW SUMMARY AND OVERALL MASS BALANCE ******
C
      WRITE(6,5209)MCT02,MOISAR,MCISAF,MOISRF,MCT01,MOAT08,
     1PCTA,MAT03,PCTO,MCT05,MAT04,MNAT09,MWVT13,GWVT13,MNAT11,
     2MNAT10,MTT13,MKT14,MPT15,MTIT,MTCT
 5209 FORMAT('1',//,T30,'***** MHD TOPPING CYCLE MODEL *****',/,
     12X,'MCT02=',E10.5,2X,'MOISAR=',E10.5,2X,'MCISAF=',
     2E10.5,2X,'MCISRF=',E10.5,2X,'MCT01=',E10.5,2X,'MOAT08=',
     3E10.5,2X,'PCTA=',E10.5,2X,/,2X,'MAT03=',E10.5,2X,'PCTO=',
     4E10.5,2X,'MCT05=',E10.5,2X,'MAT04=',E10.5,2X,'MNAT09=',
     5E10.5,2X,'MWVT13=',E10.5,2X,'GWVT13=',E10.5,/,2X,
     6'MNAT11=',E10.5,2X,'MNAT10=',E10.5,2X,'MTT13=',E10.5,
     72X,'MKT14=',E10.5,2X,'MPT15=',E10.5,2X,'MTIT=',E10.5,
     82X,'MTOT=',E10.5,/)
      WRITE(6,5210)MAT04,MCT05,MNAT09,MAT03,MOAT08,MCT05
 5210 FORMAT(T31,'MHD TOPPING CYCLE - MASS FLOW SUMMARY'
     1,//,T20,'MASS INFLOWS',T70,'MASS OUTFLOWS',/,
     2T33,'***** AIR SEPARATION UNIT *****',//,
     3T5,'DESCRIPTION',T42,'QUANTITY(LBM/HR)',10X,
     4'DESCRIPTION',
     5T95,'QUANTITY(LBM/HR)',//,T5,
     6'AIR TO AIR SEPARATION UNIT',T42,
     7F12.1,10X,'PURE OXYGEN PRODUCT',T95,F12.1,//,T64,
     8'N2 AND AR EFFLUENT',T95,F12.1,///,T30,
     9'***** MHD OXIDANT COMPRESSOR *****',//,T5,
     1'DESCRIPTION',T42,
     2'QUANTITY(LBM/HR)',10X,'DESCRIPTION',T95,
     3'QUANTITY(LBM/HR)',//,
     4T5,'AIR TO COMPRESSOR',T42,F12.1,10X,
     5'ENRICHED AIR FROM COMPRESSOR',
     6T95,F12.1,//,T5,'PURE O2 TO COMPRESSOR',T42,F12.1,//)
      WRITE(6,5211)MCT01,MCT02,MNAT11,MTT13
 5211 FORMAT(T30,
     1'***** PULVERIZERS, FANS, & BAGHOUSE *****',//,T5,
     2'DESCRIPTION',T42,
     3'QUANTITY(LBM/HR)',10X,'DESCRIPTION',T95,
     4'QUANTITY(LBM/HR)',//,
     5T5,'COAL FROM STOCK PILE',T42,F12.1,10X,
     6'DRIED COAL TO MHD COMBUSTOR',T95,F12.1,//,T5,
     7'N2 AND AR DRYING GAS',
     8T42,F12.1,10X,'DRYING GAS & MOISTURE TO STACK',
     9T95,F12.1,//)
```

```
C
      WRITE(6,5212)MCT02,MPT15,MCAT08,MKT14
 5212 FORMAT(125,
     1'***** MHD COMBUSTOR, CHANNEL AND DIFFUSER *****',//
     2,T5,'DESCRIPTION',T42,'QUANTITY(LBM/HR)',10X,
     3'DESCRIPTION',T95
     4'QUANTITY(LBM/HR)',//,T5,'DRIED COAL TO MHD COMBUSTOR',
     5T42,F12.1,10X,'FLUE GAS TO RADIANT FURNACE',T95,F12.1,//
     6,T5,'02 ENRICHED AIR TO MHD COMBUSTOR',T42,F12.1,//,T5,
     7'SEED TO MHD COMBUSTOR',T42,F12.1,//)
      WRITE(6,5213)MAT03,MNAT10,MAT04,MTT13,MCT01,MPT15,MKT14,MTIT,MTOT
 5213 FORMAT(131,'MHD TOPPING CYCLE - OVERALL MASS BALANCE',//,
     1T20,'MASS INFLOWS',T70,'MASS OUTFLOWS',//,T5,
     2'DESCRIPTION',T42,'QUANTITY(LBM/HR)',10X,'DESCRIPTION',T95,
     3'QUANTITY(LBM/HR)',//,T5,'AIR TO MHD COMPRESSOR',T42,F12.1,10X,
     4'N2 & AR EFFLUENT TO ATMOSPHERE',T95,F12.1,//,T5,
     5'AIR TO AIR SEPARATION PLANT',T42,F12.1,10X,
     6'N2, AR, AND MOISTURE TO STACK',T95,F12.1,//,T5,
     7'COAL FROM STOCK-PILE',T42,F12.1,10X,
     8'FLUE GAS TO RADIANT FURNACE',
     9T95,F12.1,//,T5,'POTASSIUM FORMATE SEED',T42,F12.1,/,T42,
     1'----------',10X,T95,'----------',//,
     2T5,'TOTAL INFLOW',T42,F12.1,10X,'TOTAL OUTFLOW',T95,F12.1,/)
      IF(MTOT.GT.MTIT) GO TO 5235
      GO TO 5236
 5235 WRITE(6,*)'*** WARNING - MASS IS CREATED IN TOPPING CYCLE ***'
 5236 IF(MTOT.LT.(0.99*MTIT)) GO TO 5237
      GO TO 8713
 5237 WRITE(6,*)'*** MHD TOPPING CYCLE IS NOT MASS BALANCED ***'
      GO TO 8713
C
 8713 CONTINUE
C
C     **** SINGH CALCULATES ENERGY QUANTITIES, THERMODYNAMIC
C          PROPERTIES, AND GEOMETRY FOR THE MHD TOPPING CYCLE ****
C
C     POWERC IS THE SHAFT POWER REQUIRED FROM THE ASP TURBINE (WATTS)
      POWERC=101.75*MOT05
C     POAT07 IS THE PRESSURE REQUIRED FROM THE OXIDANT
C     COMPRESSOR DISCHARGE.
      POAT07=14.7*PRINT+15.
C     AFLOV IS THE OXIDANT FLOW VOLUME TO THE OXIDANT COMPRESSOR (CFM)
      AFLOV=13.56*MOAT08/60.
C     PCOMP IS THE SHAFT POWER DELIVERED TO THE OXIDANT COMPRESSOR (WATTS)
      PCOMP=3.25*14.7*AFLOV*3.5*(((POAT07/14.7)**.286)-1)/0.89
C     TOAT07 IS THE TEMPERATURE OF THE MHD OXIDANT AT THE COMPRESSOR
C     EXIT (RANKINE)
      TOAT07=(540.*(POAT07/14.7)**.286)/.89
C     QOAT07 IS THE RATE AT WHICH HEAT IS GAINED BY THE OXIDANT DURING
C     COMPRESSION (BTU/HR)
      QOAT07=MOAT08*(1.1875E-05*((TOAT07**2)-(540.**2))+0.224*
     1(TOAT07-540.))
C     ELOST IS THE ENERGY LOST DURING THE OXIDANT COMPRESSION
C     PROCESS (WATTS)
      ELOST=PCOMP-0.2931*QOAT07
C     QHEOAT IS THE HEAT ADDED TO OXIDANT IN HRSR HEAT EXCHANGER (BTU/HR)
      QHEOAT=MOAT08*(1.1875E-05*(((TAIC*1.8)**2)-(TOAT07**2))+
     10.224*(TOAT07-540.))
C     QOAT08 IS THE RATE OF HEAT ADDITION TO COMBUSTOR BY THE
C     OXIDANT FLOW (BTU/HR)
      QOAT08=QOAT07+QHEOAT
C     PPFT IS THE ELECTRIC POWER REQUIRED TO DRIVE THE PULVERIZERS
C     AND DRYING FANS (WATTS)
      PPFT=7.*MCT01
C     QNAT12 IS THE HEAT TRANSFERRED TO THE NITROGEN AND ARGON
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C     DRYING GAS FROM FLUE GAS (BTU/HR)
      QNAT12=131.*MNAT11
C     QLCDT IS THE DRYING HEAT LOST TO COAL HEATING AND THEN TO
C     THE ATMOSPHERE (BTU/HR)
      QLCDT=0.25*QWVT13
C     QNAT13 IS THE HEAT RETAINED BY THE COAL DRYING GAS (BTU/HR)
      QNAT13=QNAT12-QWVT13-QLCDT
C
C
C     **** SINGH CALLS NASA SP-273 TO CALCULATE AND STORE FLUE
C          GAS PROPERTY DATA AT FOUR DIFFERENT STATES, THEY ARE
C          STATE POINTS FOR SECONDARY COMBUSTOR INLET,
C          ECONOMIZER INLET, STACK AND REFERENCE CONDITION ****
C
      TP=.TRUE.
C     NPT=2 IDENTIFIES PROPERTIES AT THE EXIT OF THE STEAM PLANT
      ISV=-NPT
      NPT=7
C     NPT=7 IDENTIFIES PROPERTIES AT THE SECONDARY COMBUSTOR INLET
      CALL SAVE
      ISV=1
      CALL SAVE
      PP=1.00
      TT=1866.7
      CALL EQLBRM
      ISV=-7
      CALL SAVE
      AMIX=EQRAT
      EQRAT=.9524
      CF=(-EQRAT*VMIN(2)-VPLS(2))/(VPLS(1)+EQRAT*VMIN(1))
      CALL NEWOF
C     NPT=6 IDENTIFIES PROPERTIES AT THE ECONOMIZER INLET
      NPT=6
      TP=.TRUE.
      ISV=7
      CALL SAVE
      TTOLD=2000.
 4002 TT=TTOLD
      PP=1.00
      TT=2000.
      CALL EQLBRM
      ISV=-6
      CALL SAVE
      CALL OUT2
      NPT=6
      ISV=6
      CALL SAVE
      TT=1600.
      PP=1.00
      CALL EQLBRM
      ISV=-6
      CALL SAVE
      CALL OUT2
      IF(TT.NE.0.0) GO TO 4001
      TTOLD=TTOLD+100.
      NPT=2
      GO TO 4002
 4001 CONTINUE
      NPT=6
      ISV=6
      CALL SAVE
      TT=1200.
      PP=1.00
      CALL EQLBRM
      ISV=-6
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      CALL SAVE
      CALL OUT2
      NPT=6
      ISV=6
      CALL SAVE
      TT=900.
      PP=1.00
      CALL EQLBRM
      ISV=-6
      CALL SAVE
      CALL OUT2
      NPT=6
      ISV=NPT
      CALL SAVE
      TT=644.4
      PP=1.00
      CALL EQLBRM
      ISV=-6
      CALL SAVE
      CALL OUT2
      NPT=2
      ISV=6
      CALL SAVE
      PP=1.00
      TT=395.
      CALL EQLBRM
      ISV=-2
      CALL SAVE
      CALL OUT2
C     NPT=5 IDENTIFIES PROPERTIES AT THE CHOSEN REFERENCE CONDITION:
C     T=298 DEG K., AND P=1.0 ATM.
      NPT=5
      ISV=2
      CALL SAVE
      PP=1.
      TT=300.
      CALL EQLBRM
      CALL OUT2
      IF(TT.NE.0.0) GO TO 5003
      NPT=8
      ISV=2
      CALL SAVE
      PP=1.00
      TT=200.
      CALL EQLBRM
      CALL OUT2
      STOP
C
 5003 EQRAT=AMIX
      CF=(-EQRAT*VMIN(2)-VPLS(2))/(VPLS(1)+EQRAT*VMIN(1))
      CALL NEWOF
C
      TP=.FALSE.
C
C     **** SINGH RESUMES CALCULATION OF ENERGY QUANTITIES,
C          THERMODYNAMIC PROPERTIES, & GEOMETRY FOR MHD TOPPING
C          CYCLE. ****
C
C     QKT14 IS THE ENERGY REQUIRED TO FREE POTASSIUM FROM FORMATE
C     (BTU/HR)
      QKT14=4.*WKT14
C     QLCOMB IS THE HEAT FROM THE COMBUSTOR LOST TO THE COOLING
C     WATER (BTU/HR)
      QLCOMB=QLCPUM*WCT02
C     EQKT15 IS THE KINETIC ENERGY AND HEAT TRANSPORTED FROM THE
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C       COMBUSTOR BY THE PLASMA (BTU/HR)
        EQKT15=(HSUM(1)-HSUM(5))*1.8*MPT15*R
C       ECT15 IS THE UNRELEASED CHEMICAL ENERGY TRANSPORTED FROM THE
C       COMBUSTOR BY THE PLASMA (BTU/HR)
        ECT15=THIN+GOAT08-EQKT15-QLCOMB
C
C       **** SINGH CALCULATES NOZZLE GEOMETRY AND PLASMA THERMODYNAMIC
C            PROPERTIES ****
C
C       SONVEL(1) IS THE VELOCITY OF SOUND THROUGH THE PLASMA AT
C       COMBUSTOR CONDITIONS (METERS/SEC)
        SONVEL(1)=(RR*GAMMAS(1)*TTT(1)/WM(1))**.5
C       RHOC IS THE PLASMA DENSITY IN THE COMBUSTOR (KG/CUBIC METER)
        RHOC=1./(VLM(1)*0.001)
C       RHOT IS THE PLASMA DENSITY AT THE NOZZLE THROAT (KG/CUBIC METER)
        RHOT=RHOC/((1.+(GAMMAS(1)-1.)/2.)**(1.0/(GAMMAS(1)-1.)))
C       AT IS THE CROSS SECTIONAL AREA OF THE NOZZLE THROAT (SQUARE METERS)
        AT=(MPT15*.45359)/(SONVEL(1)*RHOT*3600.)
        AN=1.+(GAMMAS(1)-1.)*((EMACH**2)/2.)
        BN=2./(GAMMAS(1)+1.)
        CN=1./(BN*(GAMMAS(1)-1.))
C       AE IS THE CROSS SECTIONAL AREA OF THE NOZZLE EXIT (SQUARE METERS)
        AE=(AT/EMACH)*((BN*AN)**CN)
C       RE IS THE PLASMA DENSITY AT THE NOZZLE EXIT (KG/CUBIC METER)
        RE=RHOC/(AN**(1./(GAMMAS(1)-1.)))
C       TE IS THE STATIC TEMPERATURE AT THE NOZZLE EXIT (DEGREES KELVIN)
        TE=TCOMB/AN
C       PENZ IS THE STATIC PRESSURE AT THE NOZZLE EXIT (ATM)
        PENZ=PRINT/(AN**(GAMMAS(1)/(GAMMAS(1)-1.)))
C
C       **** MHD GENERATOR CHANNEL ANALYSIS ****
C
C       GDMF IS THE GENERATOR DESIGN MASS FLOW IN LBM/HR
C       HFF IS THE FRACTIONAL ENTHALPY EXTRACTION BY GENERATOR CHANNEL
        HFF=HF*((1.+(MPT15/GDMF))*0.5)**0.35
C       GEFF IS THE FRACTIONAL MHD GENERATOR EFFICIENCY
        GEFF=GEF*((1.+(MPT15/GDMF))*0.5)**0.5
C       ENTA IS THE ENTRANCE AREA OF THE CHANNEL IN (SQUARE METERS)
        ENTA=(MPT15/GDMF)*ENT
C       AREAR IS THE AREA RATIO OF THE CHANNEL--EXIT AREA OVER ENTRANCE
C       EXTA IS THE GENERATOR CHANNEL EXIT AREA (SQUARE METERS)
        EXTA=AREAR*ENTA
C       PEXM IS THE D.C. ELECTRIC POWER DEVELOPED BY MHD CHANNEL (WATTS)
        PEXM=(HSUM(1)-HSUM(5))*R*1.8*.2931*HFF*MPT15
C       CEFFI IS THE INVERTER EFFICIENCY
C       POUTM IS THE A.C. ELECTRIC POWER AVAILABLE TO GRID (WATTS)
        POUTM=CEFFI*PEXM
C       QLMHD IS THE PLASMA ENERGY TRANSFERRED TO CHANNEL COOLING
C       WATER AS HEAT (BTU/HR)
        QLMHD=(PEXM*3.4129*(1.-GEFF))/GEFF
C       EQKT16 IS THE KINETIC ENERGY AND HEAT TRANSPORTED FROM CHANNEL
C       BY PLASMA (BTU/HR)
        EQKT16=EQKT15-(PEXM*3.4129)-QLMHD
C       ETT16 IS THE TOTAL ENERGY TRANSPORTED FROM CHANNEL BY PLASMA
        ETT16=EQKT16+ECT15
C       CLEN IS THE CHANNEL LENGTH IN METERS
C       PMAG IS THE ELECTRIC POWER REQUIRED TO OPERATE THE SUPER-
C       CONDUCTING MAGNET (WATTS)
        PMAG=CLEN*1000.*(13.4*((ENTA**.5)+((ENTA*AREAR)**.5))
     1+7.*BMAX*ENTA)
C
        WRITE (6,3014) CLEN,ENTA,AREAR,HFF,GEFF,PSIAT,PRECM
C
C       THE NEXT STEPS UTILIZE SP-273 TO FIND THE OTHER THERMODYNAMIC
C       PROPERTIES FOR THE ENTHALPY AND PRESSURE AT THE EXIT OF THE MHD
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C     DUCT
C
C     **** SINGH CALLS NASA SP-273 SUBROUTINES FOR CHANNEL EXIT
C          PROPERTIES (NPT=3) ****
C
C     NPT=3 IDENTIFIES PROPERTIES AT THE EXIT OF THE DUCT(ENTRANCE OF
C     THE DIFFUSER)
      NPT=3
      ISV=1
      CALL SAVE
      HP=.TRUE.
C     PSTAT IS THE STATIC PRESSURE AT OUTPUT OF DUCT
      PP=PSTAT
      TT=2400.
      HSUB0=HSUB0-PEXM*3.413/(MPT15*1.8*R*GEFF)
      CALL EQLBRM
C
C     **** DIFFUSER ANALYSIS ****
C
      BBB=(ENTA*AREAR)**.5*100.
C     DLEN IS THE DIFFUSER LENGTH (CM)
      DLEN=(3.79*BBB)
C     TWALL IS THE WALL TEMPERATURE
      TWALL=1200.
C     QLDIF IS THE HEAT TRANSFERRED FROM THE PLASMA TO DIFFUSER
C     COOLING WATER (BTU/HR)
      QLDIF=4.*(TTT(3)-TWALL)*(.0316*BBB*DLEN+.0316*.0349*DLEN*DLEN
     1-3.53E-06*BBB*DLEN*DLEN-(1.412E-05*.0349*(DLEN**3))/3.)*3.4129
C     ETT17 IS THE TOTAL ENERGY TRANSPORTED FROM DIFFUSER BY FLUE
C     GAS (BTU/HR)
      ETT17=ETT16-QLDIF
C     EQKT17 IS THE KINETIC ENERGY AND SENSIBLE TRANSPORTED ENERGY
C     FROM DIFFUSER BY FLUE GAS (BTU/HR)
      EQKT17=ETT17-ECT15
C
C     **** SINGH CALLS NASA SP-273 SUBROUTINES TO DETERMINE FLUE
C          GAS PROPERTIES AT DIFFUSER EXIT (NPT=4) ****
C
C     PDO IS THE STAGNATION PRESSURE AT OUTPUT OF DIFFUSER IN PSIA
      PDO=((.25*1.E+03*(SONVEL(3)**2))/(VLM(3)*101385.)+PSTAT)*14.7
      NPT=4
      ISV=3
      CALL SAVE
      HP=.TRUE.
      HSUB0=(HSUM(3)-QLDIF)/(R*1.8*MPT15)-((.4*SONVEL(3))**2)/(5.39
     1E 05*R*1.8)
      TT=2000.
      PP=PDO/14.7
      CALL EQLBRM
C
C     MHD TOPPING CYCLE ENERGY BALANCE
      WRITE(6,1210)PCWERC
 1210 FORMAT('1',T31,'MHD TOPPING CYCLE - ENERGY QUANTITIES'
     1,/,   T31,'--- ------- ------ - ------ ----------'
     1,//,T20,'ENERGY IN',T70,'ENERGY OUT',/,
     1    T20,'------ --',T70,'------ ---',//,
     2T33,'***** AIR SEPARATION PLANT *****',/,
     2T33,'----- --- ---------- ----- -----',///,
     3T5,'DESCRIPTION',T42,'QUANTITY(BTU/HR OR WATTS)',10X,
     4'DESCRIPTION',
     5T95,'QUANTITY(BTU/HR OR WATTS)',//,T5,
     6'SHAFT POWER REQUIRED BY TURBINE',T42,
     7F12.1,'WATTS',///)
C
      WRITE(6,1211)PCOMP,QOAT07
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 1211 FORMAT(T30,'** PRIMARY OXIDANT COMPRESSOR **',//,T5,
     1'DESCRIPTION',T42,
     2'QUANTITY(BTU/HR)',10X,'DESCRIPTION',T95,
     3'QUANTITY(BTU/HR)',//,
     4T5,'SHAFT POWER REQUIRED BY TURBINE',T42,F12.1,'WATTS',5X,
     5'OXIDANT THERMAL ENERGY',T95,F12.1,//)
      WRITE(6,1212)PPFT,QLCD1,QNAT12,QNAT13
 1212 FORMAT(T30,
     1'*** COAL PULVERIZERS & DRYERS ***',//,T5,
     2'DESCRIPTION',T42,
     3'QUANTITY(BTU/HR OR WATTS)',10X,'DESCRIPTION',T95,
     4'QUANTITY(BTU/HR OR WATTS)',//,
     5T5,'ELECTRIC POWER FOR PULVERIZERS & FANS',T42,F12.1,
     6'WATTS',5X,'HEAT LOST TO COAL',T95,F12.1,//,T5,
     7'THERMAL ENERGY OF NITROGEN DRYING STREAM',T42,F12.1,10X,
     8'THERMAL ENERGY IN EXITING GAS',
     9T95,F12.1,//)
C
      WRITE(6,1213)THIN,QKT14,QCAT08,QLCOMB,EQKT15,ECT15
 1213 FORMAT(T25,
     1'***** MHD COMBUSTOR *****',//
     2,T5,'DESCRIPTION',T42,'QUANTITY(BTU/HR OR WATTS)',10X,
     3'DESCRIPTION',T95,
     4'QUANTITY(BTU/HR OR WATTS)',//,T5,'COAL CHEMICAL ENERGY',
     5T42,F12.1,10X,'SEED DECOMPOSITION',T95,F12.1,//
     6,T5,'OXIDANT THERMAL ENERGY',T42,F12.1,10X,
     7'COMBUSTOR HEAT LOSS',T95,F12.1,//,
     8T64,'PLASMA THERMAL & KE',T95,F12.1,//,
     9T64,'PLASMA CHEMICAL ENERGY',T95,F12.1,//)
C
      WRITE(6,1214)EQKT15,POUTM,QLMHD,ECT15,EQKT16,PMAG,ECT15
 1214 FORMAT(T25,
     1'***** MHD GENERATOR CHANNEL *****',//
     2,T5,'DESCRIPTION',T42,'QUANTITY(BTU/HR OR WATTS)',10X,
     3'DESCRIPTION',T95,
     4'QUANTITY(BTU/HR OR WATTS)',//,T5,
     4'PLASMA KINETIC & THERMAL ENERGY',
     5T42,F12.1,10X,'ELECTRIC POWER TO GRID',T95,F12.1,
     6'WATTS',//,T64,'HEAT LOST TO COOLING WATER',T95,F12.1,
     7//,T5,'PLASMA CHEMICAL ENERGY',T42,F12.1,10X,
     8'PLASMA THERMAL & KE',T95,F12.1,//,
     9T5,'MAGNET POWER',T42,F12.1,10X,'PLASMA CHEMICAL ENERGY',
     1T95,F12.1,//)
C
      WRITE(6,1215)EQKT16,QLDIF,ECT15,EQKT17,ECT15
 1215 FORMAT(T25,
     1'***** MHD DIFFUSER *****',//
     2,T5,'DESCRIPTION',T42,'QUANTITY(BTU/HR OR WATTS)',10X,
     3'DESCRIPTION',T95,
     4'QUANTITY(BTU/HR OR WATTS)',//,T5,
     4'FLUE GAS THERMAL & KINETIC ENERGY',
     5T42,F12.1,10X,'HEAT LOST TO COOLING WATER',T95,F12.1,//
     6,T5,'FLUE GAS CHEMICAL ENERGY',T42,F12.1,10X,
     7'FLUE GAS THERMAL & KE',T95,F12.1,//,
     8T64,'FLUE GAS CHEMICAL ENERGY',T95,F12.1,//)
C
C     **** SEED REGENERATION VIA THE FORMATE PROCESS *****
C
C     MKSR01 IS DRY K2SO4 FROM HSR EQUIPMENT LBM/HR
      MKSR01=5.44*MCT02*XS*.98
C     KLHRSR IS THE POTASSIUM LOST IN THE RADIANT
C     FURNACE (LBM/HR)
      KLHRSR=(39./94.)*MKT14-(78./174.)*MKSR01
      IF(KLHRSR.GE.0) GO TO 9898
      WRITE(6,*)'INSUFFICIENT POTASSIUM FOR SULFUR RECOVERY'
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      KLHRSR=0.0
      MKSR01=(174./78.)*(39./84.)*MKT14
 9898 CONTINUE
C     MSWR02 IS SERVICE WATER FORM K2SO4 SLURRY LBM/HR
      MSWR02=0.11*MKSR01
C     MKWR03 IS K2SO4 SLURRY TO DISSOLVER LBM/HR
      MKWR03=MKSR01+MSWR02
C     MCR04 IS COAL TO GASIFIER LBM/HR
      MCR04=0.34*MKSR01/(1-1.85*XS)
C     MKR05 IS THE MASS FLOW RATE OF POTASSIUM FORMATE TO
C     MIXING TANK (LBM/HR)
      MKR05=(78./32.)*XS*MCR04
C     MSWR06 IS SERVICE WATER FOR GASIFIER COAL SLURRY LBM/HR
      MSWR06=0.52*MCR04
C     MCWR07 IS COAL SLURRY TO GASIFIER LBM/HR
      MCWR07=MCR04+MSWR06+MKR05
C     MAR08 IS AIR TO GASIFIER LBM/HR
      MAR08=4.02*MCR04
C     MASR09 IS THE COAL SLAG FROM THE GASIFIER (LBM/HR)
      MASR09=XAAR*MCR04
C     MKSR10 IS DRY K2SO4 FROM GASIFIER LBM/HR
      MKSR10=5.44*XS*MCR04
C     MGR11 IS PRODUCT GAS FROM GASIFIER LBM/HR
      MGR11=MCWR07+MAR08-MASR09-MKSR10
C     MSWR12 IS SERVICE WATER FOR K2SO4 SLURRY LBM/HR
      MSWR12=0.11*MKSR10
C     MKWR13 IS K2SO4 SLURRY TO DISSOLVER LBM/HR
      MKWR13=MKSR10+MSWR12
C     MCAR14 IS LIME TO K2SO4 DISSOLVER LBM/HR
      MCAR14=0.32*(MKSR01+MKSR10)
C     MKSR43 IS RECYCLE K2SO4 FROM FILTER LBM/HR
      MKSR43=0.20*(MKSR01+MKSR10)
C     MKSR31 IS K2SO4 COMPONENT OF RECYCLE STREAM R29 LBM/HR
      MKSR31=0.01*(MKSR01+MKSR10)
C     MKCR31 IS KCO2H COMPONENT OF RECYCLE STREAM R29 LBM/HR
      MKCR31=4.85*MKSR31
C     MWR31 IS WATER COMPONENT OF RECYCLE STREAM R29 LBM/HR
      MWR31=324.07*MKSR31
C     MTR31 IS RECYCLE K COMPOUND SLURRY FROM FLASH TANK AND
C     GYPSUM FILTER LBM/HR
      MTR31=MKSR31+MKCR31+MWR31
C     MKSR32 IS K2SO4 COMPONENT OF RECYCLE STREAM R30 LBM/HR
      MKSR32=0.08*(MKSR01+MKSR10)
C     MKCR32 IS KCO2H COMPONENT OF RECYCLE STREAM R30 LBM/HR
      MKCR32=4.95*MKSR32
C     MWR32 IS WATER COMPONENT OF RECYCLE STREAM R30 LBM/HR
      MWR32=12.62*MKSR32
C     MTR32 IS RECYCLE K COMPOUND SLURRY LBM/HR
      MTR32=MKSR32+MKCR32+MWR32
      MKSR15=MKSR01+MKSR13+MKSR31+MKSR32+MKSR43
      MKFR15=MKFR31+MKFR32
      MWR15=MWR02+MWR12+MWR31+MWR32
      MCHR15=(16335./12364.)*MCAR14
C     MTR15 IS K AND CA COMPOUND SLURRY FROM DISSOLVER LBM/HR
      MTR15=MKSR15+MKFR15+MWR15+MCHR15
C     QTR18 IS HEAT REQUIRED FROM HEAT EXCHANGER B  BTU/HR
      QTR18=101.7*MTR15
C     MSR16 IS STEAM TO HEAT EXCHANGER B LBM/HR
      MSR16=QTR18/993.6
C     MWR17 IS CONDENSATE FROM HEAT EXCHANGER B LBM/HR
      MWR17=MSR16
C     MTR18 IS K AND CA COMPOUND SLURRY TO REACTOR LBM/HR
      MTR18=MTR15
C     MGR21 IS PRODUCT GAS TO SCRUBBER LBM/HR
      MGR21=MGR11
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C      MCDR20 IS CO2 FROM REGENERATOR TO ATMOSPHERE LBM/HR
       MCDR20=0.085*MGR21
C      MGR21 IS PRODUCT GAS TO REACTOR LBM/HR
       MGR21=MGR21-MCDR20
C      MGR22 IS PRODUCT GAS TO HEAT RECOVERY LBM/HR
       MGR22=0.93*MGR21
C      MTR23 IS K AND CA COMPOUND SLURRY TO FLASH TANK LBM/HR
       MTR23=MTR18+MGR21-MGR22
C      MSR25 IS STEAM FROM FLASH TANK LBM/HR
       MSR25=0.12*MTR23
C      MTR24 IS K AND CA COMPOUNDS FROM FLASH TANK LBM/HR
       MTR24=MTR23-MSR25
C      MSWR26 IS SERVICE WATER TO HEAT EXCHANGER A  LBM/HR
       MSWR26=1.80*MGR11
C      MSWR27 IS SERVICE WATER FROM HEAT EXCHANGER A  LBM/HR
       MSWR27=MSWR26
C      MYWR28 IS GYPSUM AND WATER TO DISPOSAL LBM/HR
       MYWR28=0.24*MTR24
C      MTR29 IS RECYCLE K COMPOUND SLURRY FROM GYPSUM FILTER LBM/HR
       MTR29=MTR31-MSR25
C      MTR30 IS K COMPOUND SLURRY FROM GYPSUM FILTER LBM/HR
       MTR30=MTR24+MSWR27-MYWR28-MTR29
C      MKWR33 IS K COMPOUND SLURRY TO EVAPORATOR LBM/HR
       MKWR33=MTR30-MTR32
C      MSR34 IS STEAM VENTED FROM K COMPOUND SLURRY LBM/HR
       MSR34=0.50*MKWR33
C      MKWR35 IS K COMPOUNDS TO SPRAY DRYER LBM/HR
       MKWR35=MKWR33-MSR34
C      MGR36 IS GAS FROM EVAPORATOR LBM/HR
       MGR36=MGR22
C      MFGR37 IS FLUE GAS TO SPRAY DRYER LBM/HR
       MFGR37=14.12*MKWR35
C      MKR38 IS K COMPOUNDS TO HEAT EXCHANGER C LBM/HR
       MKR38=0.636*MKWR35
C      MFGR39 IS FLUE GAS AND MOISTURE TO STACK LBM/HR
       MFGR39=MFGR37+MKWR35-MKR38
C      MKR40 IS K COMPOUNDS TO K2SO4 FILTER LBM/HR
       MKR40=MKR38
C      QKR40 IS THE HEAT REQUIRED FROM HEAT EXCHANGER C (BTU/HR)
       QKR40=MKR38*40.
C      MSR41 IS STEAM TO HEAT EXCHANGER C  LBM/HR
       MSR41=QKR40/983.6
C      MWR42 IS CONDENSATE FROM HEAT EXCHANGER C LBM/HR
       MWR42=MSR41
C      MKCR44 IS POTASSIUM FORMATE TO MKC CYCLE LBM/HR
       MKCR44=MKR40-MKSR43
C      SGMFR IS MASS FLOW RATE OF STACK GASES (LBM/HR)
       SGMFR=CFLOW+SFLOW+AFLOW+SAFLO
      1-SRRF-MFGR37+MFGR39+MGR22
C
C      SO20524 IS SUM OF MSWR02+MSWR06+MSWR26
       SO20524=MSWR02+MSWR06+MSWR26
C      TOTALI IS SUM OF ALL ABOVE INPUT FLOW STREAMS
       TOTALI=MKSR01+SO20524+MCR04+MAR08+MCAR14+MFGR37
C      TOTALO IS SUM OF ALL ABOVE OUTPUT FLOW STREAMS
       TOTALO=MCDR20+MGR22+MYWR28+MSR34+MFGR39+MKCR44+MASR09
C
       WRITE(6,719)XS,MCT02,MKSR01,MSWR02,MKWR03,MCR04,MSWR06,
      1MCWR07,MAR08,MGR11,MKSR10,MSWR12,MKWR13,MCAR14,
      2MKSR31,MKCR31,MWR31,MTR31,MKSR32,MKCR32,MWR32,MTR32,
      3MTR15,QTR18,MSR16,MWR17
  719 FORMAT('1',T20,'******* FORMATE SEED REGENERATION MODEL ******',
      1/,2X,'XS=',E10.5,2X,'MCT02=',E10.5,2X,'MKSR01=',E10.5,2X,
      2'MSWR02=',E10.5,2X,'MKWR03=',E10.5,/,2X,'MCR04=',E10.5,2X,
      3'MSWR06=',E10.5,2X,'MCWR07=',E10.5,2X,'MAR08=',E10.5,2X,
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```
     4'MGR11=',E10.5,/,2X,'MKSR10=',E10.5,2X,'MSWR12=',E10.5,2X,
     5'MKWR13=',E10.5,2X,'MCAR14=',E10.5,/,2X,
     6'MKSR31=',E10.5,2X,'MKCR31=',E10.5,2X,'MWR31=',E10.5,2X,
     7'MTR31=',E10.5,2X,'MKSR32=',E10.5,/,2X,'MKCR32=',E10.5,2X,
     8'MWR32=',E10.5,2X,'MTR32=',E10.5,2X,'MTR15=',E10.5,2X,
     9'QTR18=',E10.5,/,2X,'MSR16=',E10.5,2X,'MTR15=',E10.5)
      WRITE(6,721)MTR18,MGR21,MCDR20,MGR21,MGR22,
     1MTR23,MSR25,MTR24,MSWR26,MSWR27,MYWR28,MTR29,MTR30,
     2MKWR33,MSR34,MKWR33,MSR34,MGR36,MFGR37,MKR38,MFGR39,
     3MKR40,MSR41,MWR42,MKSR43,MKCR44
  721 FORMAT(2X,'MTR18=',E10.5,2X,'MGR21=',E10.5,2X,
     *'MCDR20=',E10.5,2X,'MGR21=',E10.5,2X,'MGR22=',E10.5,/,2X,
     1'MTR23=',E10.5,2X,'MSR25=',E10.5,2X,'MTR24=',E10.5,2X,
     2'MSWR26=',E10.5,2X,'MSWR27=',E10.5,/,2X,'MYWR28=',E10.5,
     32X,'MTR29=',E10.5,2X,'MTR30=',E10.5,2X,'MKWR33=',E10.5,
     42X,'MSR34=',E10.5,/,2X,'MKWR33=',E10.5,2X,'MSR34=',E10.5,
     52X,'MGR36=',E10.5,2X,'MFGR37=',E10.5,2X,'MKR38=',E10.5,/,
     62X,'MFGR39=',E10.5,2X,'MKR40=',E10.5,2X,'MSR41=',E10.5,
     72X,'MWR42=',E10.5,2X,'MKSR43=',E10.5,/,2X,'MKCR44=',
     8E10.5,//////)
C
      WRITE(6,722)
  722 FORMAT(131,'MHD/STEAM COMBINED CYCLE POWER PLANT',/,
     1       T31,'--------- -------- ----- ----- -----',//,
     2       T29,'FORMATE SEED REGENERATION PROCESS SUMMARY',/,
     3       T29,'-------- ---- ---------- ------- -------',//,
     4       T34,'OVERALL SYSTEM MASS BALANCE',/,
     5       T34,'------- ------ ---- -------',/,
     6       T28,'(ALL MASS FLOWS ARE IN UNITS OF POUNDS/HOUR)',///)
      WRITE(6,729)MKSR01,MCDR20,S020524,MGR22,MCR04,MYWR28,
     1MAR08,MSR34,MCAR14,MFGR39,MFGR37,MKCR44,MASR09,TOTALI,TOTALO
  729 FORMAT(T20,'FLOW STREAMS IN',T70,'FLOW STREAMS OUT',/,T20,'----
     * ------- --',T70,'---- ------- ---'
     *,//,T5,'POTASSIUM SULFATE FROM HSR EQUIPMENT',T42,F12.1,10X,'CO2
     *FROM REGENERATOR',T95,F12.1,//,T5,'SERVICE WATER',T42,F12.1,10X,
     *'PRODUCT GAS TO HEAT RECOVERY',T95,F12.1,//,T5,'CCAL TO GASIFIER'
     *,T42,F12.1,10X,'GYPSUM AND WATER TO DISPOSAL',T95,F12.1,//,T5,
     *'AIR TO GASIFIER',T42,F12.1,10X,'VENTED STEAM',T95,F12.1,//,T5,
     *'LIME TO DISSOLVER',T42,F12.1,10X,'FLUE GAS AND MOISTURE TO STACK',
     *T95,F12.1,//,T5,'FLUE GAS TO SPRAY DRYER',T42,F12.1,10X,'POTASSIUM
     7 FORMATE FOR RECYCLE',T95,F12.1,//,T64,'SLAG FROM GASIFIER',T95,
     8F12.1,///,T5,'TOTAL',T42,F12.1,T95,F12.1
     8,/////////////////)
C
CC
CC      ************ HRSR SYSTEM MODEL **************
CC
CC      MSKH01 IS THE SLAG, POTASSIUM, AND SULFUR REMOVED FROM FLUE
C       GAS AT RADIANT FURNACE TAP (LBM/HR)
        MSKH01=(0.60+MCT02*XAAR*(100.-MOISAF)/(100.-MOISAR))
     1*KLHRSR+(0.02*MCT02*XS)
C       EQH01 IS THE QUANTITY OF HEAT LOST WITH MSKH01 (BTU/HR)
        EQH01=431.*MSKH01
C       MFGH02 IS THE MASS FLOW RATE OF FLUE GAS EXITING THE RADIANT
C       FURNACE AND ENTERING THE SECONDARY COMBUSTOR (LBM/HR)
        MFGH02=MFGT17-MSKH01
C       EQH02 IS THE THERMAL ENERGY TRANSPORTED FROM THE RADIANT FURNACE
C       BY THE FLUE GAS (BTU/HR)
        EQH02=MFGH02*(HSUM(7)-HSUM(5))*R*1.8
C       ETH02 IS THE TOTAL ENERGY TRANSFERRED FROM THE RADIANT FURNACE BY
C       THE FLUE GAS (BTU/HR)
        ETH02=EQH02+ECT15
C       EQSRF IS THE HEAT TRANSFERED FROM THE FLUE GAS IN THE RADIANT
C       FURNACE FOR STEAM GENERATION (BTU/HR)
        EQSRF=EQKT17-EQH01-EQH02
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C     MAH04 IS THE MASS FLOW RATE OF SECONDARY COMBUSTION AIR (LBM/HR)
      MAH04=((1.05-SR)/SR)*(MAT03+MAT04)
C     MFGH05 IS THE MASS FLOW RATE OF FLUE GAS FROM THE SECONDARY
C     COMBUSTOR (LBM/HR)
      MFGH05=MFGH02+MAH04
C     QAFGH5 IS THE HEAT REQUIRED TO RAISE SECONDARY AIR TEMPERATURE
C     FROM TAH04 TO 2900 DEG F (BTU/HR)
      QAFGH5=(1.1875E-05*(3360.**2-TAH04**2)+.224*(3360.-TAH04))*MAH04
C     EQSSC IS THE HEAT AVAILABLE FOR STEAM GENERATION IN THE SECONDARY
C     COMBUSTION WATER WALLS (BTU/HR)
      EQSSC=ECT15-QAFGH5
C     EQH04 IS THE HEAT TRANSPORTED INTO SECONDARY COMBUSTOR BY
C     SECONDARY COMBUSTION AIR (BTU/HR)
      EQH04=(1.1875E-05*(TAH04**2-540.**2)+.224*(TAH04-540.))*MAH04
C     EQH05 IS ENERGY TRANSPORTED FROM THE SECONDARY COMBUSTOR
C     BY THE FLUE GAS (BTU/HR)
      EQH05=EQH02+EQH04+QAFGH5
C     QRFG56 IS THE AMOUNT OF HEAT REMOVED FROM THE FLUE GAS BY
C     THE SUPERHEATER, REHEATER, & OXIDANT HEATER (BTU/HR)
      QRFG56=MFGH05*(HSUM(7)-HSUM(6))*R*1.8
C     EQH06 IS THE QUANTITY OF HEAT TRANSPORTED FROM THE SUPERHEATER,
C     REHEATER, & OXIDANT HEATER BY THE FLUE GAS (BTU/HR)
      EQH06=EQH05-QRFG56
C     EQSSR IS THE QUANTITY OF HEAT AVAILABLE FOR SUPERHEATING AND
C     REHEATING STEAM (BTU/HR)
      EQSSR=QRFG56-QHECAT
C     QRFG67 IS THE QUANTITY OF HEAT REMOVED FROM THE FLUE GAS IN
C     THE SECOND HEAT TRANSFER SECTION (BTU/HR)
      QRFG67=MFGH05*(HSUM(6)-HSUM(2))*R*1.8
C     EQSE IS THE HEAT AVAILABLE FOR THE ECONOMIZER (BTU/HR)
      EQSE=QRFG67-QTR18-QKR40-QNAT12-EQH04
C     EQH07 IS THE HEAT TRANSPORTED FROM THE SECOND HEAT TRANSFER
C     SECTION BY THE FLUE GAS (BTU/HR)
      EQH07=EQH06-QRFG67
C     MSH08 IS THE QUANTITY OF COAL ASH REMOVED IN THE ESP (LBM/HR)
      MSH08=0.20*(MCT02*XAAR*(100.-MCISAF)/(100.-MCISAR))
C     MTH08 IS THE TOTAL K2SO4 AND COAL ASH REMOVED BY ESP (LBM/HR)
      MTH08=MKSR01+MSH08
C     MFGH09 IS THE MASS FLOW RATE OF FLUE GAS FROM THE ESP TO
C     THE INDUCED DRAFT FAN. (LBM/HR)
      MFGH09=MFGH05-MTH08-MFGR37
C     MFGH10 IS THE TOTAL FLUE GAS MASS FLOW RATE TO THE STACK
      MFGH10=MFGH09+MFGR39
C     PFAN IS THE ELECTRIC POWER REQUIRED BY I.D. FAN (WATTS)
      PFAN= MFGH10*0.4
C
C     OUTPUT HRSR VARIABLES
      WRITE(6,7209)MSKH01,EQH01,MFGH02,EQH02,ETH02,EQSRF,MAH04,
     1MFGH05,QAFGH5,EQSSC,EQH04,EQH05,QRFG56,EQH06,EQSSR,QRFG67,
     2EQSE,EQH07,MSH08,MTH08,MFGH09,MFGH10
 7209 FORMAT('1',/,T30,'***** HRSR SYSTEM MODEL *****',/,
     12X,'MSKH01=',E10.5,2X,'EQH01=',E10.5,2X,'MFGH02=',
     2E10.5,2X,'EQH02=',E10.5,2X,'ETH02=',E10.5,2X,'EQSRF=',
     3E10.5,2X,'MAH04=',E10.5,2X,/,2X,'MFGH05=',E10.5,2X,'QAFGH5=',
     4E10.5,2X,'EQSSC=',E10.5,2X,'EQH04=',E10.5,2X,'EQH05=',
     5E10.5,2X,'QRFG56=',E10.5,2X,'EQH06=',E10.5,/,2X,
     6'EQSSR=',E10.5,2X,'QRFG67=',E10.5,2X,'EQSE=',E10.5,
     72X,'EQH07=',E14.7,2X,'MSH08=',E10.5,2X,'MTH08=',E10.5,
     82X,'MFGH09=',E10.5,/,2X,'MFGH10=',E10.5,//)
      WRITE(6,7210)MFGT17,MSKH01,MFGH02,MFGH05,MAH04
 7210 FORMAT('1',T31,'HRSR SYSTEM MODEL - MASS FLOW SUMMARY'
     1,/,    T31,'---- ------ ----- - ---- ---- -------'
     1,//,T20,'MASS INFLOWS',T70,'MASS OUTFLOWS',/,
     1    T20,'---- -------',T70,'---- --------',///,
     2T33,'***** RADIANT FURNACE *****',/,
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     2T33,'----- ------- ------- -----',//,
     3T5,'DESCRIPTION',T42,'QUANTITY(LBM/HR)',10X,
     4'DESCRIPTION'
     5T95,'QUANTITY(LBM/HR)',//,T5,
     6'FLUE GAS FROM RADIANT FURNACE',T42,
     7F12.1,10X,'SLAG, SEED, & SULFUR',T95,F12.1,//,T64,
     8'FLUE GAS TO SEC. COMBUSTOR',T95,F12.1,///,T30,
     9'***** SECONDARY COMBUSTOR *****',//,T5,
     1'DESCRIPTION',T42,
     2'QUANTITY(LBM/HR)',10X,'DESCRIPTION',T95,
     3'QUANTITY(LBM/HR)',//,
     4T5,'FLUE GAS FROM RADIANT FURNACE',T42,F12.1,10X,
     5'FLUE GAS FROM SEC. COMBUSTOR',T95,F12.1,//,
     6T5,'SECONDARY COMBUSTION AIR',T42,F12.1,//)
      WRITE(6,7211)MFGH05,MTH08,MFGH09,MFGR37
 7211 FORMAT(T30,
     1'***** ELECTROSTATIC PRECIPITATOR *****',//,T5,
     2'DESCRIPTION',T42,
     3'QUANTITY(LBM/HR)',10X,'DESCRIPTION',T95,
     4'QUANTITY(LBM/HR)',//,
     5T5,'FLUE GAS FROM CONVECTIVE SECTION',T42,F12.1,10X,
     6'POTASSIUM SULFATE & ASH',T95,F12.1,//,T64,
     7'FLUE GAS TO ID FAN',T95,F12.1,//
     8T64,'FLUE GAS TO SEED REGEN',
     9T95,F12.1,//)
C
      WRITE(6,7212)MFGH09,MFGH10,MFGR39
 7212 FORMAT(T25,
     1'***** INDUCED DRAFT FAN *****',//
     2,T5,'DESCRIPTION',T42,'QUANTITY(LBM/HR)',10X,
     3'DESCRIPTION',T95,
     4'QUANTITY(LBM/HR)',//,T5,'FLUE GAS FROM ESP',
     5T42,F12.1,10X,'FLUE GAS TO STACK',T95,F12.1,//
     6,T5,'FLUE GAS FROM SEED REGENERATION',T42,F12.1,//)
C
      Q18P40=QTR18+QKR40
C
      WRITE(6,8210)EQKT17,EQSRF,EQH01,EQH02,ECT15,ECT15
 8210 FORMAT('1',T31,'HRSR SYSTEM MODEL - ENERGY SUMMARY'
     1,/,    T31,'---- ------ ----- - ------ -------'
     1,//,T20,'ENERGY IN',T70,'ENERGY OUT',/,
     1   T20,'------ --',T70,'------ ---',//,
     2T33,'***** RADIANT FURNACE *****',//,
     2T33,'----- ------- ------- -----',//,
     3T5,'DESCRIPTION',T42,'QUANTITY(BTU/HR)',10X,
     4'DESCRIPTION'
     5T95,'QUANTITY(BTU/HR)',//,T5,
     6'FLUE GAS THERMAL & KE FROM DIFFUSER',T42,
     7F12.1,10X,'STEAM GENERATION',T93,F14.1,//,T64,
     8'SLAG, POTASSIUM, & SULFUR',T95,F12.1,//,T64,
     9'FLUE GAS THERMAL ENERGY',T95,F12.1,//,T5,
     1'UNRELEASED CHEM. ENERGY IN FLUE GAS',T42,
     2F12.1,10X,'FLUE GAS CHEMICAL ENERGY',T95,F12.1,///)
C
      WRITE(6,8211)EQH02,EQH05,ECT15,EQSSC,EQH04
 8211 FORMAT(T30,'***** SECONDARY COMBUSTOR *****',//,T5,
     1'DESCRIPTION',T42,
     2'QUANTITY(BTU/HR)',10X,'DESCRIPTION',T95,
     3'QUANTITY(BTU/HR)',//,
     4T5,'FLUE GAS THERMAL ENERGY',T42,F12.1,10X,
     5'FLUE GAS THERMAL',T95,F12.1,//,
     6T5,'FLUE GAS CHEMICAL ENERGY',T42,F12.1,10X,
     7'STEAM GENERATION',T95,F12.1,//,T5,
     8'SECONDARY COMBUSTION AIR',T42,F12.1,//)
      WRITE(6,8212)EQH05,EQH06,QHECAT,EQSSR
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 8212 FORMAT(T30,
     1'*** SUPERHEATER, REHEATER & OXIDANT HEATER ***',//,T5,
     2'DESCRIPTION',T42,
     3'QUANTITY(BTU/HR)',10X,'DESCRIPTION',T95,
     4'QUANTITY(BTU/HR)',//,
     5T5,'FLUE GAS THERMAL',T42,F12.1,10X,
     6'FLUE GAS THERMAL',T95,F12.1,//,T64,
     7'OXIDANT HEATING',T95,F12.1,//
     8T64,'SUPERHEAT, REHEAT & BOILER',
     9T95,F12.1,//)
C
      WRITE(6,8213)EQH06,EQH07,EQH04,QNAT12,Q18P40,EQSE,EQH07
 8213 FORMAT(T25,
     1'***** 2ND CONVECTIVE HEAT TRANSFER SECTION *****',//
     2,T5,'DESCRIPTION',T42,'QUANTITY(BTU/HR)',10X,
     3'DESCRIPTION',T95,
     4'QUANTITY(BTU/HR)',//,T5,'FLUE GAS THERMAL',
     5T42,F12.1,10X,'FLUE GAS THERMAL',T95,F12.1,//
     6,T64,'SECONDARY COMBUSTION AIR',T95,F12.1,///,
     7T64,'COAL DRYING NITROGEN',T95,F12.1,//,
     8T64,'SEED REGENERATION STEAM',T95,F12.1,///,
     9T64,'ECONOMIZER',T95,F12.1,///,
     1T64,'ENERGY LOST THROUGH STACK =',T95,F12.1,//)
C
C     ************ STEAM PLANT CALCULATIONS (PRESTC) ************
      DO 540 I=1,12
      PE(I)=0.0
      PPE(I)=DBLE(PE(I))
      EXTSER(I)=0.0
      EEXTSER(I)=DBLE(EXTSER(I))
  540 CONTINUE
C     GT IS THE STEAM FLOW RATE TO THE AIR COMPRESSOR TURBINE AND
C     OXYGEN PLANT.  UNITS ARE LB/HR STEAM.
      GT=3.413*(PCOMP+POWERC)/(HSTEAMA*.35)
      QGT=DBLE(GT)
      GTD=GT
      QGTD=DBLE(GTD)
      PT=2414.7
      PPT=DBLE(PT)
      WSHFT=(PCOMP +POWERC)*1.0E-06
      WWSHFT=DBLE(WSHFT)
      WRATE=.97*WSHFT
      WWRATE=DBLE(WRATE)
      WRITE(6,3130)
 3130 FORMAT('1')
      WRITE(6,*)'FROM SINGH'
      WRITE(6,3939)QGT,QGTD,WWSHFT,WWRATE
 3939 FORMAT(2X,'QGT= ',D8.3,1X,'GQTD= ',D8.3,1X,'WWSHFT= ',D8.3,
     11X,'WWRATE= ',D8.3,////)
C
      ITEST=0
C
      IITEST=0
C
      CALL PRESTC
C
C     CMCISR IS FRACTIONAL COAL MOISTURE, AS RECEIVED
      CMCISR=.089
C     CMCISF IS FRACTIONAL COAL MOISTURE, AS FIRED
      CMCISF=.002
C
C     THE FOLLOWING CALCULATION ESTIMATES THE THERMAL INPUT
C     TO THE NITROGEN USED FOR PULVERIZING AND DRYING EASTERN
C     COAL BY CALCULATING THE WATER TO BE EVAPORATED AND
C     ASSIGNING AN EFFICIENCY (60%) TO ACCOUNT FOR LOSSES AND
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C     ENTHALPY EXHAUSTED FROM THE COAL/GAS SEPARATOR.
C
C     QLCD IS THE ENTHALPY REMOVED FROM THE FLUE GASES FOR COAL DRYING
      QLCD=(CMOISR-CMOISF)*CFLCH*1123.3/.60
C
C     QLPE IS THE ENTHALPY ADDED TO THE FEEDWATER IN THE
C     LOW PRESSURE ECONOMIZER SECTION.
C     QHPE IS THE ENTHALPY ADDED TO THE FEEDWATER IN THE
C     HIGH PRESSURE ECONOMIZER.
C     THE FOLLOWING CALCULATION ASSUMES AN ARBITRUARY DIVISION
C     BETWEEN HIGH AND LOW PRESSURE ECONOMIZER OF 55% TO HPE (JNC)
C
      QHPE=0.55*EQSE
      QQHPE=DBLE(QHPE)
      QLPE=.45*EQSE
      QQLPE=DBLE(QLPE)
      EXTSER(7)=QLMHD+QLPE
      EEXTSER(7)=DBLE(EXTSER(7))
      EXTSER(3)=QHPE
      EEXTSER(3)=DBLE(EXTSER(3))
      WRITE (6,4023) HSUM(1),HSUM(7),TFLO,HSUM(8),HSUM(6),SAFLC,
     1R,PEXM,QLSR,QHPAH,QLCCMB,QLM,QLPE,QHPE,QLCD,HSUM(2)
 4023 FORMAT(//,2X,'HSUM(1)= ',E12.5,1X,'HSUM(7)= ',E8.1,1X,'TFLO= ',
     1E8.3,/,2X,'HSUM(8)= ',E8.1,1X,'HSUM(6)= ',E8.1,1X,'SAFLC= ',
     2E8.3,1X,'R= ',F9.3,/,2X,'PEXM= ',E8.3,1X,'QLSR= ',E8.3,1X,
     3'QHPAH= ',E12.5,1X,'QLCCMB= ',E12.5,1X,'QLM= ',E8.3,1X,'QLPE= ',
     4E12.5,1X,'QHPE= ',E12.5,/,2X,'QLCD= ',E12.5,2X,'HSUM(2)= ',E12.5,/)
      EXTRNL=(QLCCMB+QLCIF+EQSPF+EQSSC+EQSSR+QLMHD+EQSE)*.2931*1.0E-06
      EEXTRNL=DBLE(EXTRNL)
      DO 541 I=1,12
      ND(I)=0
      NND(I)=ND(I)
  541 CONTINUE
      QTB=-QT
      QQTB=DBLE(QTB)
      NRH=1
      NNRH=NRH
      PE(1)=1497.6
      PPE(1)=DBLE(PE(1))
      PE(2)=883.5
      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)=105.6
      PPE(6)=DBLE(PE(6))
      PE(7)=6.57
      PPE(7)=DBLE(PE(7))
      DO 542 I=8,12
      PE(I)=0.0
      PPE(I)=DBLE(PE(I))
  542 CONTINUE
      NSHAFT=3
      NNSHAFT=NSHAFT
      NF=7
      NNF=NF
      NFH=3
      NNFH=NFH
      NFI=2
      NNFI=NFI
      NFL=2
      NNFL=NFL
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      NIP=1
      NNIP=NIP
      NRH=1
      NNRH=NRH
      NDSGN=1
      NNDSGN=NDSGN
      PBIP=459.
      PPBIP=DBLE(PBIP)
      QT=(EXTRNL*3.413*1.0E+06)/(HSTEAMA+HSTEAMR)
      QQT=DBLE(QT)
      QTD=QT
      QQTD=DBLE(QTD)
C     THE FOLLOWING ESTIMATES THE ELECTRICAL POWER OUTPUT, WRATE,
C     BASED ON ASSUMING 35% CONVERSION EFFICIENCY. (ADDED BY JNC)
      WRATE=.35*EXTRNL
      WWRATE=DBLE(WRATE)
      WRITE(6,2929)EXTRNL,QTB,QT
 2929 FORMAT(2X,'EXTRNL= ',E8.3,1X,'QTB= ',E12.5,1X,'QT= ',E8.3,/)
C
      WSHFT=0.
      WWSHFT=DBLE(WSHFT)
      QGEN=0.
      QQGEN=DBLE(QGEN)
C
      IITEST=1
C
      ITEST=1
C
      CALL PRESTC
C
      QQTT=SNGL(QT)
C
C
      WWGEN=SNGL(WWGEN)
C
      WRITE(6,4197)EXTRNL,WWGEN
 4197 FORMAT(/,2X,'EXTRNL=',1E12.5,2X,'WWGEN=',1E12.5,/)
C
      HP=.TRUE.
      EQRAT=.9524
      OF=(-EQRAT*VMIN(2)-VPLS(2))/(VPLS(1)+EQRAT*VMIN(1))
      CALCH=.TRUE.
      CALL NEWOF
      NPT=8
      ISV=7
      CALL SAVE
      CALL EQLBRM
      HP=.FALSE.
C
      PEXS=WWGEN*1.0E+06
C     PAUX IS TOTAL REQUIRED AUXILIARY POWER (WATTS)
      PAUX=PMAG+PPFT+0.026*(PEXS+POUTM)+PFAN
      TPOWR=POUTM+PEXS-PAUX
C     EFFMS IS THE TOPPING AND BOTTOMING CYCLE EFFICIENCY
C     NEGLECTING SEED REGENERATION COAL
      EFFMS=TPOWR/(THIN*.2931)
C     THIN IS THE THERMAL INPUT
      THIN=THIN+(MCR04*HCC/MCISRF)
C     EFFC IS THE CALCULATED SYSTEM EFFICIENCY
      EFFC=TPOWR/(THIN*.2931)
      WRITE (6,3013) EFFC,THIN,EFFMS
      HHFF=100.*HFF
      GGEFF=100.*GEFF
      TMNET=POUTM-PCOMF
      WRITE (6,1002) HHFF,GGEFF, POUTM, PEXS, TPOWR,TMNET

 1000 FORMAT( 2E15.6,4F8.3,/,4F8.3,/,4F8.3,E15.6,
     1/,8F9.3,/,5F9.3)
 1012 FORMAT(/,2X,,2E15.6,4F8.3,/,4F8.3,/,4F8.3,E15.6,
     1/,8F9.3,/,5F9.3)
      NPT=8
      WRITE(6,1101)
 1101 FORMAT(1H1)
```

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.

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