MHD Power Plant Instrumentation And Control

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MHD POWER PLANT INSTRUMENTATION AND CONTROL

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ABSTRACT

The Electric Power Research Institute (EPRI) has awarded a contract to the MHD Development Corporation (MDC) to develop instrumentation and control requirements and strategies for commercial MHD power plants. MDC subcontracted MSE to do the technical development required. MSE is being assisted by Montana State University (MSU) for the topping cycle development.

A computer model of a stand-alone MHD/steam plant is being constructed. The plant is based on the plant design set forth in the MDC proposal to the Federal Clean Coal Technology 5 solicitation. It consists of an MHD topping plant, a Heat Recovery Seed Recovery (HRSR) plant, and a steam turbo-generator. The model is based on the computer code used for a study of the Corette plant retrofitted with an MHD plant. Additional control strategies, based on MHD testing results and current steam bottoming plant control data, will be incorporated. A model will be devised and implemented for automatic control of the plant. Requirements regarding instrumentation and actuators will be documented. Instrumentation and actuators that are not commercially available will be identified. The role and desired characteristics of an expert system in the automated control scheme is being investigated. Start-up and shutdown procedures will be studied and load change dynamic performance will be evaluated. System response to abnormal topping cycle and off-design system operation will be investigated. Alternate design approaches in the areas of stability, operating range, component stress, and environmental compliance will be investigated.

This effort attempts significant advances over previous modeling efforts. This includes use of MHD topping cycle models which couple gasdynamic and electrical behavior for the study of controlling of the MHD topping cycle. A curvefitter, which uses cubic Hermitian spline interpolation functions in as many as five dimensions, allows much more accurate reproduction of nonlinear, multidimensional functions. This project will be the first to investigate plant dynamics and control using as many as seven independent variables or control inputs to the MHD topping cycle. This effort will also catalog required instrumentation and the required characteristics of an expert system.

INTRODUCTION

Detailed instrumentation and controls required for integration of MHD topping systems into commercial utility environments have not yet been developed. There are two fundamental reasons for the lack of a commercially applicable package. First, electrical and gas dynamic characteristics of MHD subsystems have time constants on the order of milliseconds, much shorter than those found in conventional power plants and other types of advanced technology power systems. A major effect of this rapid response is that the MHD process has very tight requirements on mass flows as they affect power production. Performance rates of the order cited, coupled with need for sustained attention to mass flows, can stress or exceed the ability of human operators to react with sufficient speed and sound judgement.

Second, the accessibility of MHD equipment is limited compared to ordinary power plant units, either because of extreme operating environments or personnel hazards associated with the equipment. The combustor in a commercial application will operate at five to six times atmospheric pressure and will have core gas temperatures of about 4,500 °F. It will have a voltage of perhaps 10,000 to 20,000 volts below ground potential. The MHD generator itself will be shrouded in a magnet having a field strength of up to six Tesla, and it will have a strong electrical gradient along its length. As a safety policy, personnel should not be in proximity to the MHD system during operation.

Additionally, the thermal-to-electrical conversion process itself is internal and diffuse, making it impossible to monitor directly. Its behavior must be inferred or reconstructed from external measurements by using computer algorithms. Both operators and automatic control systems must rely strongly on instrumentation coupled with computation rather than upon direct measurement of some system variables. State estimation and real-time parameter identification solution methods are generally applicable to these situations.

This on-going project has three primary objectives:

Define suitable control strategies for commercial (utility) operation of MHD topping plants.

Define suitable control strategies for commercial (utility) operation of an integrated plant having an MHD topping cycle and conventional bottoming cycle.

Define instrumentation requirements for the objectives above, as well as required characteristics of an expert system.

Control Strategies Guidelines

The ultimate objective of the proposed work is development of a set of control strategies and diagnostic procedures for the MHD system to assist in the transfer of MHD from the test environment to a commercial utility environment. In doing this, certain fundamental guidelines should be followed to maximize plant availability and control system effectiveness. In no particular order, they are:

Since MHD is a new technology in power production, the MHD system should initially be subjected to the minimal level of stress (e.g. arcing, Hall voltage, current density, thermal gradients) that allows sufficient flexibility in plant operations. This applies particularly to the electrical environment within the MHD channel. Since the only direct possibility of fast electrical control on the channel duct is through the power conditioning system, particular attention is being paid to the channel, power conditioning interaction and the channel electrode current management system in studying the operational envelope. Results from earlier work on this topic are given in Reference 1.

Operator skill levels and attention levels should not be greatly in excess of those necessary in a typical power plant; although, some specialized training in MHD characteristics would be expected.

The responsibility for rapid system adjustments (in the tens of milliseconds) would necessarily reside in the automatic control system. Since the detailed channel environment cannot be extensively on-line monitored, the internal environment must be inferred through real-time state estimation, which is then input to an expert system for control actions. The remainder of the MHD system could function under fully automatic control or with some degree of operator intervention.

Next to preserving system integrity and function of all portions of the plant, the most important need is to keep the plant on line, producing power. The control system should be designed so that controller failure cannot be fatal to the total plant. Failures should either return the affected component of control to operator control, or should continue automatic operation in a gracefully degraded mode.

To the extent possible, control strategies should be realized on a commercial distributed control system (DCS); thereby, minimizing the need for specialized hardware and/or software with their attendant costs and complications. When custom equipment is required, it should interface to the DCS through standard interface hardware and protocols.

Control Strategies Issues

Several issues must be considered in developing such a control system for the MHD system. Generally, operation will be in one of three modes: Normal operation, start-up/shut-down, and emergency conditions.

Under normal operation, the MHD system will be subjected to variations of operating point within a prescribed envelope of mass flows, pressures, temperatures, electrical power extraction, magnetic fields, channel voltage gradients, etc. Within this envelope, the overall combined-cycle plant operating point should be automatically adjusted for optimal efficiency, equipment life, reliability, stability, dispatch responsiveness, and emission levels. It is expected that for a given MHD system installation, the operating bounds will be fairly narrow initially, and that they will expand as personnel become more familiar with the system.

Because the MHD system is part of a total plant, an extended view must be taken of MHD control. It must be assured that control strategies selected for the MHD system are compatible with control strategies applied to the balance of the plant; thereby, creating a complete, integrated operating package for the combined-cycle power plant.

An example of dynamic plant interaction is the effect of dynamics in MHD topping plant stoichiometry and mass flows (which are in turn related to MHD power demands) on secondary air requirements in the bottoming plant. Secondary air is required to achieve complete combustion in the heat-recovery/seed-recovery (HRSR) steam generator that is consistent with necessary control of NOx and other emissions. MHD is inherently a cleaner technology than conventional coal firing, but it must have suitable control applied.

A second example that is related to both power production and equipment integrity is the interaction of induced draft fans with MHD diffuser exit pressure conditions, and subsequent effect on MHD mass flows and power generation. The importance of maintaining a suitable combustion gas pressure profile in the steam plant is well-known.

Project Tasks and Schedule

A set of three tasks to reach the objectives of this project are outlined briefly below:

1) Create a fully detailed, dynamic computer model of a prototypical stand-alone MHD/steam plant using first-principles whenever appropriate. Concentrate especially on MHD topping cycle modeling that includes system variables that provide measures of performance at reasonable stress levels. Determine and embed into the model a control policy having suitable output power while maintaining safety and operating margins. Determine requirements for instrumentation and actuators, with special emphasis on those which are not currently commercially available. Determine role and characteristics of an expert system for use in MHD plant.

2) Use model created in 1). Develop start-up and shutdown procedures for the plant. Evaluate dynamic plant performance in response to changes in load. Evaluate characteristics of plant behavior when operating at off-design conditions. Determine outcomes of abnormalities in the MHD portion of the plant. Make any required augmentations to the computer model to enable running of the necessary conditions and cases.

3) Investigate alternative design approaches as may be suggested while completing 1) and 2). Alternatives should offer promise of overcoming a shortcoming or deficiency in the present design, or of significantly improving some aspect of the design, e.g., control stability, operating range, component stress, or environmental compliance.

Work was started in October 1991 and is scheduled to be completed in May 1995.

Responsibilities

This project is being accomplished by MSE with support from Montana State University. The flow of responsibility for this project is shown in Figure 1. Briefly, funding originates with the Electric Power Research Institute (EPRI) who has contracted with the MHD Development Corporation (MDC). MDC provides project management and direction but has contracted the technical work to MSE. MSE is responsible for creating computer models of the bottoming cycle components and for system integration and operation. MSE has contracted with MSU to do the challenging work associated with modeling the topping cycle.

Concept Change

The original contract was based on the concept of a retrofit plant to be installed on the Corette plant in Billings, Montana (Reference 2). As work started on the submittal to the U.S. Department of Energy (DOE) for Clean Coal 5 (Reference 3) support, the concept changed to a stand-alone plant occupying the same site as the Corette plant but not having any operating ties to it. The original tasks were to be 1) modelling the Corette plant as it existed, 2) creating a stand-alone MHD model, and 3) combining the two to develop integrated control policies. Due to the change in the proposed plant the tasks to do Corette plant and integrated modelling were deleted and the task to do stand-alone plant modelling was expanded as described in this paper.

DYNAMIC PLANT MODEL DESCRIPTION

The dynamic plant model carries the form, structure, and many of the hardware models from previously completed studies, see, for example, References 4 and 5. The current work involves creating models for the Billing MHD Plant, which contains features not found in any previously proposed plant, and using a much more detailed and higher fidelity topping cycle model which allows coupling of internal gasdynamics to external electrical circuits. The current work also features use of up to five dimensional spline curvefits for use with the algebraic topping cycle model and steam table data.

Model Formulation

A diagram showing the process involved in creating the dynamic plant model is shown in Figure 2. A number of steps and a number of other computer codes are used. Many of the other computer codes are existing from previous work on this subject and will be briefly described in the next section, Ancillary Model Descriptions.

A significant portion of the dynamic plant model is the topping cycle model. The topping cycle model is represented to the plant model as an algebraic set of curvefits. This is possible, even necessary, because the time constants of the topping cycle are on the order of milliseconds or less, while time constants of the balance of the plant are on the order of seconds. These curvefits are generated using a database of successive runs with a steady-state topping cycle model at operating points, which span the necessary region of validity. The algebraic model describes (1) the fluid state at the topping cycle/bottoming cycle interface, (2) power output, and (3) cooling water requirements as a function of seed fraction, stoichiometric ratio, oxygen fraction, preheat temperature, magnetic field strength, coal flow, and exit pressure. The steady-state model, in turn, uses data in the form of curvefits from a combustor code and from a thermodynamic equilibrium code. These codes are described later in this paper.

Other portions of the dynamic plant model are modules (subroutines) each representing a piece of equipment. Hardware characteristics and physical laws are embedded in the code to create first-principle, lumped-parameter models, which can be interconnected to represent the overall plant. Control laws are likewise embedded in a separate subroutine, which monitors the state of the plant and returns appropriate control actions. Information on superheated steam is curvefit in the same manner as other data in the model, and is available to the routines as functions to ensure thermodynamic laws are obeyed. Specific hardware configuration is encoded in the mainline routine. Run-specific data is input from data files at run-time.

A dynamic computer model of the MHD topping cycle, made compatible with the steady-state model, is being used to devise and implement control strategies for automatic control of the MHD topping cycle. It is also being used to document response to abnormal topping cycle operation, study start-up and shutdown procedures, evaluate load change alternatives, and investigate alternate design approaches to expand operating range.

Plant Description

A block diagram of the Billings MHD Plant, as represented in the dynamic plant model, is shown in Figure 3. It is apparent that the plant is highly interconnected; it is exactly this interconnectedness that makes this control study necessary. The plant, as represented here, has simplifications made to eliminate items which will have no effect on its controllability.

For example, the coal process loop and the seed regeneration cycle are complex systems in their own right, but are represented here as single blocks with minimal dynamics since the internal complexities of these loops are not reflected onto the power generation plant.

Nomenclature for Figure 3 is as follows. All plant components are represented in rectangles with a brief text identifier and reference number in them. Circles represent convergences or divergences; places where streams are separated or brought together and material properties need to be calculated. These convergences or divergences do not represent physical components, but may represent things like a pipe tee. Control points are shown with the schematic symbol for a valve (an X with lines at the ends), whether or not the control point actually is a valve or not. This is done for drawing simplicity. A number beside each symbol identifies it. Table 1 contains a list of all plant components, including convergences and divergences with a longer description and the name used to identify it in the dynamic model. The reference number inside the rectangle corresponds to the identifying number in this table. Table 2 contains a list of the control points and what is being controlled. The number beside the control symbol corresponds to the identifying number in this table.

For purposes of illumination, two of the major flow paths will be described here. Again, it must be stressed that what is described is the system from a control and instrumentation perspective only. It may or may not be useful for other purposes.

The combustion gas path starts with the combustor/nozzle/channel and goes to the diffuser/transition and then the radiant boiler. After, the radiant boiler additional air is added to complete combustion. The heat exchanger components following that are the primary oxidant preheater, the superheater, the reheater, a parallel path consisting of the high temperature economizer and the secondary air heater, and the low temperature economizer. The baghouse and an induced draft fan complete the path. Control variables considered that affect this path are the material streams into the combustor to maintain mass flow, stoichiometry, and seed fraction; secondary air flow to maintain final stoichiometry; and vacuum drawn by the ID fan to maintain atmospheric to slightly subatmospheric pressure at the exit of the diffuser.

The water/steam flow path can be considered to start at the condensor. Only the main path will be described; other minor paths can also be found. The condensor is sensitive to river temperature and circulating water flow rate. From the condensor the condensate pump boosts pressure to send flow through the low temperature heat exchanger and the low temperature economizer and into the deaerator storage tank. From the deaerator storage tank the boiler feed pump sends flow through the combustor heat exchanger and the high temperature heat exchanger into the steam drum. The steam drum has circulation forced from it through the diffuser/transition and radiant boiler and back to it. Steam is taken from it, attemperated by spray flow if necessary, and sent through the superheater to the high pressure turbine. Return from the HP turbine may be attemperated by spray and is sent through the reheater to the intermediate pressure and low pressure turbines. Flow is returned to the condensor. Control points include flow from the condensate pump and the boiler feed pump, flow through the diffuser/transition and radiant boiler, and superheat and reheat spray flow. The HP turbine governor valve is also a major control point.

Computer Code Description

The dynamic plant model is coded in FORTRAN and is comprised of driving routines, which allow execution of subroutines representing various hardware components (e.g. pumps, heat exchangers, fans, generators), another subroutine, which embodies the control laws and policies, and a subroutine which represents the combustor, MHD channel, and diffuser. The model accepts input from data files, which specify the initial state of the plant, control parameters, and plant parameters.

A diagram showing the layout of the computer model is shown in Figure 4. The module called MAIN5 (the numeral "5" appended to many of the module names indicates the version of the module that is appropriate to the Clean Coal 5 proposal, as opposed to numerous previous versions for other plant configurations) is the mainline routine. Its role is to open appropriate input/output data files, read necessary plant data and run specification data from these files, maintain the master timing variable, initialize data arrays, initialize the plant models, and control the integration steps. Currently a fourth order Runge-Kutta, fixed step-size integration algorithm is being used. Other algorithms will be explored, as will introducing a variable step-size. MAIN5 calls two other modules as subroutines. One of these is OUTPUT, which, true to its name, outputs selected data from the plant model in the specified format. OUTPUT makes no calls of its own.

PLANT5, true to its name, handles the calls to the modules which represent pieces of plant equipment. It is essentially a sequential list of subroutine calls to all of the models which represent pieces of plant equipment. A typical subroutine call to a fictitious piece of equipment might be:

```
CALL EQUIP5 (GAS1, 102, 103, WATER1, 26, 27, WATER2,
53, 54, STATE, 3)
```

In this FORTRAN call statement, GAS1, WATER1, WATER2, and STATE are dummy arguments for the programmer's convenience to provide a cue on the nature of the variable being passed by the following number or numbers. The numbers following the dummy arguments , except for STATE, are the node number for the material exchange between two modules; one would treat it as an output, the other as an input. The number following the dummy variable STATE is also a dummy variable for the programmer's convenience to indicate the number of state variables in the module. Each node, as indicated by a number, corresponds to a three-wide row of numbers in the matrix representing the state variables of the plant. The three numbers represent the state of some material at the node point by indicating its enthalpy, flow rate, and pressure. The last subroutine called is named CNTRL5 and contains the control algorithms for the plant.

The modules representing plant equipment are, whenever possible, based on first-principles modelling of the information in Reference 3 supplemented by information per Reference 6. A listing of all currently used plant models is given in Table 1. Heat exchanger models rely on concepts from Reference 7. The turbine model has as its basis Reference 8. Pumps, fans and compressor models utilize characteristic curves from equipment manufacturers that are representative of the size and use as in the proposed plant. The module representing the MHD power train required substantial effort to produce a highly accurate and useable model. It is described more thoroughly in the next section. All modules that have steam connections rely on curvefits representing properties of steam that are not passed directly as variables but are required within a module for computations.

The subroutine which represents the combustor, nozzle, and MHD channel (named CNC5) was prepared to predict the Billings plant characteristics. The electrical portion of the model was based on the Proof-of-Concept channel configuration being tested by MSE at the CDIF in Butte, Montana. One electrode is chosen at each of the anode and cathode consolidation regions to serve as a master to the other consolidation electrodes. It is assumed for this model that current is shared equally between all consolidated electrodes. Each electrode in the model represents about ten channel electrodes. No attempt was made to address fringing effects. A schematic of the modeled channel and inverter is shown in Figure 5. The channel area profile used is shown in Figure 6. The predicted magnetic field profile assumed by the model is shown in Figure 7. Further information on how CNC5 was generated can be found in the section titled Steady-state Model.

The module containing the control laws, named CNTRL5, is separate from the hardware modules, although it is still called from PLANT5. All of the required plant control algorithms are gathered into this single module. The list of control points is given in Table 2. Typical industry standard algorithms will be chosen for control where they are applicable and can be shown to work, although alternatives will be explored as well.

Four major input files are required for the dynamic plant model to run. The first of these supplies the program control parameters such as the length of the run, the integration step-size, and so forth. The second of these input files supplies the initial values for the state variables. At the end of each run the updated set of the values are output, so that a future run can be continued from a previous run, with or without changes, if desired. The third file specifies control parameters to the control algorithm found in CNTRL5. the last file allows input of hardware characteristics at runtime, without requiring a recompile, to any of the hardware modules. Examples of this use might be a parametric study of the system and control effects of degraded heat transfer from the superheater, where a number of runs would be made from the same starting point with different heat transfer coefficients for the superheater.

ANCILLARY MODEL DESCRIPTIONS

Combustor Model

The combustor model used in generating data for the overall plant is a simple two-stage model without internal dynamics. Its purpose in the context of this work is strictly to provide equilibrium data on (1) heat loss from the combustor and from the nozzle, and (2) enthalpy of exit gas (from which temperature can be calculated) as a function of input control point variables. It consists basically of two volumes (first stage and second stage) with material inflow, internal equilibrium chemistry, wall heat transfer, and material outflow. Equilibrium temperature is calculated by balancing heat release, heat flow with exiting combustion gas, slag heat flow, and wall losses. As a result of the assumed liquid slag rejection fraction, the model also calculates the total mass flow of slag and of combustion gas. Internally, it contains an equilibrium code that is also used to determine thermodynamic and transport properties of combustion gas for the range of temperatures and pressures expected in the channel. Assumptions are made that coal particulate burnout is complete, i.e., all carbon in the coal is converted to CO_2 or CO in the combustion process. Neither chemical kinetics nor fluid flow relations are employed in the model.

Input variables are coal flow rate, enriching oxygen mass flow rate, oxidant mass flow rate to the first stage, oxidant mass flow rate to the second-stage, oxidant preheat temperature, seed mass flow rate, and combustor pressure. During operation of the complete plant model, the first six of these variables are controlled by the plant control system. Combustor pressure is a result of the first six variables and is calculated in the modeling of the topping cycle, as described below. Parameters for operation are coal composition, first and second-stage geometry, sidewall temperature of each stage, slag rejection fraction, convection heat transfer coefficient, sidewall thermal emissivity, and seed type.

Coal composition is that of typical Montana Rosebud coal, and is given below:

Carbon	63.32%
Hydrogen	4.37%
Oxygen	13.68%
Nitrogen	0.95%
Sulfur	1.05%
Ash	12.63%
Moisture	5.00%

Spline Curvefitter

A FORTRAN program has been developed at MSU under a separate, independent contract to create and interpret cubic Hermitian spline interpolation functions for a set of known discrete data points in as many as five dimensions. This program was used in the current modeling effort.

Formation of the spline function requires that magnitude and variational data be compiled and saved for all available data points. The variational data is approximated by centered differences. Interpolation is performed by summing weighted products of four basis functions for each of the independent variables. The program allows one to use quadratic methods near variable domains,where variational data may be questionable. It also allows one to extrapolate beyond the original domains using a linear extrapolation. These options are performed within the FORTRAN routine by altering the four basis functions.

The advantages of the method are as follows: (1) They have guaranteed C1 continuity throughout the domains. (2) They are fully multidimensional, which allows one to accurately create a dynamic model affected by all inputs. (3) They are very general and do not require subjective interpretations required in other fitting schemes.

The disadvantage of the method is that considerable computer storage and computation is required to effect the functions.

The splines are used to fit superheated steam data, equilibrium data for fluid properties and combustor data resulting from the combustor model, and to compile data from numerous operating points throughout the potential operating domain of the topping cycle model. This project will be the first to investigate plant dynamics and control using as many as seven independent variables or control inputs.

Steady-State Model

The MHD steady-state model has two fluid states and three electrical states. The boundary conditions (e.g. pressure and temperatures) for the fluid states include an assumed stagnation pressure at the diffuser exit. At the combustor inlet, stagnation temperature is known as a function of stagnation pressure and other constant inputs according to combustor data. A point of interest exists at the choke point of the nozzle. At this point the fluid flow may become supersonic, and the point has only one true state. In other words, temperature becomes an implicit function of pressure at the nozzle choke should the duct operate in the transonic region. Therefore, the boundary conditions include a strong exit boundary, a weak input boundary , and a third point of interest which is a cause of numerical instabilities in less robust numerical solution schemes. Shocks pose additional problems.

The three electrical states correspond to two electrode and one core node voltages. The node voltages are part of a single 4-terminal MHD channel circuit model.

The MHD model is prepared to predict as closely as possible the proposed Billings MHD plant.

Numerous operating points must be modeled using the MHD model. Data are extracted from the numerous operating conditions to describe the fluid state at the interface between the diffuser and HRSR, cooling requirements for the duct sections, combustor state, and MHD power output. This compiled data will form an input-output algebraic model of the MHD topping cycle for use in the overall dynamic plant model. Additional outputs will be collected to approximate operating stresses, and these variables will be used to define an allowable operating region for the topping cycle portion of the plant.

Because of the numerous operating conditions to be modeled, a computer method must be chosen to balance computer speed, robustness and accuracy in determining steady-states. The numerical methods investigated have included relaxation, integration, conjugate gradient search, and relaxation of the time dependent MHD model. As of now, it seems that a conjugate gradient search method looks promising for simultaneously solving finite difference approximations to the fluid state equations and the electrical voltage profile in the steady-state. It shows a good mix of robustness, accuracy and convergence speed.

A summary of input parameters is given in Table 3.

Dynamic Model

The time-dependent model is a one-dimensional, pseudo-two-dimensional model which solves the time dependent fluid and electrical MHD partial differential conservation equations using a Lax-Wendroff integration scheme and variable time step. The time-dependent model will be used to model transient behaviors in the MHD duct and predict effects of proposed topping cycle controls. For example, transient conditions must occur during start-up procedures as the channel first becomes transonic or as seed is introduced. The time-dependent model should prove useful in these instances. This model is further described in Reference 9.

SUMMARY

Instrumentation and controls required for integration of MHD topping systems into commercial utility environments have not been developed for several reasons including the mismatch in dominant time constants between the MHD portion and the steam plant portion of the plant, the unusual nature of the MHD process, and the inaccessibility of the MHD process, both for people and direct instrumentation. A study has been funded by EPRI, through MDC, to address this deficiency. The objectives of this study, which is being done by MSE and MSU, are to define control strategies for MHD topping cycles and integrated plants having an MHD portion and to define instrumentation and required characteristics of an expert system for such plants. Three tasks are currently defined to reach these objectives. They are: 1) create a dynamic plant model of a prototypical MHD/steam plant and use it to determine control policies, instrumentation and expert system requirements, 2) use the model to explore operation off of design center, and 3) investigate alternative design approaches as may suggest themselves while doing the foregoing work. Work was started in October 1991 and is scheduled to be completed in May 1995. The plant is based on the plant design set forth in the MDC proposal to the Federal Clean Coal Technology 5 solicitation.

Several other computer models are required to generate the database necessary to build the plant dynamic model. These include a combustor model to provide equilibrium data on heat loss from the combustor and from the nozzle and enthalpy of exit gas as a function of input control point variables. Also both steady-state and dynamic MHD topping cycle models were created. The steady-state model is used to generate a database on various operating points of the topping cycle that can be used in the plant model. The dynamic model is used to explore control policy ramifications on the topping cycle. A program was developed under a separately funded effort which creates and interprets cubic Hermitian spline interpolation functions for a set of data points in as many as five dimensions. This program was used to prepare the data from the steady-state model for use in the plant dynamic model. As a result of the use of this method, this project is the first to investigate plant dynamics and control using as many as seven independent variables or control inputs to the MHD topping cycle.

ACKNOWLEDGEMENTS

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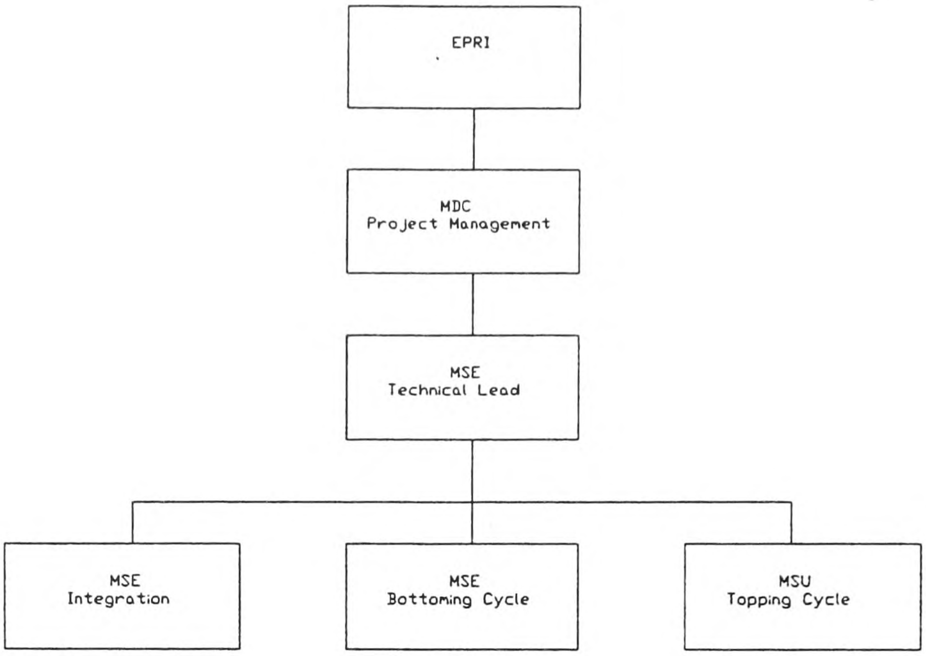

FIGURE 1 - PROJECT RESPONSIBILITIES

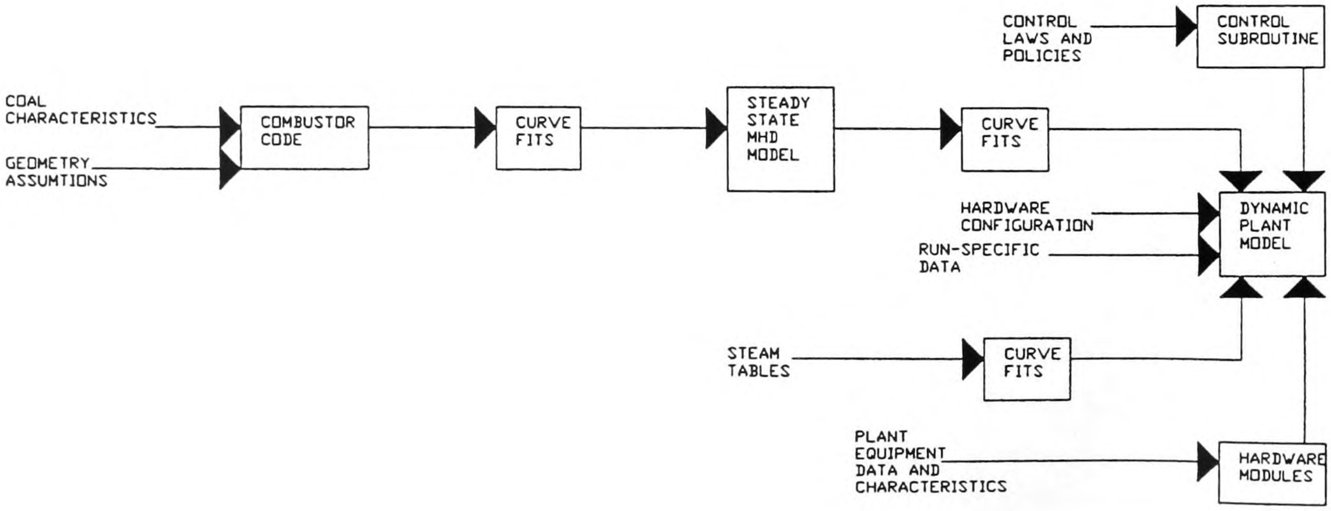

FIGURE 2 - CREATION PROCESS FOR DYNAMIC PLANT MODEL

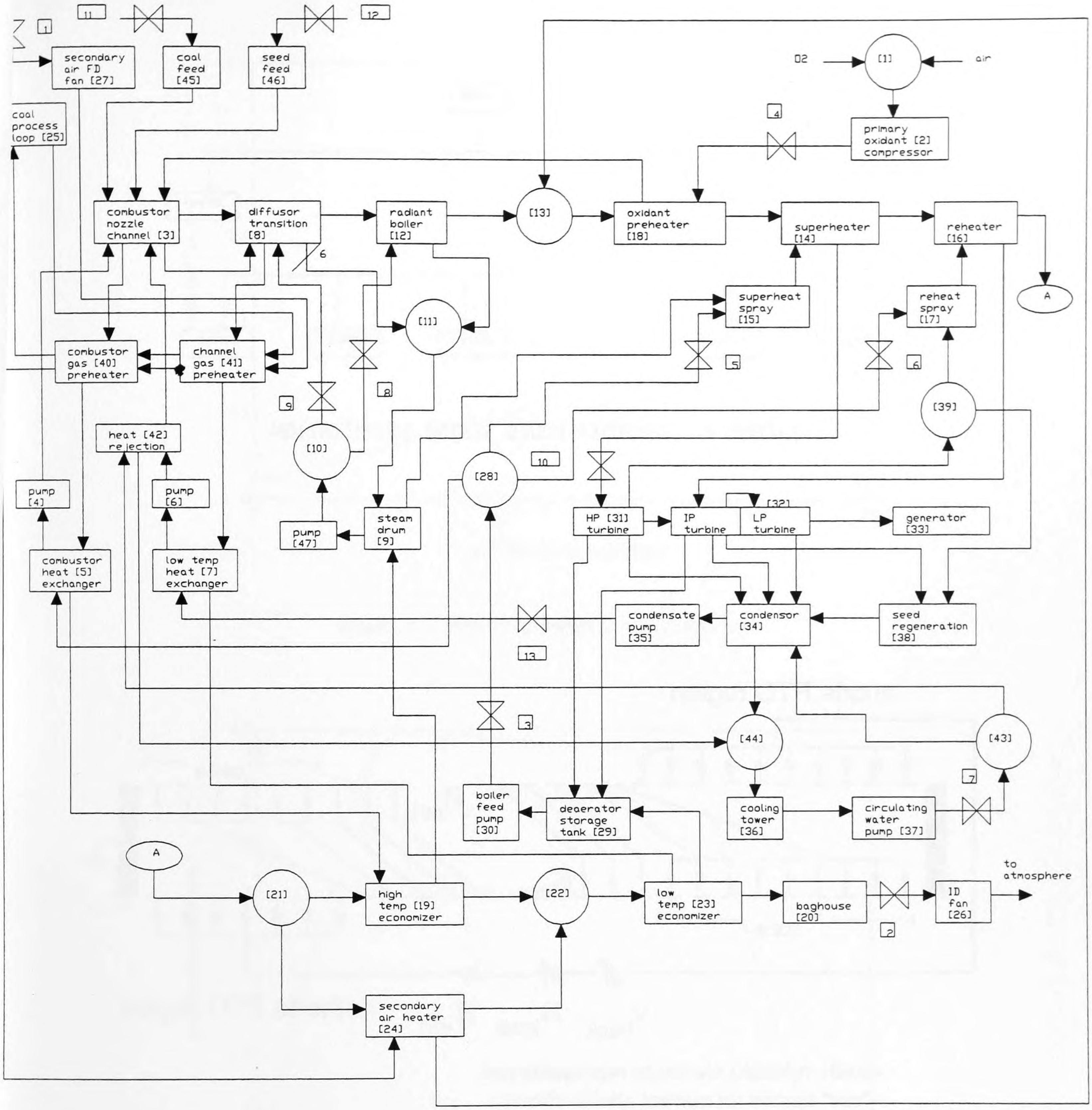

FIGURE 3 - BLOCK DIAGRAM OF BILLINGS MHD PLANT

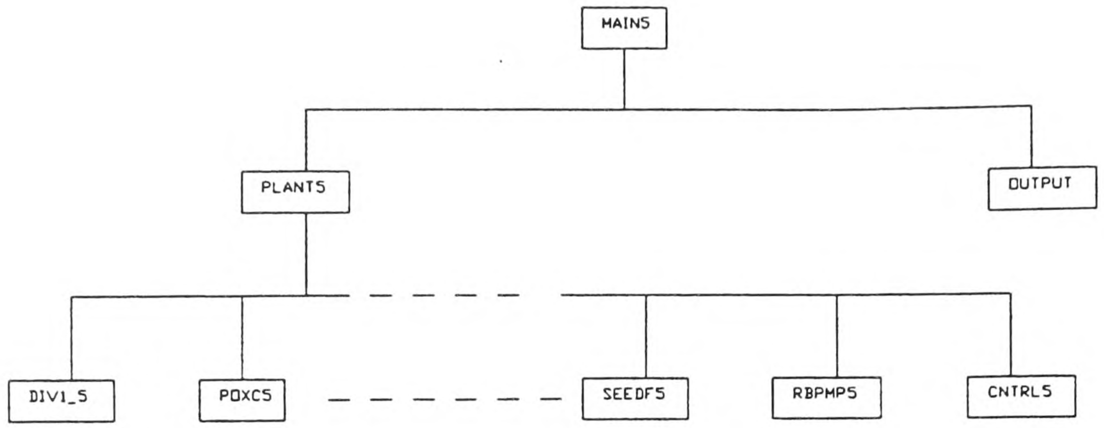

FIGURE 4 - COMPUTER MODEL SYSTEM ORGANIZATION

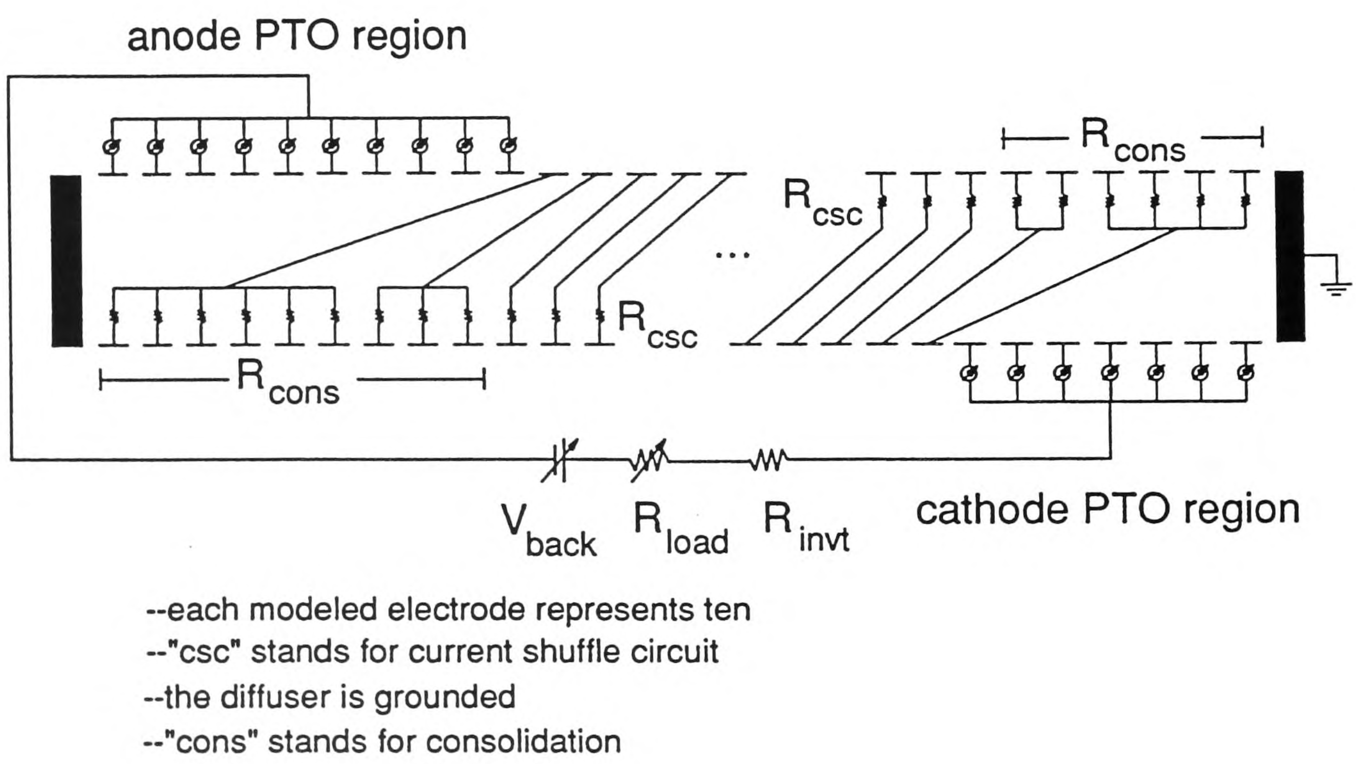

FIGURE 5 - CHANNEL AND INVERTER SCHEMATIC

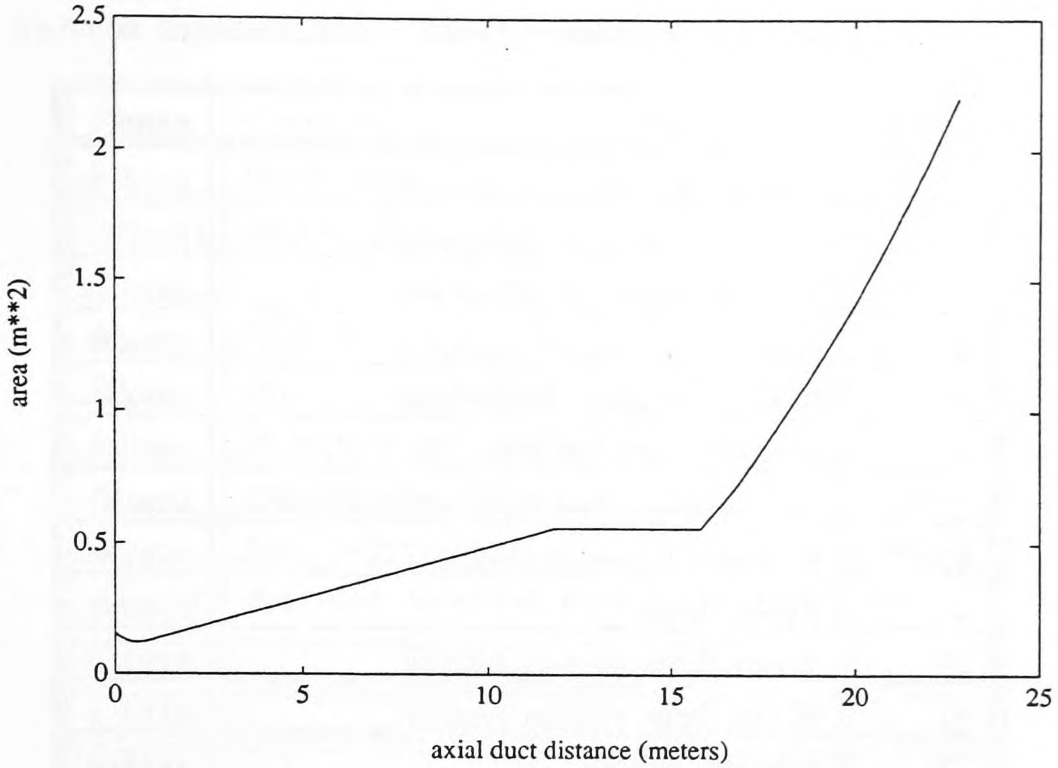

FIGURE 7 - PREDICTED MAGNETIC FIELD PROFILE

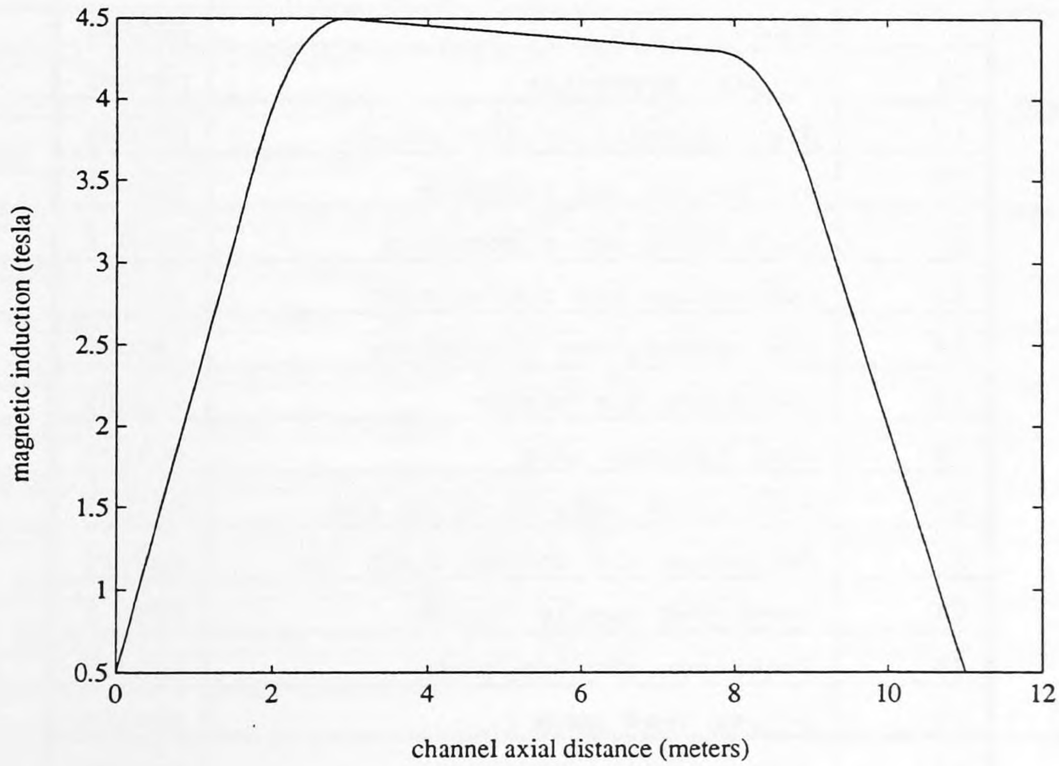

FIGURE 6 - BILLINGS PLANT CHANNEL AREA PROFILE

TABLE 1 - DYNAMIC PLANT MODEL HARDWARE MODULES

NUMBER	DESCRIPTION	NAME
1	Air/O_2 mixer	DIV1_5
2	Primary oxidant compressor	POXC5
3	Combustor/nozzle/channel	CNC5
4	Combustor cooling pump	CBPMP5
5	Combustor heat exchanger	CBHX5
6	Channel cooling pump	CHPMP5
7	Low temperature heat exchanger	LTHX5
8	Diffusor/transition	DIFTR5
9	Steam drum	STMDR5
10	Steam drum supply header	DIV3_5
11	Steam drum return header	DIV4_5
12	Radiant boiler	RADBL5
13	Secondary air mixer	DIV2_5
14	Superheater	SH5
15	Superheat spray	SPRAT5
16	Reheater	RH5
17	Reheat spray	RHSPR5
18	Oxidant preheater	OXPRH5
19	High temperature economizer	HECON5
20	Combustion gas baghouse	CBGBH5
21	Combustion gas divergence	DIV6_5
22	Combustion gas convergence	DIV7_5
23	Low temperature economizer	LECON5
24	Secondary air heater	SECAH5
25	Coal process loop	COALP5
26	Main stack induced draft fan	MSIDF5
27	Secondary air forced draft fan	SAFDF5
28	Feedwater supply header	DIV5_5
29	Deaerator storage tank	DEAST5
30	Boiler feed pump	BFPMP5
31	High pressure turbine	HPTURB
32	Intermediate/Low pressure turbine	IPTURB
33	Generator	MGEN

TABLE 1 - DYNAMIC PLANT MODEL HARDWARE MODULES

34	Condenser	COND5
35	Condensate pump	CDPMP5
36	Cooling tower	COOLT5
37	Circulating water pump	CWPMP5
38	Seed regeneration	SDREG5
39	Cold high pressure steam header	DIV8_5
40	Combustor gas preheater	CBGPH5
41	Channel gas preheater	CHGPH5
42	Heat rejection	HTREJ5
43	Circulating water pump divergence	DIV9_5
44	Cooling tower convergence	DV10_5
45	Coal feed	COALF5
46	Seed feed	SEEDF5
47	Diffuser/radiant boiler pump	RBPMP5

TABLE 2 -- DYNAMIC PLANT MODEL CONTROL POINTS

1	Secondary combustor air forced draft fan flow rate
2	Combustion products stream induced draft fan flow rate and pressure drop
3	Boiler feed pump flow rate
4	Oxidant compressor flow rate and ratio of O_2-enriched air to regular air
5	Superheat spray flow rate
6	Reheat spray flow rate
7	Circulating water pump flow rate
8	Radiant boiler water flow rate
9	Diffusor/transition water flow rate
10	Governor valve of high pressure turbine
11	Coal flow rate
12	Seed flow rate
13	Condensate feed pump flow rate

TABLE 3 - SUMMARY OF INPUT PARAMETERS FOR STEADY-STATE MODEL

INPUTS	COMMENTS
CONSTANT INPUTS	**Invariant between trials**
Channel geometry	Close to Billings specifications
Coal composition	Montana Rosebud
Magnet profile	See Figure 7
PTO configuration	Diagonal scaled version of POC channel
Slag removal	Assumed 70% removal
Other modeling assumptions	First principle assumptions, where possible
INDEPENDENT INPUTS	**Variables used in defining operational range**
Coal flow	
Exit stagnation pressure	Only small variation about subatmospheric
Magnet strength	Keeping same magnet profile
Oxygen fraction	
Preheat temperature	
Seed fraction	
Stoichiometric ratio	