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10 MW SOLAR THERMAL
PILOT PLANT DYNAMIC
SIMULATION

VOLUME I

COMPUTER PROGRAM
DESCRIPTION

1 December 1978

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FOREWORD

This report is written as a partial account of work performed for the Department of Energy, on the 10 MW Solar Thermal Pilot Plant Project, under Letter Contract Number ET-78-C-03-2028.

The report is in two parts:

Volume I - Computer Program Description

Volume II - Computer Program Source Listing

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1. INTRODUCTION

1.1 GENERAL

The Department of Energy (DOE) is currently in the initial phase of a development project to produce a prototype Solar 10 MW (electric) Pilot Power Plant near Barstow, California. As part of this early development, The Aerospace Corporation has developed a digital computer simulation of this pilot power plant. This report documents that simulation program.

The simulation program has been designated STMPPS (Solar Ten Megawatt Pilot Plant Simulation). This simulation is operative on The Aerospace Corporation Control Data Corporation (CDC) 7600 digital computer, with use of the CDC SCOPE 2.1 operating system.

1.2 PROGRAMMING LANGUAGE/SIMULATION SYSTEM

The entire simulation program is programmed in the CDC FORTRAN extended 4.5 language, which is designed to comply with American National Standards Institute FORTRAN language, as described in X3.9-1966. The CDC FORTRAN extended 4.5 language is described in detail in Reference 1-1.

The simulation program (STMPPS) utilizes the GASP-IV simulation system which provides the overall simulation control mechanisms and facilities and is itself programmed in the CDC FORTRAN extended language. The GASP-IV simulation system is described in detail in Reference 1-2. A simulation program written in GASP-IV consists of two parts: a user part and a GASP-IV part. This report will describe the user part in depth but will not describe the GASP-IV part, since that part is described in the copyrighted Reference 1-2. The GASP-IV simulation system consists of a collection of proprietary FORTRAN subprograms

which may be purchased for moderate cost from Pritsker and Associates, West Lafayette, Indiana. This system is required for the operation of STMPPS and is not included in the STMPPS source file.

The GASP-IV simulation system was chosen for the STMPPS implementation for the following reasons:

- GASP-IV is the only well documented simulation language with the combined (discrete and continuous) modeling capability required for STMPPS.
- It is the most widely distributed combined simulation language in the world (introduced in September 1973 and presently installed in 350 computer systems worldwide).
- GASP-IV provides a world view and a logic structure which simplifies complex model building.
- It is FORTRAN-based and is modular. It can be used on all machines that have a FORTRAN IV compiler.
- GASP-IV is easy to learn, since the host programming language is usually known and only the simulation concepts need to be mastered. It is easily modified and extended to meet the needs for particular applications.

GASP-IV provides many facilities (see Reference 1-2) which are of considerable value in simulation development. A subset of these facilities that are of particular value in the STMPPS implementation are:

Overall simulation control. Provides overall control of the simulation including the sequencing of discrete timed events.

Differential equation solution technique. Provides a Runge-Kutta-England integration method with variable integration step-size control, which provides optimum execution speed for the requested allowable absolute and relative local truncation error.

State event detection. Provides standardized mechanisms for the detection of threshold traversals by state variables and implementation of associated simulation model changes.

Simulation state recording. Saves specified simulation variables representative of simulation state at user-specified intervals for subsequent processing of plot output.

Event file. Provides for the filing of future simulation time-ordered events and the execution of those events at the scheduled simulation time.

1.3 PROGRAM ORGANIZATION

The user/non-GASP part of STMPPS is divided into modular subprograms. Each of these subprograms has a defined function in the total simulation. Communication of data between subprograms is largely accomplished by FORTRAN named COMMON blocks. The function of each of these subprograms and its approximate size as measured in number of source statements is listed in Table 1-1. The listed subprogram sizes exclude COMMON blocks which are part of those subprograms. COMMON block characteristics are listed separately in that table. Subprograms in Table 1-1 are grouped by general functional capability. The ordering of the user subprograms on the STMPPS source tape is different and is presented in Table 1-2. It will be noted from Table 1-2 that the source tape ordering is the main program (STMPPS) followed by all user subprograms (except steam/water properties) in alphabetical order followed by the steam/water properties subprograms. This ordering of the source tape was chosen to permit ready access to a given subprogram in a rather large complete listing.

The organization of STMPPS is also illustrated in an alternate manner in Figure 1-1. This figure presents the subprogram CALL hierarchy of all user subprograms in STMPPS except the steam/water properties subprograms. This tree-like structure permits ready visualization of the flow of program control and the scope of utilization of the various subprograms.

Table 1-1. Program/Subprogram Characteristics

<u>Name</u>	<u>Function</u>	<u>No. of Source Statements</u>
<u>Simulation Control</u>		
STMPPS	Main simulation program	62
STATE	Controls model derivative calculations	41
SCOND	Performs state event detection	142
EVNTS	Executes model changes at state events	268
<u>Data Communication</u>		
/ADATA/	Executive and program control	16
/CDATA/	Master control subsystem	59
/CONSTS/	Fundamental physical constants	10
/EDATA/	Environmental data	10
/GDATA/	Electrical power generation subsystem variables	87
/GCDATA/	Electrical power generation subsystem constants	91
/HDATA/	Heliostat/collector subsystem	9
/RDATA/	Receiver subsystem variables	213
/RCDATA/	Receiver subsystem constants	37
/TDATA/	Thermal storage subsystem variables	45
/TCDATA/	Thermal storage subsystem constants	57
/USECOM/	Compressed water/superheated steam data	9
<u>Data Initialization</u>		
INIT	Initialize non-GASP program constants	313
INTLC	Initialize GASP program variables	12

Table 1-1. Program/Subprogram Characteristics (Continued)

<u>Name</u>	<u>Function</u>	<u>No. of Source Statements</u>
<u>Data Input</u>		
INP	Reads simulation model input data	100
READPL	Reads plot request data	51
READVL	Reads plot request data	37
<u>Data Output</u>		
OTPUT	Control print/plot output	8
SSAVE	Save sim state for print/plot output	61
PLT	Generate plot output	63
PLOT	Generate plot output	78
ERR	Process plot request errors	35
<u>Environmental Model</u>		
EDATIN	Reads and interpolates environmental data file	273
<u>Collector Model</u>		
FLUX	Reads and interpolates solar data file	93
AT	Calculates area covered by a cloud	12
CLDINT	Initialize cloud model parameters	147
CLOUD	Performs cloud model calculations	158
KSER	Search function used in cloud model	13
SETH	Sets heliostat efficiencies	49
QABS	Calculates flux distribution on receiver	64
<u>Receiver Model</u>		
RECVR	Perform receiver model calculations	291
RSP	Perform receiver panel model calculations	555
<u>Thermal Storage Model</u>		
TSS	Perform TSS model calculations	239

Table 1-1. Program/Subprogram Characteristics (Continued)

<u>Name</u>	<u>Function</u>	<u>No. of Source Statements</u>
<u>EPGS Model</u>		
EPGS	Perform EPGS model calculations	240
PIPELOS	Compute pipe heat loss	95
FRLOSS	Compute pipe friction pressure drop	36
RECFEED	Compute receiver feedwater parameters	202
FTANK	Model flash tank	87
H	Model turbine state curves	44
HRSYS	Model heat rejection subsystem	19
CFWHTR	Model closed feedwater heater	57
PUMPSS	Compute pump output parameters	37
RIAUXC	Compute division of receiver steam flow	247
MCSAUX	EPGS/MCS interface	76
TSSIAUX	Compute TSS/EPGS steam/water flows	245
<u>Master Control Model</u>		
MASTER	Initializes plant variables to desired mode of operation	248
EVNTS	Controls plant operations	268
SCOND	Detects plant performance anomalies	167
<u>Steam/Water Properties</u>		
STEAM	Steam/water properties	127
USEVAL	Steam/water properties	1547
A1INIT	Steam/water properties	109
A2SATB	Steam/water properties	99
A1INTM	Steam/water properties	56
A1INTS	Steam/water properties	49
A1TBLK	Steam/water properties	50
A1SPHE	Steam/water properties	60
A1THEM	Steam/water properties	65
A1VISC	Steam/water properties	62
A1INTP	Steam/water properties	117
A1PRWA	Steam/water properties	24
A1REWA	Steam/water properties	22
A1HTAR	Steam/water properties	39

Table 1-2. STMPPS Source Tape Entry Order

STMPPS	READPL
AT	READVL
CFWHTR	RECFEED
CLDINT	RECVR
CLOUD	RIAUXC
EDATIN	RSP
EPGS	SCOND
ERR	SETH
EVNTS	SSAVE
FLUX	STATE
FRLOSS	TSS
FTANK	TSSLAUX
H	A1INIT
HRSYS	A2SATB
INIT	A1INTM
INP	A1INTS
INTLC	A1TBLK
KSER	A1SPHE
MASTER	A1THEM
MCSAUX	A1VISC
OTPUT	A1INTP
PIPELOS	A1PRWA
PLT	A1REWA
PLOT	A1HTAR
PUMPSS	STEAM
QABS	USEVAL

Figure 1-1. Subprogram CALL Hierarchy

2. INPUT DATA

2.1 SINGLE CASE INPUT

The input data for the STMPPS program for a specified single case run consist of three subdecks. These three subdecks are (in order):

NAMELIST input cards

GASP-IV input cards

Plot data input cards.

The three subdecks are combined in the above indicated order without intervening separators of any kind. Each of the three subdecks also has additional ordering structure. The contents of each of these subdecks will be described separately below. An example of a complete single case input deck is shown in Figure 2-1.

2.1.1 NAMELIST Input Cards

At the beginning of every case, subroutine INP reads NAMELIST input cards for that case. In general, all variables which may be assigned via NAMELIST input data have default values, which are assigned during initialization by subroutine INIT. Therefore, NAMELIST input need only be supplied for those variables in which the default value is to be overridden for the case to be run. Subroutine INP reads NAMELIST data in the following order:

NAMELIST Group Name

PROG

ENVIR

HELIO

RECEVR

THSTOR

EPGS

```

$PROG   DIAG=F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,F,
        END=.T., $
$ENVIR  $
$HELIO  XDIR=180., XVAL=29.08, XTIST=28900., XTIEND=28912.31, $
$RECEVR $
$THSTOR $
$EPGS   $
STMPPS      1    9    20 1978    1
              50    3    1  300  101  80  15    1
2
1
1  0    0.0010    0.0010    0.0010    3.000    0.000    4
1  1    28800.0    29000.0
G12      -1
G12      0
TNOW      TIME SINCE MIDNIGHT (SECONDS)
HSUM      TOTAL SOLAR POWER ON RECEIVER (MW)
RTEF7(3)  BOILER SPANEL 1 OUTLET FLUID TEMPERATURE (DEG F)
RTEF7(4)  BOILER SPANEL 2 OUTLET FLUID TEMPERATURE (DEG F)
RTEF7(5)  BOILER SPANEL 3 OUTLET FLUID TEMPERATURE (DEG F)
RTEF7(6)  BOILER SPANEL 4 OUTLET FLUID TEMPERATURE (DEG F)
RTEF7(7)  BOILER SPANEL 5 OUTLET FLUID TEMPERATURE (DEG F)
RTEF7(8)  BOILER SPANEL 6 OUTLET FLUID TEMPERATURE (DEG F)
RWVSUM    STEAM HEADER INLET FLUID FLOW RATE (LBM/SEC)
RPRSH     STEAM HEADER FLUID PRESSURE (PSIA)
RTESH     STEAM HEADER FLUID TEMPERATURE (DEG F)
GWSRG     TURBINE MAIN VALVE FLUID FLOW RATE (LBM/SEC)
GWSTSG    TURBINE ADMISSION VALVE FLUID FLOW RATE (LBM/SEC)
GEPOUT    GENERATOR POWER OUTPUT (MW)
GPFFR     TOWER RISER OUTLET FLUID PRESSURE (PSIA)
TW7A      TSS STORAGE TANK OUTLET OIL FLOW RATE (LBM/SEC)
TLT       TSS STORAGE TANK 600 F THERMOCLINE LEVEL (0/0)
TW8       TSS STEAM GENERATOR OUTLET STEAM FLOW RATE (LBM/S)
END
HSUM      TOTAL SOLAR POWER ON RECEIVER VS TIME
RTEF7(3)  BOILER SPANEL 1 OUTLET FLUID TEMPERATURE VS TIME
RTEF7(4)  BOILER SPANEL 2 OUTLET FLUID TEMPERATURE VS TIME
RTEF7(5)  BOILER SPANEL 3 OUTLET FLUID TEMPERATURE VS TIME
RTEF7(6)  BOILER SPANEL 4 OUTLET FLUID TEMPERATURE VS TIME
RTEF7(7)  BOILER SPANEL 5 OUTLET FLUID TEMPERATURE VS TIME
RTEF7(8)  BOILER SPANEL 6 OUTLET FLUID TEMPERATURE VS TIME
RWVSUM    STEAM HEADER INLET FLUID FLOW RATE VS TIME
RPRSH     STEAM HEADER FLUID PRESSURE VS TIME
RTESH     STEAM HEADER FLUID TEMPERATURE VS TIME
GWSRG     TURBINE MAIN VALVE FLUID FLOW RATE VS TIME
GWSTSG    TURBINE ADMISSION VALVE FLUID FLOW RATE VS TIME
GEPOUT    GENERATOR POWER OUTPUT VS TIME
GPFFR     TOWER RISER OUTLET FLUID PRESSURE VS TIME
TW7A      TSS STORAGE TANK OUTLET OIL FLOW RATE VS TIME
TLT       TSS STORAGE TANK 600 F THERMOCLINE LEVEL VS TIME
TW8       TSS STEAM GENERATOR OUTLET STEAM FLOW RATE VS TIME
END

```

Figure 2-1. Single Case Example Input Deck

The format of NAMELIST input data cards is described in detail in Section I-9 of Reference 1-1.

The parameters included in each NAMELIST group permit the input of essentially all subsystem model parameters for that subsystem. A complete compilation of accessible parameters ordered by NAMELIST group is shown in Figure 2-2. The reader is referred to Section 3 of this document for a definition of these parameters.

2.1.2 GASP-IV Input Cards

The second input subdeck consists of GASP-IV input cards which are read by GASP subroutine DATIN. The format of these cards is described in detail in Chapter 3 of Reference 1-2.

2.1.3 Plot Data Input Cards

The third input subdeck consists of two parts in order:

- a. The variables/labels cards
- b. The plot request cards.

The variables/labels cards are read by subroutine READVL and are terminated by an END card (END in columns 1, 2, and 3). The plot request cards are read by subroutine READPL and are also terminated by an END card.

2.1.3.1 Variables/Labels Cards

The variables/labels cards must correspond in number and order to the variables in a single fixed-length record on the plot data tape (TAPE8). A record on the plot data tape is written on each call to subroutine SSAVE. The simulation time interval between such records is controlled by GASP-IV input data (see Section 2.1.2).

NAMELIST /PROG/ OUTFG,END,ATILCL,ATITST,ATIMO,ATIDAY,DIAG
 NAMELIST /ENVIR/ ETEAMB,EPRAMB,EVWAMB,EINDIR,EDWAMB,ETDAMB
 NAMELIST /HELIO/ HFLRN,HCEF,HREF,HCFL,XTIST,XTIEND,XVAL,XDIR
 NAMELIST /RECEVR/ RKCM,RKDNM,RKEESP,RKHFC,RKHFR,RKIDTB,RKODTB,
 1 RKWSP,RKL17,RKNTB,RKNPSP,RKNBSP,RKFF2,RKFF4,RKFF6,RKFV,RKAAV,
 2 RKVSH,RKINTC,RKPROC,RKTHSC
 NAMELIST /THSTOR/ TT3,TT4,TT5,TT6,TT8,TP8,TH8,TPDTSH,TC5,TC6,TW5M,
 1 TW5MF,TW7M,TW7MF,TKHC,TKTMTSH,TKTMSG,TKTMECS,TKG,TPPA,TPPCM,
 2 TPPM,TPL1,TPL2,TPL3,TAK1,TBK1,TCK1,TDK1,TAK2,TBK2,TCK2,TDK2,
 3 TAK3,TBK3,TAK4,TBK4,TK5,TK6,THTSUM,TLTU1,TLTU2,TLTL1,TLTL2,
 4 TTSC,TTSE
 NAMELIST /EPGS/ GMVR,GMVT,GMVE,VRATE,GMVRO,GMVTO,GMVEO,SSP,TZERO,
 1 GPSPT3,GETAT3,GLZT3,GKLCT3,GPSPT1,GMCT1,GPSPT2,GETAT2,GLZT2,
 2 GKLCT2,GRIDC,GRODC,GLDC,GTC,GRISP,GROSP,GLSPTG,NPORTS,IFAN,
 3 GPTED,GTEFF,GFHRD,GWHRD,GTHRD,GMEFF,GKEFF,GKGAIN,GKINERT,
 4 GPFPSR,GFPHR,GFPSR,GWFPR,GFPTR,GVFPR,GRIRC,GRORC,GLRC,GRIDS,
 5 GRODS,GLDESP,GPFPSR,GLFWP,GRIFWP,GROFWP,TNOM,VNOM,BPUMP,HPUMP,
 6 H1PARM,H2PARM,H4PARM,H5PARM,GMCH3,GMCHW

Figure 2-2. NAMELIST Group Definitions

A variables/labels card contains two fields:

- a. Columns 1-10 contain a variable.
- b. Columns 11-70 contain a corresponding label which serves as the descriptor for that variable.

The first variables/labels card must contain the variable "TNOW" and the associated label. This label will serve as the X axis descriptor for all plots. Other variables/labels cards will contain the various variables and associated labels for the Y axis.

2.1.3.2 Plot Request Cards

The plot request cards consist of a sequence of card packets with one to six cards per packet and one packet for each desired plot. The first card of a packet contains two fields:

- a. Columns 1-10 contain a Y axis variable.
- b. Columns 11-70 contain the first line of plot descriptor information.

Each subsequent card of a packet contains an additional line of plot descriptor information in columns 11-70. The descriptive information contained in a packet is printed in the top central portion of a plot.

2.2 MULTIPLE CASE INPUT

Input for multiple cases is constructed by simple serial stacking of single case data. For the last case, the logical variable END in NAMELIST group name PROG should be set to TRUE.

3. PROCESSING MODULES

3.1 ENVIRONMENTAL MODULE

The environmental module of the STMPPS program is a subroutine, EDATIN, which extracts the required environmental information from a previously prepared data base, converts units, and interpolates in time to provide the environmental values for the time requested. The data base itself is described in detail in Reference 3-1.

The data tape contains an entry for every 15-minute interval of all 366 days of 1976. The insolation observations were made at 15-minute intervals by the Southern California Edison Company at a site in Barstow, some 10 miles west of the pilot plant site. The meteorological values were interpolated from hourly observations made at the Federal Aviation Agency Flight Service Station at the Daggett/San Bernardino County Airport about two miles east of the pilot plant site. This data tape is written in a modified form of the standard SOLMET format used by the Department of Energy and the National Oceanic and Atmospheric Administration for storing insolation data sets, and contains considerably more information than is needed by STMPPS.

EDATIN is written such that reading the environmental data base tape is transparent to the user after the file structure is defined, so that each read statement obtains one data entry from the tape. On the Aerospace CDC 7600 computer, with the SCOPE 2 operating system, this is accomplished by the control card FILE(TAPE10, RT=F, BT=K, RB=96, FL=163, CM=YES).

When the routine is called, it first decides whether data for the requested date are available in storage. If not, then the data tape (TAPE10) is searched for the requested date. If the date is not found, the flag AENERR is set and control is returned to the calling program. If the date is found, the data for the entire day are read into array ENIN(I, J).

I indicates the time during the day for this entry and J indicates the meteorological variable for that time. Table 3-1 defines the array ENIN in detail. Since the units on the data tape are not those used in STMPPS, immediately after the array is filled the units are converted to STMPPS units, as indicated in Table 3-1. For efficiency, an entire day's data are stored at one time, since STMPPS calls to EDATIN may not be strictly in time sequence.

When data for the desired date with correct units are in place in the array ENIN, a flag, IDATIN, is set and all subsequent contiguous calls for environmental data for that date are satisfied by interpolation between values in the ENIN array. Insolation, dew point, dry bulb temperature, and atmospheric pressure are determined by linear interpolation. Wind direction and speed are determined by taking the closest values in time. The solar time is computed from the standard time assuming the offset, TIDSOL, is constant for the entire day.

Table 3-2 lists all the variables in use in EDATIN, with the exception of obvious items such as DO loop indices. The variables are grouped in the table according to function. Listed first are the five quantities which tell EDATIN what data are to be employed. Of these five, AEIST and ATIYR are defined only internal to EDATIN, but have been included for ease in adopting the simulation program to data sets for other years and locations. The other three variables in this group are set by the program calling EDATIN.

The next eight variables listed in Table 3-2 are set by EDATIN to values appropriate for the requested time. The following nine variables are identifying information from the data tape, and indicate the data tape type, location, and time for that entry. All of these parameters are checked to assure that the information read is that which was requested. The final 11 variables in Table 3-2 are internally generated and used in EDATIN for the purposes listed in the table.

There are no equations used in EDATIN beyond the familiar ones for linear interpolation and units conversion.

Table 3-1. Definition and Units for One Data Entry in ENIN(I, J)

Index J	Quantity	Input Units From Data Tape	Units as Stored in Memory
1	Direct Insolation	kJoules/m^2	kW/m^2
2	Station Pressure	kPascals	lb/in.^2
3	Dry Bulb Temperature	$^{\circ}\text{C}$	$^{\circ}\text{F}$
4	Dew Point Temperature	$^{\circ}\text{C}$	$^{\circ}\text{F}$
5	Wind Direction	deg azimuth	deg azimuth
6	Wind Speed	m/sec	ft/sec

Table 3-2. Variables Used in EDATIN Environmental Input Routine

Engineering Symbol	Program Symbol	Description	Units	External Use
		<u>Input or Predefined Values</u>		
	AEIST	5 digit station number (set to 23161)		
	ATIYR	Last 2 digits of data year sought (set to 76)		
	ATIMO	Data month sought (1-12)		I
	ATIDAY	Data day sought (1-31)		I
	ATILCL	Local standard time for which data are sought	sec from midnight	I
		<u>Output Values</u>		
	AENERR	Error flag = 1, Data requested before start of tape = 2, Data requested after end of tape = 3, Parity error on tape = 4, Wrong deck or station num- ber on tape Not changed, then no error		O
	ATITST	True solar time	sec from midnight	O
	EDWAMB	Wind direction	deg azimuth	O
	EINDIR	Direct insolation	kW/m ²	O
	EPRAMB	Ambient atmospheric pressure	lb/ft ²	O
	ETDAMB	Ambient dew point temperature	°F	O
	ETEAMB	Ambient dry bulb temperature	°F	O
	EVWAMB	Wind speed	ft/sec	O
		<u>Read From Data Tape</u>		
	IDK	Tape type (should be 9724)		
	IST	Station number		
	IY	Year (last two digits)		
	IM	Month (1-12)		
	ID	Day (1-31)		

Table 3-2. Variables Used in EDATIN Environmental Input Routine (Continued)

Engineering Symbol	Program Symbol	Description	Units	External Use
	STHR	Hour, standard time	hr	
	STMN	Minute, standard time	min	
	TSHR	Hour, true solar time	hr	
	TSMN	Minute, true solar time	min	
		<u>Internally Generated</u>		
	DELS	Difference in time between data tape entries	min	
	NELM	Number of entries found on tape for one day		
	ST	Standard time of current data tape entry	min	
	STO	Standard time of immediately previous data tape entry	min	
	TIDSOL	Offset between standard and solar time	min	
	ENIN	Array for storing one day's data	see Table 3-1	
	NREAD	Number of entries read from data tape		
	IMAX	The maximum number of entries allowed per day (set to 98)		
	IN	Array containing one data entry from tape before decoding		
	ILST	Internal flag		
	IDATIN	Flag to indicate data in place in ENIN		

3.2 COLLECTOR MODULE

3.2.1 Introduction

The optical interface of the STMPPS program uses values of insolation from Barstow, California for 1976, and data from an optical simulator, to generate the power absorbed on a large number of nodes at the receiver as a function of time.

The Aerospace Central Receiver Optical Simulation Program (Program CONCEN) was used to generate the file for each day selected for systems simulation. The files consist of optical flux data for each of 160 receiver nodes, from each of 121 cells in the collector field, for a sufficient number of times in the day to properly describe the daily variation in field optical efficiency. There are 13 to 19 records in each file, representing points in time during the day. Each record is a 20 by 8 by 121 matrix of the power absorbed (watts) on each of 20 evenly spaced nodes along the height of the receiver, on each of 8 superpanels surrounding the receiver, from each of 121 regions (cells) in the heliostat field. When the file is generated, the data are normalized to an insolation level of 1.0 kW/m^2 , a heliostat reflectivity of 1.0, and a receiver absorptivity of 0.95.

The optical interface program (a) reads the flux files, (b) interpolates the data to the simulation time of day, (c) applies the field efficiency matrix to the flux data, and (d) sums over the data to get the total flux in each node. Simulation-provided current values of direct normal insolation, heliostat reflectivity, and receiver absorptivity are then used to obtain the correct power into each receiver node.

3.2.2 Representative Days of the Year and Time of Day

From insolation and weather data for Barstow, California, three clear days have been chosen as representative for the system simulation. These days are June 24 (near summer solstice), March 21 (spring equinox), and December 21 (winter solstice). Program CONCEN has been

run at hourly intervals for each of these days. The results are shown in Figure 3-1. The data are based on the McDonnell Douglas (MDAC) baseline Pilot Plant design. The vertical scale is the overall optical efficiency, defined as the ratio of optical energy incident on the receiver to the total optical energy available (insolation times total collector area).

For efficiency of execution and computer storage in the simulation, it is desirable to have optical flux data for the collector field at a sufficient number of time points in each day so that only two points need be in storage at once, and thus a simple linear interpolation can be done to determine the optical power at the receiver at a given time. The data of Figure 3-1 show that hourly intervals during the middle of the day are adequate, but that greater resolution is desirable during the 1.5 to 2 hours just after sunrise and just before sunset. During these periods of time the data are generated at half-hour intervals. Thus, from sunrise to sunset, June 24 is represented by 19 points in time in half-hour intervals from 5:00 a.m. to 7:00 a.m. and 5:00 p.m. to 7:00 p.m., and hour intervals from 7:00 a.m. to 5:00 p.m. Similarly, March 21 is represented by 17 time points and December 21 by 13 time points.

3.2.3 Receiver Nodes and Collector Field Representation

The thermal inputs to the receiver are represented by the absorbed optical flux at 160 nodes on the receiver surface. The locations of the nodes are shown in Figure 3-2. The 24 receiver panels are grouped in sets of three, so that there are eight circumferential node regions called superpanels. Each of the three groups of panels is divided into 20 equal vertical regions along the height of the receiver.

The simulation of collector field dependent effects is implemented by dividing the collector field into an 11 by 11 array of 121 cells. An example of this division is shown for the MDAC baseline Pilot Plant in Figure 3-3. Program CONCEN generates the flux arriving at each node of the receiver from each cell in the field. Thus, at each time point during

8-8

Figure 3-1. Daily Optical Efficiency for the McDonnell Douglas PDR Pilot Plant Design

Figure 3-2. Location of Thermal Nodes on the Receiver Surface

Figure 3-3. Sample Field Layout and Cell Grid

the day, CONCEN generates a record on a file consisting of the time of day and 19,360 values ($20 \times 8 \times 121$) of the power in watts absorbed at each node from each cell in the field.

During a simulation, a cell efficiency matrix is available which can be set, for example, by the MCS. The matrix consists of 121 fractions representing the fraction of heliostats in a cell which are redirecting energy toward the receiver. If a cell is inactive or totally obscured, its efficiency is 0.0. If a cell is fully active, its efficiency is 1.0. A field-dependent phenomenon is simulated by setting appropriate values in the cell efficiency matrix at the proper time.

The optical interface subroutine (FLUX) is called each time the main program needs updated flux values. Subroutine FLUX reads data from the permanent file until those data encompass the current time. The flux data are multiplied by the efficiency matrix and summed over the field cells to get the total flux into each node. A linear interpolation gives the flux data for the current time period. These data are multiplied by the current value of insolation, heliostat reflectivity, and receiver absorptivity to calculate the final flux values. For compatibility with the receiver routine, the flux value (in watts) is converted to Btu's per second.

3.2.4 Pilot Plant Scaling to a Solar Multiple of 1.24

The data generated for the systems simulation are based on a version of the MDAC Preliminary Design Review Pilot Plant (solar multiple of 1.1) scaled to a solar multiple of 1.24. The characteristics of the field are given in Table 3-3. The performance efficiencies of the scaled field are similar to that of the original field. The scaled field appears to be a good representation of the characteristics of a field with a solar multiple of 1.24 without benefit of a re-design process.

Table 3-3. Scaled Pilot Plant Field Characteristics
(Solar Multiple = 1.24)

Field Size, m	
Tower to north edge	403
Tower to east (west) edge	363
Tower to south edge	198
Total Number of Heliostats	1903
Number of Active Heliostats	1860
Tower Height at Receiver Centerline, m	83.3
Receiver Diameter, m	7.3
Receiver Height, m	13.0
Heliostat Type	baseline 6 facet - invertable
Heliostat Collection Area, m ²	37.9
Total Collection Area, m ²	72195
Heliostat Configuration	radial-stagger
Focusing Method	flat facets canted for a focal length of 340 m
Mirror Reflective Efficiency	0.88
Mirror Waviness (standard deviation of normally distributed surface elements), mr	1.0
Tracking Error (standard deviation of a normally distributed reflected beam), mr	2.0
Receiver Normal Incidence Visible Wavelength Absorptance	0.95
Atmospheric Absorption	$1.4 \times 10^{-4}/\text{m}$

3.2.5

Optical Performance Input Data Tape

Number of Files - 3 provided with STMPPS program.

File No. 1 - 17 records of data for March 21 (equinox).

The first word of each record is the solar time in hours from midnight (and fractions thereof) at which the flux data apply, followed by 19,360 floating point binary values (CDC binary) of the flux absorbed in watts on the nodes of the receiver (20 nodes vertical, 8 superpanels in surround) from each of 121 cells in the field.

The following CDC statement will correctly read a record:

```
READ (20) TIME      [FLUX(I,J,L), I = 1,20 , J = 1,8 , L = 1,121]
```

where I is the vertical node index, J is the panel index, and L is the field cell index.

The times for the 17 records are (in order on the tape):

6:00 (a.m.), 6:30*, 7:00, 7:30, 8:00, 9:00, 10:00, 11:00, 12:00;
1:00 (p.m.) (13.00 on the tape), 2:00, 3:00, 4:00, 4:30, 5:00,
5:30, 6:00 (p.m.).

File No. 2 - 19 records of data for June 24 (near-summer solstice).

The times for the records are:

5:00 (a.m.), 5:30, 6:00, 6:30, 7:00, 8:00, 9:00, 10:00, 11:00,
12:00; 1:00 (p.m.), 2:00, 3:00, 4:00, 5:00, 5:30, 6:00, 6:30,
7:00 (p.m.).

File No. 3 - 13 records of data for December 21 (winter solstice).

The times for the records are:

7:30 (a.m.), 8:00, 8:30, 9:00, 10:00, 11:00, 12:00; 1:00 (p.m.),
2:00, 3:00, 3:30, 4:00 4:30.

* Half-hours are shown on the tape as the decimal equivalent (6.50).

3.2.6

Definition of Variables for Subroutine FLUX

Engineering Symbol	Program Symbol	Description	Units	Input Output
	ATITST	True solar time from midnight	sec	I
	TM	Same as above	hr	
	HFLRN(I, J)	Flux absorbed at node I, panel J	W	O
	HCEF(L)	Operating efficiency of field cell L (fraction of heliostats in each cell currently redirecting energy to the receiver)	0.0-1.0 (numeric)	I
$\dot{q}$	EINDIR	Current direct normal insolation	kW/m ²	I
ρ	HREF	Heliostat reflective efficiency	numeric	
α	RAB	Receiver normal incidence absorptivity	numeric	I
	TA	Earlier solar time of a record pair	hr	I
	TB	Later solar time of a record pair	hr	I
	SFA(I, J, L)	Flux on node I, panel J, from cell L at time TA	W/(kW/m ²)	I
	SFB(I, J, L)	Flux on node I, panel J, from cell L at time TB	W/(kW/m ²)	I
	HA(I, J)	Total flux on node I, panel J at time TA	W/(kW/m ²)	
	HB(I, J)	Total flux on node I, panel J at time TB	W/(kW/m ²)	
	NR	Number of records read from the data file	numeric	
	0.948047×10^{-3}	Conversion factor from watts to Btu's/sec	$\frac{\text{Btu/sec}}{\text{W}}$	

3.2.7

Subroutine FLUX Flow Chart

A logic flow diagram for FLUX is given in Figure 3-4.

Figure 3-4. FLUX Flow Chart

3.3

RECEIVER MODULE

3.3.1

Receiver Subsystem Description

The function of the pilot plant receiver subsystem (Figure 3-5) is to (a) transfer efficiently the energy from the concentrated solar radiation reflected from the mirrors of the collector subsystem into the water supplied by the electrical power generation subsystem, and (b) deliver steam at precisely controlled superheat conditions to the plant turbine-generator and thermal storage subsystem. Nominally, the receiver will be required to accept water from the flow distribution system at 2000 psia and 401° F, and deliver superheated steam at rated conditions of 1465 psia and 950° F to the electrical generation subsystem. Any rated steam generated in excess of turbine power requirements will be diverted to the thermal storage subsystem. The receiver subsystem also must be capable of delivering steam at 1465 psia and 660° F, when it is required to divert the total receiver energy output into thermal storage.

The pilot plant receiver must safely and efficiently absorb incident solar radiation at a maximum flux of 0.30 MW/m². In addition, the receiver must be able to accept, without damage, thermal gradients imposed by radiation transients due to the intermittent passage of clouds over the collector field.

The receiver unit consists of six modular preheater panels and 18 boiler panels, flow control and instrumentation equipment, and the supporting structure. All panel subassemblies are constructed of 73 tubes (0.50 in. O.D. × 0.269 in. I.D.) of high-strength corrosion-resistant Incoloy 800 laid side-by-side, joined together thermally and structurally, and made opaque to incident light by full-length longitudinal seam welds. The individual tubular panel assemblies of the receiver unit are mounted on a central core steel support structure to form a single large, essentially circular (24-sided) cylinder 23.8 ft in diameter by 43 ft in length. The heliostats surrounding the receiver tower direct their collected insolation onto the full 360-degree external surface of the receiver unit.

3-18

Figure 3-5. Pilot Plant Receiver

The receiver tower is of steel construction and extends 213 ft above grade to the interface with the receiver unit steel support structure, which continues up through the receiver unit to an elevation of 285 ft.

Functioning of the receiver can best be described by following a typical day's operation. To initiate start-up, water from the water treatment equipment of the electrical power generation subsystem is forced up the receiver tower riser by the receiver feed pumps and into the receiver inlet filter assembly. Leaving the filter assembly, the water enters a manifold which distributes the flow into the inlets of the three parallel sets of two panels in series located on the south side of the receiver, designated as preheaters. The water absorbs heat as it flows through a preheater panel, until it joins the flow from the other preheaters in a ring manifold supplying the remaining 18 panel assemblies, designated as boiler panels.

Passing through a modulating flow control valve located at the inlet to each boiler panel, the water flows vertically upward, again absorbing heat from the incident solar radiation and leaving the upper end of the boiler panels as superheated steam. The individual boiler panel inlet valves provide the flow control necessary to maintain constant outlet temperature, despite diurnal and seasonal variations in heat load at each panel. The control valves also control cloud-induced transients and regulate the start-up and shutdown sequences. With this arrangement, active control of the water flow through the preheater panels is not required.

As the steam exits from each of the panel discharge manifolds, it passes through a cyclone-type water separator as a precautionary measure to ensure absolutely dry steam. The steam enters the steam downcomer collection manifold, where it is mixed with the discharge flow from the other boiler panels and is finally carried away by the downcomer to the turbine of the electrical power generation subsystem, or to the thermal storage subsystem, or both, as directed by master control. During start-up or conditions when solar insolation is too low to produce the proper superheat conditions, a

combination of valves is used to divert receiver discharge flow away from the downcomer and into a receiver flash tank assembly, until proper superheat conditions are achieved.

A detailed description of the design of the receiver subsystem is found in Reference 3-2.

3.3.2 Receiver Subsystem Modeling Approach*

The primary assumption used in the development of the receiver model was that a distributed parameter process could be represented by a lumped parameter model with the concept of control volumes. A set of nonlinear, ordinary differential and algebraic equations could then be developed by sectioning the receiver subsystem into appropriate control volumes and applying fundamental equations, well-known semi-empirical formulae, and steady-state system design data.

For efficient digital simulation, the selection of the receiver subsystem control volumes must optimize both computation cost and accuracy. By grouping three receiver panels into one "superpanel" of 219 tubes (Figure 3-6), and then characterizing the performance of each superpanel by the performance of a typical tube, a relatively fast, efficient, and accurate receiver subsystem model results. Whereas the size of the superpanels determines the fidelity with which the external flux and flow distributions are simulated, the modeling of a typical tube poses the greatest obstacle to obtaining both accurate performance predictions and fast computation speed. The solution is the formulation of a tube model by use of the concept of time-varying phase boundaries.

To organize the model equations, a solution diagram was developed. A simplified version is shown in Figure 3-7. Each block in the diagram represents a physical component or a group of components (Figure 3-8). The lines interconnecting the blocks indicate direction of information flow or "model causality." The diagram shows how individual component models mathematically interface with each other, and ensures consistent causality for the complete set of equations defining the receiver subsystem.

*Much of this section is taken from, or patterned after, Ray, Berkowitz, and Sumaria, Reference 3-11. Their original work has been extended however, by incorporating into the model the capability to simulate complete start-ups and shut-downs, i. e., the transitioning from subcooled liquid, saturated mixture, and superheated vapor states.

RECEIVER PANEL

W = 3.13 ft

73 TUBES

SUPERPANEL

W = 9.38 ft

219 TUBES

Figure 3-6. McDonnell Douglas Receiver Panel

Note: Nomenclature is given in Table 3-4

Figure 3-7. Simplified Receiver Subsystem Model Solution Diagram

Figure 3-8. Pilot Plant Receiver Subsystem Schematic

By following the arrangement in Figure 3-7, the task of modeling was accomplished in two steps:

- Step 1: Modeling of individual components or groups of components
- Step 2: Formulation of an overall receiver subsystem model by appropriate interconnection of the individual component models.

Step 1 includes determination of steady-state solutions and component time constants at various operating points. Steady-state solutions of individual models are verified with design data, and the time constants are examined for frequency range.

Step 2 incorporates sequential interconnection of component models according to the model solution diagram. In this process, steady-state solutions and time constants of the augmented models are examined at each interconnection phase. Due to the highly interactive nature of the process, time constants of the augmented model may be significantly different from those of the individual component models.

The next section describes the five component models with special emphasis on the receiver tube (or superpanel) model. The engineering parameters (variables and constants) used in the component models development and the FORTRAN symbols used in the computer program are listed in Tables 3-4 and 3-5.

3.3.3 Receiver Subsystem Model Description *

3.3.3.1 Thermal/Hydraulic Models

The receiver subsystem thermal/hydraulic models are formulated from the following basic equations:

- a. Fundamental equations of mass, momentum and energy conservation
- b. Semi-empirical relationships for fluid flow and heat transfer
- c. State relations for thermodynamic properties of working fluids.

*Much of this section is taken from, or patterned after Adams, Clark, Louis and Spanbauer, Reference 3-12; and Ray and Bowman, Reference 3-13.

Table 3-4. Receiver Subsystem Constants

Symbol		Description	Value	Units
Engineering	Program			
F_v	RKFV	Fluid flow coefficient	210.0	psi, sec ² /lbm, ft ³
F_{f2}	RKFF2	Fluid flow coefficient	1.6	psi, sec ² /lbm, ft ³
F_{f4}	RKFF4	Fluid flow coefficient	1.6	psi, sec ² /lbm, ft ³
F_{f6}	RKFF5	Fluid flow coefficient	0.3	psi, sec ² /lbm, ft ³
ϵ	RKEESP	Emissivity of external receiver coating	0.90	
l_{17}	RKL17	Length of receiver superpanel	42.64	ft
U_{fr}	RKHFR	Free convection heat transfer constant	5.278×10^{-5}	
U_{fc}	RKHFC	Forced convection heat transfer constant	9.2956×10^{-5}	
V_{sh}	RKVSH	Volume of steam header	45.0	ft ³
W	RKWSP	Width of receiver superpanel	9.378	ft
C	RKCSP	Heat capacity of a metal panel per linear distance	14.142	Btu/ft, °F
α	RKAAV	Flow control valve pressure drop ratio	0.95	
K_i	RKINTC	Controller integral gain	0.001	sec/°F
K_p	RKPROC	Controller proportional gain	0.001	1/°F

Table 3-5. Receiver Subsystem Variables

Symbol		Description	Units	I/O
Engineering	Program			
w_{ps}	RWSP(1)	Flow rate at preheater superpanel inlet	lbm/sec	Output, Internal
P_{fw}	RPRF1(1)	Pressure at preheater superpanel inlet	psia	Input, Internal
h_{fw}	RHF1(1)	Enthalpy at preheater superpanel inlet	Btu/lbm	Input, Internal
w_{sh}	RWOSH	Flow rate exiting steam header	lbm/sec	Input, Internal
v_{sh}	RVSH	Specific volume within steam header	ft ³ /lbm	Internal
P_{sh}	RPRSH	Pressure within steam header	psia	Output, Internal
h_{sh}	RHSH	Enthalpy within steam header	Btu/lbm	Output, Internal
u_{sh}	RUSH	Internal energy within steam header	Btu/lbm	Internal
w_v	RWV	Flow rate through control valve	lbm/sec	Internal
v_v	RVIV	Specific volume at control valve inlet	ft ³ /lbm	Internal
L_v, L	RLV, RLSUMC	Valve stem position of control valve	%	Internal
w_{f1}	RWSP	Flow rate at superpanel node 1	lbm/sec	Internal
P_{f1}	RPRF1	Pressure at superpanel node 1	psia	Internal
h_{f1}	RHF1	Enthalpy at superpanel node 1	Btu/lbm	Internal
w_{f2}	RWSP	Flow rate at superpanel node 2	lbm/sec	Internal
v_{f2}	RVF2	Specific volume at superpanel node 2	ft ³ /lbm	Internal

Table 3-5. Receiver Subsystem Variables (Continued)

Symbol		Description	Units	I/O
Engineering	Program			
T_{f2}	RTEF2	Fluid temperature at superpanel node 2	$^{\circ}\text{F}$	Internal
u_{f2}	RUF2	Internal energy at superpanel node 2	Btu/lbm	Internal
h_{f2}	RHF2	Enthalpy at superpanel node 2	Btu/lbm	Internal
Q_{f2}	RQF2	Heat transferred to fluid at superpanel node 2	Btu/sec	Internal
U_{f2}	RHCF2	Internal convective heat transfer coefficient at superpanel node 2	$\text{Btu}/\text{ft}^2, \text{sec}, ^{\circ}\text{F}$	Internal
T_{m2}	RTEM2	Metal temperature at superpanel node 2	$^{\circ}\text{F}$	Internal
Q_{m2}	RQM2	Heat transferred to metal at superpanel node 2	Btu/sec	Internal
Q_{am2}	RQAM2	Heat absorbed by metal at superpanel node 2	Btu/sec	Input, Internal
Q_{em2}	RQEM2	Heat loss emitted by metal at superpanel node 2	Btu/sec	Internal
Q_{cm2}	RQCM2	Heat loss convected from metal at superpanel node 2	Btu/sec	Internal
U_{m2}	RHCM2	External convective heat transfer coefficient at superpanel node 2	$\text{Btu}/\text{ft}^2, \text{sec}, ^{\circ}\text{F}$	Internal
w_{f2}	RWSP	Flow rate at superpanel node 3	lbm/sec	Internal
v_{f3}	RVF3	Specific volume at superpanel node 3	ft^3/lbm	Internal
P_{f3}	RPRF3	Pressure at superpanel node 3	psia	Internal
h_{f3}	RHF3	Enthalpy at superpanel node 3	Btu/lbm	Internal

Table 3-5. Receiver Subsystem Variables (Continued)

Symbol		Description	Units	I/O
Engineering	Program			
l_{j3}	RL13	Length of subcooled liquid superpanel control volume	ft	Internal
w_{f4}	RWSP	Flow rate at superpanel node 4	lbm/sec	Internal
v_{f4}	RVF4	Specific volume at superpanel node 4	ft ³ /lbm	Internal
T_{f4}	RTEF4	Fluid temperature at superpanel node 4	°F	Internal
u_{f4}	RUF4	Internal energy at superpanel node 4	Btu/lbm	Internal
h_{f4}	RHF4	Enthalpy at superpanel node 4	Btu/lbm	Internal
Q_{f4}	RQF4	Heat transferred to fluid at superpanel node 4	Btu/sec	Internal
U_{f4}	RHCF4	Internal convective heat transfer coefficient at superpanel node 4	Btu/ft ² , sec, °F	Internal
T_{m4}	RTEM4	Metal temperature at superpanel node 4	°F	Internal
Q_{m4}	RQM4	Heat transferred to metal at superpanel node 4	Btu/sec	Internal
Q_{am4}	RQAM4	Heat absorbed by metal at superpanel node 4	Btu/sec	Input, Internal
Q_{em4}	RQEM4	Heat loss emitted by metal at superpanel node 4	Btu/sec	Internal
Q_{cm4}	RQCM4	Heat loss convected from metal at superpanel node 4	Btu/sec	Internal
U_{m4}	RHCM4	External convective heat transfer coefficient at superpanel node 4	Btu/ft ² , sec, °F	Internal

Table 3-5. Receiver Subsystem Variables (Continued)

Symbol		Description	Units	I/O
Engineering	Program			
w_{f5}	RWSP	Flow rate at superpanel node 5	lbm/sec	Internal
v_{f5}	RVF5	Specific volume at superpanel node 5	ft ³ /lbm	Internal
P_{f5}	RPRF5	Pressure at superpanel node 5	psia	Internal
h_{f5}	RHF5	Enthalpy at superpanel node 5	Btu/lbm	Internal
l_{35}	RL35	Length of two-phase mixture superpanel control volume	ft	Internal
l_{15}	RL15	Length of subcooled liquid and two-phase mixture superpanel control volumes	ft	Internal
w_{f6}	RWSP	Flow rate at superpanel node 6	lbm/sec	Internal
v_{f6}	RVF6	Specific volume at superpanel node 6	ft ³ /lbm	Internal
T_{f6}	RTEF6	Fluid temperature at superpanel node 6	°F	Internal
u_{f6}	RUF6	Internal energy at superpanel node 6	Btu/lbm	Internal
h_{f6}	RHF6	Enthalpy at superpanel node 6	Btu/sec	Internal
Q_{f6}	RQF6	Heat transferred to fluid at superpanel node 6	Btu/sec	Internal
U_{f6}	RHCF6	Internal convective heat transfer coefficient at superpanel node 6	Btu/ft ² , sec, °F	Internal
T_{m6}	RTEM6	Metal temperature at superpanel node 6	°F	Internal
Q_{m6}	RQM6	Heat transferred to metal at superpanel node 6	Btu/sec	Internal

Table 3-5. Receiver Subsystem Variables (Continued)

Symbol		Description	Units	I/O
Engineering	Program			
Q_{am6}	RQAM6	Heat absorbed by metal at superpanel node 6	Btu/sec	Input, Internal
Q_{em6}	RQEM6	Heat loss emitted by metal at superpanel node 6	Btu/sec	Internal
Q_{cm6}	RQCM6	Heat loss convected from metal at superpanel node 6	Btu/sec	Internal
U_{m6}	RHCM6	External convective heat transfer coefficient at superpanel node 6	Btu/ft ² , sec, °F	Internal
w_{f7}	RWSP	Flow rate at superpanel node 7	lbm/sec	Internal
v_{f7}	RVF7	Specific volume at superpanel node 7	ft ³ /lbm	Internal
P_{f7}	RPRF7	Pressure at superpanel node 7	psia	Internal
T_{f7}	RTEF7	Fluid temperature at superpanel node 7	°F	Internal
h_{f7}	RHF7	Enthalpy at superpanel node 7	Btu/lbm	Internal
l_{57}	RL57	Length of superheated steam superpanel control volume	ft	Internal
w_{bs}	RWISH	Flow rate at boiler superpanel node 7	lbm/sec	Internal
T_{bs}	RTSENC	Fluid temperature at boiler superpanel node 7	°F	Internal
h_{bs}	RHISH	Enthalpy at boiler superpanel node 7	Btu/lbm	Internal
e_T	RERRTC	Temperature controller error signal	°F	Internal
L_i	RLINTC	Integral valve stem position command signal	%	Internal

Table 3-5. Receiver Subsystem Variables (Continued)

Symbol		Description	Units	I/O
Engineering	Program			
L_p	RLPROC	Proportional valve stem position command signal	%	Internal
T_{sp}	RTSETC	Temperature set point	°F	Input, Internal
T_{amb}	ETEAMB	Ambient temperature	°F	Input
V_{amb}	EVWAMB	Ambient wind velocity	ft/sec	Input

The primary assumption in this study is that an infinite-dimensional distributed parameter process can be represented by a finite-dimensional lumped parameter model, with use of the concept of control volumes. Additional assumptions are: (Ref. 3-11 to 15)

- a. Uniform fluid properties at any cross-section
- b. Uniform metal properties
- c. Uniform heat flux over any surface
- d. Uniform flow distribution in multitube devices
- e. Insignificant heat transfer by conduction
- f. Insignificant temporal acceleration and momentum transport contributions to fluid flow dynamics
- g. Insignificant kinetic energy contributions to fluid flow dynamics
- h. Fully developed, turbulent, single-phase fluid flow.

Other assumptions specific to individual component models are stated where model equations are described.

3.3.3.1.1 Receiver Superpanel Model

The receiver superpanel model is based on the performance of a typical tube shown schematically in Figure 3-9. The tube is partitioned into three sections, i. e., subcooled (or compressed) water, saturated two-phase mixture, and superheated steam. This results in six control volumes or two for each section - one enclosing working fluid and one enclosing metal mass. The length of each control volume is allowed to vary with time. Consequently, the other process variables such as pressure, temperature, enthalpy, etc., at these phase boundaries are also time-varying.

LEGEND

Node 1 - inlet properties	$\triangle$ - tube metal nodes
2 - average subcooled properties	$\bigcirc$ - working fluid nodes
3 - saturated liquid boundary	l_{13} - subcooled length
4 - average saturated properties	l_{35} - two-phase length
5 - saturated vapor boundary	l_{57} - superheated length
6 - average superheated properties	l_{17} - insulation exposed length
7 - outlet properties	

Figure 3-9. Receiver Superpanel Model Schematic

The basic model equations, subject to the assumptions of negligible mass storage effects and a linear variation of fluid properties between a fluid control volume inlet and outlet, are presented in Table 3-6 for each of the six control volumes at the following three conditions:

- a. The panel containing only subcooled water
- b. The panel containing subcooled water and saturated two-phase mixture
- c. The panel containing all three fluid states - subcooled water, two-phase mixture, and superheated steam.

Different equation sets are required for each of the above conditions to ensure continuity at the phase boundaries and to optimize computation speed. All the fluid properties not explicitly solved for in Table 3-4 are evaluated by either spatial averaging or thermodynamic state relations.

The convective heat transfer coefficients used in the subcooled water and superheated steam control volumes are a slightly modified form of the Dittus-Boelter correlation (Reference 3-4). Heat transfer in the saturated two-phase region takes place by nucleate boiling in the low-quality area and then shifts to film boiling in the higher-quality region. The heat transfer correlation proposed by Thom, et al., (Reference 3-5) is used for nucleate boiling, and the correlation proposed by McDonnell Douglas (Reference 3-3) is used for the film boiling coefficient. The average heat transfer coefficient between the tube wall and the saturated two-phase mixture is determined by integrating the two local heat transfer coefficients over the entire length of the two-phase control volume surface.

The external convective heat transfer coefficient is the vectorial sum of a free convection coefficient expressed as $U_{fr}(\Delta T)^{1/3}$, where U_{fr} is a constant and ΔT is the Fahrenheit temperature difference between the tube surface and the atmosphere, and a forced convection coefficient evaluated from $U_{fc}V^{0.8}$, where U_{fc} is a constant and V is the wind velocity. The value of U_{fr} was obtained from Reference 3-4; U_{fc} was evaluated from information supplied in Reference 3-3.

Table 3-6. Receiver Superpanel Model Equations

Condition 1 - Receiver Panel Containing Subcooled Water

$$w_{f3} = w_{f2} = w_{f1}$$

$$P_{f3} = P_{f1} - \frac{g}{v_{f2}} l_{13} - F_{f2} v_{f2} w_{f2}^2$$

$$Q_{f2} = U_{f2} S l_{13} (T_{m2} - T_{f2})$$

$$Q_{m2} = Q_{am2} - Q_{em2} - Q_{cm2}$$

$$Q_{em2} = \sigma \epsilon_m W l_{13} (T_{m2}^4 - T_{amb}^4)$$

$$Q_{cm2} = U_{m2} W l_{13} (T_{m2} - T_{amb})$$

$$l_{13} = l_{17}$$

$$\frac{du_{f2}}{dt} = \frac{v_{f2}}{l_{13} A} [w_{f2} (h_{f1} - h_{f3}) + Q_{f2}]$$

$$\frac{dh_{f3}}{dt} = \frac{v_{f2}}{l_{13} A} [2w_{f2} (h_{f2} - h_{f3}) + Q_{f2}]$$

$$\frac{dT_{m2}}{dt} = \frac{Q_{m2} - Q_{f2}}{C_m l_{13}}$$

Condition 2 - Receiver Panel Containing Subcooled Water and Saturated Two-Phase Mixture

$$w_{f5} = w_{f4} = w_{f3}$$

$$P_{f3} = \text{equation for condition 1}$$

Table 3-6. Receiver Superpanel Model Equations (Continued)

$$P_{f5} = P_{f3} - \frac{g}{v_{f4}} l_{35} - F_{f4} v_{f4} w_{f4}$$

$$Q_{f2} = \text{equation for condition 1}$$

$$Q_{m2}, Q_{em2}, Q_{cm2} = \text{equations for condition 1}$$

$$Q_{f4} = U_{f4} S l_{35} (T_{m4} - T_{f4})$$

$$Q_{m4} = Q_{am4} - Q_{em4} - Q_{cm4}$$

$$Q_{em4} = \sigma \epsilon_m W l_{35} (T_{m4}^4 - T_{amb}^4)$$

$$Q_{cm4} = U_{m4} W l_{35} (T_{m4} - T_{amb})$$

$$h_{f3} = h_{fsat}$$

$$h_{f5} = h_{f3} + \frac{Q_{f4}}{w_{f4}}$$

$$l_{35} = l_{17} - l_{13}$$

$$l_{15} = l_{17}$$

$$\frac{dT_{m2}}{dt} = \frac{Q_{m2} - Q_{f2}}{C_m l_{13}} + \frac{(T_{m4} - T_{m2})}{l_{15}} \frac{dl_{13}}{dt}$$

$$\frac{dT_{m4}}{dt} = \frac{Q_{m4} - Q_{f4}}{C_m l_{35}} + \frac{(T_{m4} - T_{m2})}{l_{15}} \frac{dl_{13}}{dt}$$

$$\frac{dl_{13}}{dt} = - \frac{v_{f3}}{A} \frac{[w_{f2}(h_{f1} - h_{f3}) + Q_{f2}]}{(h_{f3} - u_{f2})}$$

Condition 3 - Receiver Panel Containing Subcooled Water, Saturated Two-Phase Mixture, and Superheated Steam

$$w_{f7} = w_{f6} = w_{f5}$$

$$P_{f3} = \text{equation for condition 1}$$

Table 3-6. Receiver Superpanel Model Equations (Continued)

P_{f5} = equation for condition 2

$$P_{f7} = P_{f5} - \frac{g}{v_{f6}} \ell_{57} - F_{f6} v_{f6} w_{f6}^2$$

Q_{f2} = equation for condition 1

Q_{m2}, Q_{em2}, Q_{cm2} = equations for condition 1

$$Q_{f4} = w_{f4}(h_{f5} - h_{f3})$$

Q_{m4}, Q_{em4}, Q_{cm4} = equations for condition 2

$$Q_{f6} = U_{f6} S \ell_{57} (T_{m6} - T_{f6})$$

$$Q_{m6} = Q_{am6} - Q_{em6} - Q_{cm6}$$

$$Q_{em6} = \sigma \epsilon_m W \ell_{57} (T_{m6}^4 - T_{amb}^4)$$

$$Q_{cm6} = U_{m6} W \ell_{57} (T_{m6} - T_{amb})$$

$$h_{f3} = h_{fsat}$$

$$h_{f5} = h_{vsat}$$

$$h_{f7} = h_{f5} + Q_{f6}/w_{f6}$$

$$\ell_{35} = \frac{Q_{f4}}{v_{f4} S (T_{m4} - T_{f4})}$$

$$\ell_{15} = \ell_{13} + \ell_{35}$$

$$\ell_{57} = \ell_{17} - \ell_{15}$$

$$\frac{dT_{m2}}{dt} = \text{equation for condition 2}$$

Table 3-6. Receiver Superpanel Model Equations (Continued)

$$\frac{dT_{m4}}{dt} = \frac{Q_{m4} - Q_{f4}}{C_m \ell_{35}} + \frac{(T_{m4} - T_{m2})}{\ell_{15}} \frac{d\ell_{13}}{dt}$$

$$\frac{dT_{m6}}{dt} = \frac{Q_{m6} - Q_{f6}}{C_m \ell_{57}}$$

$$\frac{d\ell_{13}}{dt} = \text{equation for condition 2}$$

Nomenclature

- Parameters

A = cross-sectional area

C_m = panel heat capacity per unit length

F = steady-state flow coefficient

g = local acceleration due to gravity

h = specific enthalpy

ℓ = length

L = valve stem position

P = pressure

Q = rate of heat transfer

S = surface area per unit length

T = temperature

u = specific internal energy

U = heat transfer coefficient

v = specific volume

Table 3-6. Receiver Superpanel Model Equations (Continued)

V = velocity or volume
 w = mass flow rate
 W = width
 α = % total system pressure drop across a valve
 ϵ = emissivity
 σ = Stefan-Boltzmann constant

• Subscripts

am = absorbed by metal
 amb = ambient
 bs = boiler superpanel
 cm = convected from metal
 em = emitted from metal
 f = fluid
 fw = feedwater
 m = metal
 ps = preheater superpanel
 sh = steam header
 v = valve
 1 = inlet properties
 2 = average subcooled properties
 3 = saturated liquid boundary
 4 = average saturated properties
 5 = saturated vapor boundary
 6 = average superheated properties
 7 = outlet properties

The steady-state flow coefficients used in the momentum equations were evaluated from the values of the process variables (e.g., pressure, specific volume, length, etc.) for each fluid control volume at the receiver subsystem's rated design conditions.

A receiver superpanel model solution diagram indicating the input and output variables is given in Figure 3-10.

3.3.3.1.2 Receiver Flow Control Valve Model

The receiver flow control valve is a pneumatic modulating throttle valve. The actuator of the valve is a double-acting piston type, which, in combination with the linear positioner and the relatively high feed-water pressure level, provides fast response to maintain steady-state fixed positions. The position of the valve is controlled by electrical position-command signals from the temperature controller.

Because the valve is fast acting, the dynamics associated with its actuator were not modeled. In other words, it is assumed that the valve responds instantaneously to temperature controller command signals.

Although valve design data are not available, it is assumed that the valve possesses an equal-percentage or parabolic flow characteristic, i.e., for a constant pressure drop across the valve, flow rate is roughly proportional to the square root of steam travel. If the pressure drop used to calculate the valve's flow rate is not measured directly across the valve, but rather at upstream or downstream piping locations, the flow characteristic of the valve plus the piping can be expressed by

$$w = \frac{L^2}{[\alpha + (1-\alpha)L^4]^{1/2}} w_{\max} \quad (3-1)$$

where L , α , and w are defined in Table 3-6.

Figure 3-10. Receiver Superpanel Solution Diagram

The two expressions, subject to the assumptions in Section 3.3.3.1, modeling the flow control valve, are given by

$$w_v = \left\{ \frac{\alpha L_v^4}{[\alpha + (1-\alpha)L_v^4]} \frac{\Delta P_s}{v_v F_v} \right\}^{1/2} \quad (3-2)$$

and

$$\Delta P_v = F_v v_v w_v^2 / L_v^4 \quad (3-3)$$

where ΔP_s is the system pressure drop, ΔP_v is the valve pressure drop, and the remaining parameters are defined according to Table 3-6.

The valve model is given the receiver subsystem inlet and outlet pressures, the last preheater's outlet pressure and enthalpy, and the valve position. The valve's inlet specific volume is determined from thermodynamic state relations. With this information, the valve model outputs an unchanged enthalpy (an adiabatic valve is assumed), a pressure, and the flow rate. Figure 3-7 illustrates this process with a solution diagram.

3.3.3.1.3 Receiver Steam Header Model

The receiver steam header accumulates all individual boiler panel flows at the top of the tower downcomer. This mixing process not only serves to join individual panel flows, but also minimizes any individual panel output variations, thus stabilizing receiver output. The model for the steam header assumes the steam header is adiabatic, the state of matter within the control volume is uniform at any instant of time, and potential energy effects are negligible. The resulting model equations are

$$\frac{d}{dt} v_{sh} = - \frac{v_{sh}^2}{V_{sh}} \left[(\Sigma w_{bs}) - w_{sh} \right] \quad (3-4)$$

$$\frac{d}{dt}u_{sh} = \frac{v_{sh}}{V_{sh}} \left[\sum w_{bs}(h_{bs} - u_{sh}) \right] - w_{sh}(h_{sh} - u_{sh}) \quad (3-5)$$

The equations' parameters are defined in Table 3-6. Additional properties such as P_{sh} , T_{sh} , and h_{sh} are found from the thermodynamic state relations with v_{sh} and u_{sh} as inputs.

A simplified solution diagram of the steam header model is illustrated as part of Figure 3-7.

3.3.3.2 Receiver Temperature Controller Model

The receiver temperature controller model strives to maintain the receiver superpanel outlet temperature at a selected set-point value by commanding the position of the inlet flow control valve. The control logic proposed by MDAC could not be implemented due to the unavailability of the controller gain constants. Therefore, a simple proportional-and-integral controller (Figure 3-11) was implemented in the simulation.

The set of equations used to model the temperature controller is shown in Table 3-7.

NOTE: Nomenclature is
defined in Table 3-7.

Figure 3-11. Receiver Temperature Controller Block Diagram

Table 3-7. Temperature Controller Model Equations

Equations

$$e_T = T_{bs} - T_{sp}$$

$$L_p = K_p e_T$$

$$\frac{d}{dt} L_i = K_i e_T$$

$$L = L_p + L_i$$

Nomenclature

e_T = Temperature error

K_i = Integral gain constant

K_p = Proportional gain constant

L_i = Integral valve position command signal

L_p = Proportional valve position command signal

L = Commanded valve position

T_{bs} = Boiler superpanel outlet temperature

T_{sp} = Temperature set point

3.4

THERMAL STORAGE SUBSYSTEM MODULE

3.4.1

Introduction

The Thermal Storage Subsystem performs two active functions and the passive function of maintaining a supply of energy in storage. The charging function accepts superheated steam as an input to the subsystem, extracts energy from that steam, and stores the energy. The extraction function responds to a request for superheated steam by extracting energy from storage and adding it to water to produce the requested flow of steam. Figure 3-12 represents the basic parts of the subsystem in block diagram form. Tables 3-8 and 3-9 list the variables and the constants that are involved in this part of the simulation.

3.4.2

Charging Function

In the charging function, the incoming steam is passed through a desuperheater to cool it to the desired temperature for operation of the heat exchanger. The desuperheater adds water to the steam to produce an increased flow with a reduced specific enthalpy. In the simulation, it is assumed that there is no pressure drop for the steam through the desuperheater and that there are no heat losses in the desuperheater. Thus, the mass flow rate of the output steam is the sum of the mass flow rates of the input steam and the water, and the enthalpy flow rate of the output steam is the sum of the enthalpy flow rates of the input steam and the water. The water flow is controlled to maintain a constant output steam temperature. This control is sufficiently tight that its dynamics are neglected.

The above assumptions result in the following set of equations for the desuperheater:

$$W_3 = K_{DSH} W_1 \quad (3-6)$$

$$K_{DSH} = (H_1 - H_2)/(H_3 - H_2) \quad (3-7)$$

$$W_2 = W_3 - W_1 \quad (3-8)$$

Figure 3-12. Thermal Storage Subsystem

Table 3-8. Thermal Storage Subsystem Variables

Symbol		Description	Units	I/O
Equation	Program			
F_C F_E	TCONC	Number of charging pumps operating in last time interval	Dimensionless	
	TCONE	Number of extraction pumps operating in last time interval	Dimensionless	
	TFC	Fraction of maximum charging oil flow	Dimensionless	
	TFE	Fraction of maximum extraction oil flow	Dimensionless	
	TFLAGL	2 is normal, 0 cuts off extraction, 1 warns of depletion and prevents start of extraction		
	TFLAGU	2 is normal, 0 cuts off charging, 1 warns of overcharging and prevents start of charging		O
H_1	TH1	Enthalpy of steam into desuperheater	Btu/lbm	I
H_2	TH2	Enthalpy of water into desuperheater	Btu/lbm	I
H_3	TH3	Enthalpy of steam from desuperheater	Btu/lbm	
H_4	TH4	Enthalpy of water from storage heater	Btu/lbm	
H_9	TH9	Enthalpy of water into steam generator	Btu/lbm	I
H_{TSU}	THTSU	Heat stored in thermal storage unit	Btu	
K_1	TK1	Y intercept of charging pump power curve	W	

Table 3-8. Thermal Storage Subsystem Variables (Continued)

Symbol		Description	Units	I/O
Equation	Program			
K_2	TK2	Slope of charging pump power curve	W/lbm/sec	
K_3	TK3	Y intercept of extraction pump power curve	W	
K_4	TK4	Slope of extraction pump power curve	W/lbm/sec	
K_{DSH}	TKDSH	Flow rate gain factor of desuperheater (reciprocal of specific enthalpy loss factor)	Dimensionless	
K_{SG}	TKSG	Ratio of specific enthalpy gain of water to specific enthalpy loss of oil in steam generator	Dimensionless	
K_{TSH}	TKTSH	Ratio of specific enthalpy gain of oil to specific enthalpy loss of steam in thermal storage heater	Dimensionless	
L_T	TLT	Fractional position of thermocline	Dimensionless	O
P_1	TP1	Pressure of steam into desuperheater, and pressure of desuperheated steam	psia	I
P_4	TP ₄	Pressure of water from storage heater	psia	O
P_{PC}	TPPC	Charging oil pumping power	W	
P_{PE}	TPPE	Extraction oil pumping power	W	
P_{PT}	TPPT	Total subsystem pumping power	W	O
W_1	TW1	Steam flow available to desuperheater	lbm/sec	I

Table 3-8. Thermal Storage Subsystem Variables (Continued)

Symbol		Description	Units	I/O *
Equation	Program			
W_{1A}	TW1A	Actual steam flow to desuperheater	lbm/sec	O
W_{1M}	TW1M	Maximum steam flow to desuperheater	lbm/sec	
W_2	TW2	Water flow to desuperheater	lbm/sec	
W_3	TW3	Steam flow from desuperheater	lbm/sec	
W_5	TW5	Nominal oil flow into storage	lbm/sec	
W_{5A}	TW5A	Actual oil flow into storage	lbm/sec	
W_7	TW7	Nominal oil flow from storage	lbm/sec	
W_{7A}	TW7A	Actual oil flow from storage	lbm/sec	O
W_8	TW8	Steam flow from steam generator	lbm/sec	
W_E	TWE	Requested steam flow from steam generator	lbm/sec	

*I = Input to subsystem simulation
O = Output of subsystem simulation

Table 3-9. Thermal Storage Subsystem Constants

Symbol		Description	Units	Default Value
Equation	Program			
C ₅ C ₆	TAK1	TK1 for one pump at low speed	W	0.07
	TAK2	TK2 for one pump at low speed	W/lbm/sec	0.22
	TAK3	TK3 for one pump	W	0.28
	TAK4	TK4 for one pump	W/lbm/sec	0.4
	TBK1	TK1 for two pumps at low speed	W	0.13
	TBK2	TK2 for two pumps at low speed	W/lbm/sec	0.22
	TBK3	TK3 for two pumps	W	0.4
	TBK4	TK4 for two pumps	W/lbm/sec	0.6
	TC5	Heat capacity of oil into storage	Btu/lbm °F	*
	TC6	Heat capacity of oil from storage	Btu/lbm °F	*
	TCK1	TK1 for one pump at high speed	W	0.28
	TCK2	TK2 for one pump at high speed	W/lbm/sec	0.38
	TDK1	TK1 for two pumps at high speed	W	0.40
	TDK2	TK2 for two pumps at high speed	W/lbm/sec	0.60
H ₈	TH8	Enthalpy of steam from steam generator	Btu/lbm	*

* Calculated by program from other constants

Table 3-9. Thermal Storage Subsystem Constants (Continued)

Symbol		Description	Units	Default Value
Equation	Program			
$H_{T\SUM}$	THTSUM	Capacity of thermal storage unit	Btu	455.6×10^6
K_5	TK5	Heat loss from storage unit with thermocline at top	Btu/sec	100
K_6	TK6	Additional heat loss from storage unit with thermocline at bottom	Btu/sec	100
K_G	TKG	Gain of extraction control system	Dimensionless	12
K_{HC}	TKHC	Specific enthalpy gain of oil in thermal storage heater or loss in steam generator	Btu/lbm	*
K_{TMT}	TKTMTSH	Time constant of thermal storage heater	sec	200
K_{TMS}	TKTMSG	Time constant of steam generator	sec	200
K_{TME}	TKTMECS	Time constant of extraction control system (Response of oil flow to error in output steam flow)	sec	5
	TLTL1	TFLAGL=0 when $TLT < TLTL1$, 1 or 2 when $TLT \geq TLTL1$		0.05
	TLTL2	TFLAGL=2 when $TLT > TLTL2$, 1 or 2 when $TLT \leq TLTL2$		0.0502
	TLTU1	TFLAGU=0 when $TLT > TLTU1$, 1 or 2 when $TLT \leq TLTU1$		0.985
	TLTU2	TFLAGU=2 when $TLT < TLTU2$, 1 or 2 $TLT \geq TLTU2$		0.9848

* Calculated by program from other constants

Table 3-9. Thermal Storage Subsystem Constants (Continued)

Symbol		Description	Units	Default Value
Equation	Program			
P_8	TP8	Pressure of steam from steam generator	psia	400
P_{DT}	TPDTSH	Pressure drop through thermal storage heater	psia	65
	TPL1	Upper limit of TFC for one pump, low speed	Dimensionless	0.2
	TPL2	Lower limit of TFC for two pumps, high speed	Dimensionless	0.66
	TPL3	Lower limit of TFE for two pumps	Dimensionless	0.2
P_{PA}	TPPA	Auxiliary pumping power	W	7460
P_{PCM}	TPPCM	Maximum charging oil pumping power	W	119360
P_{PEM}	TPPEM	Maximum extraction oil pumping power	W	104440
T_3	TT3	Temperature of desuperheated steam	°F	650
T_4	TT4	Temperature of water from storage heater	°F	475
T_5	TT5	Temperature of oil from storage heater	°F	575
T_6	TT6	Temperature of oil into storage heater	°F	425
T_8	TT8	Temperature of steam from steam generator	°F	530
	TTSC	0 for hot start charge, 1 for steady state		1
	TTSE	0 for hot start extraction, 1 for steady state		1

Table 3-9. Thermal Storage Subsystem Constants (Continued)

Symbol		Description	Units	Default Value
Equation	Program			
W_{5M}	TW5M	Maximum oil flow into storage	lbm/sec	282
W_{5MF}	TW5MF	Minimum non-zero oil flow into storage	lbm/sec	14.1
W_{7M}	TW7M	Maximum oil flow from storage	lbm/sec	310
W_{7MF}	TW7MF	Minimum non-zero oil flow from storage	lbm/sec	15.5

where W_1 and H_1 are the input steam mass flow rate and specific enthalpy, W_2 and H_2 are the input water mass flow rate and specific enthalpy, and W_3 and H_3 are the output steam mass flow rate and specific enthalpy. W_1 , H_1 , H_2 , and the input steam pressure, P_1 , are provided as inputs to the Thermal Storage Subsystem (TSS) from the Electric Power Generating Subsystem (EPGS). Since the output temperature T_3 is held constant and there is no pressure drop, H_3 is calculated from T_3 and P_1 by use of subroutine ALENT. Then the equations are used to calculate W_3 and W_2 as outputs of the desuperheater simulation.

The thermal storage heater is a counterflow heat exchanger that transfers thermal energy from the desuperheated steam to the oil of the thermal storage unit. It is assumed that the output oil from the heat exchanger is kept at a constant temperature, T_5 , by controlling its flow through the heat exchanger. After the thermocline in the storage unit has been established, it is assumed that the input oil to the heat exchanger is also at a constant temperature, T_6 . Assuming a constant heat exchanger effectiveness over the range of operation, the temperature, T_4 , of the output condensate from the steam is also constant. Also, it is assumed that within the range of variation of the steam pressure, P_1 , the pressure drop P_{DT} through the heat exchanger is constant.

If the pressure effects in the liquid oil (Caloria HT43) are neglected, the specific enthalpy gain, K_{HC} , of the oil is simply the average heat capacity times the temperature gain. The data show that the heat capacity of the oil varies linearly with temperature. Thus, the linear average of the heat capacities, C_6 and C_5 , at the input and output oil temperatures may be used:

$$K_{HC} = 0.5(C_5 + C_6)(T_5 - T_6) \quad (3-9)$$

If heat losses are neglected, the ratio of the mass flows of the oil and the steam/water is the reciprocal of the ratio K_{TSH} of the specific enthalpy changes, where

$$K_{TSH} = (H_3 - H_4)/K_{HC} \quad (3-10)$$

The value of H_4 is computed from T_4 and $P_4 = P_1 - P_{DT}$ by use of A1ENTH. The thermal inertia involved in heating the tubes of the heat exchanger is characterized in the simulation as a first-order time lag with a time constant, K_{TMT} . The resulting differential equation for the oil mass flow is

$$\dot{W}_5 = (K_{TSH} W_3 - W_5)/K_{TMT} \quad (3-11)$$

After calculating the flow of oil into the storage unit, the simulation calculates the electric power, P_{PC} , that is used to pump the oil. There are two two-speed pumps, each of which pumps oil through one of two heat exchangers. The power consumption curves are approximated by straight-line segments in the different oil flow regions, as shown in Figure 3-13. The equations are

$$P_{PC} = P_{PCM}(K_1 + K_2 F_C) \quad (3-12)$$

$$F_C = W_5/W_{5M} \quad (3-13)$$

where P_{PCM} is the maximum pump power for both pumps at high speed, and K_1 and K_2 take on different values in the different regions. The values in the hysteresis region, from P_{L1} to 0.5, depend on whether one or two pumps were operating in the previous time period (flag TCONC equals 1 or 2). There is also a threshold, based on the turn-down ratio of the heat exchanger, below which no oil will be pumped. In the simulation, it is assumed that sub-threshold levels of heat in the heat exchanger have no effect on the system.

W_{5M} is the maximum value of W_5 .

Figure 3-13. Charging Pump Power vs. Flow Rate

3.4.3

Extraction Function

In simulating extraction, it is assumed that the temperature and pressure of the output steam are held constant. Therefore, the request is simply for a flow rate, W_E . In response to the request, an error signal is generated that is equal to the difference between W_E and the actual flow rate, W_8 . The error signal, multiplied by the control system gain, K_G , is used to request a change in the extraction oil flow, W_7 , from the value that would produce W_8 in a steady-state condition. The response to this request has a first-order lag with a time constant, K_{TME} , representing a linearized valve function. The resulting differential equation for oil flow is

$$\dot{W}_7 = [(W_8/K_{SG}) + K_G(W_E - W_8) - W_7]/K_{TME} \quad (3-14)$$

$$K_{SG} = K_{HC}/(H_8 - H_9) \quad (3-15)$$

where H_8 and H_9 are the specific enthalpies of the output steam and the input water to the steam generator. H_9 is an input to TSS, and H_8 is a constant that is calculated once from the controlled output temperature, T_8 , and pressure, P_8 , by use of A1ENTH. The value of W_7 that results from the equation is limited so that it will always lie between zero and the maximum allowable flow, W_{7M} .

The oil flow produced by the extraction control system in turn produces a flow of steam from the steam generator. The steam generator is characterized as a unit that has a first-order lag with a time constant K_{TMS} . K_{SG} plays the same role as K_{TSH} in the thermal storage heater.

$$\dot{W}_8 = (K_{SG}W_7 - W_8)/K_{TMS} \quad (3-16)$$

The extraction system has two single-speed pumps, one for each of two steam generators. The electric power, P_{PE} , to pump the oil is approximated by straight line functions as for the charging function. The equation is

$$P_{PE} = P_{PEM}(K_3 + K_4 F_E) \quad (3-17)$$

$$F_E = W_7 / W_{7M} \quad (3-18)$$

where P_{PEM} is the maximum pump power for both pumps, and K_3 and K_4 take on different values in the different regions. The values in the hysteresis region, from P_{L3} to 0.5, depend on whether one or two pumps were operating in the previous time period (flag TCONE equals 1 or 2). There is a lower threshold for pumping just as in the charging function.

3.4.4 Storage Function

The net oil flow, $W_5 - W_7$, that is pumped through the storage unit produces a rate of increase or decrease of the heat content, H_{TSU} , of the storage unit. Losses to the outside of the tank provide an additional rate of decrease of the heat content. It is assumed that the total rate of heat loss consists of a constant, K_5 , equal to the loss with the thermocline at the top of the tank, plus a second constant, K_6 , times the fractional position, L_T , of the thermocline from the top toward the bottom. The second constant is the additional loss that would occur with the thermocline at the bottom of the tank. The storage differential equation is

$$\dot{H}_{TSU} = K_{HC}(W_5 - W_7) - K_5 - K_6 L_T \quad (3-19)$$

$$L_T = H_{TSU} / H_{TSUM} \quad (3-20)$$

where H_{TSUM} is the total capacity of the storage tank. The initial value of L_T is an input to the program, and the initial value of H_{TSU} is calculated from it. Subsequent values of L_T are provided as outputs of the TSS.

3.4.5 Ancillary Functions

There are ancillary pumps, assumed to be in constant operation, which consume P_{PA} watts of electric power. The total pumping power, P_{PT} , is given by

$$P_{PT} = P_{PC} + P_{PE} + P_{PA} \quad (3-21)$$

There are also limiting functions in the TSS. The input steam flow rate, W_1 , is limited to be no more than the value W_{1M} that would produce the maximum charging oil flow rate, W_{5M} , in a steady state. The limited value of W_1 is W_{1A} . In using the program, if more steam is sent to the TSS than it can handle, a discrepancy will exist. No such discrepancy can exist in extraction. The TSS produces steam only to its maximum capability, no matter what amount is requested.

There are also limits associated with the position of the thermocline. If overcharging or depletion of the storage unit is threatened, a warning occurs at one limit and a cutoff of charging or extraction occurs at a further limit. Specifically, when $L_T \geq L_{TU2}$, overcharge warning occurs ($TFLAGU = 1$). When $L_T > L_{TU1}$, $TFLAGU = 0$ and W_{1A} is set to zero. When charging is cut off, it cannot be restarted until $L_T < L_{TU2}$ ($TFLAGU = 2$). Similarly, when $L_T \leq L_{TL2}$, depletion warning occurs ($TFLAGL = 1$). When $L_T < L_{TL1}$, $TFLAGL = 0$ and W_E is set to zero. When extraction is cut off, it cannot be restarted until $L_T > L_{TL2}$ ($TFLAGL = 2$). The charging limits should be set so that when charging is cut off, the residual heat in the thermal storage heater will not produce overcharge. Also, the depletion limits should be set so that the storage unit can be in a "hold" status for a reasonable time after extraction cutoff without being fully depleted.

3.5 ELECTRICAL POWER GENERATION SUBSYSTEM (EPGS) MODULE

3.5.1 Model Description

The EPGS portion of the STMPPS dynamic simulation program is schematically shown in Figure 3-14, and consists of the following components:

- Turbine/Generator
- EPGS Feedwater Auxiliaries
 - Condenser/Condensate Receiver (Hotwell)
 - Condensate Pump
 - Low-Pressure Heaters (2)
 - Deaerator/Deaerator Surge Tank
 - Receiver Feed Pump
 - Associated Controls and Piping
- Receiver Drain System
 - Start-Up Flash Tank
 - Associated Controls and Piping
- Thermal Storage Heater Drain System
 - Drain Tank
 - Flash Tank (2)
 - Associated Controls and Piping
- Master Control Interface
 - Flow control valves
 - Turbine extraction valves.

The EPGS model also includes piping losses between the EPGS and other subsystems where significant piping distances are involved. In particular, tower riser and downcomer losses are contained in the model. A component approach was taken in developing the EPGS model. Each component of the system was modeled separately, with the final EPGS model being the logical

Figure 3-14. EPGS Thermal Component

interconnection of the components. Although the "plumbing" is more difficult, this method facilitates component modifications by increasing or decreasing the component detail, or by removal or replacement of components.

The description of the EPGS model is organized into five major discussion areas:

- Turbine/Generator
- EPGS Feedwater System
- Auxiliary Drain Systems
- Master Controller Interface
- Miscellaneous.

Turbine/Generator

The EPGS centers around the Turbine/Generator System, whose function is to convert thermal energy to electrical energy. The 15 MW_e General Electric Company automatic admission turbine/generator was selected as the baseline for the EPGS model. The turbine is a non-reheat, condensing, 3600 rpm-type turbine with four extraction ports for regenerative feedwater heating. Data are available on this turbine/generator from the preliminary designs of MDAC (Reference 3-2) and Honeywell (abbreviated HNWL) (Reference 3-6); from the recent work conducted by SCE (Reference 3-7); and from G.E. (Reference 3-8).

Since the dynamic response of the turbine/generator is several orders of magnitude faster than other expected transient effects, a thermodynamic quasi-steady-state model was developed for the turbine/generator. The turbine is characterized by two expansion lines (see Figure 2-16, Reference 3-2), one for main throttle steam and one for admission steam. Each characteristic is described in terms of enthalpy and pressure, as shown in Figure 3-15 for main throttle steam. A composite turbine characteristic is obtained by using a weighted average of these two expansion lines based on flow rates. The steady-state data from References 3-6, 3-7 and 3-8 were examined, and each of the extraction pressures was found to vary linearly with the apparent

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Figure 3-15. Turbine Expansion Characteristic, Main Throttle

flow (main throttle plus admission) through the low-pressure section of the turbine (see Figure 3-16). This model of extraction pressures as a function of flow and the expansion characteristic allows the determination of the state (pressure, temperature, enthalpy) of the turbine at each extraction port and at the exhaust port for every flow condition.

The generator is modeled empirically and based upon steady-state data. The gross generator output is a linear function of the net heat flow through the turbine.

Turbine/generator performance varies as a function of back pressure. The back pressure (turbine exhaust pressure) is determined by the exhaust steam flow and ambient air temperature, using empirical condenser/heat rejection characteristics obtained from References 3-2 and 3-6.

EPGS Feedwater System

The Feedwater System consists of a condensate collection system and a feedwater supply system. The collection system condenses the turbine exhaust steam and delivers water from the condenser hotwell to the deaerator through the low-pressure feedwater heaters No. 4 and No. 5. The feedwater supply system functions are to (a) pump feedwater from the deaerator storage tank to the receiver and the thermal storage unit, (b) provide regenerative feedwater heating, and (c) provide water to the thermal storage desuperheater.

The following description of the Feedwater System components begins with the condenser/hotwell and progresses from this low-pressure device to the high-pressure heaters and finally the receiver feed pump.

- Condenser/Hotwell. The condenser itself is modeled using the first law of thermodynamics; i. e., the difference between the incoming and outgoing heat flows is the heat rejected. The condenser pressure, a function of design, turbine exhaust flow and the ambient temperature, is modeled empirically (References 3-2 and 3-6). The hotwell is modeled as an open tank with a mean residence time of five minutes. Two ordinary first-order differential equations are used, one for the rate of change of mass in the tank and one for the rate of change of enthalpy of the fluid in the tank.

- Condensate Pump. An isentropic model is employed which relates the enthalpy change to the increase in head. The pump is modeled as a single-speed pump whose head is a function of flow rate. The auxiliary power required to run the pump is the pump work (flow $\times$ change in enthalpy) divided by the efficiency.
- Low-Pressure Heaters. The closed heater model uses the design terminal temperature difference and the first law of thermodynamics. The assumption is made that thermal storage effects are small and a quasi-steady-state model is used.
- Deaerator/Surge Tank. The deaerator model is based entirely upon the first law. The surge tank is modeled as an open tank with five minutes of surge capability. Two ordinary first-order differential equations, one for mass and one for enthalpy, are used to model the water in the tank.
- High-Pressure Heaters. These are modeled the same as the low-pressure heaters.

The feedwater supply to the receiver consists of a variable speed pump, a feedback control system which maintains receiver inlet pressure, and a feedwater pipe. The variable speed pump is modeled by use of a first-order differential equation which relates pump acceleration and load torque. Pump head and torque are computed functions of speed and flow rate. The control system is modeled as a proportional controller. The feedwater pipe model includes a pressure drop due to frictional losses, convective heat losses to the environment, enthalpy drop due to changes in potential energy, and an enthalpy transport delay equation. The delay equation relates the rate of change of the exit enthalpy to the total enthalpy drop and the heat losses.

Figure 3-16. Extraction Pressure Data (H)

The feedwater supply model to the desuperheater uses the output state of the receiver feedpump and a supply pipe. The supply pipe model contains a frictional pressure drop, convective heat losses, and an enthalpy transport delay equation.

The feedwater supply model to the steam generator uses the output state of the feedwater boost pump and a supply pipe. The boost pump is modeled as a single-speed pump whose head is a function of flow rate. The pipe model accounts for frictional pressure drop, convective heat losses, and enthalpy transport delay.

Auxiliary Drain Systems

The Auxiliary Drain Systems consist of a receiver start-up flash tank (tank No. 3) and the thermal storage heater drain system. The function of the receiver start-up flash tank is to provide a means of establishing flow through the receiver during the start-up mode before generation of rated steam conditions. The function of the thermal storage heater drain system is to distribute flashed steam to the feedwater heaters and to distribute the remaining condensate to the feedwater system. The flash tank is modeled based on the first law of thermodynamics (under steady flow conditions), which yields an equation giving the percent of incoming fluid flashed to steam. Condensate collection is modeled as an open tank by use of two first-order ordinary differential equations, one for mass and one for enthalpy. A proportional level controller, which relates the condensate output flow to the rate of mass in the tank, was modeled for tank No. 2 and tank No. 3.

The TSS drain control system is used to proportion the condensate output from tank No. 2 to the condenser and heaters No. 3 and No. 5. The

proportions are a function of operating mode and were calculated from steady-state data contained in Reference 3-7. The receiver drain control system currently has all condensate output going to heater No. 3.

Master Controller Interface

The purpose of the Master Controller Interface is to calculate actual valve positions using master control-supplied valve set points and a dynamic valve model. The dynamic model uses an S-shaped characteristic that relates percent change in valve position to change in time.

Two types of valves are modeled: a flow distribution type (R1-R4, and T1-T2), and an extraction type. The flow distribution valves are operated in valve pairs ((R1, R2), (R3, R4), (T1, T2)) and proportion the flow through the valves by use of a relative weighting of the actual positions. The extraction valve position is calculated in terms of the percent flow extracted from the total turbine input steam flow.

Miscellaneous

The receiver downcomer model accounts for frictional pressure drop, convective heat losses, enthalpy rise due to change in potential, and enthalpy transport delay. The steam pipe from the TSS steam generator to the turbine admission part is modeled by frictional pressure drop, convective heat losses, and enthalpy transport delay.

3.5.2 Definition of Variables and Constants

Table 3-10 shows the program symbols (with their description and physical units) used to represent variables and constants defined in the EPGS model. The corresponding engineering symbol used in the following section of model equations is also shown in Table 3-10 for cross-reference. The last column of the table indicates the disposition of the variable; I = input to EPGS, O = output from EPGS, and blank is neither.

R

Table 3-10. Program Symbols and Descriptions (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
l	GLT2	Condensate level in tank No. 2	ft	
	GWCTC	Condensate flow to condenser from TSS drain	lbm/sec	
	GWCTH3	Condensate flow to FW heater No. 3 from TSS	lbm/sec	
	GWCTH5	Condensate flow to FW heater No. 5 from TSS	lbm/sec	
w_{LP}	GWTALP	Turbine apparent LP steam flow	lbm/sec	
w_5	GWTEXH	Turbine exhaust flow	lbm/sec	
	GPTEXH	Turbine exhaust pressure	psia	
h_5	GHTEXH	Turbine exhaust enthalpy	Btu/lbm	
w_{1-4}	GWTEXT(4)	Turbine extraction flows	lbm/sec	
	GPTEXT(4)	Turbine extraction pressures	psia	
h_{1-4}	GHTEXT(4)	Turbine extraction enthalpies	Btu/lbm	
$\dot{W}$	GTPOWER	Thermal availability	Btu/sec	
P	GEPOUT	Electrical power	MW	O
P_R	GPFPR	Recvr inlet pressure	psia	O
h_{loss}	GHLOSSR	Riser heat losses	Btu/hr	
	GTPFR	Recvr inlet temperature	°F	O
	GPOUT	Recvr feed pump output pressure	psia	
h_p	GHOUTP	Recvr feed pump output enthalpy	Btu/lbm	
P_{aux}	GFPAUX	Recvr feed pump aux power	kW	
w	GWFTP	Total recvr feed pump flow	lbm/sec	I
H	GFPH	Recvr feed pump head	ft	
T	GFPT	Recvr feed pump torque	ft/lb	

Table 3-10. Program Symbols and Descriptions (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
h_{loss} h_{loss}	GPDSI	FW pressure at desuperheater inlet	psia	O
	GIDSI	FW temperature at desuperheater inlet	°F	O
	GPCTSG	Pressure at TSS steam generator inlet	psia	O
	GTCTSG	Temperature at TSS steam generator inlet	°F	O
	GHLOSDS	Heat loss in desuperheater FW pipe	Btu/hr	
	GHLOTSG	Heat loss in TSS steam generator FW pipe	Btu/hr	
	GTAUXP	Total AUX power required by feedwater pumps	kW	O
	APBP	AUX power required by boost pump	kW	
	APHP	AUX power required by hotwell pump	kW	
	GPSH1	Pressure of steam to heater No. 1	psia	
	GPSH2	Pressure of steam to heater No. 2	psia	
	GHS1	Enthalpy of steam to heater No. 1	Btu/lbm	
	GHS2	Enthalpy of steam to heater No. 2	Btu/lbm	
	GHCH4C	Enthalpy of heater No. 4 condensate drain	Btu/lbm	
	GHCH5C	Enthalpy of heater No. 5 condensate drain	Btu/lbm	
	GHCH23	Enthalpy of heater No. 2 condensate drain	Btu/lbm	
	GHCH12	Enthalpy of heater No. 1 condensate drain	Btu/lbm	
g_i	GMVR(4)	Setting for EPGS servo-controlled values R1-R4, range is 0. to 1.0		
g_i	GMVT(2)	Setting for EPGS servo-controlled values T1 and T2, range is 0. to 1.0		
g_i	GMVE(4)	Setting for EPGS servo-controlled values E1-E4, range is 0. to 1.0		

Table 3-10. Program Symbols and Descriptions (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
t_R	VRATE(10)	Max rate for valves to move from open to close positions		
	GPSPT3	Pressure set point for tank No. 3 (recvr flash)	psia	
η	GETAT3	Sizing constant for tank No. 3 (max level divided by max output flow rate)		
ℓ	GLZT3	Nominal water level for tank No. 3	ft	
K	GKLCT3	Constant for level control in tank No. 3		
	TNOM	Nominal temp of air surrounding FW system components		
	VNOM	Nominal air velocity about FW system components (normally set to 0.0)	ft/sec	
	GPSPT1	Pressure set point for tank No. 1 (TSS drain system)	psia	
m	GMCT1	Mass of condensate in tank No. 1	psia	
	GCMODE(7, 2)	TSS drain control set points as a function of operating mode		
	GPSPT2	Pressure set point for tank No. 2 (TSS drain system)	psia	
η	GETAT2	Sizing constant for tank No. 2 (max level/ max flow)		
ℓ	GLZT2	Nominal water level in tank No. 2	ft	
K	GKLCT2	Level control gain for tank No. 2		
r_1	GRISP	Inside radius of steam pipe (TSS to EPGS)	ft	
r_2	GROSP	Outside radius of steam pipe (TSS to EPGS)	ft	
L	GLSPTIG	Length of steam pipe (TSS to EPGS)	ft	
r_1	GRIDC	Inside radius of downcomer	ft	

Table 3-10. Program Symbols and Descriptions (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
r_2	GRODC	Outside radius of downcomer	ft	I
K_c	GTC	Thermal conductivity of downcomer insulation	Btu/hr-ft -deg R	
L	GLDC	Length of downcomer	ft	
	NPORTS	Number of turbine extraction ports		
	IFAN	Cooling tower fan conditions 1 2 fans full speed 2 1 half 1 full 3 2 fans half speed		
	GPTED(4)	Extraction pressure per unit of apparent LP flow	psia	
η	GTEFF	Turbine/generator efficiency		
	GPHRD(3, 6)	Condenser pressure at GWHRD(3) and GTHRD(6)		
	GWHRD(3)	Condenser flow data at 3 different values	lbm/hr	
	GTHRD(6)	Ambient temp data at 6 different values	°F	
	GMEEFF	Electro-mechanical efficiency of recvr feed pump		
η	GKEFF	Feed pump efficiency		
K	GKGAIN	Feed pump control gain		
I	GKINERT	Feed pump moment of inertia		
P_{set}	GPFRSP	Recvr inlet pressure set point	psia	
HR	GFPHR	Feed pump rated head	ft	
ω_R	GFPSR	Feed pump rated speed	rpm	
w_R	GWFPR	Feed pump rated flow	lbm/sec	

Table 3-10. Program Symbols and Descriptions (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
T_R	GFPTR	Feed pump rated torque	ft-lb	
v_{fr}	GVFPR	Specific volume at rated conditions	ft**3/lbm	
r_1	GRIRC	Inside radius of riser	ft	
r_2	GRORC	Outside radius of riser	ft	
L	GLRC	Length of riser	ft	
r_1	GRIDS	Inside radius of FW pipe feed pump to desuperheater	ft	
r_2	GRODS	Outside radius FW pipe feed to desuperheater	ft	
L	GLDESP	Length of FW pipe feed pump to desuperheater	ft	
	GFPSP	Recvr inlet pressure set point	psia	
	GLFWP	Length of FW pipe EPGS to TSS steam generator	ft	
r_1	GRIFWP	Inner radius of FW pipe EPGS to TSS steam generator	ft	
	BPUMP(5)	Parameters for boost pump		
	HPUMP(5)	Parameters for hotwell pump		
TTD, γ , TTD _{drain}	H1PARM(3)	Parameters for heater No. 1		
↑ ↓ ↓	H2PARM(3)	Parameters for heater No. 2		
↑ ↓ ↓	H4PARM(3)	Parameters for heater No. 4		
TTD, γ , TTD _{drain}	H5PARM(3)	Parameters for heater No. 5		
m_t	GMCH3	Mass of condensate stored in heater No. 3	lbm	
m_t	GMCHW	Mass of condensate stored in condenser hotwell	lbm	
r_2	GROFWP	Outer radius of FW pipe EPGS to TSS steam generator	ft	

Table 3-10. Program Symbols and Descriptions (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
m_T	GMCT3	Condensate mass in tank No. 3 (recvr flash tank)	lbm	O
h_o	GHCOT3	Enthalpy of condensate out of tank No. 3	Btu/lbm	
w_{out}	GWCOT3	Flow of condensate out of tank No. 3	lbm/sec	
h_{dc}	GHSBDC	Enthalpy of steam at bottom of downcomer	Btu/lbm	
h_{tsg}	GHSTSG	Enthalpy of admission steam	Btu/lbm	
h_o	GHCOT1	Enthalpy of condensate out of tank No. 1	Btu/lbm	
h_o	GHCOT2	Enthalpy of condensate out of tank No. 2	Btu/lbm	
m_T	GMCT2	Mass of condensate in tank No. 2	lbm	
w_{out}	GWCOT2	Flow of condensate out of tank No. 2	lbm/sec	
w	GFPS	Recvr feed pump speed	rpm	
h_R	GHRCI	FW enthalpy at recvr inlet	Btu/lbm	O
h_d	GHDSI	FW enthalpy at desuperheater inlet	Btu/lbm	O
h_{out}	GHCOH3	FW enthalpy out of FW HRTR No. 3	Btu/lbm	O
	GHCTSG	Enthalpy at TSS steam generator inlet	Btu/lbm	
h_{sg}	GHCHW	Enthalpy of condensate in condenser hotwell	Btu/lbm	

3.5.3 Model Equations

The equations describing EPGS components are organized into the five groups discussed in the previous paragraphs.

Turbine/Generator

The turbine shaft power is calculated using the first law of thermodynamics:

$$\dot{W} = w_m h_m + w_a h_a - \sum_{i=1}^5 w_i h_i \quad (3-22)$$

where $\dot{W}$ is shaft power, w is flow rate, and h denotes enthalpy. The subscript m denotes main throttle, a is used for admission, and $i = 1, 4$ denotes the extraction ports while $i = 5$ is the turbine exhaust.

The exhaust enthalpy is computed by using a condenser map which gives back pressure as a function of exhaust flow and ambient temperature, and the turbine expansion characteristic. This is accomplished using bi-cubic spline two-dimensional interpolation on the condenser map. The current computer subroutine (IBCIEU) used to implement this technique is a member of the IMSL Library 3 (Reference 3-9), a proprietary product of IMSL, Inc., The extraction enthalpies are computed using Figure 3-16, which gives extraction pressure and the turbine expansion characteristic. The turbine characteristic (Figure 3-15 for main throttle) is composed of the weighted average (based on flow) of the main throttle curve and the admission port curve. Thus, if the admission flow is zero, the characteristic would be identical to that shown in Figure 3-15. The electrical power generated, P , is computed by multiplying $\dot{W}$ by a gross turbine/generator efficiency, i.e.,

$$P = \eta \dot{W} \quad (3-23)$$

EPGS Feedwater System

The pressure at the receiver inlet is calculated using the following equation:

$$p_R = p_1 + \frac{(H-L)}{144 v_f} - \Delta p_{\text{fric}} \quad (3-24)$$

where p_1 is the output pressure at heater No. 1, Δp_{fric} is the frictional pressure drop in the riser (see miscellaneous group), H is the head produced by the feedpump, L is the length of the riser, and v_f is the specific volume of the feedwater. The equation used for computing head is given by

$$H = H_R \left[1.3 \left(\frac{\omega}{\omega_R} \right)^2 - 0.3 \left(\frac{w}{w_R} \right)^2 \right] \quad (3-25)$$

where H_R = rated head, ω = pump speed, ω_R = rated speed, w = total pump flow, w_R = rated flow. Pump dynamics are modeled using

$$\dot{\omega} = \frac{\Delta T}{I} \quad (3-26)$$

with the change in load torque given as

$$\Delta T = \frac{\eta K (p_R - p_{set})}{\omega} \quad (3-27)$$

I denotes moment of inertia, η is the pump efficiency, p_{set} is the operating set-point for the receiver inlet pressure, and K is the control loop gain. The pump and pressure control system is shown schematically in Figure 3-17 [$P(\omega)$ is defined above as p_R]. The auxiliary power required by the pump is calculated as $P_{aux} = \frac{\omega T}{\eta}$. T is the instantaneous load torque, given by the following equation:

$$T = T_R \left(\frac{v_{fR}}{v_f} \right) \left[0.5 \left(\frac{\omega}{\omega_R} \right)^2 + \frac{5}{9} \left(\frac{\omega}{\omega_R} \right) \left(\frac{w}{w_R} \right) \right] + T_{fR} \left(\frac{w}{w_R} \right) \quad (3-28)$$

where

T_R = rated torque

v_{fR} = specific volume at rated conditions

T_{fR} = frictional torque.

The enthalpy at the receiver inlet is calculated with the following transport delay equation:

$$\dot{h}_R = \frac{2}{m_R} \left[w_{REC} (h_p - h_R) + \frac{w_{REC} L}{778} - \frac{h_{loss}}{3600} \right] \quad (3-29)$$

where h_R = feedwater enthalpy at the receiver inlet, h_p = feedwater at the feed pump, w_{REC} is the receiver flow rate, h_{loss} is the riser heat loss (Btu/hr) to the environment (see miscellaneous group), and m_R is the mass in the riser.

Figure 3-17. Feedpump Control Loop

The pressure and enthalpy of the feedwater at the desuperheater water inlet are given by

$$p_d = \frac{H}{144 v_f} - \Delta p_{\text{fric}} \quad (3-30)$$

$$\dot{h}_d = \frac{2}{m_d} \left[w_d (h_p - h_d) - \frac{h_{\text{loss}}}{3600} \right] \quad (3-31)$$

where p_d and h_d are the pressure and enthalpy, m_d is the fluid mass in the desuperheater feedwater pipe.

The pressure and enthalpy of the feedwater at the steam generator inlet are given by

$$p_{sg} = \frac{H_{\text{BOOST}}}{144 v_f} - \Delta p_{\text{fric}} \quad (3-32)$$

$$\dot{h}_{sg} = \frac{2}{m_{sg}} \left[w_{sg} (h_{\text{BOOST}} - h_{sg}) - \frac{h_{\text{loss}}}{3600} \right] \quad (3-33)$$

where p_{sg} and h_{sg} are pressure and enthalpy, H_{BOOST} and h_{BOOST} are head and enthalpy at the boost pump, and m_{sg} is the fluid mass in the supply pipe.

The boost pump and the hotwell pump are modeled as single speed pumps. The head, torque, and auxiliary power equations are identical to those used to model the receiver fuel pump with the exception that $(\omega/\omega_R) = 1.0$.

The regenerative feedwater heating system is modeled on an input/output basis. The system inputs, whose thermodynamic states are known, are the heating fluids (extraction steam and condensate from the thermal storage drain system) and the feedwater being collected in the condenser hotwell. The primary system outputs, whose thermodynamic states are calculated, are the feedwater flows out of heater No. 1 and heater No. 3. The feedwater flow rates out of heaters No. 1 and No. 3 are calculated externally and considered as input quantities to the system model.

The modeling is performed at the component level using four closed feedwater heaters, one open feedwater heater or deaerator, and two single-speed pressure boosting pumps. The single-speed pump model has been previously discussed. A schematic of the closed feedwater heater is shown in Figure 3-18. The feedwater output temperature T_{out} is given by

$$T_{out} = T_{cond} - TTD \quad (3-34)$$

where T_{cond} is the saturation temperature of the fluid and TTD is the terminal temperature difference, a heater parameter to which the system was designed. The output pressure P_{out} is given by

$$P_{out} = \gamma \cdot P_{in} \quad (3-35)$$

where P_{in} is the feedwater input pressure and γ is a heater parameter giving the normalized pressure drop across the heater. The enthalpy of the exiting feedwater is calculated using the steam properties

$$\lambda_{out} = TP(T_{out}, P_{out}) \quad (3-36)$$

where TP represents a temperature, pressure call to the steam properties subroutine. The condensate drain temperature is calculated as

$$T_{\text{drain}} = T_{\text{in}} + \text{TTD}_{\text{drain}} \quad (3-37)$$

where T_{in} is the temperature of the entering feedwater and $\text{TTD}_{\text{drain}}$ is the terminal temperature difference of drain cooler. The condensate drain pressure is equated to the pressure of the input heating fluid. The condensate drain enthalpy is calculated using the first law of thermodynamics:

$$h_{\text{drain}} = [w_{\text{fin}}(h_{\text{out}} - h_{\text{in}}) + w_{\text{cin}}h_{\text{cin}} + w_{\text{sin}}h_{\text{sin}}]/w_{\text{drain}} \quad (3-38)$$

where

w_{fin} = incoming feedwater flow rate

h_{in} = incoming feedwater enthalpy

w_{cin} = incoming drain condensate flow rate

h_{cin} = incoming drain condensate enthalpy

w_{sin} = incoming heating fluid flow rate

h_{sin} = incoming heating fluid enthalpy

w_{drain} = outgoing drain condensate flow rate.

Also

$$w_{\text{drain}} = w_{\text{cin}} + w_{\text{sin}} \quad (3-39)$$

A schematic for the deaerator or open feedwater model is shown in Figure 3-19. The operating pressure of the deaerator, P_o , is set equal to the pressure of the heating steam, and the pressure of the outgoing feedwater is taken to be P_o . The derivation of the enthalpy of the outgoing feedwater is given by

$$\dot{m}_t h_{out} = w_{in}(h_{in} - h_{out}) + P_o v \dot{m}_t \quad (3-40)$$

$$\dot{m}_t = w_{in} - w_{out} \quad (3-41)$$

where

$\dot{m}_t$ = condensate mass in the surge tank

v = specific volume of the condensate in the surge tank

w_{in} = condensate flow into the surge tank

w_{out} = condensate flow out of the surge tank

h_{in} = enthalpy of condensate into the surge tank.

A steady-state model is used to calculate w_{in} and h_{in} :

$$w_{in} = w_{sin} + w_{fin} + \sum_k w_{cin}^k \quad (3-42)$$

and

$$h_{in} = (w_{fin} h_{sin} + w_{fin} h_{fin} + \sum_k w_{cin}^k h_{cin}^k) / w_{in} \quad (3-43)$$

where

w_{sin} = heating steam flow rate

w_{fin} = incoming feedwater flow rate

w_{cin}^k = k-th incoming condensate flow rate

h_{sin} = heating steam enthalpy

h_{fin} = incoming feedwater enthalpy

h_{cin}^k = k-th incoming condensate enthalpy.

3-85

Figure 3-18. Closed Feedwater Heater Model

Figure 3-19. Deaerator Model

An idealized surge controller is used to calculate w_{fin} :

$$w_{fin} = \max(0, w_{out} - w_{sin} - \sum_k w_{cin}^k) \quad (3-44)$$

The temperature of the outgoing feedwater is calculated using the steam properties routine:

$$T_{out} = HP(h_{out}, P_{out}) \quad (3-45)$$

The pressure of the feedwater exiting the condenser hotwell is taken to be the pressure at the turbine exhaust. The equations governing the exiting feedwater enthalpy are given by equations (3-40) and (3-41) where

m_t = condensate mass in the hotwell

v = specific volume of the condensate in the hotwell

w_{in} = condensate flow into the hotwell

w_{out} = condensate flow out of the hotwell

h_{in} = enthalpy of condensate into the hotwell.

The steady-state model used to calculate w_{in} and h_{in} is given by equations (3-42) and (3-43) where

w_{sin} = exhaust steam flow rate

$w_{fin} = 0.0$

w_{cin}^k = k-th incoming condensate flow rate

h_{sin} = exhaust steam enthalpy

$h_{fin} = 0.0$

h_{cin}^k = k-th incoming condensate enthalpy.

Auxiliary Drain Systems

The major dynamic component is the flash tank. The percent of fluid flashed to steam is given by

$$\frac{h_{f1} - h_{f2}}{h_{fg}} \quad (3-46)$$

where h_{f1} is the enthalpy of the incoming condensate, h_{f2} enthalpy of saturated liquid at the tank pressure, h_{fg} is the heat of vaporization at the tank pressure. The pressure of the exiting steam is equal to the tank pressure, and the enthalpy is $h_{f2} + h_{fg}$. The pressure of the condensate drain is equal to the tank pressure. The enthalpy of the output condensate is given by

$$\dot{m}_T h_o = w_{in}(h_{in} - h_o) + pv(w_{in} - w_{out}) \quad (3-47)$$

$$\dot{m}_T = w_{in} - w_{out} \quad (3-48)$$

$$w_{in} = (1 - \text{percent flashed})w_{tot} \quad (3-49)$$

where m_T is the mass of condensate in the tank, w_{tot} is the tank input condensate flow rate, w_{out} is the tank drain flow rate, h_o is the enthalpy of the drain condensate, $h_{in} = h_{f1}$, p is the tank pressure, and v is the specific volume of the drain condensate.

Where a proportional level control is modeled,

$$\ell = \ell_o + \eta w_{out} \quad (3-50)$$

and

$$K\dot{w}_{out} + w_{out} = w_{in} \quad (3-51)$$

where ℓ denotes condensate level, ℓ_o is the nominal level, η is a proportionality constant, and K is the control loop gain.

Master Control Interface

The master control subsystem defines all value set-points for the EPGS model. The actual value positions are computed as follows for each EPGS value:

$$g_i(t) = sp_i + [g_i(t_o) - sp_i] e^{-\left(\frac{t - t_o}{t_R}\right)^2} \quad t \geq t_o \quad (3-52)$$

where $g_i(t)$ is the i th value position at time t , sp_i is the current set-point for the i th value, t_o is the time at which the current set-point was defined by master control, and t_R is one-half the time required for the valve to move from full open to full closed.

Miscellaneous

The pressure drop along a length of pipe L is given by

$$\Delta p_{\text{fric}} = \frac{f}{2pg_c} \left(\frac{\mu Re}{D} \right)^2 \frac{L}{D} \quad (3-53)$$

where D is the inside diameter, μ is the dynamic viscosity of the fluid, ρ is the fluid density, Re is the Reynolds number, and $g_c = 32.174 \text{ lbm-ft/lbf-sec}^2$. The friction factor, f , is a function of the Reynolds number:

$$Re \leq 2000 \quad , \quad f = 64/Re \quad (3-54)$$

$$Re > 2000 \quad , \quad f = 0.154 - 0.019 \ln Re + 6.22 \times 10^{-4} (\ln Re)^2 \quad (3-55)$$

The convective heat loss from a fluid in a pipe of length L is given by

$$h_{\text{loss}} = \frac{2\pi L(T_s - T_a)}{\left[\frac{\ln(r_2/r_1)}{K_c} + \frac{1}{r_2 h} \right]} \quad (3-56)$$

where

T_s = fluid temperature

T_a = ambient temperature

r_1 = inside radius

r_2 = outside radius

K_c = thermal conductivity of the insulation

h = film coefficient.

The resultant film coefficient, h , is calculated by

$$h = \sqrt{h_f^2 + h_{fr}^2} \quad (3-57)$$

where h_f is the film coefficient for forced convection, and h_{fr} is the film coefficient for free convection. Equations for h_f and h_{fr} are detailed in Reference 3-10.

Enthalpy transport delay along the downcomer is given by

$$\dot{h}_{dc} = \frac{2}{m_{dc}} \left[w_{dc}(h_{in} - h_{dc}) - \frac{w_{dc} L_{dc}}{778} - \frac{h_{loss}}{3600} \right] \quad (3-58)$$

and along the TSS to EPGS steam pipe is given by

$$\dot{h}_{tsg} = \frac{2}{m_{tsg}} \left[w_{tsg}(h_{in} - h_{tsg}) - \frac{h_{loss}}{3600} \right] \quad (3-59)$$

where h_{in} is receiver output enthalpy and the TSS output enthalpy for the first and second equation, respectively.

3.6 MASTER CONTROL SUBSYSTEM (MCS) MODULE

3.6.1 Introduction

The function of the Pilot Plant Master Control Subsystem is to provide these capabilities:

- Balanced and coordinated operation of all subsystems in any defined mode of operation
- Monitoring and detection of perturbations, anomalies or other changes in system operation
- Selection of operating reference set-points for each subsystem
- Logical testing of parameter values to determine necessary adjustments
- Selection of the optimum permissible operating mode for given system state and environmental conditions
- Mode switching based on predefined conditions
- Safe operation and shut-down logic.

The general design of the MCS is based on the requirement that an operator may be substituted for automatic control, and that each subsystem may be operated as a closed-loop "stand-alone" system.

3.6.2 MCS Simulation (Top Level)

The MCS simulation is designed for operation with GASP-IV. Figure 3-20 provides a general functional diagram of the MCS interrelations with the other modules of the STMPPS program. MCS defines and initializes the STMPPS mode of operation and control settings (set-points) for the subsystems; monitors critical temperature and pressure points; and provides incremental control and compensation when parameters cannot be maintained within their nominal operating range.

3.6.3 MCS Control and Monitoring Points

MCS controls the plant operation by providing 16 set-point inputs to the Receiver (RS), Thermal Storage (TS), and Electrical Power Generating

Figure 3-20. MCS Top Level Simulation

(EPGS) subsystems, as shown in Figure 3-21. A 10-level incremental control of the collector heliostat field efficiencies is also provided (see paragraph 3.2.3). Monitoring of critical parameter values is performed directly at four points, as shown in Figure 3-21. Set-points and monitored variables are listed in Table 3-11.

3.6.4 Operating Modes and Transitions

The modes for simulated operation are the following:

Mode 1 - Receiver steam to EPGS

Mode 2 - Receiver steam to EPGS and to thermal storage

Mode 3 - Receiver steam to EPGS; thermal storage steam to EPGS

Mode 4 - Receiver steam to thermal storage; thermal storage steam to EPGS

Mode 5 - Receiver steam to thermal storage

Mode 6 - Thermal storage steam to EPGS

Mode 7 - Overnight shutdown and hold.

The permissible mode transitions are given in Figure 3-22.

3.6.5 Master Control Operation

Master Control consists of subroutine MASTER, part of the subroutine SCØND, the major part of subroutine EVNTS, and three tables. The first table consists of numbers that define the values of 16 controller and valve set-points for the subsystems for the seven modes of operation. The second table defines the operating limits for the monitored variables. The third table defines, for each mode of operation, the action taken by the MCS in response to a detected limit.

The detailed operation of Master Control is diagrammed in Figure 3-23. When subroutine MASTER is called by STMPPS, the values in the three tables are initialized. The next step is to set the operating mode. The mode designation is used to define the subsystem operation set-points for

Figure 3-21. MCS Control and Monitoring Schematic

Table 3-11. MCS Set-Points and Monitored Variables

Engineering Symbol	Program Symbol	Description	Units	I/O
--	CSPTBL(I, 1)	Receiver discharge valve to downcomer (R1)	Dimensionless	O
--	CSPTBL(I, 2)	Receiver discharge valve to flash tank No. 3 (R2)	Dimensionless	O
W	CSPTBL(I, 3)	Downcomer output to TS desuperheater (R3)	lbm/sec	O
--	CSPTBL(I, 4)	Turbine main steam input valve (R4)	Dimensionless	O
--	CSPTBL(I, 5)	Turbine steam input from TS (T1)	Dimensionless	O
--	CSPTBL(I, 6)	Thermal storage discharge valve to flash tank No. 2 (T2)	Dimensionless	O
--	CSPTBL(I, 7)	Flash tank No. 2 drain control	Dimensionless	O
--	CSPTBL(I, 8)	Condenser drain control	Dimensionless	O
W	CSPTBL(I, 9)	Turbine exhaust valve (E1)	lbm/sec	O
W	CSPTBL(I, 10)	Turbine exhaust valve (E2)	lbm/sec	O
W	CSPTBL(I, 11)	Turbine exhaust valve (E3)	lbm/sec	O
W	CSPTBL(I, 12)	Turbine exhaust valve (E4)	lbm/sec	O
--	CSPTBL(I, 13)	Condenser exhaust fan	Dimensionless	O
P	CSPTBL(I, 14)	Receiver feedpump pressure	psia	O
T	CSPTBL(I, 15)	Receiver outlet temperature	°F	O
W	CSPTBL(I, 16) TWE	Thermal storage outlet steam flow rate	lbm/sec	O
--	HCEF(121)	Heliostat field cell efficiencies	Dimensionless	I/O
P	RPRNR8	Receiver output pressure	psia	I

Table 3-11. MCS Set-Points and Monitored Variables (Continued)

Engineering Symbol	Program Symbol	Description	Units	I/O
T	RTENR8	Receiver outlet temperature	°F	I
P	GPFPR	EPGS feedwater pressure	psig	I
L	TLT	TSS thermocline level	Dimensionless	I
N(1)	CMØDE	Current mode of operation	Dimensionless	O
N(1)	CNMODE	Number of different modes	Dimensionless	O
N(1)	CSP	Setpoints for current mode	See CSPTBL	O
(Multiple)	CMVLTBL	Table of operating limits for monitored variables	See table	O
(Multiple)	CMVL	Current mode variable limits	See array	O
	CNMV	Number of monitored variables	Dimensionless	O
±N(1)	CMVRTBL	MCS responses for monitored variables exceeding operating limits	See table	O
NA	CMVLA	Monitored variable limit argument	See variable	O
NA	CMVPA	Monitored variable argument	See variable	O
N(1)	CMVRC	Response codes for monitored variables crossing limits	Dimensionless	O
N(1)	CNM	Potential new modes to correct limit crossing	Dimensionless	O
N(1)	CNMVEL	Number of monitored variables exceeding limits at a given time	Dimensionless	O
N(1)	CNNM	Number of new mode requests	Dimensionless	O

<u>FROM MODE</u>	<u>CONFIGURATION</u>	<u>TO MODE</u>
1	RS → EPGS	2, 3, 7
2	RS → EPGS └→ TSS	5, 7
3	RS → EPGS TSS →	6, 7
4	RS → EPGS └→ TSS →	5, 6, 7
5	RS └→ TSS	7
6	TSS → EPGS	7
7	SHUT DOWN	3, 4, 6

Figure 3-22. Permissible Mode Transitions

Figure 3-23. Master Control Operation

the valves and controllers and limits for the monitored variables. In sequence, the Receiver, EPGS and TSS subsystem integrated variables and algebraic variables are initialized to values consistent with the initial operating mode and time of day. When the initialization operation is completed and the values are passed to the subsystems via COMMON Blocks, the Master Control functions are shifted to subroutines SCØND and EVNT.

Master Control performs a monitoring function in SCØND to detect pressure, temperature, or flow excursions from nominal values. If potential emergency conditions exist, flags (variable LFLAG) are set and MCS operation is passed to subroutine EVNTS. Subroutine EVNTS determines the number of variables that have exceeded their operating limits, obtains response codes for each limit crossing from CMVRTBL, and executes a corrective measure corresponding to the response code of highest priority. A typical corrective measure may be made in the collector field by altering the heliostat field efficiencies (HCEF) array. After initially testing the efficiency array for permitted adjustments, the adjustment is made in incremental steps of 10 percent. If the sequential adjustments are not adequate to produce operation within the defined operating limits, a mode change requirement is indicated. The logical decision for switching to a given mode is based on a predetermined hierarchy derived for optimum efficiency. The operating set-points corresponding to the new mode selection are defined from table CSPTBL. In addition, the new operating limits and responses to state changes that may occur in the new operating mode are obtained from tables CMVLTBL and CMVRTBL, respectively.

3.6.6 Logic Equations and Operations

The logical decisions for nominal operation or transition are derived from tests of parameter values that are monitored during the on-going plant simulation. The tables for set-points, operating limits, and responses were described in the previous section. These tables are used as the operating references for the logic operations.

The detection of state events (monitored variables exceeding operational limits) is performed in subroutine SCØND. Figure 3-24 is a basic diagram which shows operational limits about a reference value for a given variable in an operating mode. The interval for normal operation and independent control within a given subsystem is ± 10 percent about this "normal" value. If the ± 10 percent boundaries are exceeded, a flag is set and an adjustment is made by Master Control. For example, if the Receiver outlet temperature exceeds the expected value by more than 10 percent, the collector field-cell efficiencies are reduced by 10 percent. If necessary, this reduction is repeated. However, if the temperature cannot be maintained within the 20 percent limit, a mode change operation is initiated.

The general GASP expression for the test function may be written as

$$y = f(x, z, M, \alpha, D, T\alpha) \quad (3-60)$$

where

- y = a computed flag value or other test variable
- f = the GASP-IV function KRØSS
- x = the monitored variable value, state variable (or its derivative)
- z = a defined value or another variable for comparison
- M = a multiplier for z
- α = an operating limit or boundary value that may be added to z
- D = the direction of crossing
- T = the tolerance.

In MCS usage, for testing the monitored variables, z and M are set to zero. The value for D corresponds to the direction of boundary crossing; i. e., +1, 0, -1 corresponds to crossing in a positive direction, no crossing, or crossing in a negative direction, respectively. Logical values of ± 1 are computed

for the function when a crossing occurs within the tolerance limits shown in Figure 3-24. When a crossing occurs beyond the boundary plus tolerance, a +2, -2 is returned for the upper boundary and lower boundary, respectively.

The MCS response for each boundary crossing of the monitored variables are given in Tables 3-12, 3-13, and 3-14. When a new operating mode is defined, the corresponding set-points are also defined, as given in Table 3-15. Also, the operating limits for each monitored variable are defined as given in Table 3-16. This reinitialization completes the mode transition operation.

Table 3-12. Receiver Outlet Temperature/
Pressure Response Table
(CMVRTBL) (Table applies to
both temperature and pressure.)

Modes of Operation*	Events	Flag Values				
		-2	-1	0	+1	+2
1		7	7	1	*8	7
2		7	7	2	8	7
3		7	7	3	8	7
4		7	7	4	8	7
5		7	7	5	8	7
6		6	6	6	6	6
7		7	7	7	7	7

*8 Adjust collector field cell efficiency.
Numbers 1-7 are modes to which plant
operation is switched.

Table 3-13. EPGS Feedwater Pressure
Response Table (CMVRTBL)

Modes of Operation	Events	Flag Values				
		-2	-1	0	+1	+2
1		7	7	1	7	7
2		7	7	2	7	7
3		7	7	3	7	7
4		7	7	4	7	7
5		7	7	5	7	7
6		6	6	6	6	6
7		7	7	7	7	7

(Note: See footnote on Table 3-12)

Table 3-14. Thermocline Level Response
Table (CMVRTBL)

Modes of Operation*	Events	Flag Values				
		-2	-1	0	+1	+2
1		2	2	1	1	1
2		5	5	2	*8	7
3		7	7	3	6	6
4		5	5	4	8	7
5		5	5	5	8	7
6		7	7	6	7	7
7		4	4	7	7	7

*8 Adjust collector field cell efficiency

(Note: See footnote on Table 3-12)

Table 3-15. Operating Limits Table (Limits apply in all modes.)

	<u>Lower</u>	<u>-10%</u>	<u>+10%</u>	<u>+20%</u>
Steam Pressure	0.0	1310	1610	1760
Steam Temperature	0.0	855	1045	1140
Feedwater Pressure	0.0	1800	2200	2400
Thermocline Level	0.0500	0.0502	0.9848	0.9850

Table 3-16. Operating Set-Point Table

Setpoint	Mode						
	1	2	3	4	5	6	7
1	1.0,	1.0,	1.0,	1.0,	1.0,	0.0,	0.0,
2	0.0,	0.0,	0.0,	0.0,	0.0,	0.0,	1.0,
3	0.0,	13.750,	0.0,	16.250,	45.417,	0.0,	0.0,
4	31.667,	31.667,	23.611,	0.0,	0.0,	0.0,	0.0,
5	0.0,	0.0,	1.0,	1.0,	0.0,	1.0,	0.0,
6	0.0,	0.0,	0.0,	0.0,	0.0,	0.0,	0.0,
7	0.0,	0.4,	0.0,	0.5,	0.0,	0.0,	0.4,
8	0.0,	0.6,	0.0,	0.5,	0.6,	0.0,	0.6,
9	.0737,	.0754,	.0561,	0.0,	0.0,	0.0,	0.0,
10	.0623,	.0596,	.0474,	0.0,	0.0,	0.0,	0.0,
11	.0579,	.0588,	.0610,	.0657,	0.0,	.0733,	0.0,
12	.0675,	.0359,	.0710,	.0466,	0.0,	.0816,	0.0,
13	1.0,	1.0,	1.0,	1.0,	1.0,	1.0,	4.0,
14	2000.0,	2000.0,	2000.0,	2000.0,	2000.0,	0.0,	0.0,
15	950.0,	950.0,	950.0,	950.0,	660.0,	400.0,	400.0,
16	0.0,	0.0,	7.917,	29.167,	0.0,	29.167,	0.0/

3.7 CLOUD TRANSIT MODULE

3.7.1 Introduction

Subroutine CLOUD has been written to simulate the passage of a cloud front and rear across the collector field of the Pilot Plant. The calling program specifies the drift speed and direction of the cloud (any direction can be accommodated), the time the cloud intercepts the field, and the time the cloud rear begins to leave the field. When CLOUD is called and given the current time, it sets the values of the collector field efficiency matrix (see paragraph 3.2.3) with the fraction of cell area left open by the cloud.

3.7.2 Simulation Description

A schematic for the CLOUD transit simulation is shown in Figure 3-25. The collector field is fully contained within the 11 by 11 matrix of field cells. The flux arriving at the receiver is represented in the collector simulation by the totality of flux received from each cell in the field. A cell efficiency matrix is available which represents the fraction of heliostats active in each cell at a particular time, and the flux redirected from each cell is multiplied by the efficiency for that cell before the total flux on the receiver is formed. Since it is assumed that the distribution of the heliostats in each cell is uniform, the fraction of heliostats interrupted by a cloud is equal to the fraction of cell area intercepted by the cloud.

The cloud front and rear are represented as straight lines of infinite extent perpendicular to the direction of motion of the cloud, and the cloud is assumed to be totally opaque. Any speed and direction can be specified, with South taken as 0° , and East as $+90^\circ$. The cloud intercepts and leaves the nearest corner of the field at times specified in seconds of local time from midnight.

Each time CLOUD is called it uses the current local time to determine the positions of the cloud front and rear with respect to the field and sets the efficiency matrix to the fraction of each cell area left open.

Figure 3-25. Cloud Simulator Geometric Conventions

Subroutine FLUX then multiplies these fractions by the flux redirected from the cell, to develop the net flux incident on the receiver as a function of time.

Each time a cloud passage is to be simulated, an initialization subroutine, CLDINT, is called once. This subroutine is provided the four required descriptive inputs of cloud start and stop times, velocity, and direction.

Table 3-17 lists all the variables used in the CLOUD Transit Module. Logic flow diagrams for the associated subroutines are shown in Figures 3-26 to 3-30.

Table 3-17. Variables Used in CLOUD Transit Subroutines
Subroutine CLOUD

Engineering Symbol	Program Symbol	Description	Units	Input Output
	XTIST	Cloud from start time	sec from midnight local time	I
	XTIEND	Cloud rear start time	sec from midnight local time	I
v	XVEL	Cloud drift velocity	m/sec	I
θ	XDIR	Cloud drift direction	deg	I
t	ATILCL	Local standard time	sec from midnight	I
	HCEF	Field cell operating efficiency	numeric 0 to 1.0	O
ϵ	HCFL	Field size integer	m (11 times a cell size)	I
	ID	Direction category (below)	integer	

7

North

6 West East 8

1 4

South

5

Table 3-17. Variables Used in CLOUD Transit Subroutines (Continued)
Subroutine CLOUD (Continued)

Engineering Symbol	Program Symbol	Description	Units	Input Output
b	DE -	Distance the rear has penetrated into the field	m	
	IPP -	Processing flag, = 0 front is being processed; = 1 rear is being processed		
	FS -	Cell efficiency, fraction of cell area open		
	XP, YP	Coordinates of a point on the front (rear)	m	
	B -	Y intercept of the front (rear)	m	
	I -	Field cell row index		
	J -	Field cell column index		
	L -	Cell number		
	II	Inverted row index		
	KS -	Sum of the status of a cell's corners (0 to 4)		
	IP(K) -	Status of the Kth corner, = 0 not intercepted by the front (rear); = 1 intercepted by the front (rear)		
	XC(K), YC(K)	Coordinates of the cell's corners		
	AS	Area within a cell intercepted by the front (rear)		
	K	Cell corner index (1 to 4)		
	DX -	Coordinate of the front (rear) when ID is greater than 4		
	KS -	Index of the row or column containing the front (rear) when ID is greater than 4		
	DS -	Distance the cell has been intercepted (ID GT 4)	m	

Table 3-17. Variables Used in CLOUD Transit Subroutines (Continued)
Subroutine CLOUD (Continued)

Engineering Symbol	Program Symbol	Description	Units	Input Output
m	TH -	Slope angle of the front with respect to the X-axis	deg	
	M	Front (rear) slope		
	M1 =	-M/2		
	M2 =	-1/2M		
	STH -	Sine of the slope angle		
	CTH	Cosine of the slope angle		
	DC -	Width of a field cell	m	
	AC -	Area of the field cell	m ²	
	BC -	Coordinates of the cell boundaries	m	
	X -	Coordinate of the first point (or side) of the field intercepted	m	
	Y -	Coordinate of the first point intercepted	m	
	SY -	+1.0 if Y is increasing, -1.0 if Y is decreasing		
	ISY	1 if Y is increasing, 2 if Y is decreasing		
	SX -	+1.0 if X is increasing, -1.0 if X is decreasing		
	DL -	Maximum distance the front or rear must travel to transit the field	m	
	D -	Distance the front has penetrated into the field	m	

Table 3-17. Variables Used in CLOUD Transit Subroutines (Continued)

Subroutine SET

Engineering Symbol	Program Symbol	Description	Units	Input Output
	KS -	Same as above		
	IK	ID minus 4		
	IS	Flag, = 0 set all cells fully intercepted; = 1 set all cells partially intercepted		
	FS	Efficiency to be used in setting the cell efficiencies		
	K1	Starting index, rows or columns		
	K2 -	Ending index, rows or columns		
	K -	Index along row or column perpendicular to the front		
	N	Index along row or column parallel to the front		
<p>Function AT (See page following)</p> <p>Function KSER (See next page following)</p>				

Table 3-17. Variables Used in CLOUD Transit Subroutines (Continued)

Function AT

Engineering Symbol	Program Symbol	Description	Units	Input Output
x, y	XP, YP -	Coordinates of a point	m	
b, m	B, M -	Y intercept and slope of a line		
A	AT	Area of the triangle bounded by the line $X = MX + B$ and the lines $X = XP$, $Y = YP$	m^2	

Table 3-17. Variables Used in CLOUD Transit Subroutines (Continued)

Function KSER

Engineering Symbol	Program Symbol	Description	Units	Input Output
	KS -	Index of the corner where the search is to begin		
	IP -	Array of corner status		
	KC -	Searching condition		
	KSER	Index of the corner whose status is KC

Figure 3-26. CLDINT Flow Chart

Figure 3-26. CLDINT Flow Chart (Continued)

Figure 3-26. CLDINT Flow Chart (Continued)

Figure 3-26. CLDINT Flow Chart (Continued)

Figure 3-26. CLDINT Flow Chart (Continued)

Figure 3-27. CLOUD Flow Chart, Section 2 (Continued)

Figure 3-27. CLOUD Flow Chart, Section 3 (Continued)

Figure 3-27. CLOUD Flow Chart, Section 4 (Continued)

Figure 3-27. CLOUD Flow Chart, Section 5 (Continued)

This subroutine determines the area of the right triangle formed by a line with a slope M and Y intercept, B , with a point (X_P, Y_P) . The triangle is bounded by the lines $Y = MX+B$, $X = X_P$, and $Y = Y_P$.

Figure 3-28. Function AT Flow Chart

THIS SUBROUTINE LOCATES A SPECIFIED CONDITION IN AN ARRAY.

Figure 3-29. Function KSER Flow Chart

THIS SUBROUTINE SETS THE EFFICIENCY ARRAY TO THE VALUE, FS, FOR ALL CELLS FULLY OR PARTIALLY INTERCEPTED.

Figure 3-30. Function SET Flow Chart

4. OUTPUT DATA

There are two major types of output (viz., print and plot) from the STMPPS program. Each of these output types will be described separately below.

4.1 PRINT OUTPUT

All STMPPS print output is written to FORTRAN logical unit 6 (TAPE6). The total print output is divided into two major types.

4.1.1 Diagnostic Output

Facilities are provided throughout STMPPS for the printing of diagnostic information during the calculations performed in each subsystem model. Although a major use of this printed information is for diagnostic purposes, considerable value is also obtained in normal production operation of the simulation. These print blocks are selectively activated by input data read by NAMELIST group name PROG into the logical array DIAG. The array DIAG resides in named COMMON block /ADATA/. Each print block also indicates the DIAG array entry which activates it and the subroutine in which the output statement resides.

A complete listing of the valid DIAG flags and the variables printed if the corresponding flag is set TRUE is shown in Table 4-1.

4.1.2 GASP-IV Output

The GASP-IV simulation system also provides a wide variety of printed output. The characteristics of this output is described in Reference 1-2. This print output is also selectable by the user through the GASP-IV input cards.

Table 4-1. Diagnostic Print Output

<u>I</u>	<u>Subprogram</u>	<u>DIAG(I) Variables</u>
3	SSAVE	TNOW, HSUM, (RWSP(I), RHF7(I), I=1, 2), RPRIV, (RPROV(I), I=1, 6), (RWSP(I), RL13(I), RL35(I), RL57(I), RTEF7(I), I=3, 8), RWVSUM, RHSH, RPRSH, RTESH, RWOSH, GWSBDC, GHSBDC, GPSBDC, GTSBDC, GWSRG, GWSTSG, GHSTSG, GPSTSG, GTSTSG, GEPOUT, (GWTEXT(I), I=1, 4), GWTEXH, (GPTEXT(I), I=1, 4), GPTEXH, (GHTEXT(I), I=1, 4), CHTEXH, GHCOH3, GWFPT, GHHTR1, GPHTR1, GTHTR1, GWFPT, GHOUTP, GPOUT, GHRCI, GPFPR, GTFPR, TW2, TH2, GHDSI, GPDSI, GWSRT, TW1A, TH1, TP1, TW3, TW5A, TW7A, TLT, TW8, TH9
4	INP	OUTFG, ATIMO, ATIDAY, DIAG, ATILCL, ATITST, END ETEAMB, EPRAMB, EVWAMB, EINDIR, EDWAMB, ETDAMB
5	RECVR	IV, RPRISV, RPROSV, RHIV, RPRIV, RLV(IV), RVIV, RFMV(IV), RWV(IV), RWVSUM, RPROV(IV), RHOV(IV)
6	RSP	I, TNOW, DTNOW, RHF1(I), RPRF1(I), RTEF1(I), RUF1(I), RVF1(I), RHCF2(I), RHF2(I), RPRF2(I), RQF2(I), RTEF2(I), RTEFF2(I), RUF2(I), RIUF2(I), RVF2(I), RWTF2(I), RHCM2(I), RHFCM2(I), RHFRM2(I), RTEM2(I), RQM2(I), RQAM2(I), RQCM2(I), RQEM2(I), RHF3(I), RIHF3(I), RHFSAT(I), RPRF3(I), RTEF3(I), RUF3(I), RUFSA(I), RVF3(I), RVFSAT(I), RHCF4(I), RHNBF4(I), RHFBF4(I), RHF4(I), RPRF4(I), RQF4(I), RTEF4(I), RTEFF4(I), RUF4(I), RVF4(I), RWTF4(I), RHCM4(I), RHFCM4(I), RHFRM4(I), RTEM4(I), RQM4(I), RQAM4(I), RQCM4(I), RQEM4(I), RHF5(I), RHVSAT(I), RPRF5(I), RTEF5(I), RUF5(I), RUVSAT(I), RVF5(I), RVVSAT(I), RXF5(I), RHCF6(I), RHF6(I), RPRF6(I), RQF6(I), RTEF6(I), RTEFF6(I), RUF6(I), RVF6(I), RWTF6(I), RHCM6(I), RHFCM6(I), RHFRM6(I), RTEM6(I), RQM6(I), RQAM6(I), RQCM6(I), RQEM6(I), RHF7(I), RPRF7(I), RTEF7(I), RUF7(I), RVF7(I), RL13(I), RL35(I), RL15(I), RL57(I), RDIUF2(I), RDIHF3(I), RDL13(I), RDTEM2(I), RDTEM4(I), RDTEM6(I)
7	RECVR	IC, RTSETC, RTSENC(IC), RERRTC(IC), RLPROC(IC), RLINTC(IC), RDLINTC(IC), RLSUMC(IC)
8	RECVR	I, RHISH(I), RWISH(I), RWOSH, RVSH, RDVSH, RUSH, RDUSH, RPRSH, RHSH, RTESH
9	SCOND	ISP, LFLAG(ISP), J1, J2, J3, J4, J5, J6, J7, J8, J9, J10, J11, J12, J13, SS(J1), SS(J2), RKL17, LNTOL, SS(J7), SS(J6), SS(J9), SS(J8), HTOL, SS(J12), RKTHSC, TETOL
10	EVNTS	ISP, LFLAG(ISP), J1, RCVST(ISP), RAFLGC(IC), RL13(ISP), RL15(ISP), EPSLN, RTEF7(ISP), RVF7(ISP), TNOW, ATRIB(I), ATRIB(2)
11	SSAVE	TNOW, (SS(I), I=1, NNEQT)
12	SSAVE	TNOW, (DD(I), I=1, NNEQD)

Table 4-1. Diagnostic Print Output (Continued)

<u>I</u>	<u>Subprogram</u>	<u>DIAG(I) Variables</u>
13	SSAVE	TNOW, [RHISH(I), RWISH(I), I=1, 6], RHSH, RPRSH, RTESH, RWOSH, [RFMV(I), RLV(I), I=1, 6], RHIV, RPRIV, RPRISV, RPROSV, RVIV, [RHOV(I), RPROV(I), RWV(I), I=1, 6], RWVSUM, [RHF1(I), RPRF1(I), RTEF1(I), RUF1(I), RVF1(I), RHCF2(I), RHF2(I), RPRF2(I), RQF2(I), RTEF2(I), RTEFF2(I), RUF2(I), RVF2(I), RWTF2(I), RHCM2(I), RHFCM2(I), RHFRM2(I), RQM2(I), RQAM2(I), RQCM2(I), RQEM2(I), RPRF3(I), RTEF3(I), RUF3(I), RVF3(I), RHCF4(I), RHNBF4(I), RHFBF4(I), RHF4(I), RPRF4(I), RQF4(I), RTEF4(I), RTEFF4(I), RUF4(I), RVF4(I), RWTF4(I), RHCM4(I), RHFCM4(I), RHFRM4(I), RQM4(I), RQAM4(I), RQCM4(I), RQEM4(I), RPRF5(I), RTEF5(I), RUF5(I), RVF5(I), RXF5(I), RHCF6(I), RHF6(I), RPRF6(I), RQF6(I), RTEF6(I), RTEFF6(I), RUF6(I), RVF6(I), RWTF6(I), RHCM6(I), RHFCM6(I), RHFRM6(I), RQM6(I), RQAM6(I), RQCM6(I), RQEM6(I), RHF7(I), RPRF7(I), RTEF7(I), RUF7(I), RVF7(I), RUFSAT(I), RVFSAT(I), RUVSAT(I), RVVSAT(I), RL35(I), RL57(I), RWSP(I), RCVST(I), I=1, 8], [RAFLGC(I), RERRTC(I), RLPROC(I), RLSUMC(I), I=1, 6], RTSETC
14	QABS	ISP, ICV, NZ, JCV, JLO, JHI, RL13, RL15, RKL17, ZLO, ZHI, FLO, FHI, SUM, CLO, CHI, QABS
15	EDATIN	AEIST, ATIMO, ATIYR, ATIDAY, ATILCL, ATITST, EINDIR, EPRAMB, ETEAMB, ETDAMB, EDWAMB, EVWAMB
16	FLUX	ATITST, TM, TA, TB, TX, EINDIR, HREF, EF, HFLRN
17	NOT USED	
18	EPGS	NPORTS, IFAN, GTEFF, GWTALP, GWTEXH, GHTEXH, GPTEXH, GWTEXT, GHTEXT, GPTEXT, GTPOWER, GEPOUT
19	EPGS	GWSH1, GPSH1, GHSH1, GWFPT, GPCOH2, GHCOH2, GPCOH1, GHCOH1, GTCOH1, GWCH12, GPCH12, GHCH12, GWSH2, GPSH2, GHSH2, GPCIH2, GHCIH2, GTCIH2, GWCH23, GPCH23, GHCH23, GVCH, GWCIH3, GHCIH3, GWCOH3, GHCOH3, GHDCOH3, GTCOH3, GWCTH3, GWCLP, GPCOH5, GHCOH5, GPCOH4, GHCOH4, GPCH4C, GHCH4C, GPCIH5, GHCIH5, GWCTH5, GPCOH5, GHCOH5, GPCH5C, GHCH5C, GWCIHW, GMDCHW, GHCHW, GHDCHW, GVCHW, GHSAT, GWCTC, GWCTH5, DELH, DELP, APHP, DELHBP, DELPBP, APBP, GTAUXP,
20	EPGS	GVTSG, GTCIH2, GRETSG, GMUTSG, DELPTSG, GPCTSG, GMFWP, GHCTSG, GHDCTSG, GTCTSG, GHLOTSG
21	RIAUXC	GWSIT3, GPT3, GVCT3, GWCIT3, GWCOT3, GMCT3, GHCIT3, GHCOT3, GLT3, GWSOT3, GHSOT3
22	RIAUXC	GDIDC, GDODC, GRESDC, GVSDC, GMUSDC, GLDC, GTC, GPDELD, GHLOSSD, GWSBDC, GPSBDC, GMDC, GHSBDC, GHSDBDC, GWSIDC, GTDBC, GWSRG, GWSRT

Table 4-1. Diagnostic Print Output (Continued)

<u>I</u>	<u>Subprogram</u>	<u>DIAG(I) Variables</u>
23	TSSIAUX	TWSIN, TTESG, TPRSG, THSG, GWSTSG, GWSIT2, GRESP, GVSP, GMUSP, GPDEL, GHLOSS, GPSTSG, GMSP, GHSTSG, GHDSTSG, GTSTSG
24	TSSIAUX	TWCIN, TTECH, TPRCH, GHCIN, GWSTH1, GHSTH1, GPT1, GWCIT1, GHCIT1, GHCOT1, GHDCOT1, GPOPT2, GPT2, GLT2, GVCT2, GWCIT2A, GHCIT2A, GWSOT2A, GHSOT2A, GWCIT2B, GHCIT2B, GWSOT2B, GHSOT2B, GWCIT2, GHCIT2, GWSTH2, GHSTH2, GWCOT2, GWDCOT2, GHCOT2, GHDCOT2, GMCT2, GMDCT2
25	RECFEED	GWFP, GVFP, GFPH, GFPTFR, GFPT, GFPAUX, GRESR, GMUSR, GPFPR, GPDELR, GCPEFP, GCTFP, GFPS, GDFPS, GHOUTP, GPOUT, GHLOSSR, GMRC, GHRC1, GHDCI, GTFPR, GTCIR, GRESDS, GMUSDS, GPDSI, GPDELDS, GMDS, GHDSI, GHDDSI, GTDSI, GHLOSDS
26	TSS	TT3, TT4, TT5, TT6, TT8, TP1, TP4, TP8, TPDISH, TH1, TH2, TH3, TH4, TH8, TH9, TPPC, TPPE, TPPT, TC5, TC6, TKHC, TKTMTSH, TKTMSG, TKTMECS, TKG, TKDSH, TKTSH, TKSG, TW1, TW1A, TW1M, TW2, TW3, TW5A, TW5M, TW5MF, TW7A, TW7M, TW7MF, TWE, TPPCM, TPPEM, TPPA, TFC, TFE, TK1, TK2, TK3, TK4, TK5, TK6, TAK1, TAK2, TBK1, TBK2, TCK1, TCK2, TDK1, TDK2, TAK3, TAK4, TBK3, TBK4, TPL1, TPL2, TPL3, TCONC, TCONE, TTSC, TTSE, THTSUM, TLT, TLTU1, TLTU2, TLTL1, TLTL2, TFLAGU, TFLAGL
27	SCOND	SS(ISSMV), CMVL(J, I), LCROSS, LFLAG(IFLGMV)
27	EVNTS	TNOW, LFLAG(IFLGMV), CNMVEL, CMVLA(CNMVEL), CMVPA(CNMVEL), CMVRC(I), CMODE, CNNM, CNM(CNNM), CNM(I), CMODE

4.2 PLOT OUTPUT

It is anticipated that the major STMPPS user output will be in plot form since this type of output is most readily understood by users. A total of 97 different variables may presently be plotted as functions of simulation time in the current version of the STMPPS program. These variables are listed in Section 2.1.3.1. The variables written to the plot data file may be readily changed as described in that Section of this document. Essentially any real variable may be written to the plot data file for subsequent plotting as a function of simulation time.

An example of a typical output plot is shown in Figure 4-1.

Figure 4-1. Example Plot Output

REFERENCES

- 1-1. FORTRAN Extended Version 4 Reference Manual (Revised Edition), Control Data Corp. Publication No. 60305601.
- 1-2. A. Alan B. Pritsker, The GASP-IV Simulation Language, A Wiley-Interscience Publication, John Wiley & Sons, New York (1974).
- 3-1. C. M. Randall, Barstow Insolation and Meteorological Data Base, Report No. ATR-78(7695-05)-2, The Aerospace Corp., El Segundo, CA (13 March 1978).
- 3-2. Central Receiver Solar Thermal Power System, Phase I, CDRL Item 2, Pilot Plant Preliminary Design Report, Vol. VI, McDonnell Douglas Corp. (October 1977).
- 3-3. Central Receiver Solar Pilot Plant Preliminary Design Report, Vol. IV, Report No. MDAC G6776, McDonnell Douglas Corp. (May 1977).
- 3-4. Steam, Its Generation and Use, 38th ed., The Babcock and Wilcox Co. (1972).
- 3-5. J. R. S. Thom, W. M. Walker, T. A. Fallon, and G. F. S. Reising, "Boiling in Subcooled Water During Flow Up Heated Tubes or Annuli," Proc. Institution of Mechanical Engineers, No. 3C180 (1965-1966).
- 3-6. Solar Pilot Plant, Phase 1, Preliminary Design Report, Vol. VI, Honeywell, Inc. (May 1977).
- 3-7. Unpublished Memorandum, Southern California Edison Co.
- 3-8. R. C. Spencer and K. C. Cotton, A Method for Predicting the Performance of Steam Turbine-Generators 16,600 kW and Larger, Report, General Electric Co. (1974).
- 3-9. IMSL Library 3, Edition 5, IMSL, Inc., 7500 Bellaire Blvd., Houston, TX 77036 (1975).
- 3-10. McAdams, Heat Transmission, Ch. VIII, McGraw-Hill Book Co. (1942).
- 3-11. A. Ray, D. A. Berkowitz, and V. Sumaria, "Mathematical Modeling and Digital Simulation of the MERC Component Test and Integration Unit", MITRE Technical Report MTR-3447, May (1977).
- 3-12. J. Adams, D.R. Clark, J.R. Louis, and J.P. Spanbauer, "Mathematical Modeling of Once-Through Boiler Dynamics", IEEE Transaction on Power Apparatus and Systems, PAS-84, 146-156 (1965).

REFERENCES (CONT.)

- 3-13 A. Ray and H. F. Bowman, "A Nonlinear Dynamic Model of a Once-Through Subcritical Steam Generator", Transactions of the ASME, J. of Dynamic Systems, Measurement, and Control, 98 (1976).
- 3-14 J. P. McDonald, H. G. Kwatny, and J. H. Spare, "A Non-Linear Model for Reheat Boiler-Turbine-Generator Systems: Part I - General Description and Evaluation", in Proc. 12th Joint Automatic Control Conference, 219-226 (1971).
- 3-15 H. G. Kwatny, J. P. McDonald, and J. H. Spare, "A Non-Linear Model for Reheat Boiler-Turbine-Generator Systems: Part II - Development", in Proc. 12th Joint Automatic Control Conference, 227-236 (1971).

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