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DYNAMIC SIMULATION MODEL OF THE SOLAR THERMAL TEST FACILITY (STTF)

PRELIMINARY DESCRIPTION

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FOREWORD

This report is written as a partial account of work performed for the Department of Energy, on the Solar Thermal Test Facility Project, under Contract Number E(04-3)-1101, Project Agreement No. 2.

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1. INTRODUCTION

This report presents a description of a computer program for the simulation of the Solar Thermal Test Facility (STTF) and an experiment run at that facility. The STTF is a general-purpose solar test facility with subsystems designed to provide solar thermal energy to a variety of experiments. The basic facility consists of (a) a relocatable heliostat field, (b) a tower for mounting experiments, water and electrical resouces, (c) a cooling tower, (d) a computerized control system, (e) a data acquisition system, and (f) provisions for experiments. The simulation program structure contains equivalent computer modules for each of the STTF subsystems and experiments which permit rapid simulation of the experiments or new facility configurations under differing environmental and test conditions.

The program is designed to identify and resolve potential hazards derived from any given test. It can also help to ensure an effective facility utilization consistant with the DOE solar technology program. This assurance will be provided by "pre-operational" simulation of the experiment test program prior to the actual test.

1.1 TASK APPROACH

The STTF simulation was divided into two elements. The first element is the simulation of the basic STTF facility which includes the collector field, tower, cooling system, steam depressurization, feedwater, and control systems. The second element represents the component/experiments to be tested at the STTF which can be added to the simulation as needed. These experiments include those in direct support of the 10 Megawatt Electric Pilot Plant, such as the Subsystem Research Experiment (SRE) receivers, heliostats, and possible thermal storage and turbogenerators; and experiments listed in the Solar Electric Program Plan, including advanced heliostat testing, chemical/material processing, and material tests at high solar thermal flux levels.

The objective of this work is to make available to the STTF users an analytical tool which simulates the characteristics of the STTF and which they may use for experiment design and test program planning. The program is written with a modular structure to allow the experimenter to easily incorporate a new experiment or to modify or add to the facility configuration itself. The programming is done in standard FORTRAN IV and the program size is compatible with all commonly used technical computer systems.

1.2 REPORT OUTLINE

This report covers the first phase of the STTF computer program development, which includes the simulation of the STTF subsystems and the simulation of the Martin Marietta 5 MW_t SRE receiver experiment. In the next phase of the program a computer model of the McDonnell Douglas/Rocketdyne 5 MW_t SRE receiver in its STTF configuration will be developed.

The report describes the detailed STTF plant dynamic model, the program structure, and the verification of the model by comparison of the computer results with facility and experiment data. Finally, a list of program applications is described.

2. SYSTEM DEFINITION

Figure 2-1 schematically illustrates the major components and subsystems of the STTF and their interrelationships (Ref. 1). All interfaces between subsystems as used in the simulation consist exclusively of fluid flows, energy flows, or information transfers.

The test facility presently consists of a collector field, the experiment located at the top of the tower, a depressurization/desuperheater loop, a feedwater loop, and a cooling system. The experiment in this case is the Martin 5 MW_t SRE receiver. Normal steady-state operating conditions are shown in Figure 2-1 for experiment design conditions.

2.1 COLLECTOR FIELD

The collector field consists of the heliostats, heliostat foundations, and necessary controls and power to operate them. The complete heliostat foundation field contains a large number of heliostat foundations that permit movement of heliostats to reconfigure the collector field to support a wide variety of tests, as illustrated in Figure 2-2. A total of 222 heliostats are available. A north field, as is required for the Martin SRE receiver, is set up by mounting the heliostats on the 222 foundations of Zones A and B. An annular field is set up by mounting the heliostats on the 222 foundations A, C, D, and E. For the Martin Marietta SRE receiver tests, each heliostat will be focused to one of seven different focal lengths, as shown in Figure 2-2.

Each heliostat consists of a 5 × 5 array of facets. Each facet is 4 ft × 4 ft with a total heliostat area of 400 ft^2. Solar tracking is accomplished by means of an azimuth-elevation gimbal drive system operating open loop on a calculated sun position. Resolvers sense and feed back gimbal angles to the controller.

Focusing is accomplished by dishing each facet with a pull ring to achieve the desired focal lengths. Each facet is then canted to center, its flux around the heliostat center line.

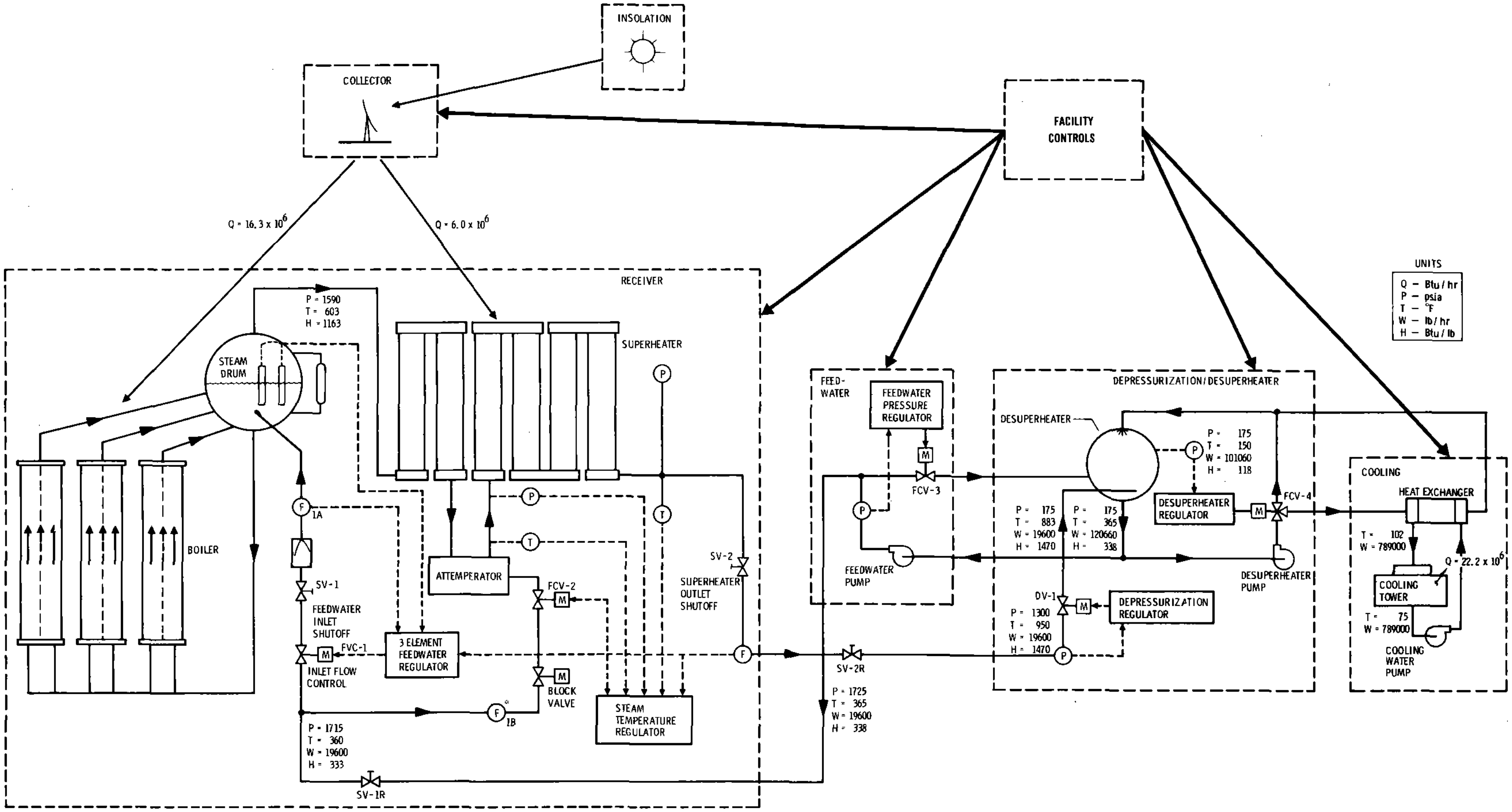


Figure 2-1. Schematic of Major Components/Subsystems of the STTF

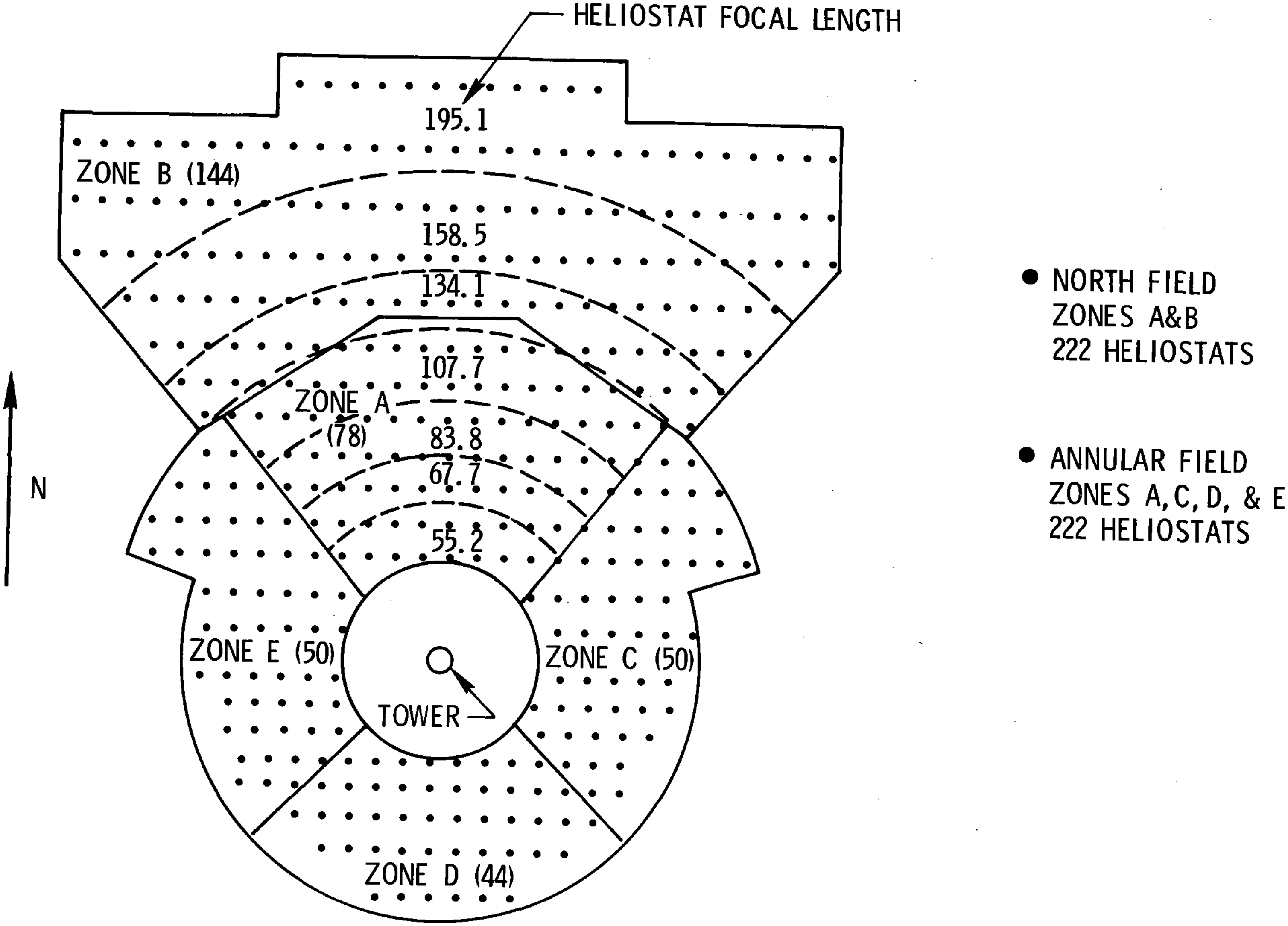


Figure 2-2. STTF Collector Field Layout

2.2 HEAT REJECTION SYSTEM (HRS)

The functions of the HRS are to supply preconditioned pressurized feedwater to the receiver experiment and then to dissipate the energy collected by the experiment. The feedwater section of the HRS can supply boiler quality feedwater at a rate of 25,000 lb/hr, a pressure of 2250 psi, and temperature of 400° F.

Steam from the receiver experiment returns down the tower in a high-pressure steam line, passes through a pressure reducing valve, and flows into the downcomer/desuperheater vessel, where it is cooled by the feedwater spray water loop. Part of the drain flow from the vessel is split and returned as condensate to the experiment, thus completing the experiment steam cycle. The remaining flow is directed to a heat exchanger, where waste heat is rejected to a dry cooling tower system. The tower cooling loop uses a 33 percent ethylene glycol-water solution for coolant and passes the coolant through the cold side of the heat exchanger in the feedwater spray water loop.

2.3 SRE RECEIVER

The SRE receiver schematic is that given in the Martin Marietta PDR report (Ref. 2). Complete mechanical details are described in that report.

Water flows in the boiler circuit under natural circulation. It flows from the steam drum, through the downcomer, and into the lower boiler headers. From there it passes through the boiler. The resulting steam-water mixture returns through risers to the steam drum. In the drum the mixture passes through centrifugal separators to separate the steam and water. Then the water is mixed with incoming feedwater and re-circulated, and the steam is dried with chevron-type driers (mist eliminators) and passed on to the superheater.

The superheater consists of 16 passes in which the steam is converted from saturated vapor to high-temperature superheated steam. An attemperator is located between the sixth and seventh pass to control outlet steam temperature.

Specific operating conditions for the receiver are shown in Figure 2-1 for the design conditions. The average circulation ratio of the boiler loop is 22.48.

2.4 CONTROL SYSTEM

The control system has three primary functions: overall mode control, subsystem interaction control, and subsystem control itself. The STTF uses a multiple-computer distributed control system to control the heliostats, experiment, and supporting functions.

The basic operating mode is selected either by the operator or automatically. After a mode is selected, the control system configures the plant to support that mode by operating valves and switching equipment on and off.

Subsystem interaction control adjusts the operation of each subsystem to maintain efficiency during normal operation and to prevent damage during emergency conditions. For example, loss of feedwater require emergency defocus of the heliostats to prevent damage to the receiver. All of the numerous interactions between subsystems are handled by this function.

The various subsystem control loops are illustrated in the schematic of Figure 2-1, and Table 2-1 lists the function, input, and output of each of the controllers. The exact form of the regulators is to be determined, however, and for the purposes of this study it is assumed that they are of the form of conventional proportional-plus-integral-plus-derivative (PID) feedback compensations.

Table 2-1. Subsystem Controller Characteristics

SUBSYSTEM	FUNCTION	INPUT	OUTPUT
Collector	Heliostat Tracking	Gimbal Angle	Gimbal Angle
Receiver	Feedwater Flow Regulator	Feedwater Flow	Feedwater Valve Position
		Steam Flow	
		Steam Drum Level	
	Steam Temperature Regulator	Attemperator Temperature	Attemperator Feedwater Valve
		Attemperator Pressure	
		Superheater Temperature	
		Steam Flow	
Depressurization/ Desuperheater	Depressurization Regulator	Receiver Pressure	Depressurization Valve Position
	Desuperheater Regulator	Desuperheater Pressure	Heater Exchanger By-Pass Valve Position
Feedwater	Feedwater Pressure Regular	Feedwater Pressure	Feedwater By-Pass Valve Position

3. COMPUTER PROGRAM DESCRIPTION

The STTF Simulation computer program is designed as a versatile building block structure in order to permit rapid simulation of a variety of experiments under differing environmental and test conditions. The generalized nature of the program is accomplished by maintaining a basic correspondence between the computer simulation modules or subroutines and the physical system components and experiment. This simulation to real system correspondence of components, along with simple and clearly defined interface COMMONS for "connections" between the various simulation components, makes for ease in quickly modifying the computer program to simulate different system components or experiments as they are developed.

The program is written in the FORTRAN IV language and has core memory requirements of approximately 40,000 octal words. The ratio of simulated to real time is approximately 50 to 1 when using the CDC-7600 computer.

3.1 PROGRAM STRUCTURE

The overall structure of the computer simulation is illustrated in Figure 3-1. There are three main sections to the program: (a) the simulation administration and calculation section, (b) the system representation section, and (c) the general service routines sections. The program administration controls the overall structure of the simulation, system configuration of the plant, input, output, and update rates. The system representation modules contain the specific modeling of each of the components and experiments of the STTF.

The main routines in the simulation are:

EXEC	(Executive Function)
INSOLA	(Insolation Values)
COLLEC	(Collector Operation)

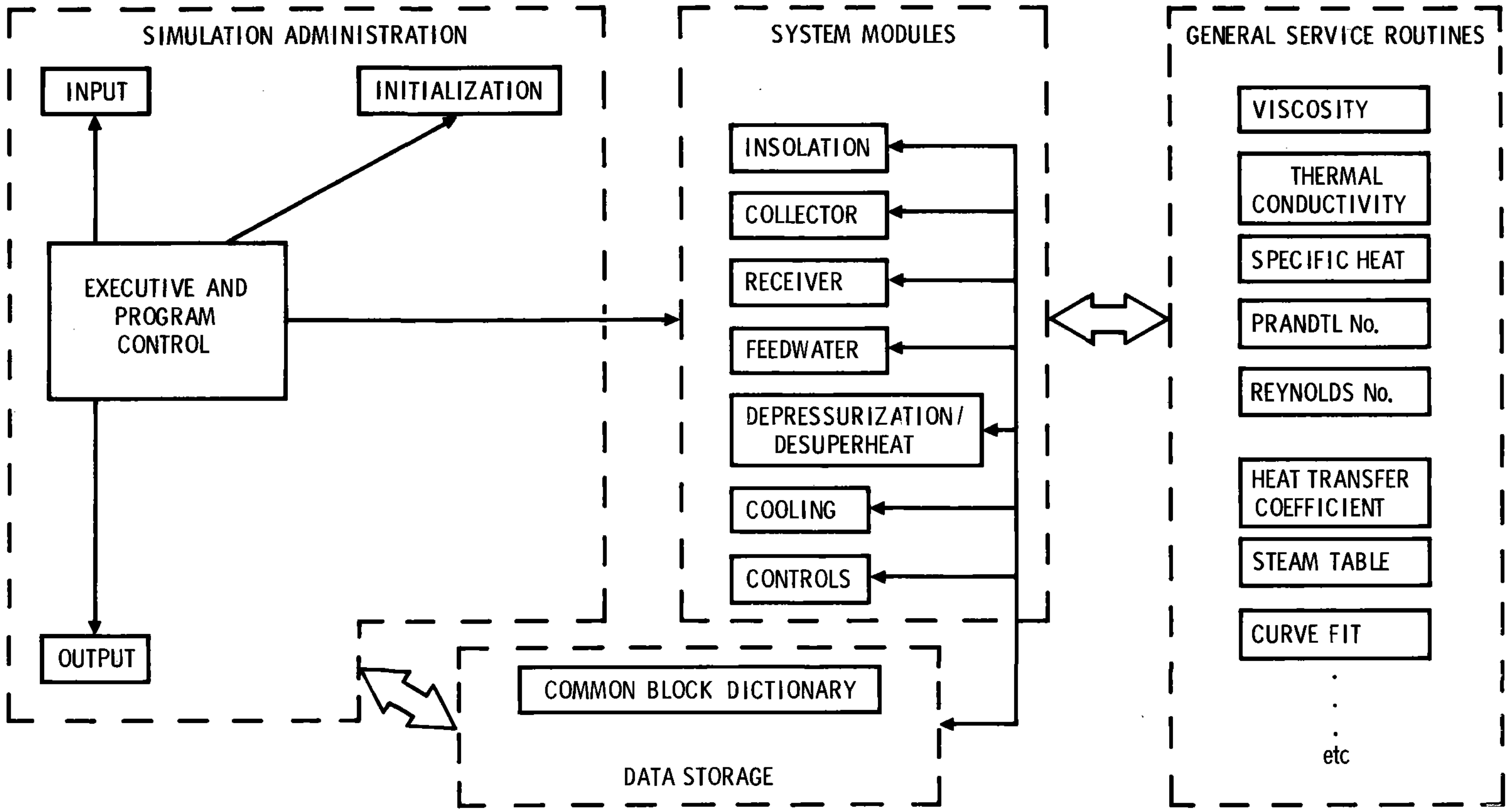


Figure 3-1. Simulation Program Structure

CONTRO	(Plant Controls)
RCVR	(Receiver Operation)
FDWTR	(Feedwater Operation)
DPDH	(Depressurization/Desuperheat Operation)
CLNG	(Cooling Operation)

There is a one-to-one correspondence between the module and the STTF subsystem. The physical boundaries of the subsystems and interfaces are identified in Figure 2-1. All data transfers between the various program administration routines and system modules are via the COMMON blocks in the data storage area.

The generalized service routines perform calculations that are relatively system-independent and are required by two or more system modules. Specific examples are listed in Figure 3-1. Data are transferred to and from the modules through call argument lists and not through the COMMON block dictionary.

3.2 EXECUTION PROCEDURES

Figure 3-2 illustrates the basic top-level flow chart of the STTF computer model.

Prior to beginning the iterative computational sequence, the following operations take place:

- Input data from the data file are read in. Table 3-1 lists the data file parameters, order, and formats utilized. The input data consist of overall program data (time step sizes, final time, print time, etc.), initial system thermodynamic states, initial valve openings, control system gains, and initial radiant heat inputs.
- The subroutines are initialized.
- The control mode is set.

The EXECUTIVE routine, now properly "primed," begins execution of the dynamic system equations by a call to each of the subsystem modules.

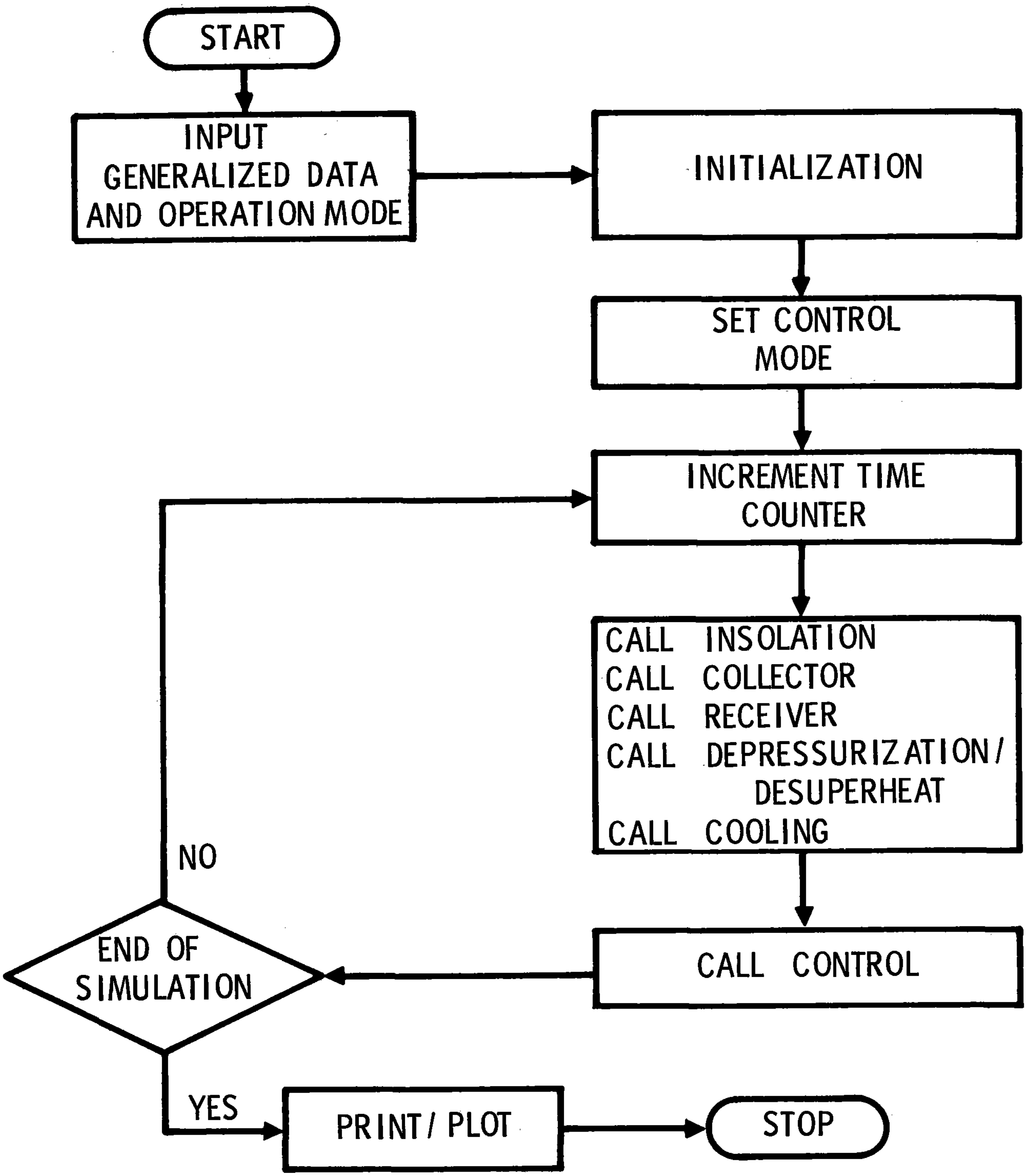


Figure 3-2. Simulation Program Structure within the EXECUTIVE Routine

Table 3-1. STTF Simulation Input Data Format

LINE No.	PARAMETER			READ FORMATS	SUBSYSTEM	PARAMETER DESCRIPTION
	1	2	3			
115	ISSNSØ, TØY, HKREFL, EKATEN, XTAIR, XVAIR			I1, F9.2, 4F10.3	COLLECTOR AND INSOLATION	ISSNSØ: FLAG TO INDICATE WHETHER BLOCK DATA INSOLATION IS USED OR WHETHER INSOLATION VALUES ARE INPUT TOY: TIME OF YEAR IN DAYS SINCE SPRING EQUINOX HKREFL: MIRROR REFLECTIVITY EKATEN: ATMOSPHERE ATTENUATION XTAIR: AIR TEMPERATURE XVAIR: AIR VELOCITY
118	TSTART, TEND, DT, DTPRINT, DTPLOT			5F10.2	EXECUTIVE PROGRAM CONTROL	TSTART: STARTING TIME OF SIMULATION TEND: ENDING TIME OF SIMULATION DT: INTEGRATION STEP SIZE DTPRINT: TIME INTERVAL FOR PRINTING CURRENT VALUES DTPLOT: TIME INTERVAL FOR PLOTTING CURRENT VALUES

Execution is continued until the desired time period has been completed. Then the results are made available through OUTPUT in either print or plot form.

3.3 DATA STORAGE

In the program structure all information flow will be handled through COMMONS. Each routine will have its own specialized values for variables and for outputting final values of those variables at the end of the simulation. Most importantly, the flow of information between simulation components during the simulation will be handled by special brief interface COMMONS. The COMMONS used between these routines are listed in Table 3-2. Each of these COMMONS will carry only the variables corresponding to the actual entities traveling between the actual system components. Thus these interface COMMONS will carry only variables such as heat flux; or fluid mass flow, pressure, temperatures and enthalpy; or plant control information and commands. This structure of interconnection between the various simulation components will allow for simple replacement of different subroutine representations for the various STTF system components.

Table 3-2. Interface Common Description

INTERFACE COMMON	FROM MODULE	TO MODULE	VARIABLES	DESCRIPTION
FTOCN	FEEDWATER	CONTROL	PFCN	A CONTROL SENSED PRESSURE
FTODD	FEEDWATER	DEPRESS, DESUPER HEAT	PFDD, TFDD, WFDD, HFDD, VFDD, PIFDD	PRESS, TEMP, FLOW, ENTHALPY, SPECIFIC VOL, FEEDBACK PRESS
FTOR	FEEDWATER	RECEIVER	PFR, TFR, WFR, HFR	PRESS, TEMP, FLOW, ENTHALPY
INTOCL	INSOLATION	COLLECTOR	SSDINS	DIRECT INSOLATION
RTOCN	RECEIVER	CONTROL	HBDRCN, WBDRCN, WSHRCN, PARCN, TARCN, TSHRCN	STEAM DRUM LEVEL, FEEDWATER FLOW TO STEAM DRUM, STEAM FLOW FROM RECEIVER, ATTEMPERATOR OUTLET PRESS, ATTEMPERATOR OUTLET TEMP, SUPERHEATER OUTLET TEMP
RTODD	RECEIVER	DEPRESS, DESUPER	PRDD, TRDD, WRDD, HRDD, VRDD	PRESS, TEMP, FLOW, ENTHALPY, SPECIFIC VOL
RTOF	RECEIVER	FEEDWATER	PIRF	FEEDBACK PRESSURE
TIME	EXECUTIVE	ALL MODULES	TOD, TOY, DT, DTPRNT	TIME OF DAY, TIME OF YEAR, INTEGRATION STEP SIZE, PRINT INTERVAL

Table 3-2. Interface Common Description (Continued)

INTERFACE COMMON	FROM MODULE	TO MODULE	VARIABLES	DESCRIPTION
CLTOR	COLLECTOR	RECEIVER	FLUX (7)	HEAT FLUXES TO 7 NODES OF RCVR
CNTOC	CONTROL	COOLING	DUM1	DUMMY CONTROL VARIABLE
CNTOCL	CONTROL	COLLECTOR	DUM2	
CNTODD	CONTROL	DEPRESSURIZATION-DESUPERHEAT	CDDV1, CDFCV4	VALVE POSITIONS
CNTOF	CONTROL	FEEDWATER	CFFCV3	VALVE POSITION
CNTOR	CONTROL	RECEIVER	CRFCV1, CRFCV2, CRSV1, CRSV2, CRFCV3, CRDOOR	VALVE POSITIONS
CTODD	COOLING	DEPRESS-DESUPER	PCDD, TCDD, WCDD, HCDD, VCDD, PICDD	PRESS, TEMP, FLOW, ENTHALPY, SPECIFIC VOLUME, FEEDBACK PRESSURE TERM
DDTOC	DEPRESS-DESUPER	COOLING	PDDC, TDDC, WDDC, HDDC, VDDC, PIDDC	PRESS, TEMP, FLOW, ENTHALPY, SPECIFIC VOLUME, FEEDBACK PRESSURE TERM
DDTOCN	DEPRESS-DESUPER	CONTROL	PVDDCN, PDDDCN	PRESSURE VALVES
DDTOF	DEPRESS-DESUPER	FEEDWATER	PDDF, TDDF, WDDF, HDDF, VDDF, PIDDF	PRESS, TEMP, FLOW, ENTHALPY, SPECIFIC VOLUME, FEEDBACK PRESSURE
DDTOR	DEPRESS-DESUPER	RECEIVER	PIDDR	FEEDBACK PRESSURE
ENVIRMT	EXECUTIVE	ALL MODULES	XTAIR, SVAIR	AIR TEMPERATURE AND PRESSURE
ETOCL	EXECUTIVE	COLLECTOR	EKATEN	ATMOSPHERICAL ATTENUATION
EXTOCL	EXECUTIVE	COLLECTOR	HKREFL	HELIOSTAT REFLECTIVITY
EXTOIN	EXECUTIVE	INSOLATION	ISSNO, STIME(65), SSGIN (65)	PROVIDES DIRECT INSOLATION

4. MODEL DESCRIPTIONS

This section describes the various analytical models which comprise the STTF dynamic simulation. The discussion is divided into the following areas, which are schematically represented in Figure 4-1:

Solar Insolation Model
Collector Model
Martin Marietta SRE Receiver Model
Feedwater Model
Depressurization/Desuperheater Model
Cooling Model
Plant Control Model

4.1 SOLAR INSOLATION MODEL

The insolation module supplies values of direct insolation, in watts per square meter, to the collector module. Insolation is calculated for a specified time of day, and day since equinox. The collector module is the only system module interfaced.

Insolation data for Albuquerque were extracted from the data tapes described in Ref. 3. These data are the accumulated direct insolation received over the preceding hour for each hour over a two-year period. For each of the 12 months, the best clear-day data were selected from among the days near the 21st of the month. The average insolation over the one-hour interval was taken as the actual insolation at the half hour. Figure 4-2 shows the insolation profiles for three representative days. Given an actual time and date, the corresponding insolation value is determined by linearly interpolating the data of Table 4-1. Other insolation models can be substituted for the described one by simply removing the table and substituting a new table representing the desired model.

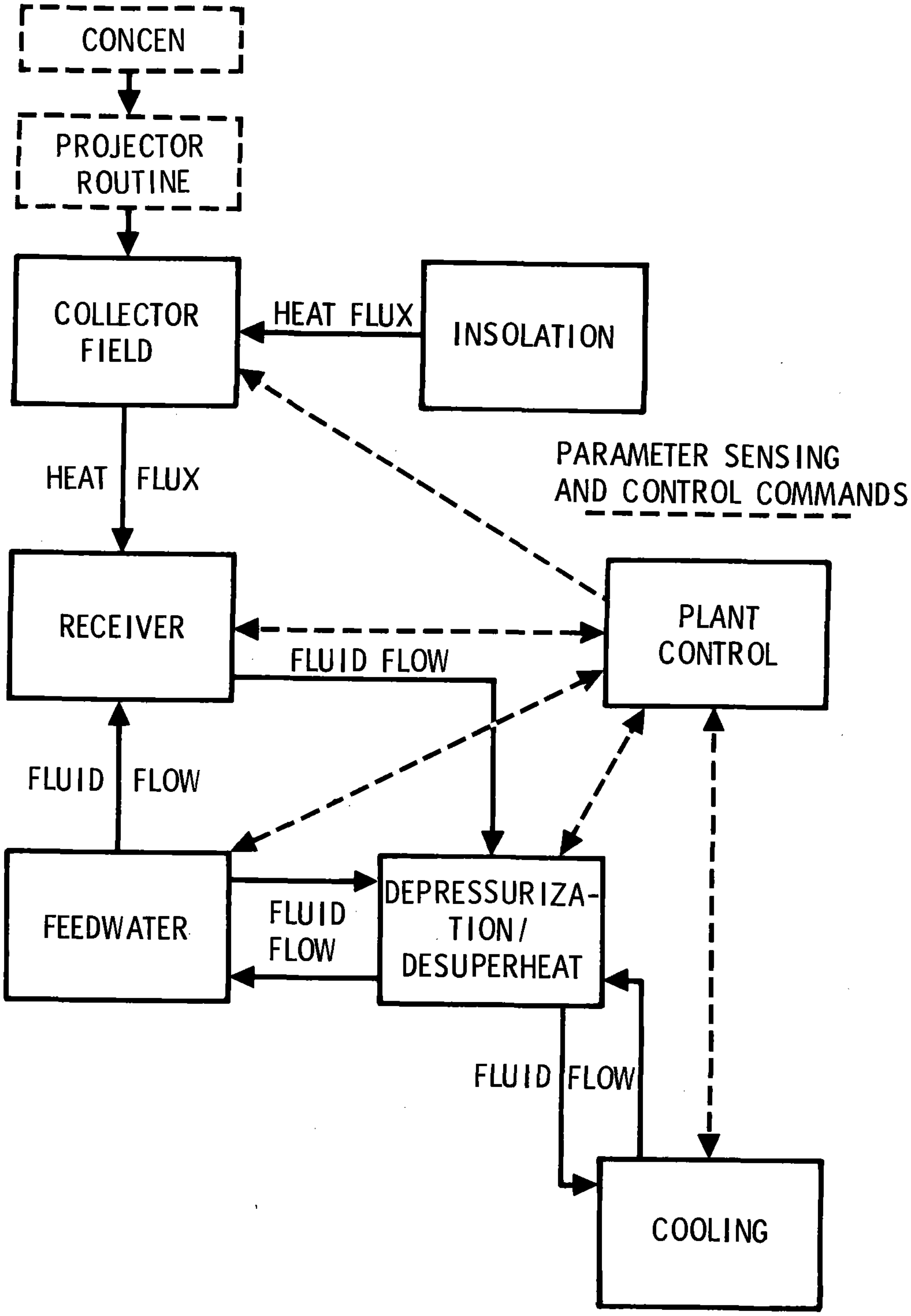


Figure 4-1. Basic STTF System Components

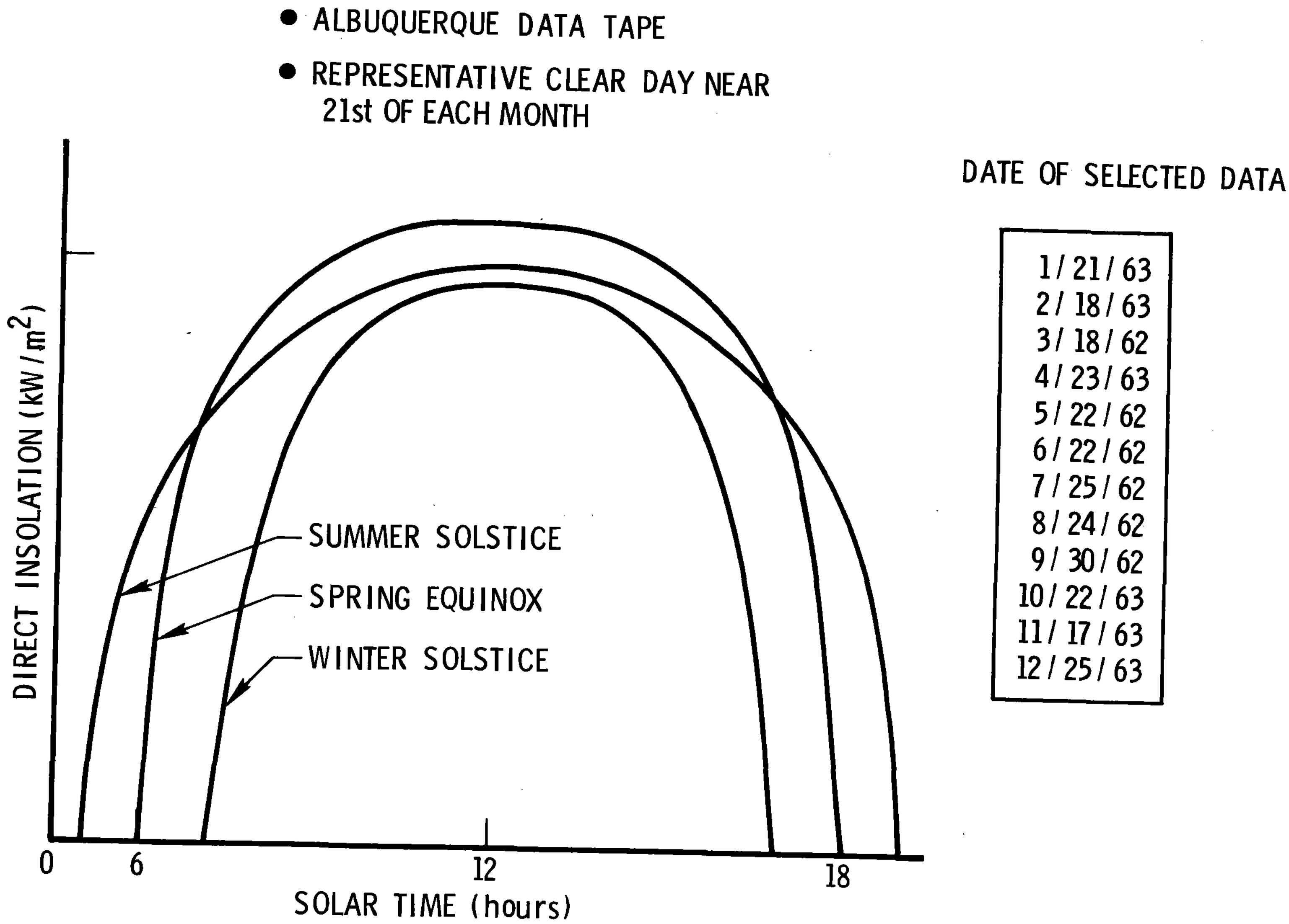


Figure 4-2. Built-In Insolation Model

Table 4-1. Solar Insolation Data (Albuquerque, NM) (kWm^2)

DATE			SOLAR HOUR 5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	21	63				50	82	91	96	96	96	95	90	80	43		
2	18	63				81	83	89	92	94	94	92	90	83	57		
3	18	52			56	86	96	103	106	106	106	105	101	94	83	46	
4	23	63		15	68	85	91	95	97	97	99	98	95	90	80	56	5
5	22	62		36	77	93	96	98	99	99	99	98	96	92	84	73	24
6	22	62		41	66	78	88	94	97	99	99	97	94	89	80	68	44
7	25	62		46	79	91	96	100	101	102	102	101	99	96	89	75	41
8	24	62		10	64	83	91	95	100	101	100	101	100	97	90	73	18
9	30	62			32	71	85	90	94	98	96	94	90	83	72	30	
10	22	63			9	55	75	83	87	88	88	87	85	77	54	6	
11	17	63				43	69	78	82	84	84	82	78	68	40		
12	25	63				30	72	87	94	96	96	94	87	74	31		

4.2 COLLECTOR MODEL

The collector module calculates total power into each of the receiver nodes for a specified time of day, and day since equinox. Internally generated values of normalized power are scaled by three parameters to calculate total power. Heliostat reflectivity and atmospheric attenuation coefficient are provided by the executive routines, direct insolation is provided by the insolation module, and output values of total power are then provided to the receiver module.

Implementing a full collector field simulation on-line would provide a high level of versatility in the simulation. However, the time and cost of running the simulation would be prohibitive, since each update would require 20-30 CPU seconds. In order to conserve resources, the expensive collector field analysis was moved off-line, leaving only an inexpensive table look-up on-line.

Collector modeling is implemented in three distinct routines, two performing off-line calculations and one performing on-line calculations. Basic collector field efficiency is performed off-line. A specially modified version of CONCEN (Ref. 4) provides flux distributions from selected representative heliostats throughout the collector field. The flux distributions, or maps, are then projected onto a specified receiver and integrated over the thermal nodes by the flux projector program. These off-line calculations provide the normalized power distribution to the receiver in the form of FORTRAN data statements suitably formatted for direct use in the collector module. The collector module is the on-line routine that actually calculates receiver power for the simulation. Each of these routines is described in subsequent sections.

4.2.1 Collector Field Efficiency

For the analysis, the collector field is divided into regions or cells. Originally, each cell was chosen such that the furthest heliostat was within ±5° in elevation and azimuth from the center of the cell. The number of cells (~70) was sufficiently large that computational effort was little reduced from considering each heliostat individually. Also, the close-in cells had as few as one heliostat each. In order to reduce the computation effort, cell boundaries were then increased to ±5° to ±10° with the smaller bounds prevailing for the distant cells and the larger bounds prevailing toward the close cells. Figure 4-3 illustrates the resulting 28 cells.

Each cell is characterized by a single heliostat located at the centroid of the actual heliostats in the cell. The resulting flux distribution is assumed to be the same for every heliostat within the cell. A specially modified version of CONCEN calculates normalized flux distribution for each cell. The modifications to CONCEN do not change the basic theory; rather, they implement the features of STTF and the particular output data formats required by the simulation. Tables 4-2 and 4-3 list the essential parameters used for the calculations on the 28 cells.

Flux maps are calculated for each cell in the east half of the field at one-hour intervals from approximately sunrise to sunset. The flux maps consist of a table of flux at 441 points centered on the nominal aim point. Compression, smoothing, and interpolation of this flood of data are accomplished by least squares fitting polynomials to the table data. Examination of a number of flux maps revealed two distinct types of flux distributions.

When the incidence angle of the incoming rays relative to the heliostat normal is small, the pattern of the reflected beam is essentially axi-symmetric. The resulting radial distributions are well approximated by a fifth degree polynominal expressing flux as a function of radius in the form

$$F_n(r) = \sum_{i=o}^{5} a_i r^i \qquad (4-1)$$

where F_n is the flux a distance r from the center of the distribution. Most of the flux distributions fall in the category.

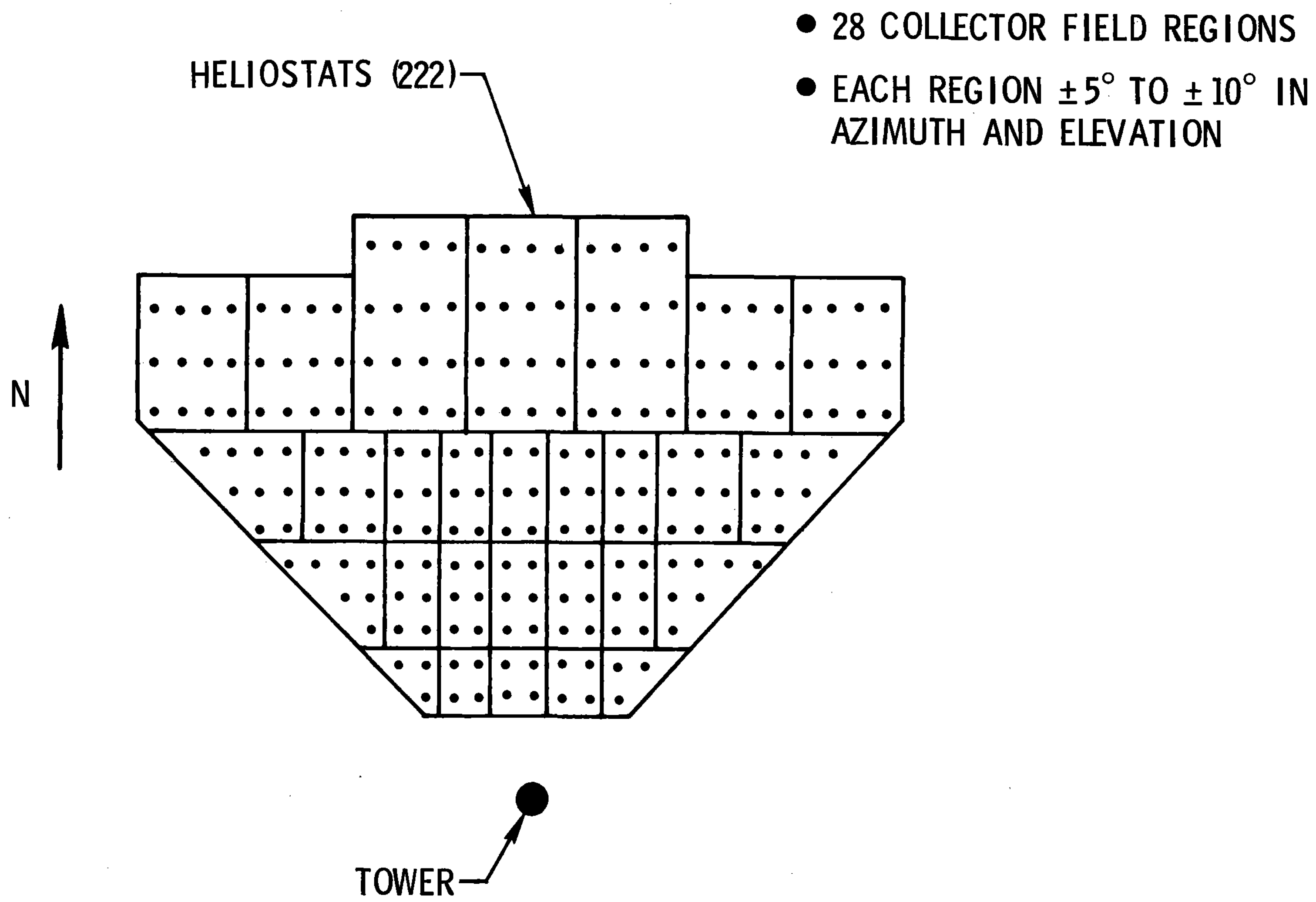


Figure 4-3. Collector Field Layout in Cells

Table 4-2. Basic Parameters for CONCEN Analysis

Category	Value
Insolation	1 W/m^2
Latitude	36.05°N
Tower Height	61 m
Reflectance	1
RMS Tracking Error	1.5 mrad
RMS Waviness Error	1.0 mrad
Heliostat Size	6.4 × 6.4 m^2
Facet Size	1.22 × 1.22 m^2

Table 4-3. Cell Parameters of CONCEN Analysis

Cell No.	Azimuth (deg)	Radial Distance (m)
1	221.91	55.98
2	206.21	44.17
3	180.00	45.72
4	153.79	44.17
5	138.09	55.98
6	220.08	98.46
7	209.10	80.23
8	195.55	72.77
9	180.00	70.10
10	164.45	72.77
11	150.90	80.23
12	139.92	98.46
13	220.23	145.15
14	210.58	124.62
15	199.98	114.16
16	190.30	109.05
17	180.00	107.29
18	169.70	109.05
19	160.02	114.16
20	149.42	124.62
21	139.77	145.15
22	217.14	193.86
23	206.79	173.12
24	193.37	168.71
25	180.00	164.14
26	166.63	168.71
27	153.21	173.12
28	142.86	193.86

During times of early morning or late afternoon, reflected flux distributions exhibit distinct 2-axis characteristics. The effects are more pronounced for cells at extreme angles from north. These distributions are adequately represented by a 2-axis fifth-degree polynomial curve fit of the form

$$F_n(x, y) = [1, x, x^2, x^3, x^4, x^5]\ C\ [1, y^1 y^2 y^3 y^4 y^5]^T \qquad (4\text{-}2)$$

where F_n is the normalized flux at point (x, y) and C is a 6 × 6 matrix of coefficients.

The characteristics of the entire collector field are contained in the coefficients of these flux maps as calculated for each cell, time, and day. Once calculated, these relatively high-cost calculations need not be repeated, since all of the relevant information is contained in the coefficient. Reconfiguration of the field or the receiver is accomplished by adjusting weighting coefficients and receiver parameters in the projector program described in the next section.

Table 4-4 illustrates a typical flux map output. The first line contains the following data in order:

- Cell number
- Time in hours since midnight date in days since equinox
- Slant range to the receiver in meters
- Azimuth of the heliostat from the tower in radians measured from south
- x offset of center of distribution in meters
- y offset of center of distribution in meters
- Maximum radius of distribution in meters
- A parameter indicating axis symmetric, or 2D distribution.

The next six lines are coefficients of the distribution.

4.2.2 Projector Routine

This routine projects the flux distributions, calculated by CONCEN, onto a receiver of specified geometry and integrates the flux over the receiver's thermal nodes. The resulting nodal power profiles are punched out on cards in the form of FORTRAN data statements directly usable in the on-line collector module routine. Table 4-5 illustrates a typical projector output.

The projector routine analyzes cavity-type receivers with rectangular apertures and one to three internally lighted flat walls. The Martin Marietta receiver is of this type. Three different coordinate systems are used. The aperture coordinate system is used to describe the geometric details of the receiver and also provides a connection between the wall coordinate and the heliostat coordinate systems. Flux is integrated in the wall coordinate systems to get total power in a thermal node, while basic flux distributions are given in the heliostat coordinate system.

4.2.3 Collector Model

The collector module in the simulation is a simple table look-up procedure. Tables of nodal power profiles are supplied via the projector program output, and these tables are interpolated for the power into each receiver node for a specified time and day. Interpolation is based on fitting a quadratic curve to the nearest points in the table, then estimating the desired value from the curve. Fluxes initially are estimated for the correct time on three days in the table. These three values are then used for an additional curve fit for the correct day. The number of curve fits are reduced appropriately if the specified time or day corresponds to a point in the table.

4.2.4 Extended Capability

Modifying the projector program from off-line to on-line would permit simulation of detailed transient phenomena, such as cloud passage,

Table 4-4. CONCEN Flux Map Parameters

```
3    7.00  0.00     45.7200     3.141593     -.143149      .185564     1.508796   1
   15.7735      -7.3294     -22.8882      6.8040       8.1256       -.1847
    1.9603      -3.5786     -12.3080      5.8245      10.8274      -2.8139
   -9.2760      22.8778     -36.1227    -20.7833      44.7961       -.3073
   -6.5690      13.0661      36.1735    -19.4929     -31.2552       7.7302
   -4.6459     -14.5450      54.4017     11.0372     -49.6608       2.4040
    5.0751      -8.6049     -25.3412     11.8020      21.5017      -3.9716
```

Table 4-5. Sample Data Statement Produced by Projector Program

```
      DATA ((FLUX(I,J,1),I=1,13),J=1,7)/0.0000,5.8056,7.2864,7.9990,
     1 8.3471,8.5386,8.5335,8.5074,8.2922,7.9863,7.3464,5.9288,0.0000,
     2 0.0000, .2575, .3577, .4492, .5101, .5504, .5917, .6031, .6204,
     3  .6838, .5943, .5016,0.0000,
     4 0.0000, .2392, .2231, .2961, .2021, .2040, .1997, .2039, .1915,
     5  .3017, .2302, .1997,0.0000,
     6 0.0000, .4591, .6005, .6900, .6061, .6097, .5894, .5547, .5058,
     7  .4518, .3702, .2824,0.0000,
     8 0.0000, .1766, .2203, .2306, .2314, .2284, .2237, .2105, .1908,
     9  .1603, .1297, .0980,0.0000,
     A 0.0000, .0860, .1252, .1616, .1925, .2070, .2225, .2236, .2294,
     B  .2270, .2198, .1918,0.0000,
     C 0.0000, .3007, .3454, .3753, .3853, .3954, .3949, .3928, .3881,
     D  .3777, .3558, .2897,0.0000/
```

heliostat tracking jitter, normal and emergency shutdown, and equipment failure. Providing this capability on-line, however, would significantly increase the program execution time.

4.3 THERMAL-HYDRAULIC MODELS

The thermal-hydraulic subsystems of the STTF Simulation are the Experimental Receiver Subsystem, Feedwater Subsystem, Depressurization/ Desuperheat Subsystem, and Cooling Subsystem. Each of these subsystems corresponds to the principal function of a group of STTF hardware components.

4.3.1 Analytical Assumptions

The modeling approach used for each of the subsystems listed above was identical and sought to meet the following criteria:

- The use of physical laws and well-established empirical correlations
- The modeling equations to be no more complex than necessary
- A model for each of the primary hardware components of the subsystems.

To meet these criteria, a lumped parameter model for each of the simulation's subsystems is developed by dividing the subsystems into a finite number of sections or control volumes. These control volumes are categorized as two types:

1. Metal control volumes which bound closed thermodynamic systems such as the walls of drums and heat exchangers.
2. Fluid control volumes which bound open thermodynamic systems corresponding to regions in space occupied by working fluids.

The general form of the describing equations developed for these control volumes, as well as the basic modeling assumptions and nomenclature, are given in Table 4-6. These equations are not applied in this form

Table 4-6. Governing Equations and Assumptions

I. EQUATIONS

- Fluid Dynamics (Fluid Control Volumes)

Mass Equation

$$\frac{d}{dt} (m)_{cv} = w_i - w_o$$

Energy Equation

$$\frac{d}{dt} (U)_{cv} = (wh)_i - (wh)_o + \dot{Q}_{cv}$$

Momentum Equation

$$\left[L \frac{d}{dt} (w)\right]_{cv} = (AP)_i - (AP)_o - \left(\frac{K_f w^2}{m}\right)_{cv} + \left(\frac{vw^2}{A}\right)_i$$

$$- \left(\frac{vw^2}{A}\right)_o + \left(\frac{A}{v}\right)_{cv} (Z_i - Z_o) g$$

- Thermal Dynamics (Metal Control Volume)

Heat Transfer Equation

$${}_1\dot{Q}_2 = h_q A_q (T_1 - T_2)$$

Energy Equation

$$\frac{d}{dt} (U)_{cv} = \left[cm \frac{d}{dt} (T)\right]_{cv} = \dot{Q}_{cv}$$

Table 4-6. Governing Equations and Assumptions (Continued)

- State Equations

  Saturated Steam Tables

  Superheated Steam Tables

II. NOMENCLATURE

- Variables

  A = flow cross-sectional area

  A_q = heat transfer surface area

  c = heat capacity

  g = local acceleration due to gravity

  h = specific enthalpy

  h_q = heat transfer coefficient

  K_f = steady-state friction coefficient

  L = length

  m = mass

  P = pressure

  $\dot{Q}$ = heat transfer rate

  T = temperature

  U = total internal energy

  v = specific volume

  w = mass flow rate

  Z = elevation coordinate

Table 4-6. Governing Equations and Assumptions (Continued)

- Subscripts

  cv = control volume

  i = inlet condition

  o = outlet condition

III. ASSUMPTIONS

- One-dimensional dynamics
- Kinetic and potential energy terms are neglected
- Homogeneous fluid phases in thermodynamic equilibrium
- Heat transfer surfaces at uniform temperature
- Heat transfer coefficients evaluated from steady-state empirical correlations

to every control volume comprising the simulation however. For thermodynamic systems with much faster dynamic responses than those providing major STTF performance parameters, or for those systems which experience only minor variations in their state variables, the steady-state form of the describing equations is considered adequate. Other assumptions related to equation development are the following:

- When heat transfer occurred between a fluid control volume and a metal control volume, only the convective mode of heat transfer is assumed to occur. Radiative and convective modes are assumed to occur when heat transfer takes place between a metal control volume and the environment.

- Pumps, which are an example of fluid control volumes, do not appreciably affect major performance parameters. Therefore, displacement pumps are assumed to generate constant flow with pressure variations dependent on the piping system. Centrifugal pumps, on the other hand, generate a pressure increase modeled by the equation

$$\Delta P = \alpha - \beta w^2 \tag{4-3}$$

  where ΔP is the pressure increase across the pump, w is the flow rate through the pump, and α and β are constants dependent on the particular pump. The energy addition to the fluid passing through a pump assumes a steady-state flow, adiabatic process, with negligible kinetic and potential energy and compressibility effects. The model equation that results is

$$\Delta h = v\Delta P \tag{4-4}$$

  where Δh is the enthalpy increase across the pump, ΔP is the pressure increase across the pump, and v is the specific volume of the fluid passing through the pump.

4.3.2 Martin Marietta SRE Receiver Model

The receiver modelled is shown schematically in Figure 4-4. (Refer to Section 2.3 for a functional description of the module.)

4.3.3 Heat Rejection Subsystem Models

The schematic of the STTF Heat Rejection Subsystem is shown in Figure 4-5. The depressurization-desuperheater model takes superheated steam from the receiver experiment and depressurizes it, using a pressure control valve, and then enters the desuperheater drum. Water sprays from the cooling module, condenses the steam, and the resulting condensate is subcooled. As the condensate flows from the desuperheater drum, a portion is extracted for feedwater purposes, while the remainder is used for the desuperheater water sprays. This spray water passes through a diverting valve which controls the pressure in the desuperheater drum by regulating the amount of spray water flow to a conventional shell-and-tube heat exchanger. (Pressure in the desuperheater drum is dependent on the spray water temperature.)

The desuperheater drum condensate extracted as feedwater passes through a displacement pump as it proceeds to the receiver experiment. The pressure of the feedwater is regulated by a bypass valve which returns feedwater to the desuperheater drum.

The cooling subsystem module takes the condenser condensate to the shell side of a heat exchanger and a cooling loop rejects heat to the environment by using six dry cooling towers.

4.4 PLANT CONTROL MODEL

All flow control systems are composed of the following essential parts:

1. Sensing or measuring elements.
2. A controller which produces output signals as a result of comparing measured values with desired values.

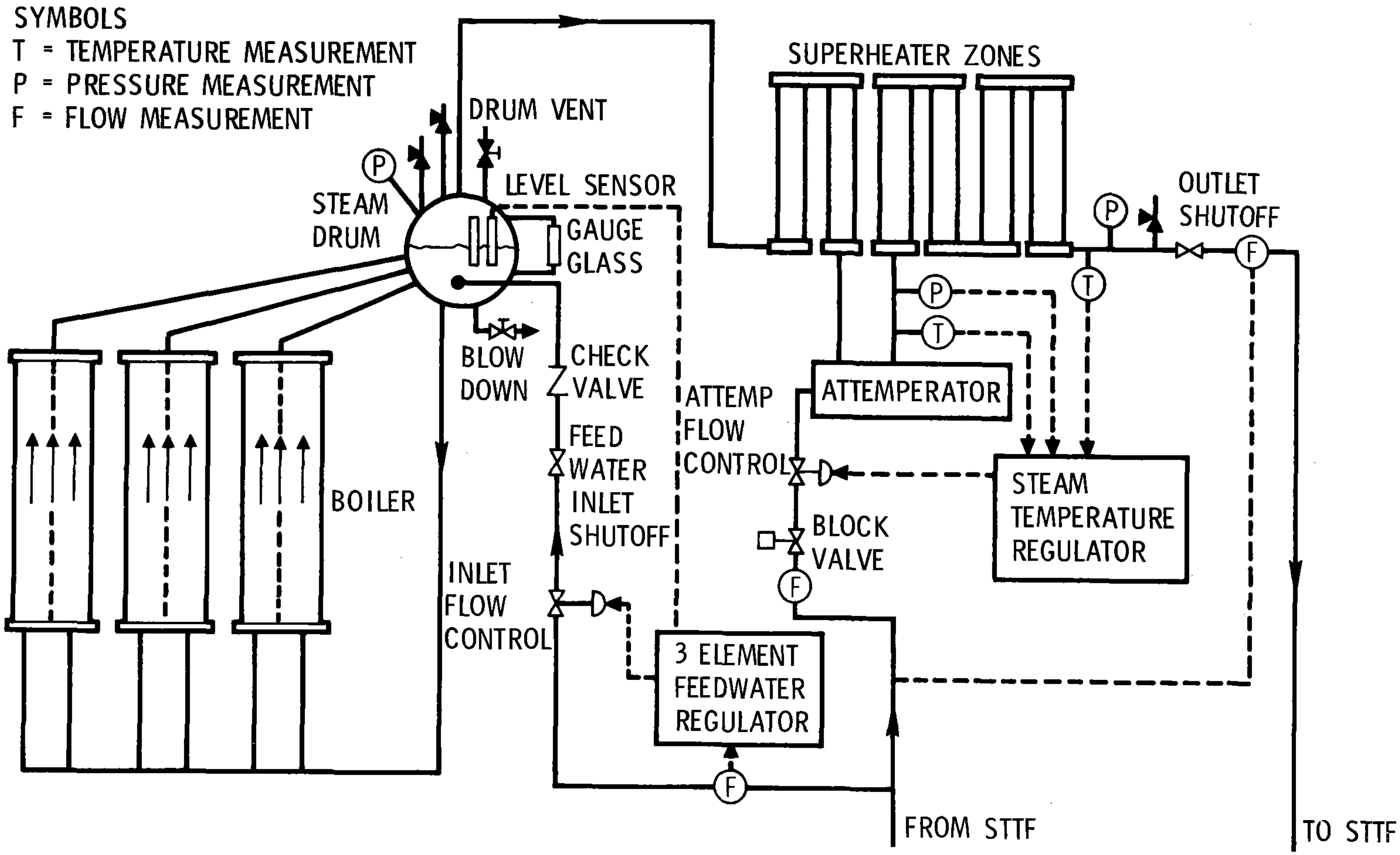


Figure 4-4. Martin 5 MW_t Receiver Schematic

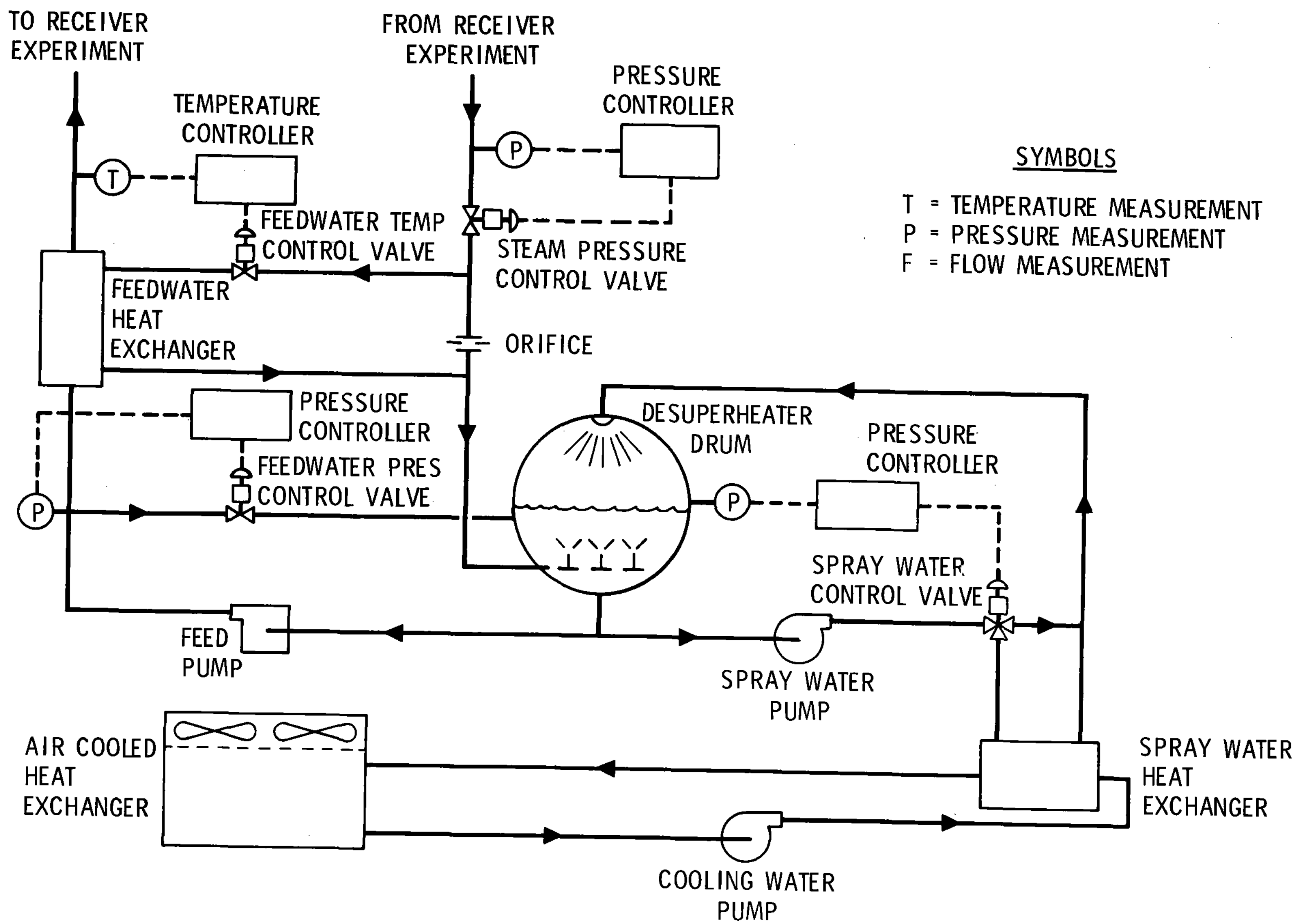


Figure 4-5. Heat Rejection Subsystem Schematic

3. Actuators which respond to the controller output signals and move the final control elements.

4. Final control elements or valves to produce a change in the measured variables.

Of these four flow control system parts, items 2 and 4 (the controller and valve characteristics) are modeled in the STTF Simulation. The dynamics of sensing or measuring elements as well as any input signal computations (such as converting a pressure drop signal to a flow rate signal) are not considered; and all valve actuators are assumed to be linear and any dynamic lag characteristics associated with the actuator and its valve are neglected.

The control valves used in the STTF are all globe valves with equal-percentage or parabolic flow characteristics. (The flow characteristic expresses the way in which the flow through a valve depends on percentage of valve stem travel.) The flow characteristics of these valves when installed in a piping network can be modeled by the equation

$$w = \frac{L^2}{\left[\alpha + (1 - \alpha) L^4\right]^{1/2}} \tag{4-5}$$

where w and L are the percent of maximum flow and stem travel, respectively, and α is defined as

$$\alpha = \frac{\text{valve pressure differential at maximum flow}}{\text{valve pressure differential at zero flow}}$$

This equation is incorporated into the describing equations for all fluid control volumes containing control valves.

The modeling equations used for the controllers correspond exactly to the control logic and transfer functions shown in the contractors' block diagrams. The control logic diagrams for the flow control loops shown in

Figure 4-5 are given in Figures 4-6 through 4-8. The legend for these diagrams is given in Figure 4-9.

The feedwater controller has three inputs: steam flow, feedwater flow, and water level. The feedwater flow is controlled to maintain boiler inlet and outlet flow rates constant and equal, and to maintain a constant fluid level in the boiler drum. Figure 4-6 illustrates the control logic.

The receiver uses an attemperator for output steam temperature control. The attemperator control logic is shown in Figure 4-7. The attemperator adiabatically mixes feedwater with the second superheat panel output steam to control the superheater outlet temperature.

The pressure controllers measure the pressure to be controlled, against a set point, and adjust the pressure control valve. The controller logic is shown in Figure 4-8.

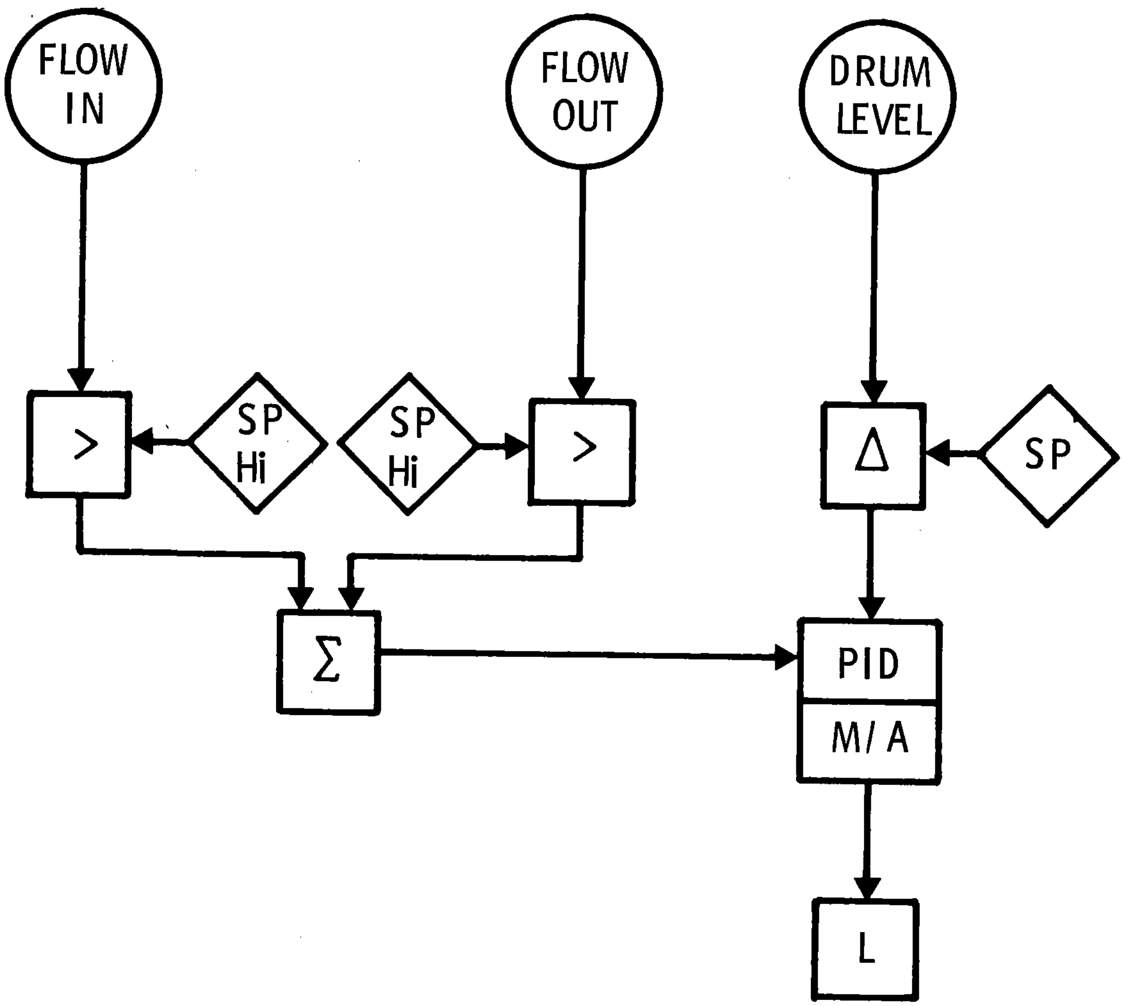
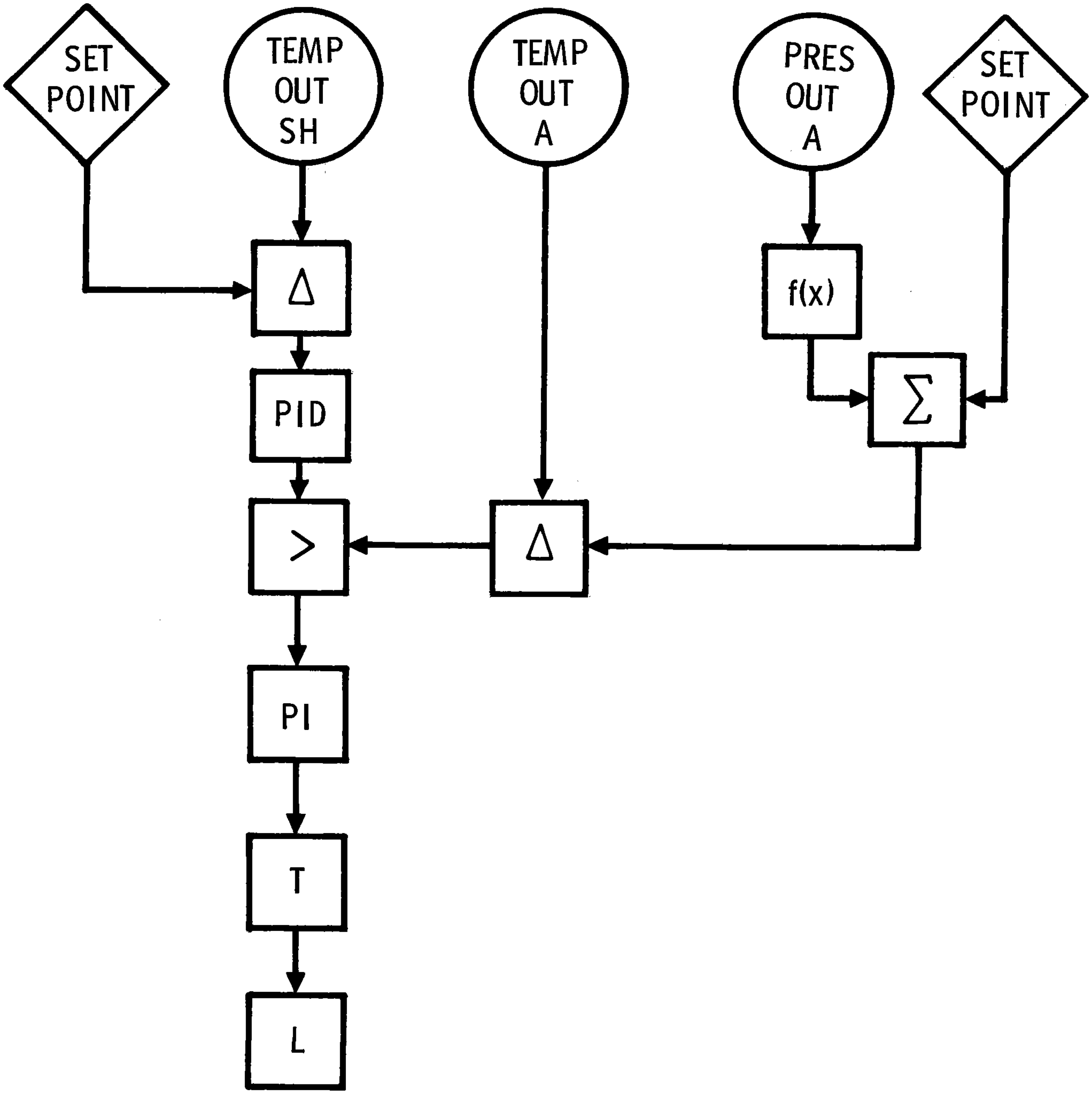


Figure 4-6. Martin Marietta Feedwater Regulator Logic



Where f(x) = saturated steam table

Figure 4-7. Martin Marietta Steam Temperature Control Logic

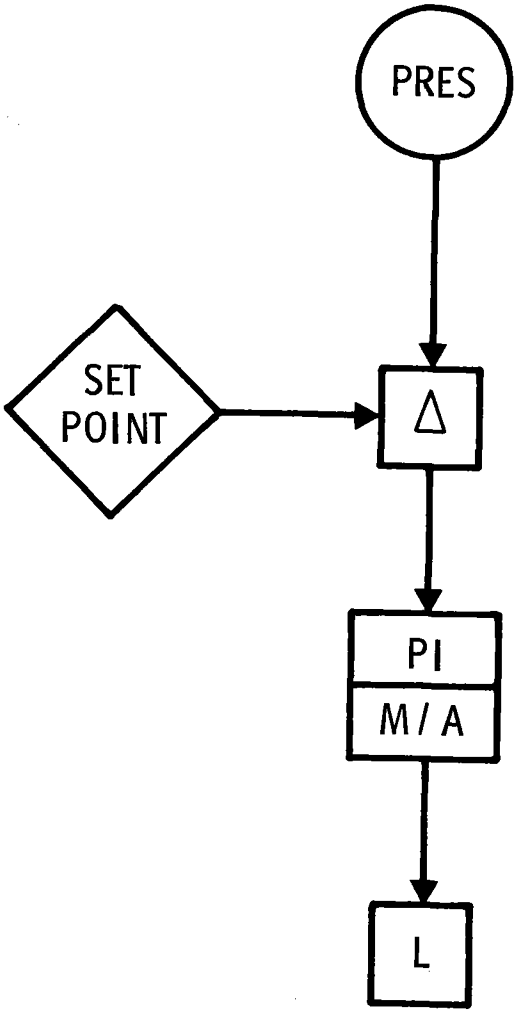


Figure 4-8. STTF Pressure Control Logic

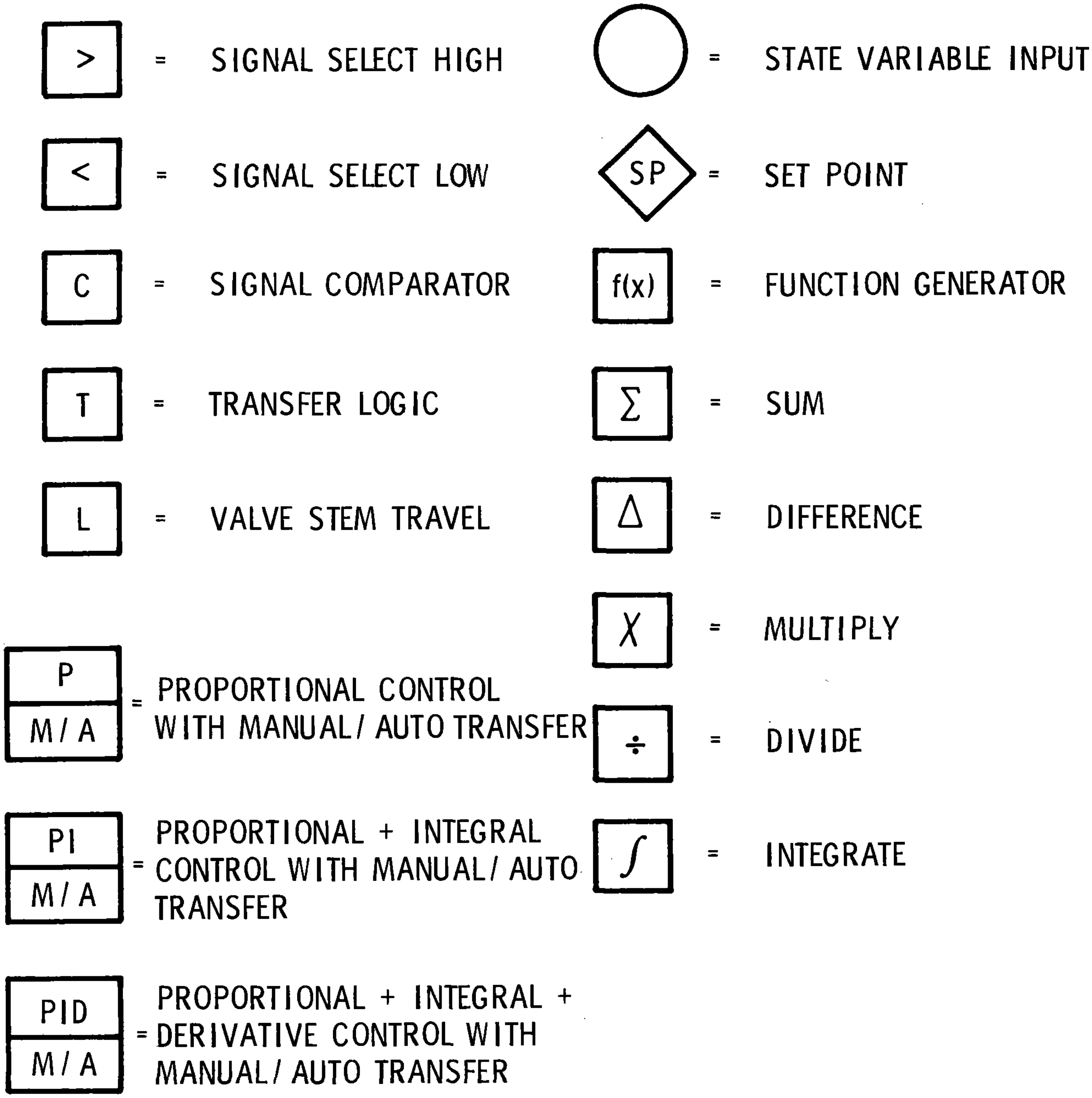


Figure 4-9. Legend for Control Logic Diagrams

5. PROGRAM VERIFICATION

Analytical models and programming techniques are verified by comparison to available test or operational data. Since the STTF facility is not yet operational, only the Martin Marietta SRE receiver model has been verified by comparison to test data. Although test data are lacking on the hardware unique to the STTF, their models are considered adequate, because the modeling philosophy for these components is identical to that used for the receiver. When test data become available a verification procedure similar to the one presented in this document for the receiver will be performed on all STTF subsystems to lend further support to this contention.

5.1 MARTIN MARIETTA SRE RECEIVER SIMULATION

To verify the Receiver Simulation the results of a computer simulation run were compared with actual test data on the Martin SRE receiver, obtained at the Sandia Laboratories Albuquerque Radiant Heat Facility during the period February 1-23, 1977 (Ref. 1). The design nominal heat-flux profile that the IR system was to produce simulates the profile predicted for the pilot-plant receiver operating at 1400 hours on the winter solstice with an insolation level of 0.8 kW/m^2.

Of the 19 test cycles the SRE receiver was subjected to, a cold-start test was selected as the most appropriate for verification purposes, because it subjects the receiver to the greatest anticipated thermal-hydraulic extremes and, therefore, produces maximum transient response. The test brings the receiver to full power, pressure, and temperature conditions from an ambient start point in a prescribed time period. For the test selected, the design superheater outlet temperature of 960°F was reached in five hours, and the design outlet pressure of 1325 psig was achieved approximately 1.7 hours later. The maximum electrical power input was 4000 kW, resulting in a final steam flow of 7000 lbm/hr. Figure 5-1 gives a comparison of the actual test data and the computer simulation results.

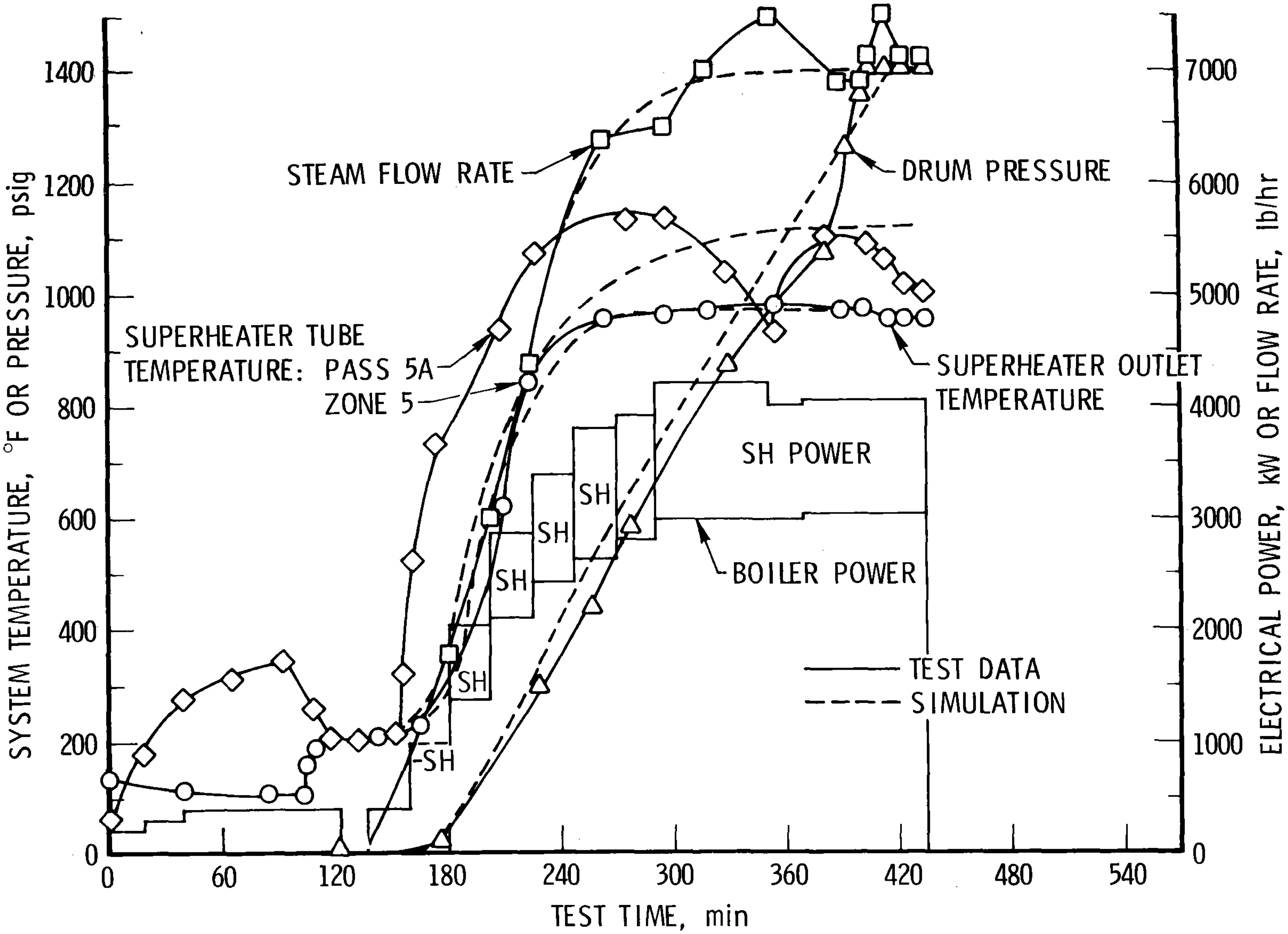


Figure 5-1. Cold Start Test 2, February 22, 1977

(Actual simulation output is given in Figures 5-2 to 5-4). For simulation purposes, the power input and outlet flow rate were controlled parameters, while steam drum pressure, superheater outlet temperature, and superheater tube temperature were system responses.

During the actual test, the boiler drum pressure and steam flow were controlled by manual operation of an outlet pressure control valve until the boiler drum pressure reached its design valve of 1325 psig, at which point the control valve was placed on "automatic" to maintain the boiler drum pressure at this value. Because superheater outlet pressure data were not available for the cold-start test, the simulation was run with the outlet conditions controlled via the steam flow rate; i.e., the outlet control valve was modeled as a flow control valve rather than a pressure control valve. The simulation response for superheater tube temperature zone 5 is not specifically representative of the test data for superheater tube temperature pass 5A. This response is an average tube temperature for the 14 tubes in zone 5, while the test data represent the front surface temperature of only one tube in zone 5.

The superheater outlet temperature was automatically maintained at its design value of 960° F by the attemperator flow control valve during the actual test and also during the simulation. The steam drum inlet flow control valve was also modeled for the simulation and maintained the drum water level at its normal operating point.

As can be seen, the SRE Simulation's pressure and temperature responses matched closely the responses of the actual system. They are considered quite adequate for the simulation's primary intent: the calculation of the transient response of major performance parameters.

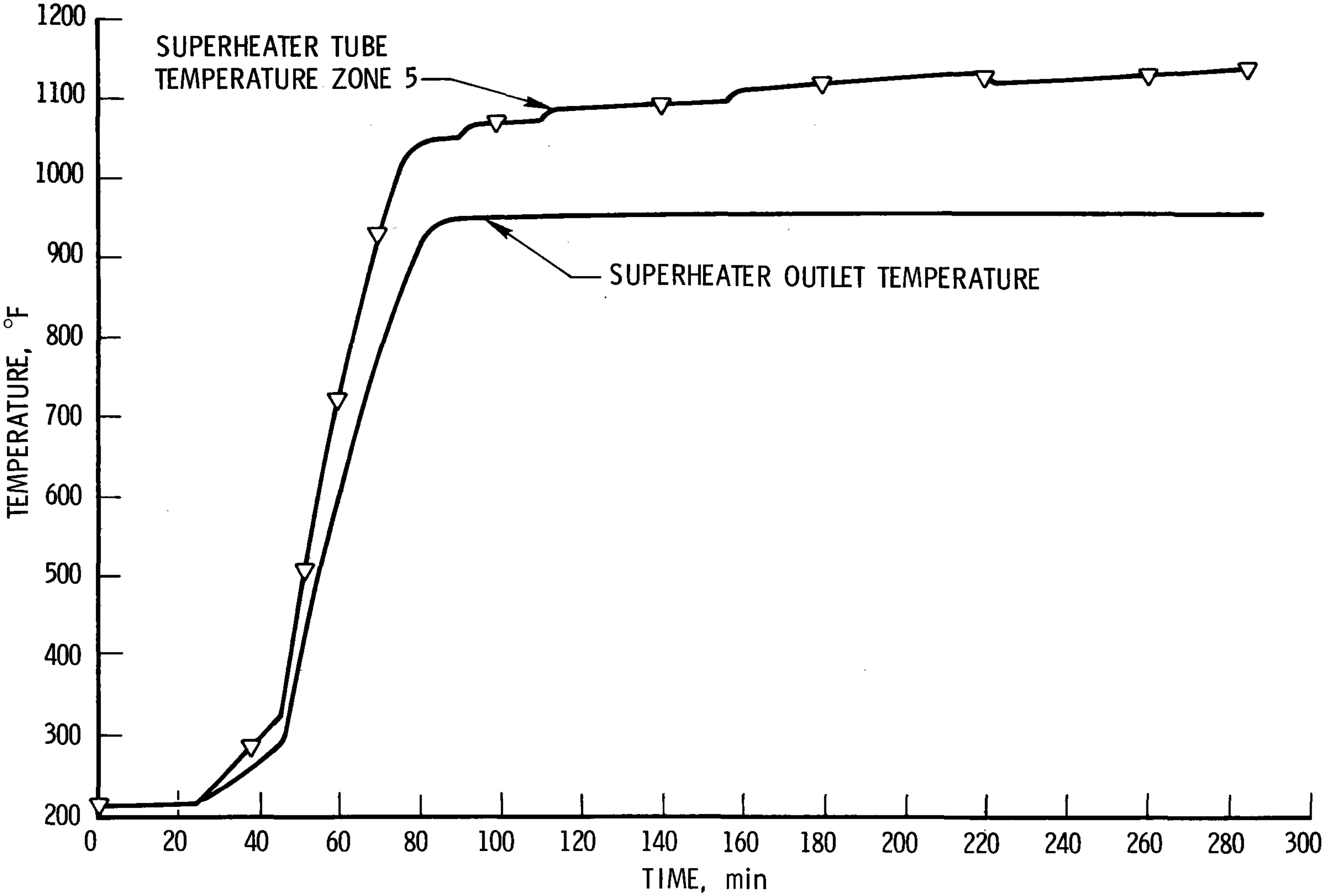


Figure 5-2. SRE Receiver Temperature

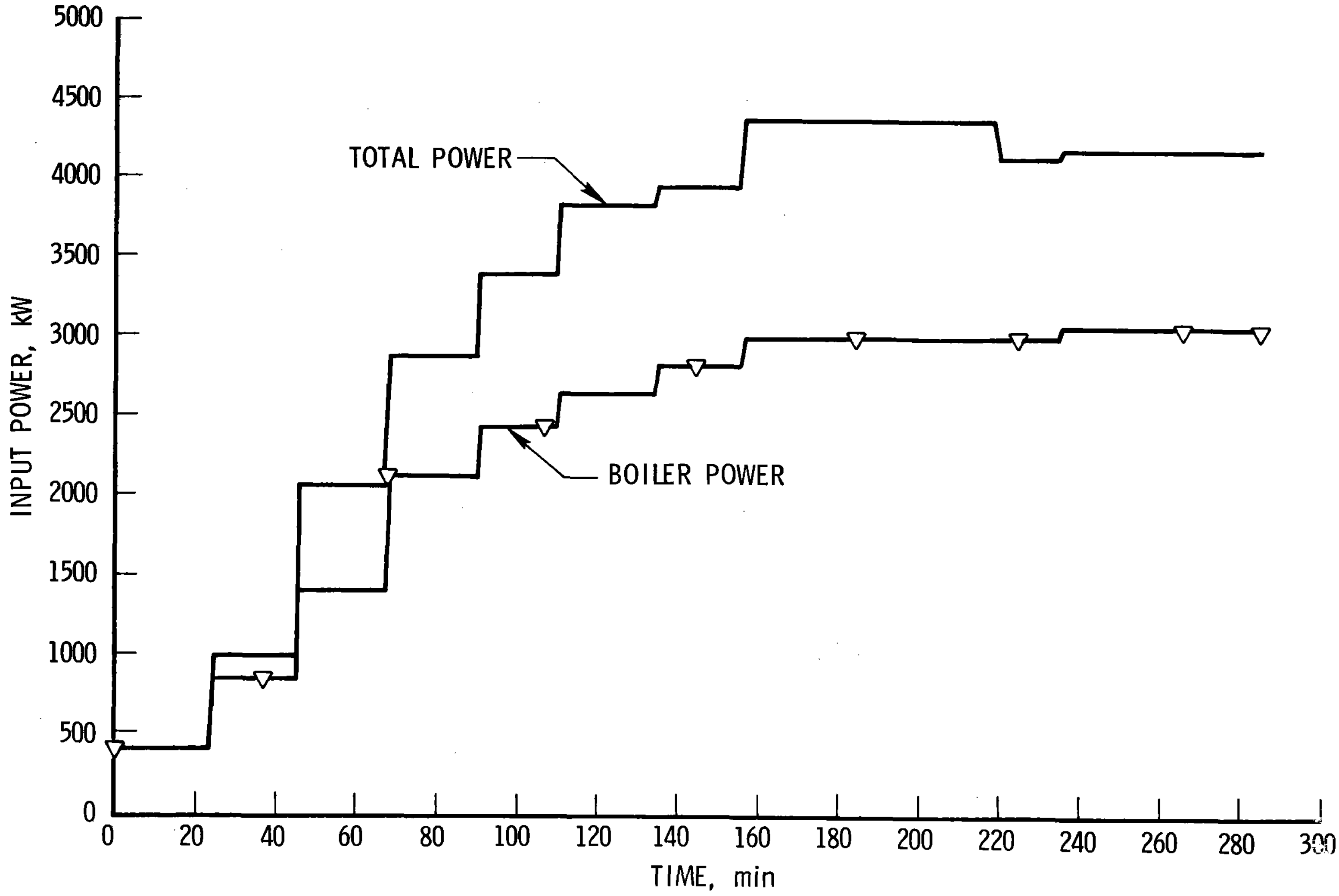


Figure 5-3. SRE Receiver Power Input

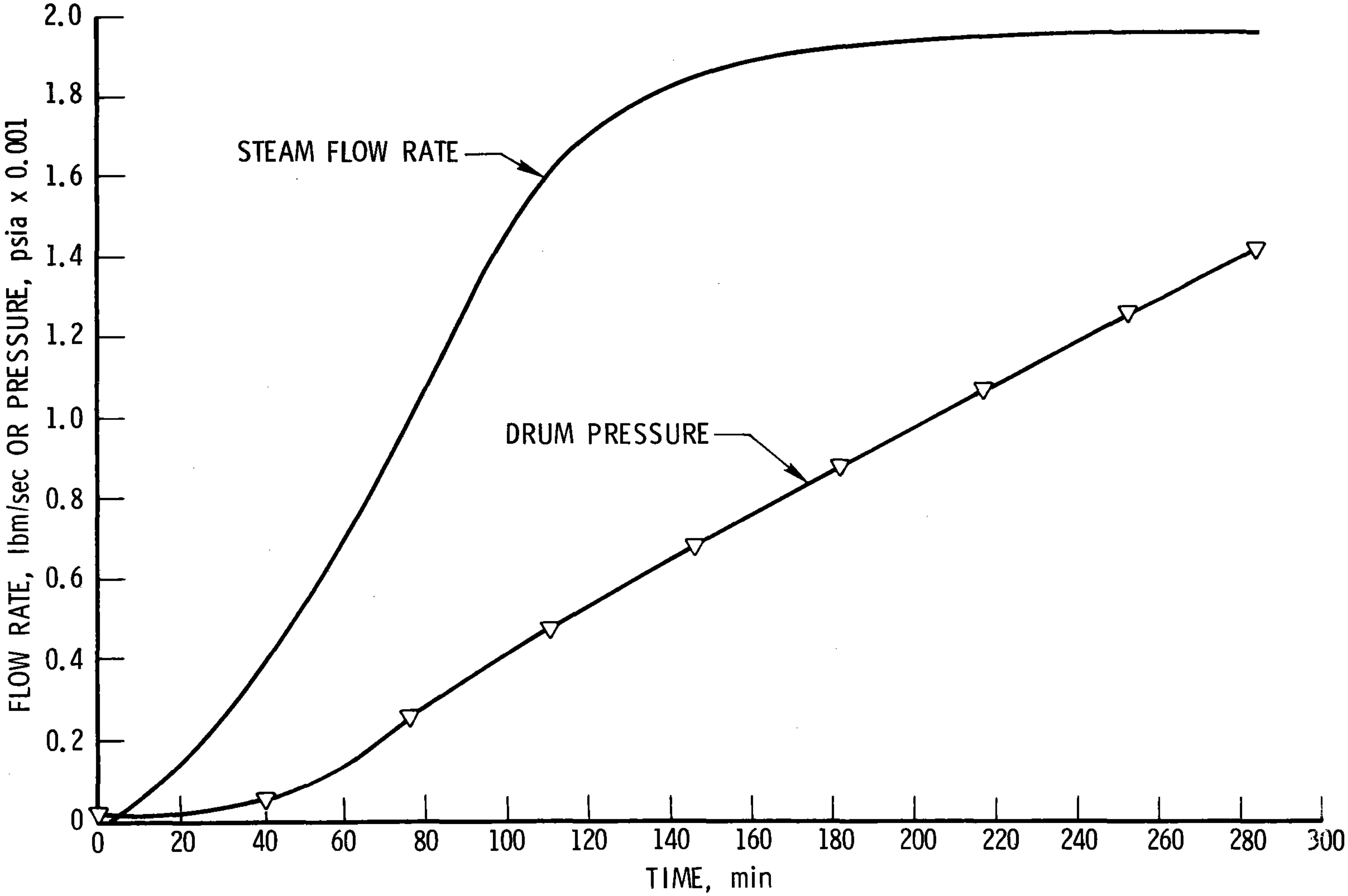


Figure 5-4. SRE Receiver Flow Rate and Pressure

6. STTF COMPUTER SIMULATION APPLICATIONS

The STTF computer simulation is an analytical tool designed to be used by the STTF experimenter in the design, test planning, test support, and data evaluation phases of an experiment. The program has its maximum use in prediction of overall system level interactions, performance, and control; rather than the prediction of detailed component information, such as temperature distributions, which are better handled by specialized programming. The computer program simulates the performance characteristics of the major optical and thermal/hydraulic systems of the STTF, and its structure allows the experimenter to insert a module which may consist of a series of subroutines to describe his particular experiment. The experimenter may then design, plan, evaluate and verify the safety of his experiment by computer prior to the test at the facility, thereby reducing test costs and improving facility utilization.

Potential program users include those organizations responsible for experiments to be performed in direct support of the Pilot Plant project. These tests are the first planned at the STTF and include SRE receivers and heliostats. Other planned experiments are those listed in the Solar Electric Program Plan. Included are tests on chemical/material processes, advanced receivers, and energy conversion systems.

6.1 PROGRAM APPLICATION SUMMARY

Effective application of the STTF computer simulation can be made in the experiment design phase, test planning phase and in support of facility operations. Examples of these applications are summarized below.

System/Subsystem Analysis

Experiment Hardware Design	Verify system design objectives/performance by operating computer model under STTF conditions.

Control System Design	Verify control system design with more severe conditions than possible at the STTF.
Sensitivity Analysis	Vary appropriate parameters such as operating or environmental conditions to determine effect on overall experiment performance.
Modification Analysis	Identify consequences of component design or performance change.
Experiment Design/Support	
Test Planning/Test Objectives Qualifications	Identify the test runs, test schedule, probable results and problem conditions which will yield the greatest information during testing.
Measurement/Instrumentation Definition	Identify required instrument sizes, sensitivities, location and quantity.
Evaluation Procedure Definition/Checkout	Check out equipment and software used to evaluate test data using computer generated test data simulation.
Test Operation/Procedure Checkout	Evaluate test procedures and time sequences to ensure economical operation of the facility. Determine support system requirements. Verify experiment/facility control system operation. Verify safety of experiment/facility control system operation. Verify safety of experiment under normal and emergency conditions.
Extend Operating Profile	First calibrate the computer model using the test data and then extend the study of the operating profile of the experiment beyond that possible during the test.

Special Studies

Experiment Planning	Scenario variations to gain component/system design point data.
Component or Module Modification	Study/evaluate experiment modifications.
System Comparisons	Evaluation of two or more concepts under STTF conditions.
Operator Training	Use computer model for feedback to operator training operations.
Reliability/Availability Analysis	Evaluate effects of failure modes.

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2. Central Receiver Solar Thermal Power System, Phase 1, Volume IV, and Receiver Subsystem, Preliminary Design Report (Draft), Section V, Report No. SAN-1110-77-2, Martin Marietta (April 1977).

3. Insolation Data Base Available from The Aerospace Corporation, Report No. ATR-76(7523-11)-9, The Aerospace Corporation (December 1976).

4. McFee, R. H., "Power Collection Reduction by Mirror Surface Nonflatness and Tracking Error for a Central Receiver Solar Power System," Applied Optics, Vol. 14, page 1493 (July 1975).