MASTER

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THE AEROSPACE CORPORATION
El Segundo, California 90245

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REQUIREMENTS STUDY
FOR THE 10MW SOLAR
THERMAL PILOT PLANT
MASTER CONTROL
SUBSYSTEM

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Prepared by:

THE AEROSPACE CORPORATION
Energy Systems Group
El Segundo, California 90245

Principal Contributors:

R. H. Leatherman, Control Engineering Department
N. A. Nelson, Electromechanical Department

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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 Contract Number E(04-3)-1101, Project Agreement No. 2.

ABSTRACT AND SUMMARY

This report defines the requirements for the Master Control Subsystem (MCS) for the Ten Megawatt Solar Thermal Pilot Plant. It includes fundamental objectives, a basic definition of pilot plant operating modes, and a mode transition matrix. Specific MCS requirements are derived in terms of a requirements tree. A detailed plant configuration diagram containing all possible combinations of modes and control methods is included. Finally, control constraints and subsystem control requirements are summarized, and areas in which further MCS work is needed are identified.

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1.0 INTRODUCTION

This report contains the results of a Master Control Subsystem (MCS) Requirements task, which derived from a need to define and develop MCS objectives, design requirements, and operational criteria in some detail before a Solar Facility Design Integration (SFDI) contractor was chosen. It was felt by the DOE Pilot Plant Project Office and others associated with the project that the MCS was not developed to the extent of the other plant subsystems at the conclusion of the Preliminary Design phase of the program. Thus, a requirements definition effort prior to SFDI award would bring this subsystem to a level facilitating its integration with the other plant subsystems and with the test and operational planning. The starting point for the task was the existing documentation from DOE, Sandia, Aerospace, and the Phase I contractors, which contains general concepts and requirements for the MCS.

The MCS is a critical element in pilot plant design and operation. It performs control management, supervision, and data collection for the plant, integrating the independent controls of the four subsystems over all steady-state and transient operating modes.

The MCS requirements task was not to design the MCS, a function to be performed by the SFDI contractor. Thus, this report presents only general design requirements and no specific hardware implementation guidelines.

The work described includes:

- fundamental pilot plant/MCS objectives (Section 2.0)
- a basic definition of operating modes (Section 3.0)
- a preliminary transition matrix defining allowable and forbidden mode transitions in terms of energy flows (Section 3.0)
- two general types of daily scenarios (clear day and cloudy day) including failure paths, in terms of the transition matrix (Section 3.0)
- a "requirements tree" which flows down overall pilot plant and MCS objectives to specific MCS requirements, and corresponding plant control constraints and subsystem requirements (Sections 4.0 and 5.0)

- a plant configuration diagram and matrix defining all possible combinations of operating modes and control methods, for both load- and sun-following operation (Section 5.0)
- summaries of the results of the above work, including areas in which further work is needed for the MCS (Section 6.0).

2.0 OBJECTIVES AND REQUIREMENTS

2.1 PILOT PLANT

To define the MCS objectives and requirements, it was first necessary to establish the objectives and requirements of the pilot plant itself. Four fundamental objectives were derived from a review of literature from several sources discussing this subject. These objectives are to:

- 1) establish the technical feasibility,
- 2) demonstrate economic operation,
- 3) determine the environmental impact,
- 4) establish public acceptance (where public is defined as utilities, manufacturers, government, and citizen's groups and the general public)

of this type of plant so that a commercial plant may be built. The objective of the commercial plant is to generate power that is competitive economically and environmentally with that generated by other types of plants.

To meet these objectives, it is then required that the pilot plant provide:

For objective 1): subsystems that adequately represent all critical technical parameters including scaling considerations of the commercial plant; data to establish that usable power is being generated.

For objective 2): data on costs of construction, manufacturing, operating, etc., and on the worth of the generated power.

For objective 3): a design that adequately represents all critical environmental parameters of the commercial plant; data to measure the environment before and after the plant is built and in operation.

For objective 4): a design that adequately answers questions or concerns about the plant by providing sufficient data to the public in useful forms.

Note that "adequately" implies subjective judgment, and that the pilot plant itself is subject to constraints of cost, schedule, and technical feasibility.

2.2 MCS

The pilot plant objectives and corresponding requirements in turn imply the following requirements on the MCS (numbers in parentheses are the driving pilot plant objectives):

2.2.1 CONTROL REQUIREMENTS

Provide automatic control as it would be used in a commercial plant (1, 2, 3, 4), encompassing:

- most efficient power generation
- least polluting power generation
- startup
- shutdown
- emergency
- test/maintenance

Provide automatic control for test and evaluation purposes where manual control is not feasible (1, 2), for reasons of:

- speed
- accuracy
- repeatability
- stability
- safety

Provide automatic control for purposes where manual control is not desirable (2, 4), such as:

- automatic control demonstration requested by some segment of the public
- costs/losses reduced (such as emergency operations)
- safety factors increased

Support manual operation with automatic functions, such as:

- alarm generation
- performance evaluation

2.2.2 DATA ACQUISITION REQUIREMENTS

Technical data needed to establish feasibility (1) includes:

- proof of operation
- stability
- life
- safety

Economic operation (2) is demonstrated with data from which the following parameters may be assessed:

- life
- efficiencies
- safety

- maintenance
- availability

Environmental impact (3) is determined by means of data on:

- pre-plant environment
- pollution due to the plant

Public acceptance (4) will be determined by data from which interested parties may obtain answers to questions or concerns about the plant:

- utilities
 - simulation correlation
- manufacturers
 - subsystem specifications vs. operational requirements
 - interface requirements
- government
 - efficacy of funding
- general public
 - sufficient information to minimize controversy
 - data in usable form

3.0 GENERAL MCS OPERATION

3.1 OPERATING MODES

Several iterations of defining the steady-state operating modes of the plant have occurred to date on the program. For purposes of working with MCS control definitions, the eight modes originally defined by the MCS Evaluation Committee were used. This set of modes includes all ways in which the four subsystems can be interconnected for steady-state operation. The subsystems are:

Collector Subsystem (CS)

Receiver Subsystem (RS)

Thermal Storage Subsystem (TSS)

Electrical Power Generating Subsystem (EPGS)

For ease of discussion, the eight modes were named in a descriptive manner as shown in Figure 1.

Since the pilot plant is an evaluation facility, all possible modes should be included in its capability. Modes which are "unrealistic" or "inefficient" can then be eliminated from commercial plant considerations based on evaluation data from the pilot plant justifying the decision. Eliminating options from the pilot plant so that operating data on a particular mode could not be obtained may, for example, result in an inability to answer questions posed by interested agencies or may even unduly constrain commercial plant design.

3.2 TRANSITION MATRIX

Using the eight defined steady-state modes, an initial effort to develop a generalized mode-to-mode flow diagram led to the transition matrix of Figure 2. This matrix was derived by looking at only the fundamental energy flow between subsystems; e.g., assuming a steam flow from the RS to the EPGS is either "on" or "off".

In Figure 2, a ninth mode has been defined for completeness. It is called Inactive Output (IO; CS→RS EPGS TSS), in which the CS is heating the RS but no other subsystems are connected. This will not be a steady-state mode, but could appear as a transient or failure condition. The notation "ok" means that a direct transition from the mode defined on the

Mode 1: Basic Normal (BN)

Mode 2: Basic Normal & Charging (BN&C)

Mode 3: Storage Boosted (SB)

Mode 4: In Line Flow (ILF)

Mode 5: Charging Only (CO)

Mode 6: Storage Discharging (SD)

Mode 7: Dual Flow (DF)

Mode 8: Inactive (I)

Figure 1
Operating Modes

From \ To	TS C-R-EPG 1 BN	TS C-R-EPG 2 BN&C	TS C-R-EPG 3 SB	TS C-R-EPG 4 ILF	EPG C-R-TS 5 CO	C R TS-EPG 6 SD	EPG C-R-TS 7 DF	C R TS EPG 8 I	C-R TS EPG 10
1 BN	----	ok	ok	(SB) (DF) X (SB) (SD)	(BN&C) X	(SB) X	(SB) (BN&C) X	ok	ok
2 BN&C	ok	----	(DF) (BN) X	(DF) (CO) X	ok	(DF) (ILF) X	ok	ok	ok ?
3 SB	ok	(DF) (SD) X	----	(DF) (SD) X	(SD) (ILF) X (CO)	ok	ok	ok ?	(BN) (SD) X
4 ILF	(DF) (BN&C) X (DF) (SB)	(DF) X	(DF) X	----	ok	ok	ok	ok	ok ?
5 CO	(BN&C) X	ok	(BN&C) (DF) X (ILF) (DF)	ok	----	(ILF) X	(BN&C) (ILF) X	ok	ok
6 SD	(ILF) (DF) X (BN&C)	(ILF) (DF) X	ok	ok	(ILF) X	----	(ILF) X	ok	ok
7 DF	(SB) X	ok	ok	ok	(ILF) (BN&C) X	(SB) (ILF) X	----	ok ?	(ILF SB SB ILF) (SD BN SD CO) X
8 I	ok	(CO) (BN) X	(BN) (SD) X	(SD) (CO) X	ok	ok	(SD CO CO SD) (ILF ILF BN&C SB) X	----	ok
10	ok	(CO) (BN) X	(SD) (BN) X	(CO) (SD) X	ok	ok	(SD BN BN SD) (ILF SB BN&C SB) X	ok	----

Figure 2
Transition Matrix

vertical axis to the mode on the horizontal axis is possible. "X" means the direct transition is forbidden. A transition is considered forbidden if more than one flow path between subsystems must be added (e.g., RS→TSS and TSS→EPCS) at the same time, or if a flow path must be added while another path must be removed at the same time. These additions and removals cannot occur simultaneously in a real system due to, for example, different thermal time constants, and hence the system must transition through one of the other modes, if only for a short time. The CS→RS path is not included under this restriction because movement of the heliostats will be in a continuous manner and can occur simultaneously with other operations. Note also that removing more than one flow path "simultaneously" may occur, particularly in a failure. This possibility is denoted on the matrix by a question mark.

For forbidden transitions, modes or mode flows shown in parentheses are the paths by which the system can change from the mode on the vertical axis to the mode on the horizontal axis. For example, from Mode 2, BN&C, the plant would transition either through Mode 7, DF, or Mode 5, CO, to arrive at Mode 4, ILF. All possible paths are not shown on the matrix; only those paths which appear likely at this time are given.

This matrix begins to point out the control complexities of transitioning the pilot plant, even for a non-eventful power generating day. Transition paths must be chosen, by the MCS, for the particular set of operating conditions in effect at the time a mode change is to occur. This choice determines such operations as valve sequencing logic and set point adjustments vs. time, while continuously assuring that plant control requirements are met.

3.3 DAILY SCENARIOS

Two types of daily scenarios were initially postulated; normal, clear day (Figure 3), and cloudy day (Figure 4). The clear day scenario begins with the plant in Mode 8, proceeds through warm-up to normal operation in Modes 1 and/or 2, and then through shutdown, using Modes 3 and 6, to Mode 8 once again. In Figure 3, failure paths are shown for each of the steady-state modes used; failure here is defined as loss of an energy flow path between two of the subsystems. For example, when the plant is in Mode 4, if flow between the TSS and EPCS is lost, the plant is by definition in Mode 5.

flow continuing power generation

FIGURE 4
OPERATION WITH CLOUDS

Figure 4 presents the mode flow diagrams for operation when clouds are encountered. Two paths are shown, beginning with the plant operating normally in Mode 1 or Mode 2. The path on the left is for flow which endeavors to continue power generation. The dotted paths to Mode 8 would be used if for some reason shutdown became desirable. The path on the right transitions the plant to shutdown. It could be used, for example, if clouds occurred late in the day and/or stored energy was depleted to a considerable extent. A failure path is shown in this diagram only for Mode 5, which is the only mode that does not appear as an operating mode in the clear day diagram. Failure paths (in terms of energy flow) for the modes are, of course, independent of the scenario in which they appear; however, the action taken subsequent to the failure may not be.

The transition matrix and the generalized scenarios define broadly the typical plant operation over which the MCS must maintain control. They provide a starting point from which detailed MCS requirements and plant configurations can be derived.

4.0 REQUIREMENTS TREE

The method used to determine specific MCS requirements from the basic ones set out in Section 2.2 was that of a "tree", in which general requirements are broken into more detailed units and these, in turn, are broken into still more detail until a desired level is reached.

Figure 5 is an overview of the upper portion of the requirements tree; the entire tree is included as Appendix I. It can be seen from Figure 5 that the MCS requirements were divided into two categories; those pertaining to MCS operations and those concerned with MCS/subsystem interfaces. Under operating requirements, three types were established:

WHAT the MCS must do: it must demonstrate all possible plant configurations and transitions; this includes all possible types of steady-state operation and all necessary transitions.

HOW the MCS must do this: it must operate the plant in a stable, optimum manner, in particular, as a commercial plant would be operated, again for steady-state operation and for transitions.

WHAT ELSE the MCS must do: it must support test operations to the required extent.

There are two categories of MCS/subsystem interfaces; Operational Control Subsystem (OCS), which provides operational control of the plant, and Data Acquisition Subsystem (DAS), which provides all evaluation data acquisition and storage, independently of the OCS. Specific requirements were not generated for the DAS in the work documented herein. However, DAS requirements are extremely important to pilot plant MCS design since the purpose of the plant is evaluation. This is discussed further in Section 6.3.

The OCS is concerned with alarms, special tests, and normal plant operation. The latter includes intersubsystem flow splits (e.g., steam to TSS and/or EPGS), with mode commands and control commands to the subsystems, and with OCS (control rather than evaluation) data inputs from the subsystems. Note that an important subsystem requirement is also elucidated here; that each subsystem must have the capability to failsafe itself with no action from the OCS.

Figure 5
Requirements Tree

The remainder of the tree is a detailed breakdown of the above categories. The actual requirements on OCS functions, derived from the tree, are described in the following section.

5.0 OCS REQUIREMENTS

The requirements described in this section are intended to be a starting point and guide for OCS design by the SFDI. They are not in any sense a technical specification. However, they contain a great deal of information for the SFDI, such as defining what is meant by pilot plant control configurations; which of these are possible for the pilot plant; what types of transitions the plant must be capable of; and what the OCS/subsystem interfaces and interactions are. In addition, incomplete areas of OCS requirements are identified, including: the development of various commercial power producing strategies to be tested and evaluated; the explicit specification of OCS/subsystem control interfaces and control data inputs, and the definition of test plans, procedures, and control strategies.

A set of basic assumptions was used when MCS requirements definition was begun. These are, briefly:

- The OCS is required to demonstrate all operating modes under receiver following, turbine following, and coordinated control. (These are standard power plant control methods for once-through boilers; see Section 5.1.1.1.).
- The MCS is to be used for evaluating plant operating modes. In other words, all mode options should be kept in the MCS so that the pilot plant may be used to gather data justifying the elimination of modes which are "unrealistic", "inefficient", etc.
- The OCS is to demonstrate commercial-type operation, including simulation of commercial plant parameters and control strategies. This must be accomplished even though pilot plant parameters (such as solar multiple) may not scale directly to the commercial plant.
- Since the subsystems must have "stand-alone" and "failsafe" capability of themselves, there are no direct control connections between subsystems.

5.1 OPERATING REQUIREMENTS

5.1.1 STEADY STATE

5.1.1.1 AUTOMATIC CONTROL

One of the most basic requirements of the OCS is to provide automatic control in all applicable combinations of operating modes and control methods for both load- and sun-following. This requirement has wide-reaching implications on the OCS design, because of the extra complexity of a solar thermal power plant which arises from the use of thermal storage. Where a conventional power plant has only one steady-state operating mode (corresponding to Mode 1), the pilot plant has seven. Further, the number of variables (pressures, temperatures, etc.) to be controlled is greater in the solar thermal plant. The complexity of plant control which results apparently has not been previously realized. The existing documentation, while giving reasonable detail on subsystem controllers, addresses overall plant control in only the most general terms, particularly when describing the role of the OCS in plant control. The plant control configurations presented here, then, are a significant result of the MCS requirements effort.

The discussion to follow begins by describing plant control methods for Mode 1 by analogy with conventional plant controls. This is then expanded upon to define all applicable plant control configurations, which are the relevant control methods in conjunction with seven steady-state operating modes. It should be recognized that the control configurations eventually used in the pilot plant may not in all cases be exactly those defined here, since some changes may become necessary as a result of subsystem control detailed design, such as a stability problem or an undesirable subsystem interaction. It is not anticipated, however, that there will be significant changes in either the layout or the number of workable configurations.

The control methods used for once-through boilers in a conventional power plant are boiler-following, turbine-following, and coordinated control. For the pilot plant, the term "receiver following" will be used as analogous to boiler following. Also, many additional plant control methods are possible in the pilot plant, since the TSS charge and/or discharge can be involved in the plant control. Figure 6 is a simplified diagram of the pilot plant, showing the essential sensed variables and controls which are used for plant control. The sensed variables are:

1. Receiver steam pressure (sensed in both the EPGS and the TSS).
2. Admission (TSS) steam pressure (sensed in both the EPGS and the TSS).
3. Steam flow for TSS charging.

Figure 6
Simplified Plant Diagram

4. Steam flow from the TSS steam generator (TSS discharging).
5. Megawatt load (sensed in the EPCS only).

Although the steam pressures are sensed in two subsystems, only one measure of a given pressure is used for control at any given time. The additional sensors are provided so that the pressure control loops may be closed entirely within the appropriate subsystem. If this were not done, the loop would have to be closed through the MCS, which is an unnecessary complication.

The controls available are:

1. Receiver steam turbine-control valve.
2. Admission steam turbine-control valve.
3. Control valve for TSS charging steam.
4. Control valve for TSS discharging steam.
5. Heliostat field defocus.

Other subsystem control loops, such as those controlling RS output temperature, TSS boiler level, etc., are not used for plant control. The term "defocus" used in the context of plant control means moving a portion of the heliostats from the RS tower to the standby position, to control the heat input to the RS.

The pilot plant control methods corresponding to conventional power plant controls will now be described using steady-state Mode 1, which corresponds to the energy flow in a conventional plant. Turbine-following control is shown in Figure 7. Receiver steam pressure is controlled by the turbine, and megawatt load is controlled by the receiver and collector subsystems. (In conventional power plant control, the functions of feed-water flow control and firing rate control are combined under an entity termed "boiler control", which has the responsibility for megawatt control in this configuration. In the pilot plant, these functions are in different subsystems, and megawatt load control is achieved through the CS heliostats focusing on the RS tower. Therefore, the analogy to a conventional plant is not exact).

Turbine-following control operates as follows. In response to an increased megawatt load demand, the MCS commands the CS to increase the number of heliostats aimed at the receiver. This causes the output steam temperature of the receiver to begin to rise. The steam temperature control loops in the RS then increase the feedwater flow to stabilize the

Figure 7
Turbine-Following Control

output steam temperature. This causes the receiver steam pressure to begin to rise. The turbine controller responds by opening the turbine-control valve to stabilize the receiver steam pressure. The result is that power output is increased. This type of control, where the subsystem control loops operate independently and follow one another through flow, temperature, and pressure interactions, is termed "cascade control".

The other conventional type of cascade control, receiver-following, is shown in Figure 8. Receiver steam pressure is controlled by the receiver and collector subsystems, and megawatt load is controlled by the turbine. In response to an increased megawatt load demand, the turbine controller opens the turbine-control valve to increase the power output. This causes a drop in receiver steam pressure. In response to pressure drop, the MCS commands the CS to increase the number of heliostats aimed at the receiver. This causes the output steam temperature to begin to rise, and the steam temperature control loops in the RS increase the feedwater flow to stabilize the temperature. The increased flow then causes the receiver steam pressure to return to its proper value. Note that for receiver-following control, the steam pressure loop is closed through the MCS, since the CS does not contain a pressure sensor.

The inherent lags in cascade control due to the subsystem controls following up the results of one another's operation can be largely eliminated by the use of coordinated control. Here, changes in megawatt demand are sent to the MCS, which commands the various subsystems in a coordinated manner to produce the desired power output. Figure 9 shows coordinated control for Mode 1. In response to changes in megawatt load demand, the MCS varies the heliostat defocus and the receiver steam pressure set point as functions of time to bring the plant to the new power level more quickly and smoothly than can be achieved with cascade control.

In the pilot plant, since thermal storage is available, many other control methods are possible. In fact, it is necessary to expand the terminology somewhat to describe all of the methods. Hence, turbine-following and receiver-following previously described will be called "turbine follows receiver" and "receiver follows turbine" respectively. As an example of a control method utilizing thermal storage, Figure 10 shows for Mode 2 a configuration which will be called "TSS charge follows turbine". In response to an increased megawatt load demand, the turbine controller opens

Figure 8
Receiver-Following Control

Figure 9
Coordinated Control

Figure 10
TSS Charge Follows Turbine

the turbine-control valve to increase the power output. This causes a drop in receiver steam pressure which is sensed by the TSS charge control loop, which actuates a control valve to reduce the charging rate and return the receiver steam pressure to its proper value. The output of the RS remains essentially constant; heliostat defocus is not required for control in this configuration. Note also that the MCS is not used for plant control in this configuration; this is true for all cascade configurations where the control loops are all closed within the subsystems.

Table 1 summarizes the control methods which would be used in the pilot plant, and shows the responsibilities for load control and steam pressure control for the cascade control methods. The first six of the cascade control methods are load-following; there is a megawatt load demand to which the plant power output is controlled. The last of the cascade control methods is sun-following, where the plant power output follows the variation in solar energy input.

For coordinated control in its most general form, all of the controls available in a given mode would be operated in a coordinated manner. However, since heliostat defocus would usually not be used for control unless necessary, there is also a coordinated control method where defocus is not used. Therefore, two types of coordinated control are indicated in Table 1: Type 1 in which all controls including defocus are used, and Type 2 where all controls except defocus are used.

Figure 11 is a matrix showing which of the control methods of Table 1 can be used in each of the power-producing modes of the plant. (Mode 5, Charging Only, does not fall under any of the methods of Table 1 and has therefore been omitted from the matrix). For the first six columns of the matrix, a control method is not applicable to a given mode (marked N/A) because the indicated equipment is not used in that mode. For example, Turbine Follows TSS Charge (TFC) cannot be used in Mode 1 because the TSS is not being charged. Coordinated control type 1 does not apply to Mode 4 because the RS is not involved in the power-producing portion of the steam flow, or to Mode 6 where the RS is inactive. For the same reasons, sun-following does not apply to Modes 4 and 6. Coordinated control type 2 does not apply to Mode 1 because there are only two controls available, the receiver steam turbine-control valve and heliostat defocus; if defocus is not used, there is only one control left and, therefore, nothing to coordinate.

CASCADE CONTROL

	Megawatt Load Control	Receiver Pressure Control	Admission Pressure Control
Turbine Follows Receiver (TFR)	Receiver	Turbine	-----
Receiver Follows Turbine (RFT)	Turbine	Receiver	-----
Turbine Follows TSS Charge (TFC)	TSS Charge	Turbine	-----
TSS Charge Follows Turbine (CFT)	Turbine	TSS Charge	-----
Admission Follows TSS Discharge (AFD)	TSS Discharge	-----	Turbine
TSS Discharge Follows Admission (DFA)	Turbine	-----	TSS Discharge
Turbine Follows Sun (TFS)	None	Turbine	-----

COORDINATED CONTROL

- Type 1 - Defocus is used.
- Type 2 - Defocus is not used.

Table 1
Plant Control Methods

Mode	Load-Following								Sun-Following
	TFR	RFT	TFC	CFT	AFD	DFA	Coord 1	Coord 2	TFS
1	✓	✓	N/A	N/A	N/A	N/A	✓	N/A	✓
2	✓	✓	✓	✓	N/A	N/A	✓	✓	✓
3	✓	✓	N/A	N/A	✓	✓	✓	✓	✓
4	N/A	N/A	N/A	N/A	✓	✓	N/A	✓	N/A
6	N/A	N/A	N/A	N/A	✓	✓	N/A	✓	N/A
7	✓	✓	✓	✓	✓	✓	✓	✓	✓

Figure 11

Power Producing Control Configuration Matrix

Figures 12 and 13 show the plant control diagrams for each of the control configurations. Modes 1, 2, 3, and 7 have been grouped together in Figure 12 since they are similar to one another in that there is a direct steam flow from the RS to the turbine. Modes 4, 5, and 6 have been grouped together in Figure 13, since they are similar to one another in that the power-producing portion of the steam flow is decoupled from the RS. The control loops shown in these figures operate in a manner similar to that which has been described in detail previously. In particular, there is a direct analogy between the operation of the TSS discharge controls and Mode 1 operation, where the admission steam turbine-control valve is analogous to the receiver steam turbine-control valve and TSS discharge rate is analogous to RS steam flow ("firing rate"). It should be noted that for Modes 3 and 7, where there are two steam flows to the turbine, the control method name is based on the flow path where megawatt load control is achieved.

Mode 4 is unique in that there are two steam flow paths which are completely decoupled. This adds a degree of freedom to the Mode 4 control configurations since the TSS charge control can be configured independently from the TSS discharge control. Consider first the TSS charge control. The two control methods possible here are shown in Figure 13 for Mode 5 as "TSS Charge Follows Receiver" and "Receiver Follows TSS Charge". (In the first control method, steam flow is monitored and heliostat defocus is used if the flow approaches the maximum TSS charging rate). Either of these TSS charge control methods may be used in Mode 4 in conjunction with any of the control methods for TSS discharge (AFD, DFA, and Coordinated Type 2), giving an extra dimensionality to the Mode 4 control configurations. Consequently, Figure 13 shows two rows for Mode 4, termed Mode 4 and Mode 4 Alternate, each row using one of the TSS charge control methods in conjunction with the load-following control methods appropriate for Mode 4. In cases where the MCS is involved in both charge and discharge control, it should be noted that these functions are independent.

It has been seen that there are a large number of control configurations possible for the pilot plant. It is desirable to retain all of them in the pilot plant MCS design for a number of reasons. First, as has been stated in the starting ground rules, all mode options should be retained in the pilot plant so that data may be gathered to justify their retention or elimination. Second, many of the control configurations may be required for transitions even if not desirable for steady-state operation. Third, all or most of the

Figure 12. Plant Control Diagrams, Modes 1, 2, 3, 7

Figure 13. Plant Control Diagrams, Modes 4, 5, 6
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columns in Figures 12 and 13 would be required anyway: TFR and RFT are needed for Mode 1, AFD and DFA are needed for Modes 4 and 6, and TFC and CFT appear to be highly desirable in Mode 2 since defocus is not used for control. Once a given control method is provided for one mode, it is probably a simple extension to provide it for all. This last point also emphasizes the need for software which is developed in modular form.

5.1.1.2 MANUAL OPERATION

Certain functions are required of the OCS when the pilot plant is under manual operation. During Subsystem-manual (i. e., when the plant is controlled by the operator from the four individual subsystem panels), or OCS-manual (when the plant is controlled by the operator from the OCS panel), the OCS continues to monitor the plant, calculating performance and generating alarms if necessary. It may be that these alarms would be generated from integrated information from two or more subsystems; in other words, by using integrated plant data the OCS may be able to alert the operator to an impending alarm condition earlier than could be achieved by using subsystem panel data only.

In addition, it may be desirable under certain conditions for the OCS to take emergency action even though the plant is under operator control. OCS action could be faster and would be implemented in a coordinated fashion, possibly reducing costs and/or losses and increasing safety factors. For example, under OCS control the plant might be transitioned to a safe configuration whereas the operator would have to resort to plant shutdown. Note that this emergency action could be automatic or could be operator initiated; i. e., if an alarm is sounded, the operator could, at his option, ask for OCS emergency takeover.

5.1.1.3 PERFORMANCE ASSESSMENT

For control purposes, such as efficiency optimization, alarm generation, and mode transitioning, the OCS must continuously assess plant performance. This is not equivalent to plant evaluation, which is the function of the DAS/Peripheral Control Subsystem complex. The extent of the assessment, in terms of sensed data and subsequent computation, will be determined as pilot plant and MCS design progresses.

5.1.2 TRANSITIONS

The OCS is required to transition the pilot plant from any configuration to any other, while maintaining plant control and maintaining power output control to the extent desired. A number of types of transitions, some with special constraints, have been identified for the pilot plant. They are:

- Those needed for commercial daily power production
- Startup
- Shutdown
- Emergency
- Transition to manual operation
- Those needed for conducting tests

Each is discussed separately below.

Transitions for the commercial plant will largely be determined by the power-producing strategies used. For example, the mode flow and plant configuration changes will be different for clear days and cloudy days, and on cloudy days, different strategies may be used if the clouds were predicted or appeared unexpectedly, and if the clouds appear early, mid-day, or late afternoon. Megawatt demand also influences these strategies--is the plant required, for example, to generate maximum power (sun-following), to generate a defined power level (8MW or 10MW) or to operate in an evening peaking or similar grid tactic?

Two examples of these power generating strategies were drawn up. These are shown in Figures 14 and 15. In Figure 14, after startup is complete, the plant is operated in Mode 1 sun-following until the desired megawatt output of 10MW is reached. At this point, megawatt output is held constant and excess energy is used to charge thermal storage, so the plant is in Mode 2 load-following. As the sun declines, the plant is again placed in Mode 1 sun-following until a certain output such as 7MW is reached. This output is maintained as long as possible, first in Mode 3 load-following and finally in Mode 6 load-following, until the plant is shut down.

In Figure 15, the initial strategy is the same. However, this strategy attempts to generate maximum power for as long as possible during the day and therefore, when rated power can no longer be generated from RS steam, the plant is operated in Mode 3 load-following at the maximum possible level and then in Mode 6 load-following until shutdown.

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Figure 14
Power Generating Strategy A

Figure 15

Power Generating Strategy B

There are other transition implications within these strategies. For instance, there is a minimum TSS charging rate. Therefore, transitions from Mode 1 sun-following to Mode 2 load-following will create a rise in megawatt output when more than 10MW is being generated in Mode 1, but the minimum TSS charge rate has not yet been reached. Also the transition from Mode 2 to Mode 3 is "forbidden", and the plant must transition through either Mode 7 or Mode 1.

Many other strategies are possible and must be derived for expected commercial operation. Then all required transitions must be identified along with methods for their implementation. This important, as yet uncompleted task will affect OCS hardware and especially software design, and possibly subsystems design also.

Startup and shutdown of the plant also must be done by OCS, for situations such as TSS full, available, or empty, clear and cloudy days, etc. Subsystem requirements, such as RS thermal transients, will probably determine the startup and shutdown procedures, which as yet have been defined only in general terms.

Another set of plant transitions still undefined is that of emergency actions. These transitions must take the plant from an unsafe to a safe configuration or to plant shutdown. Essentially, a Failure Modes and Effects Analysis must be done for the pilot plant and procedures delineated for emergency actions. These must take into account not only safety, but cost effectiveness in terms of power generation and plant equipment costs.

The OCS is required to transfer plant control to the operator in a smooth, coordinated manner. (The term "bumpless", i. e., not resulting in a control perturbation as a result of the transfer, has been used in previous documentation). It has been determined that this cannot be guaranteed for all plant conditions. For instance, the plant must be in a steady-state condition; if the plant is in a transient state, parameters may be changing too rapidly for the transfer to be accomplished without disturbance. For a smooth transition to take place, the manual set points must be within certain limits--a "bumpless" transition cannot be guaranteed if the manual set points are in error, for example. Verification of set points may be accomplished by the OCS such that when transfer to manual operation is requested, the OCS checks the manual set points, warns the operator if they are out of the prescribed limits, and asks if transfer to manual is still desired. The operator may then revise the set points or again request

the transfer, in which case the OCS will immediately relinquish control. Note that this procedure can be very rapid; as rapid as operating a "To Manual" pushbutton switch twice in succession, if desired.

The final set of plant transitions under OCS control are those required for pilot plant testing. These also are as yet undefined. Many will be those needed for production of power, but others may exist purely as "test-only" required transitions. These will be determined when test plans and procedures are drawn up and OCS control strategies completed.

For all transitions, the OCS will use subsystem set points, flow between subsystems, and possibly flow within the EPGS (in the preheaters, condenser, pumps, and drains) to control the plant. These may be commanded as functions of time--as ramps, steps, or nonlinear changes--or held constant.

System requirements for plant or subsystem transients will include:

- Control of generated power to defined limits; this may mean $10\text{MW} \pm 10\%$ or simply that turbine load not exceed recommended maximum limits.
- No unacceptable stresses on subsystems.
- The system must be damped; the plant must settle to steady-state operation within a defined time.
- Plant efficiency must be optimized if required for the particular operating conditions.
- The plant does not enter an oscillatory or a limit-cycle mode.
- Unwanted subsystem interactions are minimized or eliminated.

5.1.3 TEST OPERATIONS

Although the scope of this study did not include defining plant or MCS test operations, an initial attempt was made to outline OCS support of plant testing. Two special requirements were found. The first is that it may be desirable, while one subsystem is under manual test, for the OCS to control the remainder of the plant and hold plant operating points within certain bounds. This frees the operator and test personnel from plant management while subsystem tests are being run. In this type of test, plant or subsystem set points may be out of normal limits and OCS control must adapt to the particular conditions in effect.

The OCS also may be used for special tests. System responses to step inputs of insolation or step changes in set points or flow division may be run under OCS control. Tests in set point changes over time or in magnitude may be useful, also. Since the system is nonlinear, frequency response (small signal inputs) also might be valuable, again for insolation and/or set point changes.

5.2 SUBSYSTEM INTERFACE REQUIREMENTS

As mentioned in Section 4.0, only those interface requirements pertaining to OCS functions, and specifically plant operation, were derived. However, other subsystem interface requirements may be found as alarm/emergency operations are defined and test procedures are drawn up. This section, then, emphasizes those control parameters, functions, or responses, between the OCS and the other plant subsystems.

Two types of commands are sent to the subsystems by OCS: mode commands and control commands. Mode commands are those used to change the modes of the subsystems to transfer the plant from one operating mode to another. Control commands are those used to regulate the plant while it is in a steady-state or transient condition. Mode and control commands for each subsystem are discussed below.

5.2.1 COLLECTOR SUBSYSTEM

Mode commands for the CS are:

- Track
- Hold
- Activate
- Stow
- Emergency Stow
- Emergency Defocus

Track commands the heliostats to follow the sun and focus its energy on the tower. This is the normal power generating mode. It is currently planned that there be two sets of "aim points" on the tower which may be used in the track mode; this provides an alternate distribution of flux on the receiver tower for test purposes or other uses. The CS may be commanded by OCS to move from one set of aim points to the other set or from other heliostat positions to either set.

Hold commands the heliostats to remain fixed in the position they were in when the command was received. Note that this results in a defocus of flux on the tower as the sun moves and the heliostats remain stationary.

Activate commands the heliostats to move from the storage position to the "standby" position, where the heliostats are focused slightly off the receiver tower. For a normal power generating day, the heliostats would first receive the "Activate" command and then the "Track" command which would cause them to move from standby to focusing flux on the tower.

Stow commands the heliostats to return to the storage position from an operating position. This command would be used to end a normal power generating day.

Emergency Stow commands the heliostats to move to the storage position at the maximum possible speed.

Emergency Defocus is used to remove flux from the receiver as quickly as possible. All tracking heliostats are commanded to move at maximum speed to the standby position. It may be advantageous to provide this capability for a sector of the heliostat field or for reducing the flux level on a specific RS panel.

Note that the maximum rate at which the heliostats can be taken off or put on the RS has not yet been defined. The power drain, from the emergency power system, of stowing the entire field of heliostats at this rate may be significant and must be taken into consideration. In addition to emergency requirements, it is desirable that a sufficiently high rate be available to follow cloud transients and to permit the simulation of step inputs of flux for test purposes (the ramp of flux should be much shorter than the thermal time constant of the RS).

The control command for the CS is:

- Continuous defocus of the heliostat field.

It is recommended that the granularity of the command be one heliostat, and that the form of the command be the number of heliostats to be aimed at the tower. This level of granularity should preclude limit cycling in the plant control loops, and will allow simulation of various possible commercial plant granularities. Commanding the number of heliostats rather than a percentage avoids the possibility of confusion between controlling by percentage of heliostats (focused or available) or percentage of flux (focused or available).

It is required that the desired flux distribution on the tower be maintained as the flux is varied from zero to maximum. Thus, successive heliostats taken off or put on must be positioned around the array in a reasonably uniform manner. Although axial and radial control of the flux distribution on the RS is desirable, this control need not be real-time, but can be accomplished by off-line generation of alternate aim points which are read into the CS computer and then selected by a mode command from the OCS.

There is no requirement for the OCS to call out specific individual heliostats. Individual heliostats called out for beam characterization will be addressed by the Beam Characterization Subsystem Computer interfacing directly with the CS. Maintenance functions will be handled by the operator directly from the CS console.

5.2.2 RECEIVER SUBSYSTEM

The RS mode commands are:

- Off
- Circulate
- Normal

Off is commanded by the OCS when the RS is not being used to generate turbine steam or to charge the TSS (Modes 6 and 8). Normally, blanket steam or warm water will at all times be circulated through RS pipes, panels, and the flash tank to prevent corrosion and erosion, to minimize thermal stresses, and to reduce startup time.

Circulate is commanded when steam is being generated in the RS but is not used by the EPCS or TSS. The steam is circulated through the flash tank loop. This procedure would be used for startup, possibly for shutdown, for emergencies, and when non-rated and/or irregularly varying steam is being produced.

Normal is the RS power generating command, in which steam is produced at the rated temperature of 950°F or, if it is desired to charge TSS without using the desuperheater, at a temperature of 660°F. It has not yet been defined whether this requires a mode change or whether it is just a change in the temperature set point.

Control commands for the RS are the following set points:

- Outlet steam temperature
- Feedwater pump outlet pressure

- Receiver flash tank pressure

Receiver flash tank pressure would normally be used only to control the "off" or "circulate" configurations.

One significant emergency requirement was found for the RS - CS interface. Since the RS is the only subsystem that cannot entirely failsafe itself (cannot prevent panel overheating under failure conditions such as an inoperative feedwater pump), a hardwire connection between the RS and CS is required over which the RS can call for emergency defocus. This does not preclude the OCS or the operator from also being able to command emergency defocus. No other required hardwire interfaces between subsystems have been identified.

5.2.3 THERMAL STORAGE SUBSYSTEM

Mode commands for the TSS are:

- Charge off
- Charge on, steam pressure control
- Charge on, steam flow control
- Discharge off
- Discharge on, steam pressure control
- Discharge on, steam flow control

The TSS modes of operation may be selected independently for the charge and discharge sides. When a given side is on, the choice of pressure or flow control will depend upon the plant control configuration desired.

Control commands for the TSS are the following set points:

Charge

- Steam flow
- Steam pressure
- Desuperheater output temperature
- Heat exchanger oil output temperature

Discharge

- Steam flow
- Steam temperature
- Steam pressure

5.2.4 ELECTRICAL POWER GENERATION SUBSYSTEM

Mode commands for the EPGS are:

- Receiver steam off

- Receiver steam on, pressure control
- Receiver steam on, megawatt load control
- Admission steam off
- Admission steam on, pressure control
- Admission steam on, megawatt load control

The EPGS modes of operation may be selected independently for receiver steam and admission steam, except that megawatt load control can only be done in one place. The choice of control will depend upon the plant control configuration desired.

The control commands for the EPGS are the following set points:

- Receiver steam pressure
- Admission steam pressure
- Megawatt load demand

The demand may be simulated or actually received from the electrical power grid. Megawatt output, and hence megawatt error, is sensed only within the EPGS, and may be used for control directly by the EPGS; it must be sent through the OCS if it is used for control by other subsystems.

It appears that, from the OCS point of view, the EPGS may be the most complex subsystem in terms of plant control. Although the turbine controls themselves are fairly standard, the question of whether or not flow splits within the EPGS will be used for control has not yet been resolved. These flow paths to and from the condenser, pumps, (five) heaters, (four) turbine extraction ports, and the turbine drain, are quite complex and also interface with flash tank and other flows from the RS and TSS. Therefore, it is quite possible that a subset of the control set points within the EPGS must be made available to the OCS for control purposes in some situations. This area is closely tied to plant sizing and is an area in which definition effort is needed as soon as possible.

5.2.5 OCS INPUTS

The final area of subsystem interface requirements is that of control (as opposed to evaluation) data inputs from the subsystems to the OCS. This data consists of two types: continuously sensed variables, and discrete state verification signals. The continuously sensed parameters are those used directly for control, such as CS defocus, throttle pressures, and megawatt error; those used for performance calculation (for optimization, determining transition paths, etc.) such as feedwater temperature and

pressure, oil temperature and pressure, and extraction port measurements; and those needed for failure detection, transitions, and other uses, such as flash tank levels, heat flux, and manual set points.

The state verification discretes include mode command verification, heliostat status, motor-operated valve status, and alarms.

Pages A-19 through A-28 of Appendix I list in detail possible inputs to the OCS from each subsystem. At this time, although the listing is felt to be fairly complete, it is not known if all those listed are necessary, or if more must be added.

6.0 CONCLUSIONS

The foregoing pages have presented pilot plant control requirements that must be met with the MCS design. Each of the many functions the MCS performs has been discussed, in detail where possible, and in general terms for those areas in which further effort is needed. In addition, important basic control constraints and subsystem requirements were found as the MCS requirements were delineated. These are summarized below.

6.1 CONTROL CONSTRAINTS

As pilot plant algorithms are derived, beginning with the basic assumptions of Section 5.0, and working to the additional MCS requirements of this document, certain control constraints will have to be observed. Although each of these has been mentioned in previous sections, they are repeated here for clarity and emphasis.

1. There is no OCS control in manual operation except possibly in emergencies. (Section 5.1.1.2). The OCS may, however, continue to receive subsystem inputs and generate alarms. Emergency OCS action may be automatic or may be operator initiated.

2. "Bumpless" transition to manual cannot be guaranteed for all plant conditions. A "bumpless" transition, as the term is generally understood, cannot be ensured when the plant is in a transient state or when the manual set points are outside their prescribed limits. In general, if the plant is properly designed, it should not be difficult to ensure relatively smooth transitions with no unacceptable disturbances. Every attempt should be made to design the plant and the OCS so that transitions to and from manual under any conditions cannot result in complete loss of control.

3. Flash tank loops will not normally be used for control. These flow paths are meant to be used for startup and shutdown operations and possibly emergency conditions. It may be that they will be needed for some transitions, although this should be avoided if at all possible.

4. RS output temperature control loops are not opened for any plant control configuration. Whereas certain control loops, such as that controlling

receiver steam pressure, are closed in several different ways for various control configurations, the RS output steam temperature control loops will not be changed. They will remain closed within the RS, and the only external control interface will be the temperature set point. This temperature will normally be that required for standard turbine operation, 950°F. If RS steam is being used only to charge TSS, it may be advantageous to reset the RS output steam temperature to 660°F so that the desuperheater need not be used. During startup and shutdown, it is not clear whether the output steam temperature set point will be varied or whether simply the error in set point versus actual temperature will be used to control these two procedures. Note that this may imply a high/low switched gain in the steam temperature control loop.

5. Each control valve is considered to be within a subsystem and is controlled entirely within that subsystem. Control is accomplished by set points and subsystem mode commands sent by OCS to a subsystem; these commands are carried out completely within that subsystem. The throttling controls are in control loops which are commanded by set points and closed entirely within a single subsystem. Motor-operated on/off valves are controlled by the subsystems as a function of the subsystem mode.

6. Megawatt error is sensed only in the EPGS; it can be used by the EPGS for control directly, but the OCS must be used to send this information to other subsystems. This is because the hardware for sensing grid demand (through a preprocessor) and calculating megawatt error is, in a standard power plant, contained within the EPGS/turbine assembly. In some cases (see Section 5.1.1.1), this means that OCS is not needed for automatic control of the plant.

7. Megawatt demand and sun-following configurations are mutually exclusive; megawatt demand implies load-following. Coordinated control assumes there is a megawatt demand and is therefore meaningless in sun-following configurations. This is a clarification of the requirement that the OCS demonstrate all modes under receiver following, turbine following, and coordinated control. These exclusions are apparent in Figure 11 of Section 5.1.1.1.

6.2 SUBSYSTEM REQUIREMENTS

The significant subsystem requirements that result from the assumed OCS configuration are summarized here.

1. The OCS must be able to control, by a command to the CS, the number of heliostats focused on the RS tower. This requirement follows directly from the basic assumptions of Section 5.0 and the control configurations of Section 5.1.1.1. If this function is not commandable by OCS, a great deal of pilot plant evaluation capability and flexibility is lost.

2. The TSS must be capable of steam pressure or steam flow control for receiver steam when charging and admission steam when discharging. This again follows from the control configurations of Section 5.1.1.1.

3. The EPGS--not the OCS--is responsible for reconfiguring the turbine as modes are changed. A specific example of this requirement is that the EPGS must circulate steam through the turbine upper stages when it is operating only on admission steam.

4. Since the RS cannot failsafe itself, a hardwire connection between the RS and CS is required over which the RS can call for emergency defocus. This is the only hardwire interface required between subsystems.

5. Each subsystem shall provide its own sensors for the control quantities it needs. This means that if, for example, the TSS and the EPGS both need to know admission steam pressure, both shall provide a pressure sensor on that line. This requirement is necessary to avoid direct interfaces between subsystems and also to ease interface problems between different subsystem contractors.

6.3 AREAS REQUIRING FURTHER WORK

Essentially four areas of MCS preliminary design have been identified as incomplete. These are:

- DAS
- Control Strategies
- Subsystem/MCS Interfaces
- Testing

Defining the DAS portion of the MCS includes defining all plant parameters that are to be sensed and recorded, designing and implementing hardware sensors in the subsystems to acquire these parameters, and configuring the entire computing system (hardware and software) for data acquisition, processing, recording, and displaying, either real-time or off-line. Obviously, this represents a large part of the MCS design. Also,

since the purpose of the pilot plant is demonstration and evaluation, the basic objectives (Section 2.0) of the pilot plant effort cannot be met without a satisfactory DAS design.

Very little documented work is available at this point in time as to specific DAS requirements or implementation. Although the Requirements Tree (pages A-19 through A-28) presents a tentative list of control data (which will be a subset of evaluation data), other data points may be desirable and should be decided upon before hardware is designed. Thermistors are easily added during the design stage, but are added to finished products only at considerable expense of time and money. Thus, it is imperative that detailed DAS definition begin as soon as possible, particularly in the subsystem design area, so that DAS requirements can be incorporated into the subsystem contracts as they begin.

Two examples were given in Section 5.1.2 of typical control strategies over a power generating day and their implications on OCS design. Numerous other strategies are possible and should be derived in the near future, especially so that plant operating mode transitions can be identified. Startup and shutdown techniques for all possible plant conditions also need to be drawn up in detail to determine how these will be controlled by OCS. Finally, specific anticipated failures and the resulting OCS actions must be formulated; e.g., inoperative sensors, failed "active" components (pumps, heaters, etc.), pipe leaks or breaks, computer malfunctions, and so on. Questions of loop gains, time constants, required parameter sensing, etc., immediately become important when any of the above areas are specified in terms of OCS action. Definition of OCS requirements arising from these control strategies is needed so that MCS design is not impacted at a later date.

Although the third area, OCS/subsystem interfaces, has been defined to a large degree, some open areas remain. This is particularly true of the EPGS, where only the basic turbine control points are known with certainty. As the control strategies and plant transitions become clear, other control points needed by OCS may be found, such as extraction port pressures, heater inlet and drain flow routing, and preheater, deaerator and cooling water temperatures. It has been assumed that normal plant control will not use EPGS parameters other than turbine inlet pressures and megawatt output, but as the complexity of flow within the

EPGS becomes clear, this assumption may be modified. If so, the control requirements are needed as soon as possible since EPGS design and purchases are in progress.

Finally, MCS design cannot be completed until test objectives, operational plans, and procedures are generated to the extent that required control strategies are known. It is anticipated that most MCS requirements due to testing will be those also needed for "normal" configuration evaluation and power generating operations. However, there may be found special "test only" MCS requirements; for example, a mode transition that occurs only within an individual system or subsystem test.

7.0 SUMMARY

This report has defined the MCS requirements needed for MCS design with the exception of the areas discussed in the previous section. It can be seen that MCS design will be a significant SFDI effort. Software design, including control algorithms, transition procedures, and performance evaluation calculations, must not be neglected, as the plant evaluation capability will be a direct function of software efficiency and flexibility. Early subsystem hardware definition also is critical, since the SFDI contractor will be chosen after some subsystem contractors, but yet will have interface responsibility. Careful thought and good design procedures will be necessary to ensure success in meeting pilot plant objectives with a versatile and effective MCS design.

8.0 REFERENCES

1. Steam/Its Generation and Use ; Babcock and Wilcox, 1978.
2. 10MW Solar Project Summary of Operating Modes; Southern California Edison, December 1977, and addendum, February 1978.
3. MCS Statement of Work; MCS Evaluation Panel, September 1977.
4. MCS Design Requirements; MCS Evaluation Panel, September 1977.
5. Recommendations for the Conceptual Design of the Barstow, California, Solar Central Receiver Pilot Plant; Sandia Laboratories, October 1977.

NOTE: These are the primary documents used as a basis for the MCS Requirements task. Numerous others also provided valuable information, particularly the Phase I Design Reports from McDonnell Douglas, Honeywell, and Boeing.

Appendix I

Requirements Tree

Start

Sheet 1

Sheet 2

WHAT

Sheet 3

Sheet 4

Transitions

Sheet B

Sheet C

Sheet D

Sheet E

Sheet F

Sheet G

Sheet H

Sheet I

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Sheet K

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EPGS

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Sheet S