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SOLAR PILOT PLANT: PHASE I

Final Report, July 1, 1975—July 1, 1977

February 1, 1978

Work Performed Under Contract No. EY-76-C-03-1109

Honeywell Incorporated
Energy Resources Center
Minneapolis, Minnesota

MASTER

U.S. Department of Energy

Solar Energy

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**SOLAR PILOT PLANT
PHASE 1**

FINAL REPORT

(1 July 1975 - 1 July 1977)

(APPROVED)

CDRL Item No. 10

MASTER

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FOREWORD

This is the final submittal of the Solar Pilot Plant Final Report per Contract Data Requirements List Item 10 of ERDA Contract E(04-3)-1109. The report has been reviewed by ERDA for technical content and patent clearance, and has been released for normal distribution.

ABSTRACT

Honeywell was given a 2-year contract by the Energy Research and Development Administration on 1 July 1975 to develop a preliminary design for a 10-MW(e) solar pilot plant of the central receiver type. The program culminated in mid-1977 with delivery of a pilot plant preliminary design, estimates for its cost, and performance, and cost estimates for a 100-MW(e) plant, which will be detailed during the operation of and built as a follow-on to the pilot plant. The pilot plant preliminary design evolved through three iterations, which were verified and refined by analysis and experimentation. Subsystem research experiments (SREs) were conducted on the collector subsystem and the steam generator portion of the receiver subsystem. A lesser amount of testing was done on a latent-heat storage subsystem before a sensible-heat storage subsystem was incorporated at the direction of ERDA. All test results and analyses pointed to the feasibility of the pilot plant, and by extension to commercial-scale plants. On that basis and in light of the worsening energy situation, Honeywell recommended that Phase II of the program be undertaken as quickly as practical.

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SECTION I

PROGRAM SUMMARY

The Energy Research and Development Administration (ERDA) is conducting a multiphased program to commercialize the generation of electricity in solar thermal power plants. On 1 July 1975 ERDA awarded Honeywell Inc. a 2-year contract for the first phase of the program, the objective of which was:

"To establish the technical feasibility of a solar thermal power plant of the central receiver type with significant commercial potential and to obtain sufficient development, production, and operating data to indicate the economics of operation for commercial power plants of similar design."

The Phase I program consisted of developing a preliminary design for a solar pilot plant, conducting research experiments on three key subsystems in the design, and providing a conceptual design for a commercial plant. The complexity of the requirements and the range of technologies involved dictated a team approach to the project. The Honeywell team and member responsibilities are shown in Figure 1.

Figure 1. Honeywell Team for Phase I Solar Power Plant Program

The program was completed on time. The chronology is summarized in Figure 2.

Figure 2. Chronology of Phase I Solar Power Plant Plant

Two of the three subsystem research experiments (SREs), those for the collector and the steam generator, were carried out successfully, augmenting the confidence Honeywell has in the preliminary design. The third SRE, that for the thermal energy storage subsystem, was discontinued relatively late in the program when ERDA directed that sensible-heat storage be used rather than the more experimental latent-heat (phase-change) storage technique being developed.

The program culminated on 4-5 May 1977 with an oral presentation to ERDA of the preliminary design for a 10-MW(e) solar pilot plant, shown schematically in Figure 3. The pilot plant design and associated costs and cost and performance estimates for a commercial-scale [100-MW(e)] plant were documented in a seven-volume report.

Figure 3. Solar Pilot Plant Preliminary Design

SECTION II

SOLAR PILOT PLANT PRELIMINARY DESIGN

FUNCTIONAL DESCRIPTION

The general aspect of the solar pilot plant is a field of mirrors (collectors) surrounding a tower (Figure 4).

Figure 4. 10-MW(e) Solar Pilot Plant

In operation, the collectors redirect solar energy into an annular opening in the receiver atop the tower and onto the tubes of a boiler. Steam generated in the boiler and superheated by a two-stage superheater is fed to a conventional turbine generator or is piped to storage, depending on the load requirement on the system. Heat in the oil and rock main storage is reconverted to steam, superheated, and fed to the turbine to supplement or replace steam from the receiver subsystem as determined by the system load requirement and/or solar availability. The output of the electrical power generation subsystem is

tied into an existing power distribution grid. Control of the integrated system is through a digital master control.

The pilot plant is designed to produce exactly 10 MW(e) at 2 p.m. on 21 December, the day of the year on which the sun is lowest in the southern sky. On all other days of the year between 10 a.m. and 2 p.m., the plant can produce in excess of 10 MW(e), with the power being available to either the grid or to thermal storage. Figure 5 shows pilot plant performance at the design point, i.e., 21 December at 2 p.m. Figure 6 shows net annual energy available from the plant.

PHYSICAL ARRANGEMENT

The solar pilot plant will be built at Barstow, California. The site will contain the following major plant elements: collector field, receiver tower, thermal storage area, operating building complex at the base of the tower, cooling tower and evaporation pond, road access, and a visitors' center (Figure 7).

The area immediately surrounding the receiver tower is used for the turbine, control and maintenance, thermal storage, access roads to the collector field, and parking areas (Figure 8). Elevators and cranes are provided for storing and moving spare parts and transporting operating personnel up and down the receiver tower for maintenance inspections and repair work. The central plant area is surrounded by security fencing.

The collector field is circular, with the receiver tower one-half of the field radius south of field center, as shown in Figure 9. The 1598 heliostats in the collector field are arranged radially and tangentially to minimize shading and blocking. The ratio of mirror surface area to field area is 0.29.

Eight calibration arrays on top of the receiver provide a means for measuring the pointing accuracy and beam intensity of individual heliostats.

DESIGN METHODOLOGY

The end goal of the Phase I program was a solar pilot plant design that translates realistically to commercial scale in terms of performance and cost. The approach to the goal was to use the performance specifications and knowledge gained from earlier work in the solar field to provide a design baseline, and then to refine it through iterative analyses and experimentation. This methodology is illustrated in Figure 10.

Implicit in the performance and cost scaling requirement is the necessity for the performance to be of high level under varying conditions of solar input and weather and for the costs, capital and operating, to be acceptable. These considerations were the criteria against which the design was evaluated.

Figure 5. Pilot Plant Performance - Design Point 12/21, 2 PM

Figure 6. Pilot Plant Performance - Net Annual Energy

Figure 7. Solar Pilot Plant Site Plan

Figure 8. Solar Pilot Plant Central Complex

Figure 9. Solar Pilot Plant Collector Field

Figure 10. Approach to Pilot Plant Design

DESIGN FEATURES

The Honeywell pilot plant preliminary design is low-risk from the fabrication and operation standpoints. It features a high degree of operational flexibility, low maintenance requirements, and built-in safeguards to protect personnel and equipment. That evaluation can at this point in time be best expounded by looking at the design on a subsystem-by-subsystem basis.

Collector Subsystem

The collector subsystem consists of the heliostat field, controls, and calibration equipment (Figure 11).

Figure 11. Composition of Collector Subsystem

The critical element in the subsystem is the heliostat (Figure 12) because it is the most important cost and performance factor in the pilot plant system. The heliostat is designed to provide high reflectivity and accurate angular and spatial positioning of the redirected solar energy. The heliostat is modular in design for quick, easy installation and maintenance. Direct-current motors and trickle-charged batteries for each unit ensure the heliostat can be operated under any condition.

The computerized control subsystem can address all of the (1598) heliostats simultaneously while performing calculations of sun position and pointing direction and compensating for known fixed errors. The Honeywell Level 6/45 computer permits cross-checking input data, including weather conditions in collector field, thereby enhancing reliability and safety.

Figure 12. Heliostat

Calibration sensor arrays on top of the receiver tower provide the capability to measure beam direction and beam energy accurately. This information is used to correct minor pointing errors and determine when the mirrors need to be cleaned.

Collector Subsystem Tests -- In keeping with its primal impact on plant performance and cost, the collector subsystem was the most-tested item during the Phase I program. The SRE tests, conducted at St. Petersburg, Florida, extended over a 9-month period and included both key components and the entire subsystem, operationally and environmentally. Figure 13 shows a solar image directed onto a calibration array and a flux map generated during the tests. Overall, the results showed that the collector subsystem functions as intended, and that the heliostat offers these advantages:

- High-level performance
- No technical risk
- Simplicity in construction and installation
- Low maintenance requirements
- Safety
- Flexibility (e.g., fabrication; transportation; new mirror developments, etc.)

Receiver Subsystem

The receiver subsystem consists of a cavity receiver, steam generator, cavity barrier, support tower, piping, cables, protective shielding, and access provisions for maintenance and repair. The entire design, receiver structure and steam generator, is based on state-of-the-art technology.

Cavity Receiver -- Figure 14 shows the receiver tower. The overall height (including receiver) is 147.3 meters. The height of the support tower is 126 meters. The tower structure is designed to withstand support reactions, its own dead, live, and wind loads, and seismic (Zone 3) forces. Access to the tower at its base is through a freight door and a personnel door. Operating personnel can ascend the tower by elevator or ladder.

Figure 15 shows the receiver geometry and internal configuration. The receiver housing, which provides a means of hanging the steam generator, consists of a series of horizontal and vertical trusses interconnecting box beam steel corbels. Provision is made for thermal expansion of the steam generator and for closing the aperture at night to retain heat. Access for maintenance is through the corbels and all the way around the cavity up to the drum.

Solar Image on Calibration Array

Flux Map

Figure 13. Collector Subsystem Test Results

Figure 14. Receiver Tower Elevation and Structure

Figure 15. Receiver Geometry and Internal Configuration

Steam Generator -- The design requirements of the receiver subsystem are dictated primarily by the performance requirements for the solar steam generator. Stated briefly, its function is to absorb solar energy from the collector field and convert it to the steam-water working fluid that drives the turbine.

The steam generator is shown in Figure 16. The heat-transfer surface of the steam generator is an 18-sided polygon that forms the interior walls of the receiver cavity. The absorptance factor is approximately 0.9. While the design is based on fossil-fuel boiler technology, two considerations unique to solar steam generators had to be accommodated:

- An unusually large number of stress cycles during its 30-year design life
- Wind and seismic loads more severe than those at ground level.

Figure 16. Pilot Plant Steam Generator Configuration

The steam generator design features forced-circulation drum separation to ensure that departure from nucleate boiling (DNB) does not occur during cloud transients. Two stages of superheating are provided with spray attenuation between to control turbine inlet conditions at constant temperature (Figure 17).

The design uses prefabricated superheater tube panels plumbed together to provide the functional equivalent of the spiral design used in the SRE steam generator superheaters. Prefabrication effects a cost saving, performance of the spiral configuration is excellent, and it reduces thermal stress levels.

Figure 17. Steam Generator Flow

Steam Generator Subsystem Tests -- A steam generator with one-tenth the capacity of the pilot plant version was tested in the Riverside plant of Northern States Power Company in Minneapolis, Minnesota. The arrangement is illustrated in Figure 18. Every care was taken to ensure that the SRE design related to the pilot plant design on either a one-to-one basis or a meaningful scale.

A 9-MW radiant heat source was used to simulate the solar energy supplied by the collector field. Electric power for the solar simulator was supplied directly from the power plant distribution system. Feedwater was supplied by a fossil-fuel boiler. Procedures were essentially those of a conventional power plant, with power plant personnel operating the steam generator under the guidance of Honeywell engineers.

Side View

Cavity View

Figure 18. SRE Steam Generator in Test Facility

The tests were successful, demonstrating that the SRE steam generator (and by projection the pilot plant steam generator design) was reliable, predictable, and responsive to control commands, and that fossil-fuel boiler technology does in fact form the basis for a successful solar steam generator. Table 1 summarizes data obtained from one test. Figures 19 and 20 show, respectively, main steam pressures and temperatures obtained from step changes of the steam control valve.

Table 1. SRE Steam Generator Steady-State Data
(13 April 1977 - 11:37 a. m.)

Location	Measured			Predicted
	Flow, kg/s (lb/hr)	Temperature, °C (°F)	Pressure, MPa (psia)	Pressure, MPa (psia)
Feedwater	1.2 (9924)	243 (469)	13.2 (1915)	---
Boiler inlet	10.9 (86,900)	317 (603)	---	---
Boiler outlet	10.9 (86,900)	321 (610)	---	---
Drum	1.3 (10,136)	321 (610)	11.5 (1670)	11.5 (1670)
Primary superheater out	1.3 (10,136)	450 (830)	11.3 (1641)	11.3 (1642)
Secondary superheater out	1.3 (10,136)	514 (958)	11.04 (1601)	10.99 (1594)
Incident energy	3.2 MW			
Energy loss	0.18 MW			
Absorbed energy:	3.0 MW			
Boiler	2.1 MW			
Primary superheater	0.67 MW			
Secondary superheater	0.22 MW			

Thermal Storage Subsystem

The pilot plant thermal storage subsystem (Figure 21) is a two-stage sensible-heat storage arrangement that uses rock and oil in the first stage and an inorganic salt mixture in the second.

Guiding precepts in developing the design were modularity and the use of standard materials of construction and proven parts and components.

The main or first storage stage, which holds about 87 percent of the stored thermal energy, transfers the latent heat in receiver steam to Caloria HT-43 oil and stores it in the rock and oil tank (Figure 22).

Figure 19. SRE Steam Generator Main Steam Pressure (Steam Control Valve Step Change)

Figure 20. SRE Steam Generator Main Steam Temperature (Steam Control Valve Step Change)

Figure 21. Thermal Storage Preliminary Design Schematic

Figure 22. Main Storage Tank

Heat held in the main storage tank is discharged as saturated steam on demand. This steam is superheated to turbine admission conditions by the second stage, which stores receiver steam in a hot tank using Hitec salt as the storage medium. The salt is pumped into a second (cold) tank as it loses its heat. The superheater tanks (Figure 23) are located underground.

Figure 23. Superheater Storage Tanks

The Caloria HT-43 must be reprocessed to remain usable. Figure 24 is a diagram of the oil maintenance process.

Figure 24. Oil Maintenance Unit Schematic

Oil withdrawn from storage is heated in a charge heater. The charge enters the vacuum distillation tower where flash separation of the HT-43 occurs. High boilers are removed from the bottom of the column and low boilers from the top. The product is withdrawn and returned to the storage tank.

The ullage maintenance unit consists of liquid nitrogen storage and a two-stage ambient air vaporizer. Both maintenance units are modular.

The storage subsystem responds quickly to the command to discharge, the lag time being only that required for the valves and actuators to respond. Thermal lags are minimized by periodically cycling the oil and salt discharge auxiliary pumps to maintain boiler pressure and line heat. Thirteen setpoint analog controllers control the charge and discharge parameters (i.e., steam pressures and temperatures and liquid inventories). The storage discharge cycle is shown graphically in Figure 25.

Figure 25. Thermal Storage Discharge Cycle

In summary, the pilot plant thermal storage subsystem design, with its modularity and state-of-the-art technology, offers the following benefits:

- Low capital and operating costs
- Superior switching performance
- Flexible operating strategies
- Long service life and safe operation
- Ease of operation and maintenance
- Low development risk
- Design continuity for the commercial plant.

Electrical Power Generation Subsystem

The pilot plant electrical power generation subsystem (Figure 26) is designed around a General Electric automatic-admission, triple-extraction turbine generator (Figure 27).

Figure 26. Electrical Power Generation Subsystem Schematic

Figure 27. Turbine Generator

The turbine offers high performance in a variety of operating modes. It is this high performance in combination with flexibility of modes that makes the pilot plant a valuable test bed for the commercialization of solar power. Figure 28 shows turbine efficiency as a function of steam flow.

Figure 28. Gross Turbine Efficiency as Function of Steam Flow

As stated earlier, the pilot plant will generate 10 MW net busbar electricity at 2 pm on the winter solstice (21 December) using superheated steam from the receiver subsystem. It will generate 7 MW net busbar electricity for 3 hours using superheated steam from thermal storage, and the same quantity using steam from receiver and storage simultaneously.

In addition to supplying electrical power for the distribution grid, the electrical power generation subsystem supplies power for plant auxiliary operations and for protection systems for major plant equipment.

The electrical generation subsystem also supplies feedwater to the receiver and thermal storage subsystems in exchange for steam. Figure 29 shows the wet cooling arrangement for the steam surface condenser and the flow of feedwater back toward the receiver and storage. Figure 30 is the feedwater pumping arrangement.

Figure 29. Steam Surface Condenser with Cooling Tower

Figure 30. Feedwater Pump Arrangement

A number of ancillary chemical and mechanical support systems are required for the electrical power generation subsystem. These are listed in Table 2.

Table 2. Electrical Power Generation Subsystem Support Systems

Description	Description
• Auxiliary cooling water	• Heater vents and drains
• Chemical cleaning	• Miscellaneous vents and drains
• Chemical feed	• Service air and compressed air
• Circulating water makeup and blowdown	• Service water
• Condensate polishing	• Shutdown corrosion protection
• Condensate storage	• Space conditioning
• Condensate air removal	• Turbine seal steam and drains
• Demineralized water storage	• Waste treatment
• Demineralized water supply	• Water quality control
• Fire protection	• Turbine lubricating oil

While the electrical power generation subsystem design is based on analytical work, it has a firm basis in state-of-the-art technology. The primary problem was in matching the turbine characteristics to the input cycles of the receiver and thermal storage subsystems to provide maximal turbine efficiency. The design ensures this, meeting all performance requirements in all plant operating modes and mode transitions.

System Integration

Implicit in the design of efficient subsystems is the requirement to integrate them so as to realize their full potentials in the end product. Table 3 lists major issues that influenced the parameters of the subsystems and their interfaces. It should be stated that this list is indicative rather than exhaustive, and that some of the issues were resolved only through several iterations of design.

Resolution of the subsystem/component issues is discussed to some extent in another section of this report, as is scaling. Other issues affecting the system as a whole are summarized next, starting with system controls.

Table 3. Issues in System Integration

Subsystems/Components Affected	Issue
Collector/Receiver	<ul style="list-style-type: none"> ● Ground cover ● Tower height ● Flux density ● Aperture size ● Cloud cover ● Startup ● Sun position
Receiver/Turbine	<ul style="list-style-type: none"> ● Diurnal variation
Storage-Turbine/Storage-Receiver	<ul style="list-style-type: none"> ● Diurnal variation ● Cloud outages ● Sealing requirements ● Busbar and capital costs ● Capacity ● Operational strategy
All	<ul style="list-style-type: none"> ● Control ● Maintenance ● Safety ● Scaling

System Controls

Pilot plant control is exercised on three levels: system, subsystem, and minor loops. The master, or system, control coordinates demand signals to the collector/receiver subsystems, storage subsystem, and the turbine governor by sensing deviations in power generated from power required. A diagram of master control sequencing is shown in Figure 31.

The receiver control regulates the receiver feedwater and superheater spray flows by focusing or defocusing heliostats as required to obtain the flow balance called for by the master control (Figure 32).

Storage has storage-in and storage-out controls. Storage-in control regulates and apportions surplus steam to charge main and superheater storage as dictated by the master control. Storage-out control regulates the generation of steam by the storage subsystem for the turbine as dictated by the master control (Figure 33).

In addition to the system and subsystem operating controls, there are local loop controls (e.g., for condensate flow control and turbine lubrication oil temperature control, and protection controls for the major subsystems).

Figure 31. Pilot Plant Coordinated Master Control

Figure 32. Receiver Steam Generator Control

Figure 34. Pilot Plant Typical Day Operating Cycle

The three types of plant shutdown, as implied above, are diurnal, extended, and emergency.

In summary, the pilot plant control system provides:

- Coordination of subsystem functions
- Personnel and plant protection
- Monitoring and recording of plant conditions
- Adequate communication among operating personnel
- Four startup and three shutdown strategies

System Availability and Safety

Availability -- The practicality of a solar power plant depends not only on its capability to function as designed, but also on the amount of time it is available to function. In designing the pilot plant, the following factors affecting availability were considered:

- Compliance with code requirements
- Redundancy
- Ease of maintenance/maintenance skill levels
- Operator skill levels

In assessing system availability, the guidelines and the formula were these. The system was judged to be available when capable of 98 percent output at a given solar input. System availability was calculated as the product of subsystem availabilities and scheduled maintenance availability. Subsystem availabilities were defined as mean times between failures (MTBF) and mean time to repair (MTTR). Calculated subsystem and system availabilities are:

- Collector = 0.997
- Storage = 0.985
- Electrical power generation and receiver = 0.992
- Control = 0.997
- Planned outage = 0.962
- System = $0.999 \times 0.985 \times 0.992 \times 0.997 \times 0.962 = 0.934$.

Safety -- Another important factor in judging solar power plant practicality is safety, not only that of the equipment itself and operating personnel but of people and property in general. Design features that ensure safety in the pilot plant operation are:

- Compliance with OSHA* and standard design codes
- Control rules for collector subsystem operation

* U. S. Occupational Safety and Hazards Administration

- Protection for ground and airborne observers
- Protection of equipment against the elements
 - Wind
 - Hail
 - Rain
 - Snow and ice
 - Sand
 - Lightning
 - Earthquake (receiver tower and oil storage)

SECTION III

PILOT/COMMERCIAL PLANT RELATIONSHIP

The ultimate value of the pilot plant lies in how well it defines the requirements for and performance of the commercial plant. It is reasonable to assume that there will be a few changes when the pilot plant design is detailed, most probably to reduce costs, and those changes will be reflected in the commercial plant design. Therefore, the following pilot/commercial plant comparison must be regarded as preliminary to a more definitive analysis of requirements and characteristics at a later point in the program.

FIRST COMMERCIAL PLANT CONFIGURATION AND CHARACTERISTICS

Figure 35 shows the commercial plant conceptual layout.

Figure 35. Commercial Plant Layout

The impression is that of four pilot plant fields in juxtaposition. This arrangement is the result of a study to determine a practical number of towers/fields to meet the performance specifications for the commercial plant.

Three plant configurations that met all performance specifications were analyzed, one tower and field, four towers and fields, and 12 towers and fields. The 12-tower/field concept would be significantly more costly to implement than the other two, as shown in Figure 36.

Figure 36. First Commercial Plant Cost as Function of Configuration

The one-tower/field concept, while somewhat less expensive than the four-tower/field concept, requires a tower height that raises doubts about its practicality (Figure 37). Table 4 presents a further comparison of the three concepts, showing there is little difference in the performance characteristics. There are significant differences in the numbers of heliostats and the amounts of land required, with the four-tower/field concept being a compromise between cost on the one hand and structural practicality on the other.

The four-tower/field site plan is shown in Figure 38. A central station complex, located at the centroid of the four towers to minimize steam piping, houses the 120-MW(e) nameplate turbine and ancillary controls and support equipment for the balance of the plant. The arrangement of the main steam lines is illustrated in Figure 39.

Direct scaling between the pilot and commercial plants is the result of analysis and planning by industry and government well before the inception of the Phase I program, which serves to underline the necessity for an accurate translation of performance from the former to the latter. Table 5 is a summary of pilot and commercial plant design specifications, showing the number of parameters that are the same for both types of plant. Improvements in performance of commercial over pilot plant (e.g., design point net efficiency) reflect the difference in design points.

The scaling relationship on a subsystem basis is outlined in the paragraphs that follow.

Figure 37. First Commercial Plant Tower Height as Function of Configuration

Table 4. Comparison of Characteristics of Three Commercial Plant Configuration

Characteristic	1 Tower	4 Towers	12 Towers
<u>PHYSICAL</u>			
Number of heliostats	18,519	18,568	18,960
Tower height, m	431	215	132
Field outer diameter, m	1,832	912	533
Field inner diameter, m	343	171	100
<u>PERFORMANCE</u>			
Power available, MW(t)	704	706	720
Mirror power, MW(t)	654	656	699
Redirected power, MW(t)	572	574	585
Cavity power, MW(t)	555	557	569
Absorbed power, MW(t)	488	490	495

Figure 38. Commercial Plant Site Plan

Figure 39. Arrangement of Main Steam Lines in Commercial Plant

Table 5. Pilot/Commercial Plant Preliminary Design Specification

Parameter	Pilot Plant	Commercial
Location	Barstow, CA.	---
Nameplate capacity	15 MW(e)	120 MW(e)
Design point net power	10 MW(e) - 12/21, 2 pm	100 MW(e) - 3/21 noon
Tower height	126.5 m (415 ft)	225.8 m (740 ft), 4 towers
Heliostat size	40 m ²	Same
Solar multiple	1.23	1.7
Number of heliostats	1598	20,220
Total mirror area	63,920 m ²	808,800 m ²
Storage type	Sensible	Same
Storage capacity	7 MW(e) for 3 hours (115.2 MWhr(t))	Same (908.6 MWhr(t))
Receiver peak flux	300 kW/m ²	Same
Aperture area	118.4 m ² (1274 ft ²)	738 m ² (7944 ft ²) tower
Receiver peak/avg. efficiency	87.2/84.1	Same
Turbine cycle (from receiver)	10.1 MPA/510°C (1450/950)	Same
Turbine cycle (from storage)	3.2 MPA/380°C (460/730)	Same
Design point net efficiency (from receiver)	25.9	29.3
Design point net efficiency (from storage)	22.1	26.3
Total net annual energy (NAE)	2.22 x 10 ⁴ MWhr(e)	2.89 x 10 ⁵ MWhr(e)
NAE/Total mirror area	0.348 MWhr(e)/m ²	0.357 MWhr(e)/m ²

COLLECTOR SUBSYSTEM

Figure 40 shows parameters of the pilot and first commercial plant collector subsystems. The area of one field of the commercial plant is approximately 3.2 times that of the pilot plant field, making the total field area 12.8 times as great. That translates to a requirement for 20,220 heliostats for the commercial field.

RECEIVER SUBSYSTEM

Figure 41 compares the pilot and first commercial plant receiver subsystems. The ratio of linear dimensions of the commercial plant to those of the pilot plant is about 1.7, which places the commercial tower well within the state of the art for chimney-type structures. The validity of the scaling exercise is expressed in the identical peak incident wall fluxes and the near identical receiver efficiencies.

THERMAL STORAGE SUBSYSTEM

The capacity of the first commercial thermal storage subsystem is roughly eight times that of the pilot plant. Duration of output, hold time prior to discharge, and heat loss rate are the same for both units, as shown in Figure 42.

Figure 40. Pilot/Commercial Plant Collector Subsystem Comparison

Figure 41. Pilot/Commercial Plant Receiver Subsystem Comparison

Figure 42. Pilot/Commercial Plant Thermal Storage Subsystem Comparison

ELECTRICAL POWER GENERATION SUBSYSTEM

Table 6 is a comparison of parameters for the pilot plant and first commercial plant electrical power generation subsystems. Critical parameters, operational cycle conditions, and condenser cooling technique are the same for both. The difference in net plant efficiency reflects the difference in design point.

Table 6. Pilot/Commercial Plant Electrical Power Generation Subsystem Comparison

Parameter	Pilot Plant	First Commercial
Turbine type	Automatic admission	Same
Nameplate capacity	15 MW(e)	120 MW(e)
Cycle conditions:		
Throttle	10.2 MPa/510°C (1450/950)	Same
Admission	3.2 MPa/388°C (460/730)	Same
Number of extractions	3	5
Heat rejection type	Wet cooling	Same
Gross turbine efficiency:		
Receiver design point	34.5%	38.5%
Storage design point	28.5%	31.8%

SECTION IV

ASSESSMENT OF THE PHASE I PROGRAM

Before evaluating the findings of the Phase I program and summarizing the recommendations based on them, it would be helpful to review the objective of the program, which was:

"To establish the technical feasibility of a solar thermal power plant of the central receiver type with significant commercial potential and to obtain sufficient development, production and operating data to indicate the economics of operation for commercial power plants of similar design."

This objective was pursued through analytical studies and experimentation. The primary analytical tools were the central receiver optical model and the dynamic simulation model. These were used to determine the optimum collector/receiver arrangement, system operating parameters, and system efficiency in the various operational modes. Experiments were carried out on three key subsystems (collector, steam generator, and thermal storage) to validate the analytical work.

CONCLUSIONS

The technical feasibility of the central receiver solar power plant concept has been established, and there are no unusual requirements associated with the design. Subsystem feasibility is summarized as follows:

- Collector Subsystem -- The design of the pilot plant collector subsystem has been validated by analysis and test.
- Receiver Subsystem -- The pilot plant receiver subsystem design is based on standard construction methods and standard fossil-fuel technology. The steam generator differs from the SRE version in size only, the latter being virtually a scale model. The SRE steam generator was validated by test, wherein it demonstrated reliable performance and good response to controls.
- Thermal Storage Subsystem -- The design of the pilot plant thermal storage subsystem presents low development risk because it uses proven technology, minimizes thermal shock to the turbine, and provides steady power output during cloud transition.

- Electrical Power Generation Subsystem -- The pilot plant electrical power generation subsystem is of low risk because it is wholly based on proven technology.

The pilot plant design relates directly to the concept for the first commercial plant. All operating data and plant costs for the former can be realistically projected to the latter to predict performance and identify required expenditures.

Solar power plant economics are highly sensitive to heliostat and storage costs. While neither are prohibitive in the light of future requirements for power, both have excellent potential for cost reductions through refinements in design and/or the use of alternative materials. The other subsystems are of relatively low cost.

In summary, the objectives of the Phase II program (listed below) can be realized with low technical risk and at moderate cost. The Phase II objectives are to:

- 1) Detail the pilot plant design.
- 2) Construct the pilot plant.
- 3) Prepare a preliminary design for the first commercial plant.
- 4) Conduct in situ tests of pilot plant subsystems.

RECOMMENDATIONS

Honeywell, on the basis of findings during Phase I, recommended to ERDA that the detailed design and construction of the world's first solar electric power plant begin immediately. Specific recommendations were to:

- 1) Proceed immediately to Phase II to preserve continuity and the momentum gained during Phase I.
- 2) Establish a well-funded, flexible, ongoing program for heliostat development aimed at lowering cost.
- 3) Establish a like program for thermal storage development for the same purpose.
- 4) Proceed with sunlight tests of the receiver subsystem.
- 5) Proceed with latent-heat storage tests (discontinued in 1976).
- 6) Provide for additional SRE tests to expand the data bank.

Figure 43 is a schedule for the Phase II program.

Figure 43. Phase II Program Schedule

SECTION V

EVOLUTION OF THE PILOT PLANT DESIGN

The original baseline for the pilot plant design was that presented to ERDA by Honeywell in its proposal for conducting the Phase I program. The general aspect was a circular field with the tower in the center (Figures 44 and 45).

Figure 44. Pilot Plant Original Arrangement

Figure 45. Pilot Plant Original Site Plan

The pilot plant baseline parameters were derived from the concept of a 215-MW(e) nameplate capacity commercial plant (Table 7). The governing factor in this concept was tower height, with 457 meters (1500 feet) being regarded as the upper limit. A 10-MW(e) pilot plant was selected as an adequate size for evaluating the performance and economics of the commercial plant concept. A direct geometric scaling of mirror area with pilot plant net output gave the baseline dimensions. System and subsystem details were then selected in accord with the requirement of direct relationship to commercial plant size.

Table 7. Parameter of Original Commercial Plant Concept

Parameter	Value
Nameplate capacity	215 MW(e)
Avg. power (net - 4000 hr)	172 MW(e)
Tower height	457 m
Field O. D.	1994 m
Number of heliostats	73,829
Heliostat size	50 m ²
Turbine cycle from receiver	10 MPa/510°C
Turbine cycle from storage	4 MPa/280°C
Receiver type	Cavity
Storage type	Phase-change
Cooling type	Dry

In the original pilot plant design baseline, the heliostat was rectangular and the gimbal order was azimuth/elevation (Az-El). The receiver tower was 137 meters high, and the receiver aperture was symmetrical. Receiver steam pressure and temperature were 5.9 MPa and 510°C, respectively. Thermal storage was based on latent-heat storage, and the storage tanks were conceived as being buried. Storage steam pressure and temperature were 4 MPa/280°C. Both receiver and storage steam had primary admission to the turbine. The condenser was dry-cooled.

CHANGES TO THE DESIGN BASELINE

Within a few weeks of program inception on 1 July 1975, three changes were made in the baseline to improve system performance, and, in one case, to effect a cost saving as well.

Heliostat Configuration

The heliostat Az-El gimbal order was changed to tilt-tilt because of the high torque associated with the former. The change also yielded a cost saving by simplifying the design. The two heliostat configurations are shown in Figure 46.

Figure 46. Original and New Heliostat Configurations

Receiver Steam

The original receiver steam pressure of 5.9 MPa was changed to 10 MPa to obtain greater cyclic efficiency. The receiver steam temperature of 510°C and the storage steam values (4 MPa/ 280°C) were retained.

Turbine Configuration

The original baseline featured primary turbine admission for both receiver and storage steam. The temperature mismatch represented a potential problem. The turbine configuration was changed to permit injection of storage steam downstream from the receiver steam, thereby providing dual admission wherein receiver and storage steam could be used simultaneously.

The revised pilot plant baseline, summarized in Table 8 and shown schematically in Figure 47, formed the basis for detailing the key subsystems and designing the SREs.

Table 8. Parameters of Pilot Plant Preliminary Baseline Design

Parameter	Value
Nameplate capacity	15 MW(e)
Avg. power (net - 4000 hr)	10 MW(e)
Tower height	137 m
Field O. D.	580 m
Number of heliostats	4095
Heliostat size	40 m ²
Turbine cycle from receiver	10 MPa/510°C
Turbine cycle from storage	4 MPa/280°C
Receiver type	cavity
Storage type	Phase-change
Storage capacity	255 MWh(t)
Cooling type	Dry

Of interest is the allocation of plant costs made at that time (September 1975). While the percentages shown at the left in Figure 48 changed during the course of the program, they were reasonably representative. The allocations in both charts emphasize the desirability of cost reductions in the collector subsystem.

The design continued to change as detailing progressed. In the first quarter of 1976, two changes were made in the thermal storage subsystem.

Figure 47. Pilot Plant Baseline Design Schematic

Figure 48. Pilot Plant Cost Allocations Made at Beginning and End of Program

Storage Tank Parameters

A study showed that significant cost benefits could be obtained by placing the storage tanks at ground level, as opposed to below ground, and by not housing them. The study also showed that round tanks were less expensive than rectangular tanks.

Phase-Change Material

The phase-change material was changed from a ternary eutectic salt mixture of $\text{NaCl-NaNO}_3\text{-Na}_2\text{SO}_4$ to a mixture of $\text{NaNO}_3\text{-NaOH}$. This reduced the cost of the material, upgraded heat recovery, and increased scraper efficiency.

Collector Field Geometry

A change of major significance was made in the baseline in the second quarter of 1976. Heliostat field layout studies showed that a field with the tower south of center could more efficiently redirect the solar energy into the receiver. Figure 49 summarizes the evolution of the collector field.

MILESTONE	PROPOSAL (4/29/75)	PDBR	FIELD DETAIL DESIGN (6/1/76)
CONFIGURATION	TOWER CENTER, GC = 0.45	TOWER CENTER GC = 0.3	TOWER 1/2 SOUTH GC = 0.29 (NON-UNIFORM)
TOTAL MIRROR AREA	87,200 m ²	76,160 m ²	67,280 m ²
MIRROR AREA/HELIOSTAT	40 m ² (AZ-EL)	18.6 m ² (9/30/75) 40 m ² (1/30/76)	40 m ²
NUMBER OF HELIOSTATS	2180	4095 (9/30/75) 1904 (1/30/76)	1682
ANNUAL ABSORBED KWH/M ²	1.82	1.95	2.01

Figure 49. Changes in Collector Field Configuration

It will be noted that the number of heliostats decreased with each iteration of design after the change to tilt-tilt gimbaling, while the annual energy per unit area increased. In addition to the gain in field efficiency, the decrease in the number of heliostats represents a cost saving. Figure 50 shows tracking efficiency at three times of the year with the tower half south of center.

Figure 50. Tracking Efficiency, Tower Half South

Receiver Geometry

During the same period (mid-1976), the receiver cavity size and the aperture configuration were changed as shown in Figure 51.

Figure 51. Changes in Receiver Geometry

The increase in cavity diameter reflected the increase in mirror area per heliostat (Figure 49, PDBR* configuration), and the change in tracking error budget from 1 milliradian (1σ).

The cavity aperture configuration was made asymmetrical and the receiver supports were moved to accommodate the change in field layout and the consequent change in the pattern of redirected energy.

Thermal Storage

Work on the phase-change thermal storage SRE was discontinued late in the third quarter of 1976 at the direction of ERDA. The concept was judged to be high risk within the timeframe of pilot plant development, so a sensible-heat storage subsystem was incorporated in the pilot plant design. Figure 52 is the flow diagram for the phase-change storage subsystem. Figure 53 is a matrix of test goals for the phase-change storage subsystem SRE. These were not realized, as the work halted before the test stage was reached. (The work that was done is discussed later in this section.) Figure 54 illustrates the sensible-heat storage technique substituted for the phase-change method.

Thermodynamic Cycle

The change in receiver steam pressure discussed earlier was one in a series of changes made in the thermodynamic cycle during the course of the program. This progression is summarized in Table 9.

The first change from the design baseline was made when the latent-heat storage subsystem design was detailed in mid-1976. A later revision was carried out through an expansion-line matching exercise (Figure 55) to ensure optimum admission steam properties within allowable turbine parameters. This work was largely invalidated by the change from latent-heat to sensible-heat storage. When that change was effected, the receiver steam properties that prevailed in the preliminary design baseline were resumed, and the storage steam properties were adjusted accordingly.

Condenser Cooling

The last major change in the design baseline, that from dry to wet cooling the condenser, was made at the end of 1976 at ERDA'S direction. This change affected such turbine parameters as back pressure, gross heat rate, and efficiency positively (i. e., improved them). It also reduced the requirement for auxiliary power for fans, pumps, and various cooling system accessories by nearly half. (The wet-cooling scheme is shown in Figure 29.)

* Preliminary Design Baseline Review

Figure 52. Phase-Change Thermal Storage Flow Diagram

Figure 53. Test Matrix for Phase-Change Storage SRE

Figure 54. Sensible-Heat Thermal Energy Storage

Table 9. Thermodynamic Cycle Changes

Milestone	Turbine Throttle	Admission Port
Proposal (4/29/75)	Receiver 5.96 MPa/510°C (850 psig/950°F)	---
	Storage 3.21 MPa/266°C (450 psig/510°F)	---
PDBR (9/30/75)	10.10 MPa/510°C (1450 psig/950°F)	4.07 MPa/279°C (575 psig/534°F)
Storage DDR (6/22/76)	12.51 MPa/510°C (1800 psig/950°F)	5.86 MPa/304°C (835 psig/580°F)
Redesign for expansion line matching (9/1/76)	12.51 MPa/510°C (1800 psig/950°F)	5.34 MPa/410°C (760 psig/770°F)
ERDA redirection (9/7/76)	10.10 MPa/510°C (1450 psig/950°F)	3.28 MPa/388°C (460 psig/730°F)

Figure 55. Design Point Expansion Line for 12.5-MPa Dual-Admission Turbine

PHASE-CHANGE THERMAL ENERGY STORAGE

The latent-heat (phase-change) storage concept was carried through detailed design and fabrication of the test hardware for the SRE. At that point, ERDA directed the use of sensible-heat storage because the other was judged to be an advanced technology that introduced high risk into pilot plant development. Honeywell concurred, but believes that phase-change thermal storage has potential in a solar plant because the storage medium is relatively inexpensive and the maintenance requirements simple. These features, properly developed, represent savings in busbar energy costs.

Phase-Change Storage Concept

Stated briefly, the phase-change storage concept uses the latent heat of fusion of a eutectic salt to store thermal energy. Energy to charge the salt is obtained as heat of condensation from receiver steam. Banks of condenser tubes are located at the bottom of a salt storage tank. Heat transfer to the salt is by natural convection. Heat energy in the tank is discharged by circulating feedwater through boiler tubes at the top of the tank to obtain saturated steam, which is superheated and fed into the turbine. Salt buildup on the tubes in the tank is removed mechanically. (This concept is illustrated in Figure 52.)

Phase-Change Storage Concept Development

The investigative work done on phase change thermal storage during the first 15 months of the program fell under two general headings: phase-change materials and engineering model experiments.

Phase-Change Materials -- A number of ternary and binary salt mixtures were evaluated before a 99/1 percent by weight mixture of sodium nitrate and sodium hydroxide was selected. The selection criteria were safety, that the salt composition form a slurry during the freezing process, be easily scraped off the vaporizer tubes, and provide adequate heat transfer. Table 10 is a general summary of materials investigated. Figure 56 is the phase diagram for the mixture chosen.

Table 10. Phase-Change Materials Investigated

Class	Example	Evaluation
Acetates	KCOOCH_3	Eliminated - Health hazard
Formates	NaOOCH	Eliminated - Health hazard
Amides	KNH_2	Eliminated - Disaster hazard
Thiocyanates	NaCNS	Eliminated - Health and disaster hazard
Perchlorates	LiClO_4	Eliminated - Unstable, health and disaster hazard
Chlorates	NaClO_3	Eliminated - Health and disaster hazard
Chlorides	FeCl_3 (ZnCl_2)	Eliminated - Disaster hazard
Hydroxides	NaOH	Acceptable (when used below 700°F and with proper design, operating and handling procedures).
Nitrites	NaNO_2	Acceptable (when used below 600°F and with proper design, operating and handling procedures).
Nitrates	NaNO_3	Acceptable (when used below 700°F and with proper design, operating and handling procedures).

Engineering Model Tests -- Tests of the phase-change storage concept were conducted with progressively more sophisticated engineering models. Table 11 summarizes the types of tests conducted between May and September 1976.

Figure 56. NaNO_3 - NaOH Phase Diagram

Table 11. Thermal Storage Engineering Model Tests

Type of Test	Test Parameter
Vaporizer	<ul style="list-style-type: none"> Scrapers run at different speeds: <ul style="list-style-type: none"> - Determine heat transfer rate - Determine scraper torque versus speed Latent heat extraction rate varied: <ul style="list-style-type: none"> - Determine maximum extraction rate - Determine maximum latent heat recovery Sensible heat extraction rate measured: <ul style="list-style-type: none"> - Determine contribution of scraper speed to convection Latent heat extraction with agitation: <ul style="list-style-type: none"> - Determine bulk transport effect on heat transfer coefficient Scraper freeze-up temperature versus salt temperature
Condenser	<ul style="list-style-type: none"> Determine effect of temperature on heat transfer rate Determine effect of solidification on heat transfer Determine salt flow pattern
Scrapability	<ul style="list-style-type: none"> Vertical-type external scraper Scrapability of nitrate and hydroxide mixtures
Safety and material compatibility	<ul style="list-style-type: none"> Pulsed water injection Continuous water injection Corrosion of steel Combustion of carbon and nitrate

Figure 57 shows an external heat-exchanger arrangement used in some of the later tests.

Figure 57. External Heat-Exchanger Apparatus,
Phase Change Storage Tests

Results from the various tests indicated that the phase-change storage concept was sound and could be implemented successfully on the pilot plant scale.

SRE Test Hardware

Commitments had been made for the thermal storage SRE test hardware before the design was changed. Consequently, the hardware was assembled and stored. Had it been tested as planned, the tests would have been conducted simultaneously with, but independent of, those conducted on the steam generator in an operating power plant environment.

SECTION VI

DOCUMENTATION OF PHASE I PROGRAM

DATA SUBMITTALS

The Phase I solar pilot plant program technical activities and achievements were formally documented in accord with the Contract Data Requirements List (CDRL). The data items and the schedule to which they were submitted are shown in Figure 58.

Figure 58. Phase I Program Data Submittals

In addition to the requisite technical reports and management reports, Honeywell supplied ERDA and/or ERDA-designated agencies with materials for briefings and displays on request.

CUSTOMER ENGINEERING LETTERS

An important instrument of communication was the Customer Engineering Letter (CEL), through which Honeywell responded to Data item 11. From program inception through May 1977, one hundred eighteen CELs were submitted. These are summarized on the following pages.

PROGRAM PLAN

The original plan was submitted at program inception. It was revised in September 1975 and in March 1976. The tasks in the March 1976 plan and their disposition are summarized (following the list of CELs) as being, with a program organization chart (Figure 59), the only information necessary to a final presentation of the plan.

CUSTOMER ENGINEERING LETTERS

<u>CEL No.</u>	<u>Date</u>	<u>Subject</u>
1	8/12/75	Customer Engineering Letter
2	8/14/75	Baseline Design Conditions
3	8/15/75	CDRL Milestones and Due Dates
4	8/15/75	Thin-Film and Coating Information Request
5	9/15/75	Safety Aspects
6	9/19/75	Recent Sandia Questions
7	10/29/75	Estimate of Material Quantities
8	11/03/75	Thermodynamic States
9	11/04/75	Aerospace Economic Model
10	11/26/75	Boiling Heat Transfer Inside Horizontal Tubes-- Request for Experimental Data
11	1/21/76	Turbine and Receiver Efficiencies
12	1/27/76	Pilot Plant Cycle Efficiency
13	1/28/76	Operating Strategy
14	2/09/76	B&W Code Meeting 1/2/76
15	2/09/76	Mirror Environmental Test Data CDRL 1 PDBR
16	2/13/76	SRE Data Acquisition System
17	2/20/76	Long Lead Item Purchase Approval Prior to DDR
18	2/23/76	Receiver Operational and Configuration Characteristics
19	2/27/76	Long Lead Part Procurement (Test Bed Heliostat)
20	3/01/76	Steam Generator Long Lead Items (Valves - \$1922 Total)

<u>CEL-No.</u>	<u>Date</u>	<u>Subject</u>
21	3/--/76	Action Item Response
22	3/19/76	SRE Test Instrumentation
23	3/19/76	1801 Study Report -- SRE DAS
24	3/19/76	Approval to Fabricate Long Lead Items (Helical and Hydrotest Coils - Est. \$21,393)
25	3/26/76	Action Item Response (Various)
26	3/29/76	Heliostat Learning Curves
27	3/29/76	Approval of Long Lead Items (24 valves - Total \$46,02)
28	4/13/76	Approval of Long Lead Items (Boiler Support Steel - \$9092, Superheater and Attemperator Material - \$1517, 50 Valves - \$3321)
29	4/15/76	Characteristic Parameters for 10-MW(e) Pilot Plant Storage Subsystem
30	4/19/76	Long Lead Item Approval (Steam Generator Interstage Spray Attemperator - \$8000)
31	4/19/76	Boiler and Superheater Stress Analysis
32	4/21/76	Impact of Site Selection on Solar Pilot Plant Activities
33	4/27/76	Long Lead Item Approval (18 Valves - \$2497)
34	4/30/76	Westinghouse/EPRI Questionnaire
35	5/04/76	Long Lead Item Approval (Thermal Storage Recirculation Pump \$94.36)
36	5/05/76	Commercial Plant Cost Estimates
37	5/13/76	Cost Estimate Methodology, Commercial Solar Central Receiver Power Plants
38	5/11/76	Information on Eye Damage
39	5/14/76	Pilot Plant Receiver Characteristics
40	5/14/76	Further Question on Cost Information

<u>CEL No.</u>	<u>Date</u>	<u>Subject</u>
41	5/25/76	Long Lead Item Approval - 2 Steam Traps (\$2263)
42	5/27/76	Long Lead Item Approval - Steam Drum (\$9830)
43	6/4/76	Acceptance Angle of Cary Model 14 Spectrophotometer
44	6/7/76	Cost Estimates for 2-Year Operational Test Program
45	6/8/76	Pilot Plant Turbine Efficiency
46	6/11/76	Total Insolation Measurement
47	7/14/76	Plan and Schedule for Measuring Corrosion Under Stress of Storage Tubing
48	7/9/76	Date for Establishing the Manifolding and Integration of Storage Modules (SRE Design) for the Pilot Plant
49	7/14/76	Pilot Plant Steam Source Switching Time
50	7/15/76	Storage and Steam Generator Testing
51	7/15/76	Thermal Storage Discharge Cycle Heat Transfer Coefficient Selection for the SRE
52	7/19/76	Solar Insolation for Solar Power Plant Sizing and Performance Calculations
53	7/28/76	Delivery Schedule for Components for Thermal Storage
54	8/5/76	Steam Generator Exfoliation
55	8/12/76	Pilot Plant Site Selection Data
56	8/13/76	Data Item Submittals
57	8/25/76	Cost Estimates for a Commercial Solar Central Receiver Pilot Plant
58	8/26/76	Foam Mirror Module
59	9/1/76	Action Item I-7 -- Testing at NSP
60	9/2/76	Seismic Loads on Thermal Storage Tank
61	9/17/76	Comments on Proposed Cost Breakdown Structure

<u>CEL No.</u>	<u>Date</u>	<u>Subject</u>
62	9/29/76	Dust Devils and Thunderstorm Gusts
63	10/5/76	Design Data for Sensible Heat Storage
64	10/4/76	Pilot Plant Cloud Transient Control
65	10/18/76	Response to Action Item 2, Program Review No. 6
66	10/13/76	Requested Data on SRE Steam Generator and Rerad Work
67	10/21/76	Solar Pilot Plant Receiver Reradiation
68	10/29/76	Your 15 October Letter (L. M. Murphy)
69	11/1/76	NSP Modification Drawings
70	11/2/76	Heliostat Environmental Conditions
71	11/10/76	NSP Modification Drawings
72	11/11/76	Minutes of the Heliostat Technical Audit
73	11/11/76	Modification of the Heliostat Test Plan
74	11/12/76	SRE Test Schedule
75	11/18/76	Boiler Pricing Data
76	11/18/76	Steam Generator Technical Data
77	11/22/76	Baseline Characteristics Document
78	11/22/76	Steam Generator Data
79	11/23/76	Instruction Manual, Test Requirement and Test Schedule
80	11/24/76	Heliostat Engineering Cost Estimates
81	11/24/76	Heliostat Extended Scope Testing
82	12/3/76	Optical Calorimetry
83	12/3/76	Heliostat Gear Box Failures

<u>L No.</u>	<u>Date</u>	<u>Subject</u>
84	1/13/77	Written Summary of Presentation at Opening Meeting (12/7/76)
85	1/20/77	Steam Generator Questionnaire
86	1/21/77	Pilot Plant Steam Generator Data
87	1/26/77	Documentation of Technical Audit 20 January 1977
88	1/25/77	Documents Used at Technical Audit 20-21 January 1977
89	1/31/77	Action Items From the 25-26 January Coordination Meeting
90	1/27/77	Steam Generator Tilting
91	1/31/77	PDR Delivery Date
92	1/31/77	Recent Press Release
93	2/3/77	Response to Various Action Items
94	2/4/77	Steam Generator SRE Operation and Test
95	2/17/77	Steam Generator SRE Error Analysis
96	2/9/77	Proposed Phase 2 Schedule
97	2/15/77	Impact of New Wind Specification on Present Honeywell Design
98	2/16/77	Earthquake Problem Resolution
99	2/18/77	Cavity Convection Calculations
100	2/17/77	Computer Listing - Steam Generator Model
101	2/18/77	Action Item H-6 From 25-26 January Coordination Meeting
102	2/21/77	TWX Skinrod to Powell, Dated 28 January 1977 (re: heliostat testing at STTF)
103	Number not used	
104	3/11/77	Action Items and Statements from 8-9 March Project Review No. 8

<u>CEL No.</u>	<u>Date</u>	<u>Subject</u>
105	3/11/77	Action Items Submittal (8th Review Meeting)
106	3/11/77	Computer Listing - Steam Generator Model
107	3/15/77	Barstow Site Specific Data
108	3/17/77	Eighth Project Review Action Items (AI 2, 5, 6)
109	3/18/77	Action Items From 8-9 March Project Review No. 8 (AI 11, 15)
110	3/21/77	Confirmation of 3/15/77 Telecon Information
111	3/21/77	Action Item Response From March 8-9 Project Review No. 8 (AI9)
112	3/21/77	Heliostat Subsystem Information Request
113	3/28/77	Telecon, Powell (ERC) From M. Murphy (Sandia) 3/23/77 - Water Analysis at Barstow
114	3/28/77	Request - Predictions for SRE and Site Information 18 March 1977 (call Murphy to Powell)
115	3/29/77	Flux Corrective Curves
116	4/4/77	Proposed PDR Agenda
117	4/18/77	Standard Collector/Receiver Problem
118	5/23/77	Steam Generator Operating Instructions and Test Requirements
119	6/2/77	Action Item Response From May 4-5 PDR

PHASE I PROGRAM PLAN

The following tasks and subtasks were defined by the Work Breakdown Structure (WBS) Dictionary in the March 1976 Program Plan. The alphanumerical designators are those used by ERDA. The numerical designators in parentheses are those used by Honeywell. In instances where tasks were completed in full, that is signified by the word Complied. In instances where they were not, an explanation is given. Apparent omissions in numbering of the tasks reflect deletions made prior to March 1976.

<u>Task</u>	<u>Title and Status</u>
SC00 (0. 0)	CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEMS -- Complied with except for conducting thermal storage SRE. See SC424.
SC010 (1. 0)	CENTRAL RECEIVER PILOT PLANT -- Complied
SC110 (1. 1)	INTEGRATION AND ASSEMBLY -- Complied
SC111 (1. 1. 1)	PLANT INTEGRATION -- Complied
SC112 (1. 1. 2)	PLANT DESIGN COORDINATION -- Complied
SC210 (1. 2)	COLLECTOR SUBSYSTEM -- Complied
SC211 (1. 2. 1)	MECHANICAL TRADEOFF -- Complied
SC212 (1. 2. 2)	TRACKING AND CONTROL TRADEOFF -- Complied
SC213 (1. 2. 3)	ANALYSIS AND DESIGN COORDINATION -- Complied
SC214 (1. 2. 4)	COLLECTOR DESIGN UPDATE -- Complied
SC310 (1, 3)	RECEIVER SUBSYSTEM -- Complied

<u>Task</u>	<u>Title and Status</u>
SC311 (1.3.1)	OPTICAL DESIGN -- Complied
SC312 (1.3.2)	RECEIVER BASELINE -- Complied
SC313 (1.3.3)	SPECIFICATIONS -- Complied
SC314 (1.3.4)	STEAM GENERATOR BASELINE -- Complied
SC315 (1.3.5)	STEAM GENERATOR PRELIMINARY DESIGN -- Complied
SC316 (1.3.6)	RECEIVER SUBSYSTEM PRELIMINARY DESIGN -- Complied
SC317 (1.3.7)	DESIGN COORDINATION -- Complied
SC410 (1.4)	THERMAL STORAGE SUBSYSTEM -- Complied with, except that the subsystem SRE was not completed and the results incorporated in the preliminary design. See SC424.
SC411 (1.4.1)	ANALYSIS -- Complied
SC412 (1.4.2)	DESIGN -- Complied
SC413 (1.4.3)	PRELIMINARY DESIGN SPECIFICATIONS -- Complied
SC510 (1.5)	ELECTRIC POWER GENERATION SUBSYSTEM -- Complied
SC511 (1.5.1)	PERFORMANCE REQUIREMENTS AND OPERATIONAL ANALYSIS -- Complied
SC512 (1.5.2)	MECHANICAL DESIGN -- Complied
SC513 (1.5.3)	ELECTRICAL DESIGN -- Complied

<u>Task</u>	<u>Title and Status</u>
SC514 (1.5.4)	STRUCTURAL DESIGN -- Complied
SC515 (1.5.5)	CONTROL AND INSTRUMENTATION -- Complied
SC516 (1.5.6)	PLANT AND SUPPORT SERVICES -- Complied
SC517 (1.5.7)	PRELIMINARY DESIGN -- Complied
SC020 (2.0)	SUBSYSTEM RESEARCH EXPERIMENTS -- Complied with except for completing thermal storage subsystem SRE. See SC 424.
SC220 (2.2)	COLLECTOR SUBSYSTEM RESEARCH EXPERIMENTS -- Complied
SC221 (2.2.1)	CONCEPTUAL DESIGN -- Complied
SC221A (2.2.1.1)	MECHANICAL DESIGN -- Complied
SC221B (2.2.1.2)	TRACKING AND CONTROL DESIGN -- Complied
SC221C (2.2.1.3)	PERFORMANCE ANALYSIS -- Complied
SC221D (2.2.1.4)	TEST PARAMETER SPECIFICATIONS -- Complied
SC221E (2.2.1.5)	SPECIAL TEST EQUIPMENT AND TOOLING -- Complied
SC222 (2.2.2)	DETAILED DESIGN -- Complied
SC222A (2.2.2.1)	MECHANICAL DESIGN -- Complied
SC222B (2.2.2.2)	TRACKING AND CONTROL -- Complied

<u>Task</u>	<u>Title and Status</u>
SC222C (2.2.2.3)	SYSTEM DESIGN -- Complied
SC222D (2.2.2.4)	ENGINEERING MODEL AND TOOL DESIGN -- Complied
SC223 (2.2.3)	HARDWARE FABRICATION -- Complied
SC223A (2.2.3.1)	TOOLING -- Complied
SC223B (2.2.3.2)	PIECE-PART FABRICATION -- Complied
SC223C (2.2.3.3)	SUBASSEMBLY ENGINEERING TEST -- Complied
SC223D (2.2.3.4)	COMPONENT ASSEMBLY -- Complied
SC223E (2.2.3.5)	FINAL ASSEMBLY -- Complied
SC223F (2.2.3.6)	COMPUTER HARDWARE -- Deleted
SC224 (2.2.4)	TEST AND EVALUATION -- Complied
SC224A (2.2.4.1)	DESIGN CONFORMANCE VERIFICATION -- Complied
SC224B (2.2.4.2)	ENGINEERING TESTS -- Complied
SC224C (2.2.4.3)	PRELIMINARY QUALIFICATION TESTS -- Complied
SC224D (2.2.4.4)	DATA REDUCTION AND ANALYSIS -- Complied
SC224E (2.2.4.5)	DISASSEMBLY AND PREPARATION FOR SHIPMENT -- Will comply

<u>Task</u>	<u>Title and Status</u>
SC320 (2. 3)	RECEIVER SUBSYSTEM RESEARCH EXPERIMENTS -- Complied
SC321 (2. 3. 1)	CONCEPTUAL DESIGN -- Complied
SC321A (2. 3. 1. 1)	OPTICAL DESIGN -- Complied
SC321B (2. 3. 1. 2)	STEAM GENERATOR CONCEPTUAL DESIGN -- Complied
SC321C (2. 3. 1. 3)	TEST SETUP DESIGN CONSULTATION -- Complied
SC321D (2. 3. 1. 4)	CONCEPTUAL TEST DESIGN -- Complied
SC322 (2. 3. 2)	DETAIL DESIGN -- Complied
SC322A (2. 3. 2. 1)	OPTICAL DESIGN -- Complied
SC322B (2. 3. 2. 2)	STEAM GENERATOR DETAILED DESIGN -- Complied
SC322C (2. 3. 2. 3)	TEST DESIGN -- Complied
SC322D (2. 3. 2. 4)	NSP PLANT MODIFICATION DESIGN -- Complied
SC323 (2. 3. 3)	HARDWARE FABRICATION -- Complied
SC323A (2. 3. 3. 1)	STEAM GENERATOR FABRICATION -- Complied
SC323B (2. 3. 3. 2)	FABRICATION SUPPORT -- Complied
SC323C (2. 3. 3. 3)	ENGINEERING DESIGN FOLLOW-UP OF FABRICATION -- Complied
SC324 (2. 3. 4)	TEST AND EVALUATION -- Complied

<u>Task</u>	<u>Title and Status</u>
SC324A (2.3.4.1)	LIFE TEST -- Complied
SC324B (2.3.4.2)	PRE-QUALIFICATION TESTS -- Complied
SC324C (2.3.4.3)	DISASSEMBLY OF TEST SITE -- Will comply
SC324E (2.3.4.5)	SOLAR SIMULATOR SUBCONTRACTOR SUPPORT -- Complied
SC324F (2.3.4.6)	ENGINEERING TESTS -- Complied with except for integration of thermal storage tests. Planning did include coordination of tests. See SC424.
SC324G (2.3.4.7)	LIFE SUPPORT TEST -- Complied
SC324H (2.3.4.8)	NSP SUPPORT -- Complied
SC324I (2.3.4.9)	DATA REDUCTION AND ANALYSIS -- Complied
SC420 (2.4)	THERMAL STORAGE RESEARCH EXPERIMENTS -- Complied
SC421 (2.4.1)	CONCEPTUAL DESIGN -- Complied
SC421A (2.4.1.1)	THERMAL DESIGN -- Complied
SC421B (2.4.1.2)	MECHANICAL DESIGN -- Complied
SC421C (2.4.1.3)	ANALYSIS AND CONTROL -- Complied
SC421D (2.4.1.4)	TEST SPECIFICATION AND EQUIPMENT -- Complied
SC421E (2.4.1.5)	ENGINEERING MODEL DESIGN, FABRICATION, AND ASSEMBLY -- Complied

<u>Task</u>	<u>Title and Status</u>
SC421F (2.4.1.6)	STORAGE TEST SETUP DESIGN CONSULTATION -- Complied
SC421H (2.4.1.8)	NSP DESIGN SUPPORT -- Complied
SC422 (2.4.2)	DETAIL DESIGN -- Complied
SC422A (2.4.2.1)	MECHANICAL DESIGN -- Complied
SC422B (2.4.2.2)	CONTROL DESIGN -- Complied
SC422C (2.4.2.3)	ANALYSIS -- Complied
SC422D (2.4.2.4)	TEST PLANS AND EQUIPMENT -- Complied
SC422E (2.4.2.5)	FABRICATION SPECIFICATIONS -- Complied
SC422F (2.4.2.6)	NSP PLANT MODIFICATION DESIGN -- Complied
SC422G (2.4.2.7)	ENGINEERING MODEL TESTS -- Complied
SC423 (2.4.3)	HARDWARE FABRICATION -- Complied
SC423A (2.4.3.1)	STORAGE SUBSYSTEM COMPONENTS FABRICATION -- Complied with except that the salt was not actually procured.
SC423B (2.4.3.2)	DESIGN SUPPORT DURING FABRICATION -- Complied
SC424 (2.4.4)	TESTS AND EVALUATION -- Complied with except that the thermal storage SRE tests were not carried out at NSP due to redirection to a sensible-heat storage subsystem by ERDA in September 1976.
SC424B (2.4.4.2)	THERMAL STORAGE TESTING -- Thermal storage SRE tests not conducted for reason stated above.

<u>Task</u>	<u>Title and Status</u>
SC424C (2. 4. 4. 3)	PRE-QUALIFICATION TESTS -- See SC424 above
SC424D (2. 4. 4. 4)	LIFE TEST, DATA REDUCTION, AND ANALYSIS -- See SC424 above.
SC424E (2. 4. 4. 5)	DISASSEMBLY AND PACKING FOR SHIPMENT -- Will comply.
SC424F (2. 4. 4. 6)	NSP STORAGE TEST SUPPORT -- Complied with until redirection of thermal storage subsystem design.
SC040 (4. 0)	SUPPORT EQUIPMENT -- Complied
SC041 (4. 1)	RECEIVER SUPPORT EQUIPMENT -- Complied
SC041A (4. 1. 1)	PIPING AND MODIFICATIONS -- Complied
SC041B (4. 1. 2)	ELECTRICAL POWER -- Complied
SC041C (4. 1. 3)	RADIATION SOURCE -- Complied
SC041D (4. 1. 4)	CONTROL AND INSTRUMENTATION -- Complied
SC041E (4. 1. 5)	TEST SITE FABRICATION AND DESIGN SUPPORT -- Complied
SC041G (4. 1. 7)	MISCELLANEOUS SUBCONTRACTS -- Complied
SC042 (4. 2)	STORAGE SUPPORT EQUIPMENT -- Complied with to the point where the subsystem design effort was redirected.
SC042A (4. 2. 1)	CONTROL CENTER -- See above
SC042B (4. 2. 2)	INSTRUMENTATION -- See above
SC042C (4. 2. 3)	NSP SUPPORT -- See above

<u>Task</u>	<u>Title and Status</u>
SC042D (4.2.4)	TEST SITE PREPARATION -- See above
SC042E (4.2.5)	NSP PLANT MODIFICATIONS -- See above
SC043 (4.3)	PILOT PLANT SUPPORT EQUIPMENT -- Complied
SC043A (4.3.1)	SUPPORT EQUIPMENT -- Complied
SC043B (4.3.2)	SUPPORT EQUIPMENT (B&V) -- Complied
SC050 (5.0)	SYSTEM TEST AND EVALUATION -- Complied
SC051 (5.1)	PILOT PLANT SYSTEM TEST AND EVALUATION -- Complied
SC051A (5.1.1)	SYSTEM TEST AND EVALUATION -- Complied
SC051B (5.1.2)	SYSTEM TEST AND EVALUATION (B&V) -- Complied
SC060 (6.0)	SYSTEM/PROJECT MANAGEMENT -- Complied
SC061 (6.1)	SYSTEM ENGINEERING MANAGEMENT -- Complied
SC061A (6.1.1)	PILOT PLANT CONCEPTUAL DESIGN -- Complied
SC061A.01 (6.1.1.1)	ANALYSIS -- Complied
SC061A.02 (6.1.1.2)	DESIGN -- Complied
SC061A.03 (6.1.1.3)	INTERFACE ENGINEERING -- Complied
SC061A.04 (6.1.1.4)	SYSTEMS EFFECTIVENESS -- Complied

<u>Task</u>	<u>Title and Status</u>
SC061A.05 (6.1.1.5)	SYSTEM CONTROL -- Complied
SC061B (6.1.2)	EXPERIMENT DESIGN AND TEST COORDINATION -- Complied
SC061B.01 (6.1.2.1)	EXPERIMENT MATHEMATICAL MODELING -- Complied
SC061B.02 (6.1.2.2)	TEST PLAN SUPPORT -- Complied
SC061B.03 (6.1.2.3)	SAFETY AND CONTROL STUDIES -- Complied
SC061C (6.1.3)	DYNAMIC PLANT SIMULATION -- Complied
SC061C.01 (6.1.3.1)	DYNAMIC SIMULATION -- Complied
SC061C.02 (6.1.3.2)	ANALYSIS AND OPTIMIZATION -- Complied
SC061C.03 (6.1.3.3)	EXPERIMENTAL DYNAMIC SIMULATION -- Complied
SC061C.04 (6.1.3.4)	HELIOSTAT TEST SUPPORT -- Complied
SC061C.05 (6.1.3.5)	HELIOSTAT AND THERMAL STORAGE TRANSPORTABILITY -- Complied
SC061C.06 (6.1.3.6)	RECEIVER AND ELECTRICAL GENERATION TRANSPORT- ABILITY -- Complied
SC061D (6.1.4)	PILOT PLANT DESIGN UPDATE -- Complied
SC061D.01 (6.1.4.1)	PLANT DESIGN DOCUMENTATION UPDATE -- Complied
SC061D.02 (6.1.4.2)	SYSTEMS INTERFACE UPDATE -- Complied

<u>Task</u>	<u>Title and Status</u>
SC061D.03 (6.1.4.3)	EFFECTIVENESS STUDIES -- Complied
SC061E (6.1.5)	DESIGN REVIEWS -- Complied
SC061E.01 (6.1.5.1)	HONEYWELL ATTENDANCE -- Complied
SC061E.02 (6.1.5.2)	SUBCONTRACTOR ATTENDANCE (B&V) -- Complied
SC061F (6.1.6)	TECHNICAL LIAISON WITH VENDORS -- Complied
SC062 (6.2)	PROJECT MANAGEMENT
SC062A (6.2.1)	PROJECT REVIEWS -- Complied. See Figure 58, Item 10.
SC062A.02 (6.2.1.2)	PROJECT REVIEWS (B&V) -- Complied
SC062C (6.2.3)	COST AND SCHEDULE CONTROL -- Complied
SC062C.01 (6.2.3.1)	COST AND SCHEDULE CONTROL -- Complied
SC062C.03 (6.2.3.3)	COST AND SCHEDULE CONTROL -- Complied
SC062D (6.2.4)	B&W PROJECT MANAGEMENT -- Complied
SC063 (6.3)	SPECIAL ANALYSIS -- This was to provide information for a draft environmental impact statement. The requirement per se was waived by ERDA. Some relevant information was provided as parts of other reports (e.g., Volume II of the Preliminary Design Report).
SC064 (6.4)	COST ESTIMATING -- Complied

<u>Task</u>	<u>Title and Status</u>
SC064A (6.4.1)	PILOT PLANT PRELIMINARY COST ESTIMATE -- Complied See Figure 58, Item 2
SC064A.01 (6.4.1.1)	SYSTEM INTEGRATION COST -- Complied
SC064A.02 (6.4.1.2)	SUBSYSTEM COSTS (B&V) -- Complied
SC064A.03 (6.4.1.3)	SUBSYSTEM COST (B&W) -- Complied
SC064A.04 (6.4.1.4)	SUBSYSTEM COST -- Complied
SC064A.05 (6.4.1.5)	SUBSYSTEM COST -- Complied
SC064B (6.4.2)	FINAL PLANT COST ESTIMATES -- Complied. See Figure 58, Item 2.
SC064B.01 (6.4.2.1)	SYSTEM INTEGRATION COSTS -- Complied
SC064B.02 (6.4.2.2)	SUBSYSTEM COSTS (B&V) -- Complied
SC064B.03 (6.4.2.3)	SUBSYSTEM COSTS (B&W) -- Complied
SC064B.04 (6.4.2.4)	SUBSYSTEM COSTS -- Complied
SC064B.05 (6.4.2.5)	SUBSYSTEM COSTS -- Complied
SC065 (6.5)	METHODOLOGY (B&W) -- Complied
SC070 (7.0)	DATA
SC071 (7.1)	TECHNICAL PUBLICATIONS

<u>Task</u>	<u>Title and Status</u>
SC071A (7.1.1)	PILOT PLANT PRELIMINARY DESIGN BASELINE REPORT -- Complied. See Figure 58, Item 1.
SC071A.02 (7.1.1.2)	PILOT PLANT - PDBR (B&V) -- Complied
SC07B (7.1.2)	PILOT PLANT PRELIMINARY DESIGN REPORT -- Complied. See Figure 58, Item 2.
SC071B.01 (7.1.2.2)	PILOT PLANT - PDR -- Complied
SC071B.02 (7.1.2.2)	PILOT PLANT - PDR -- Complied
SC071C (7.1.3)	CONCEPTUAL DESIGN REPORTS
SC071C.01 (7.1.3.1)	COLLECTOR SRE CONCEPTUAL DESIGN AND DETAIL DESIGN REPORT -- Complied. See Figure 58, Items 3 and 6.
SC071C.02 (7.1.3.2)	RECEIVER SRE CONCEPTUAL DESIGN -- Complied. See Figure 58, Item 4.
SC071C.03 (7.1.3.3)	THERMAL STORAGE SRE CONCEPTUAL DESIGN -- Complied. See Figure 58, Item 5.
SC071D (7.1.4)	DETAILED DESIGN REPORTS
SC071D.01 (7.1.4.1)	RECEIVER SRE DETAIL DESIGN -- Complied. See Figure 58, Item 7.
SC071D.02 (7.1.4.2)	RECEIVER SRE DETAIL DESIGN (B&V) -- Complied
SC071D.03 (7.1.4.3)	THERMAL STORAGE SRE DETAIL DESIGN -- Complied. See Figure 58, Item 8.
SC071D.04 (7.1.4.4)	THERMAL STORAGE SRE DDR (B&V) -- Complied
SC071E (7.1.5)	ENVIRONMENTAL IMPACT DATA -- Waived by ERDA for Phase I. See Figure 59, Item 12 and SC063.

<u>Task</u>	<u>Title and Status</u>
SC071F (7.1.6)	OPERATING INSTRUCTIONS -- Complied. See Figure 58, Item 13.
SC01F.01 (7.1.6.1)	COLLECTOR SUBSYSTEM OPERATING INSTRUCTIONS
SC071F.03 (7.1.6.3)	THERMAL STORAGE SUBSYSTEM OPERATING INSTRUCTIONS -- Complied
SC071F.04 (7.1.6.4)	PILOT PLANT COMPUTER SIMULATION SOFTWARE MANUAL -- Complied
SC071F.05 (7.1.6.5)	RECEIVER OPTICAL MODEL SOFTWARE MANUAL -- Complied
SC071F.06 (7.1.6.6)	RECEIVER FLUX SIMULATOR OPERATING MANUAL -- Complied
SC071F.07 (7.1.6.7)	MISCELLANEOUS TEST AND SUPPORT EQUIPMENT -- Complied
SC071G (7.1.7)	QUARTERLY REPORTS -- Complied. See Figure 58, Item 10.
SC072 (7.2)	ENGINEERING DATA
SC072A (7.2.1)	PROGRAM ANALYSES AND DATA -- Complied. See Figure 58, Item 11 and list of CELs.
SC073 (7.3)	MANAGEMENT DATA
SC073A (7.3.1)	PROGRAM PLAN -- Complied. See Figure 58, Item 9
SC073A.01 (7.3.1.1)	PROGRAM PLAN -- Complied
SC073A.02 (7.3.1.2)	PROGRAM PLAN (B&V) -- Complied
SC073A.03 (7.3.1.3)	PROGRAM PLAN (Coordination)
SC073B (7.3.2)	PROJECT REVIEWS

<u>Task</u>	<u>Title and Status</u>
SC073B.01 (7.3.2.1)	PROJECT REVIEWS
SC073B.02 (7.3.2.2)	PROJECT REVIEWS (B&V) -- Complied
SC073B.03 (7.3.2.3)	PROJECT REVIEWS (Coordination) -- Complied
SC073C (7.3.3)	MONTHLY REPORTS (Fiscal and schedule) -- Complied
SC073C.01 (7.3.3.1)	B&V MONTHLY REPORTS -- Complied
SC073C.02 (7.3.3.2)	MONTHLY REPORTS (Coordination) -- Complied

Figure 59. Solar Pilot Plant Program Organization

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