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PHASE I OF THE FIRST SMALL POWER SYSTEM EXPERIMENT (ENGINEERING EXPERIMENT NO. 1)

Final Technical Report
Volume I – Executive Summary

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

MCDONNELL DOUGLAS CORPORATION

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PHASE I OF THE FIRST SMALL POWER SYSTEM EXPERIMENT (ENGINEERING EXPERIMENT NO. 1)

Final Technical Report
Volume I — Executive Summary

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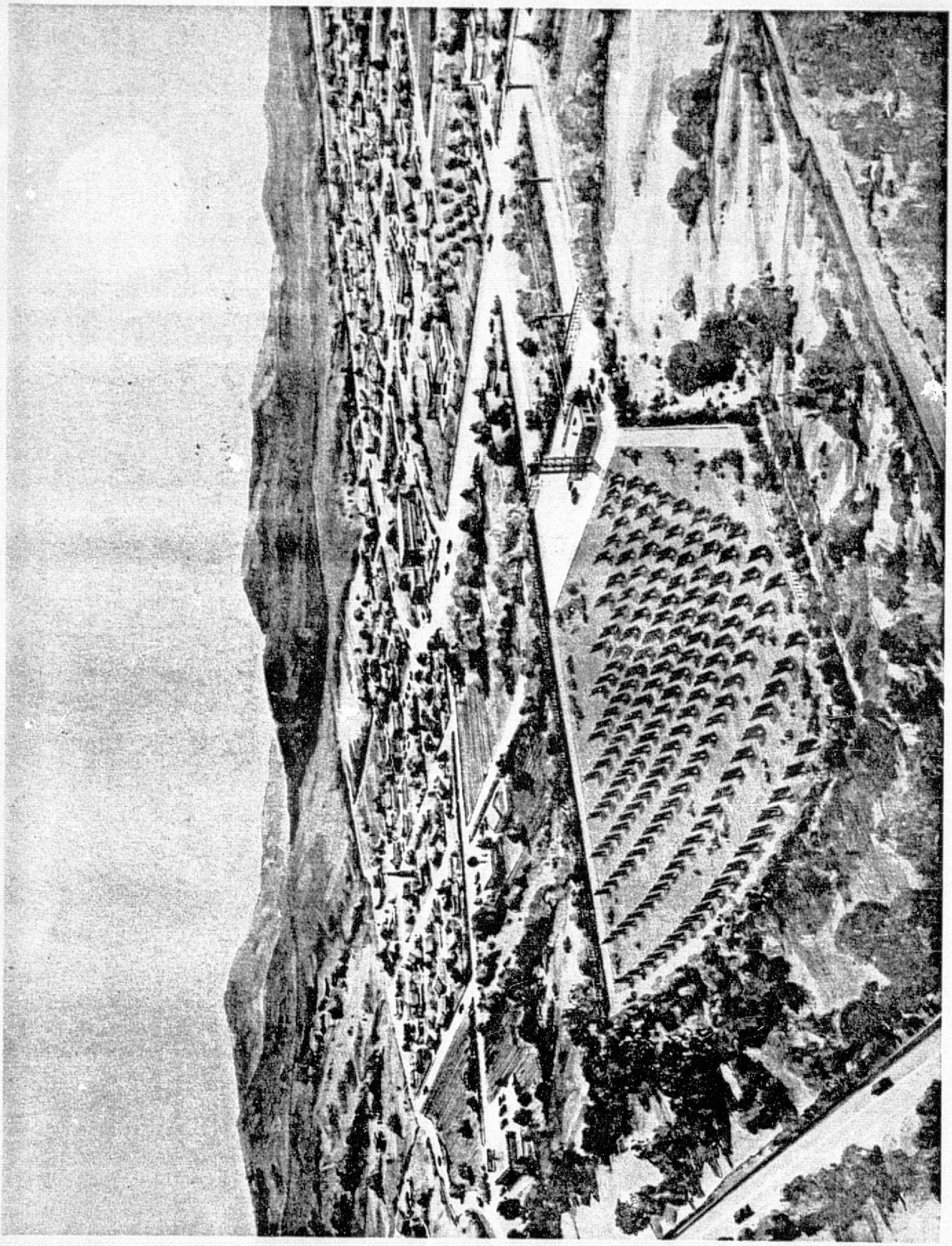

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PREFACE

This document constitutes the McDonnell Douglas Astronautics Company (MDAC) final technical report for Phase I of the First Small Power System Experiment (Engineering Experiment No. 1). Phase I is an investigation of various system concepts that will allow the selection of the most appropriate system or systems for the first small solar power system application. This 10-month study is a part of the Small Power Systems Program that is being developed under the direction of the Department of Energy (DOE) and managed by the Jet Propulsion Laboratory (JPL). The final report is submitted to JPL under Contract No. 955117.

The final technical report consists of five volumes, as follows:

Volume	I	Executive Summary
	II	System Concept Selection
	III	Experimental System Definitions (3.5, 4.5, and 6.5 Year Programs)
	IV	Commercial System Definition
	V	Supporting Analyses and Trade Studies

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CONTENTS

Section 1	PHASE I PROGRAM INTRODUCTION	1
	1.1 Study Task Approach	3
	1.2 Roles and Responsibilities	4
	1.3 System Summary	5
	1.4 Executive Summary	5
Section 2	CONCEPT SELECTION	7
	2.1 Collector	10
	2.2 Power Conversion Cycle	11
	2.3 Rankine Cycle Working Fluid	13
	2.4 Collector Fluid	14
	2.5 Energy Storage Class	16
	2.6 Thermal Storage	18
	2.7 Power Conversion Subsystem Modularity	20
	2.8 Prime Mover	21
	2.9 Preferred Systems Selected	21
Section 3	DESIGN APPROACH	23
	3.1 Flowdown From Reliability/Availability Criterion	23
	3.2 Flowdown From Program Risk Criterion	24
	3.3 Flowdown From Commercialization Criterion	25
	3.4 Flowdown From Program Cost Criterion	27
Section 4	SYSTEM DESCRIPTION	29
Section 5	SUBSYSTEM STATUS	37
	5.1 Collector Subsystem — Concentrator Assembly	37
	5.2 Collector Subsystem — Receiver Assembly	41
	5.3 Collector Subsystem — Tower Assembly	44
	5.4 Energy Transport and Storage Subsystems	47
	5.5 Power Conversion Subsystem	50
	5.6 Plant Control Subsystem	53
Section 6	SENSITIVITY TO POWER LEVEL AND STORAGE CAPACITY	57
Section 7	OVERALL EVALUATION	59

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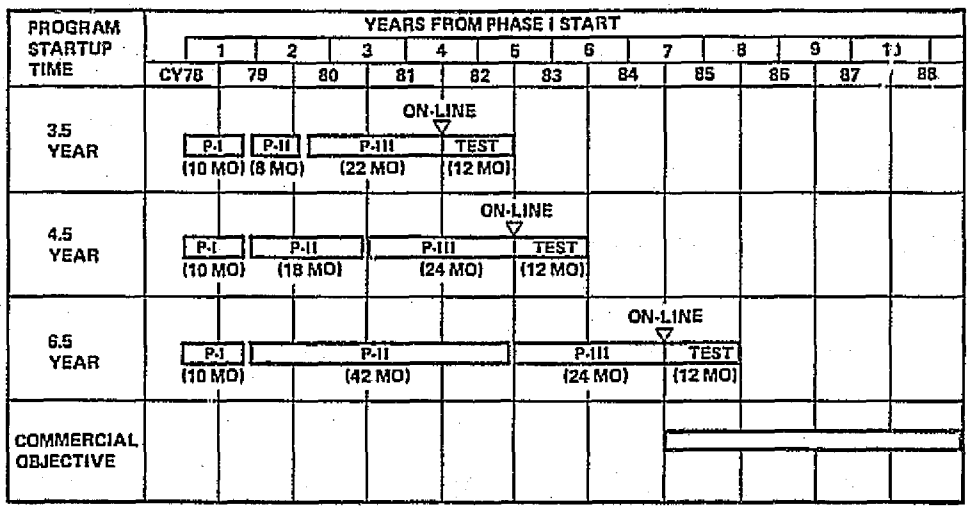
- THREE CANDIDATE PROGRAMS FOR EE NO. 1



- THREE PROJECT PHASES
  - I CONCEPT DEFINITION
  - II PRELIMINARY AND DETAILED DESIGN; COMPONENT/SUBSYSTEM DEVELOPMENT/TESTING
  - III FABRICATION, INSTALLATION, TEST AND EVALUATION
- CATEGORY A CANDIDATE SYSTEMS - GENERAL, EXCLUDING DISH CONCENTRATORS

Figure 1-1. Overall Program Scope

Phase II involves the preliminary and detailed design of the preferred system, and component and/or subsystem development testing that are needed before proceeding with plant construction in Phase III. Phase II may be from 8 to 42 months depending on the program selected by JPL as a result of Phase I.

Phase III will consist of subsystem fabrication, plant construction, installation, testing, and evaluation of the solar power facility (Engineering Experiment No. 1). A 3-year schedule is anticipated for this phase, with testing conducted during the third year.

Late in the Phase I study period, DOE concluded that a better balance of the overall solar thermal electric program could be achieved by limiting the JPL Small Power Applications activities to point-focus distributed systems. Consequently, DOE directed that JPL take the necessary steps to constrain the JPL-managed first Engineering Experiment (EE No. 1) to point-focusing distributed receiver technology for all phases beyond Phase I. Accordingly, on 3 April 1979, all MDAC efforts on Phase II program planning were terminated by JPL directive.

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1.1 STUDY TASK APPROACH

Phase I study objectives were: (1) select preferred system concepts for each of the three program durations, (2) complete conceptual designs for each of three system concepts, (3) provide sensitivity data over range; plant rating: 0.5-10 MWe; annual capacity factor: 0 storage to 0.7, (4) prepare detailed Phase II plans and cost proposal (3 versions of EE No. 1), (5) prepare Phase III program and cost estimates (3 versions of EE No. 1), and (6) recommend preferred EE No. 1 program. Three major tasks were planned for the 10-month Phase I effort. They were Task 1 - Development of Preferred System Concepts, Task 2 - Sensitivity Analyses, and Task 3 - Phase II Program Plans. The Top-Level study flow is indicated in Figure 1-2.

In Task I, three preferred concepts were defined to the conceptual design level. The concepts were consistent with the three specified program startup

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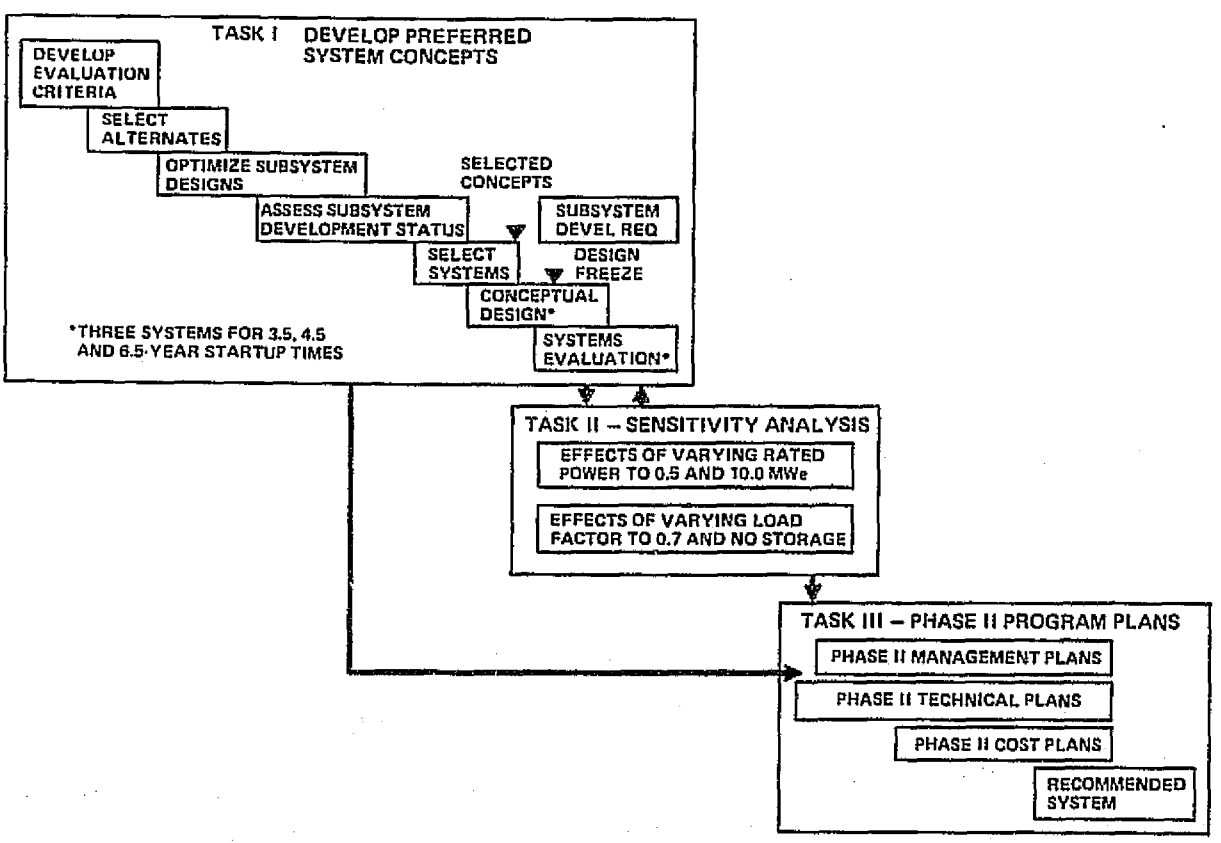

Figure 1-2. Top Level Study Flow

times of 3.5, 4.5, and 6.5 years. In Task I, power plants were considered for a nominal 1.0 MWe rated capacity and 0.4 capacity factor. Activities in Task I through the selection of the three preferred system concepts were primarily a systems engineering/evaluation conducted by MDAC. Subsystem characteristics, performance, and preliminary development requirements were supplied by the appropriate subcontractors. Following this concept selection, the conceptual design of subsystems was initiated in which descriptions, finalized development requirements, performance, reliability, and cost data for each of the three selected concepts were developed.

In Task II, the impact of varying rated power (0.5 and 10.0 MWe) and system capacity factor (zero storage case and 0.7) was investigated. Sensitivity analysis in Task II was performed by MDAC using subsystem data supplied by the subcontractors. This task featured system and subsystem reoptimization for each of the cases evaluated.

In Task III, the management, technical and cost plans for Phase II for each of the three selected concepts were to be prepared in accordance with JPL guidelines and MDAC system recommendations were to be provided. However, as reviewed above, during the latter period of the contract, JPL directed MDAC to terminate all Task III efforts. Accordingly, Task III efforts were discontinued and Phase II Program Plans are not reported.

1.2 ROLES AND RESPONSIBILITIES

A team of companies led by the McDonnell Douglas Astronautics Company (MDAC) was contracted to conduct the Phase I definition of Category A systems (general only excluding dish concentrators). The team included MDAC, Rocketdyne, Stearns-Roger, the University of Houston Energy Laboratory, and Energy Technology, Incorporated (ETI). MDAC was the prime contractor for the effort and was responsible for overall contract compliance. The four major subcontractors and their prime areas of responsibility were: (1) Rocketdyne Division of Rockwell International (receiver, dual-media energy storage),

(2) Energy Technology, Inc. (radial turbine and gearbox), (3) Stearns-Roger (tower and plant layout/equipment), and (4) University of Houston Solar Energy Laboratory (collector field optimization).

1.3 SYSTEM SUMMARY

From the preliminary design analyses efforts to date, MDAC concludes that the proposed central receiver power system concept is a feasible, low-cost, and low-risk approach for a small solar power system experiment. It is particularly suitable for early deployment under the 3.5- and 4.5-year programs. The concentrator subsystem is currently under development and low-cost, high-production rate heliostats will be available for this program. The proposed receiver subsystem using Hitec is similar to existing fossil fired Hitec heaters. The tower is a standard low-cost guyed steel tower. The energy transport system using Hitec is based on standard state-of-the art equipment and operating conditions. For the 3.5- and 4.5-year programs, a simple two-tank storage subsystem is proposed which requires no development. The power conversion system is based on existing axial steam turbines. All the balance of plant equipment involves state-of-the-art equipment and processes. The 6.5-year program contains development of a radial outflow turbine and qualification of a dual media thermocline storage subsystem. The technology employed in all programs is consistent with the development time available. Thus, the proposed MDAC concepts satisfy all of the important JPL selection criteria, namely, high operational reliability, minimum risk of failure, good commercialization potential, and low program costs.

1.4 EXECUTIVE SUMMARY

This volume contains a brief executive overview of the Phase I study. Section 2 summarizes the screening analyses used to select three preferred concepts for the three EE No. 1 program durations. In Section 3, the JPL-supplied system selection criteria are developed into the specific requirements that were imposed on the design of each EE No. 1 system. The resulting system designs and performance are summarized in Section 4, with the corresponding subsystem designs and development status described in Section 5. Sensitivity of the baseline system to changes in rated power and annual capacity factor is given in Section 6. An overall systems evaluation is made in Section 7. Supporting detailed information is contained in Volumes II, III, IV, and V.

Section 2
CONCEPT SELECTION

The MDAC study contract addressed Category A systems, which were to include, but not be limited to, central receiver and linear focusing systems. Categories B (point-focusing, distributed collectors, central power conversion) and C (point-focusing, distributed collector, energy conversion at the collector) were assigned to other contractors, and therefore excluded from this effort.

By this definition, Category A included a broad spectrum of candidate systems. To select the preferred system candidates in this category, a dual screening process was utilized in which evaluation criteria were developed that were first used for screening and then finally used to make the selection itself. The selection methodology is shown on Table 2-1. Using this screening approach, MDAC first identified those candidate subsystems and components which could qualify for the established criteria. These selections were then synthesized into systens which could be implemented in either the 3.5-, 4.5-, or 6.5-year programs. These candidates were optimized so that alternative systems wuld be compared in their best light. The status of subsystem development was assessed to determine program requirements for the different systems. Based on the above approach, a final evaluation was made to select the three preferred systems.

Candidate concepts within Category A that were screened are summarized in Figure 2-1. The first screening was the selection between distributed collectors and the central receiver. After selecting the central receiver, shown by the box, the progression continued down this tree leading toward our final preferred systems. Each selection is denoted within the boxes. Brief summaries of each of these screening processes are given below.

The selection criteria used in the screening evaluation and system/subsystem optimizations are summarized on Table 2-2. The criteria, which are listed in the order of their importance, include high operational reliability, minimum

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Table 2-1. Selection of Three Preferred System Candidates
Dual Screening Methodology

- Initial Screening Process
  - Utilize gross evaluation criteria
    - Technology readiness
    - Potential hazards
    - System costs and complexity
  - Evaluate all potential subsystem and component candidates
  - Include system impact in comparing alternate candidates
- Final Selection Process
  - Synthesize surviving subsystems/components into system candidates
  - Optimize candidate system and subsystem designs
  - Assess subsystem development status
  - Conduct formal evaluation using all selection criteria
  - Select preferred system configuration for each Engineering Experiment No. 1 program duration

risk of failure, commercialization potential, and low program costs. MDAC applied these criteria rigorously to all evaluations.

Only the highlights of concept selection are described here. Details of this evaluation process are contained in Volume II of this report.

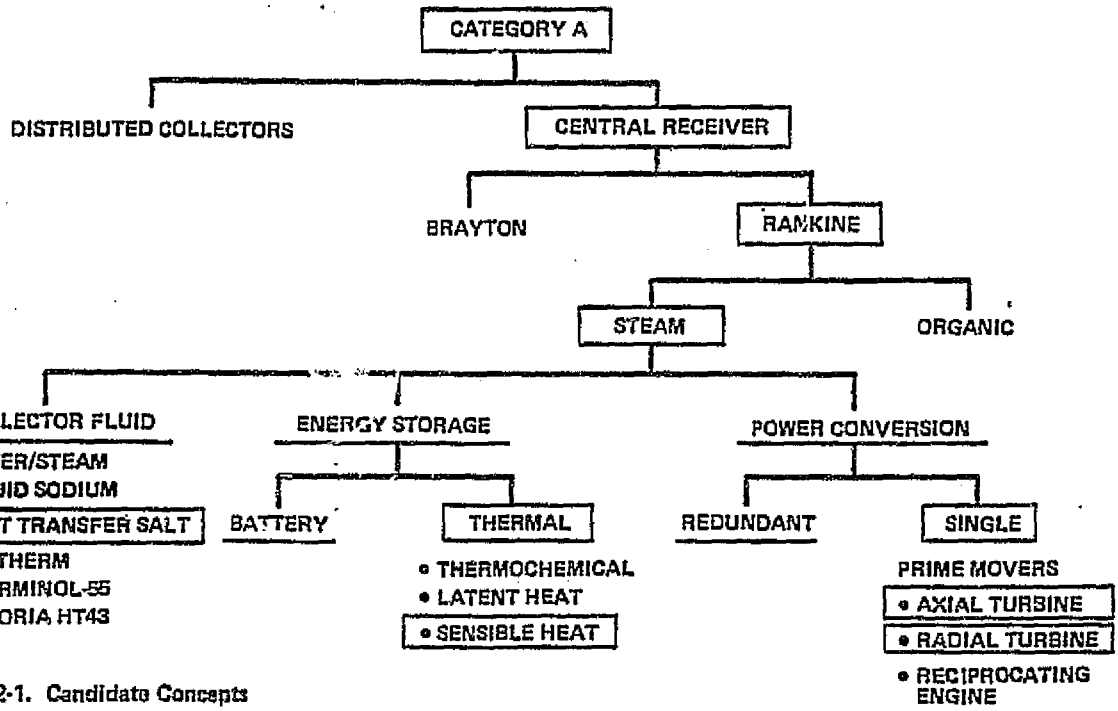


Figure 2-1. Candidate Concepts

Table 2-2. Selection Criteria (In Order of Importance)

1. High Operational Reliability — Selected system concepts should lead to:
   - A commercial plant that operates with a high reliability during its lifetime (typically 30 years)
   - An experimental plant which will start up satisfactorily and operate reliably for at least 2 years after startup with minimum forced outages attributable to design deficiencies and hardware failures

   (Enhancement of reliability through modularity/redundancy should be considered)
2. Minimum Risk of Failure — Selected concepts should minimize development risk and thereby provide high confidence that subsystem development can be achieved within Phase II times and that the experiment can be brought on-line at the specified startup times.
3. Commercialization Potential — Selected concepts should use or contribute directly to the eventual systems that are likely to achieve commercial success in the late 1980's.
   - Costs/performance
   - Flexibility (modularity should be one of primary considerations)
   - Institutional interface aspects
4. Low Program Costs — Concepts should be selected to minimize the estimated development and capital costs of Phases II and III.

2.1 COLLECTOR

The first selection to be made involved the collector subsystem. The central receiver was compared to distributed collectors for a 1 MWe system. The distributed collectors selected for the comparison utilized either parabolic troughs or segmented mirrors as the linear concentrators. These are generally considered to be the most attractive by specialists in the solar field. All common elements, such as reflectivity, were then normalized so that they could be compared on an equal basis. The idealized performance of the distributed collector, not the measured performance, was then calculated, assuming that the performance potential of the concept could be achieved. For example, the transmission efficiency of the glass was assumed to be 92%. Next, the temperature was optimized considering both collection efficiency and the efficiency of converting from thermal energy into electricity. The field and storage were then sized to achieve a common annual capacity factor. This was done because the linear concentrator has a much more peaked daily collection characteristic. Consequently, it will require a larger storage capacity to produce the same annual capacity factor. Also, line losses and the daily warmup requirements were added to the energy that must be collected by the linear concentrator.

A cost comparison was then made between the distributed collector and the central receiver. This is shown on Figure 2-2, with the central receiver constrained to the same operating conditions as the distributed collector and with the central receiver optimized. The evaluation methodology and major results are also summarized on the figure. The capital costs shown are for a 1.0 MWe system and include the energy collection and storage elements only. The cost of the distributed collector was based on $\$200/m^2$, which is a projection from one of the manufacturers. The best cost projection for trough collectors is $\$130/m^2$. However, even when normalizing and taking equal cost the central receiver has considerably lower capital costs when configured to the same operating conditions as the distributed collector concept. Additionally, the central receiver can utilize higher temperature conditions and employ a fluid such as Hitec, which is not practical for use with distributed concentrators. In summary, the central receiver was clearly the best selection.

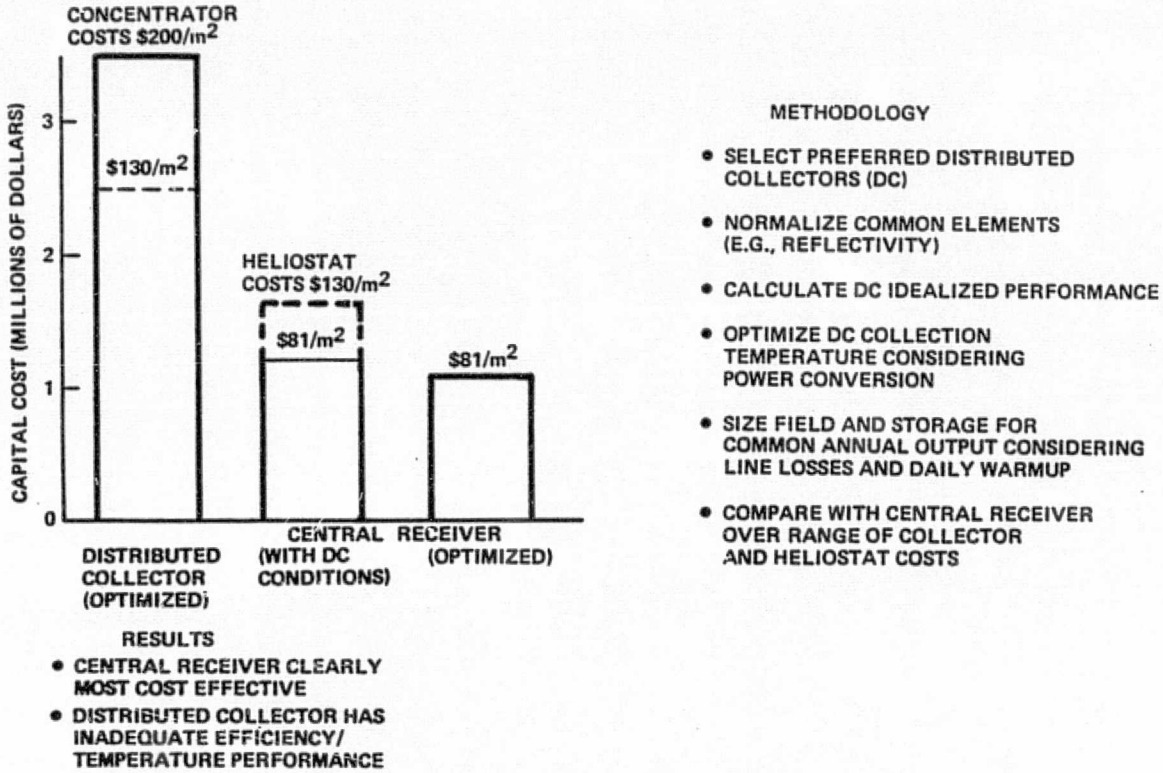
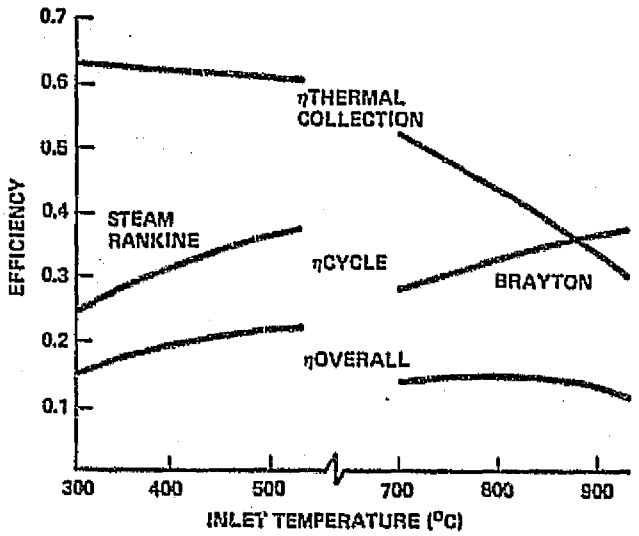


Figure 2-2. Selection of Concentrator (Central Receiver vs Distributor Collectors)

2.2 POWER CONVERSION CYCLE

The next comparison was between the Rankine cycle and the Brayton cycle for power conversion. The final system comparison, including major system characteristics and the results of the evaluation, is shown on Figure 2-3.

A somewhat similar methodology was used to compare the two cycles at their optimum performance. For the Brayton cycle, an open-loop configuration with the Centaur engine was used. For this case, the efficiency of the recuperator was increased from 0.75 to 0.9. A multi-shaft configuration was also used even though the contractors designing the solar Brayton cycle systems under Electric Power Research Institute (EPRI) contract selected the single-shaft configuration. The multi-shaft configuration gives significantly better part load capabilities. Finally, a cavity receiver was optimized for each of several inlet temperatures in terms of the spillage and thermal efficiency of the receiver. This Brayton system configuration included the best characteristics that MDAC could justify.



SYSTEMS COMPARED

- BRAYTON CYCLE
  - REGENERATIVE OPEN LOOP (CENTAUR WITH IMPROVED RECENERATOR)
  - MULTISHAFT CONFIGURATION
  - OPTIMIZED CAVITY RECEIVER APERTURE SIZE
    - SPILLAGE
    - EFFICIENCY
- RANKINE CYCLE
  - RADIAL OUTFLOW TURBINE
  - HITEC COLLECTOR FLUID
  - PARTIAL CAVITY RECEIVER

EVALUATION

- RANKINE CYCLE HAS HIGHER OVERALL CYCLE EFFICIENCY
- THERMAL STORAGE IMPRACTICAL FOR BRAYTON CYCLE - REQUIRES BATTERY STORAGE
- RANKINE CYCLE SELECTED

Figure 2-3. Selection of Power Conversion Cycle (Brayton vs Rankine)

Similarly, an optimum Rankine cycle configuration was utilized. An advanced radial outflow turbine was used which has an expansion efficiency of 84%. Heat transfer salt (HTS) was used as receiver coolant and a partial cavity receiver design employed. A comparison of the overall efficiencies of each concept is shown on Figure 2-3. The upper curves represent the product of the collector field and receiver efficiencies as a function of turbine inlet temperature. For the Rankine cycle, there is little variation with inlet temperature in the 300 to 500°C operating range. For the Brayton cycle, much higher inlet temperatures are required, and thermal collection efficiencies significantly decrease with temperatures in the 700 to 900°C operating range. Combining the thermal collection and power conversion cycle efficiencies, the optimum inlet temperatures are slightly over 500°C for the Rankine cycle and approximately 800°C for the Brayton cycle. Overall Rankine cycle efficiencies are higher than the Brayton cycle efficiencies. This is largely the result of lower collection efficiency at the higher temperatures required for the Brayton cycle. In addition, the Brayton cycle does not have the capability of thermal storage which would require either ducting the hot gas to the ground or putting the storage on the top of the tower, which is not practical. For these reasons, the Brayton cycle will require battery storage, which is a very serious penalty to impose on any system. For all of these reasons, MDAC selected the Rankine cycle.

2.3 RANKINE CYCLE WORKING FLUID

The next selection was the working fluid for the Rankine cycle — organic versus steam. Figure 2-4 shows the net cycle efficiency as a function of temperature for these two options, together with a summary evaluation. The lower curve for the steam Rankine cycle represents the best state-of-the-art multi-stage axial-turbine available. The upper curve represents the radial outflow turbine, which is the baseline for our commercial unit. The organic Rankine cycle efficiency shown on the figure uses an axial turbine which has better efficiencies than either the radial outflow or axial steam turbines in the lower temperature ranges. However, organic systems are limited to about 400°C using supercritical toluene. Most of the other organics are limited to lower operating temperatures. Toluene also has a potential explosion hazard. Moreover, the application range is limited to approximately the 1 MWe range. None of the organic turbine manufacturers have seriously considered developing larger turbines. Since a range of 1 to 10 MW is being considered for the small solar power system, an organic Rankine approach would require multiple

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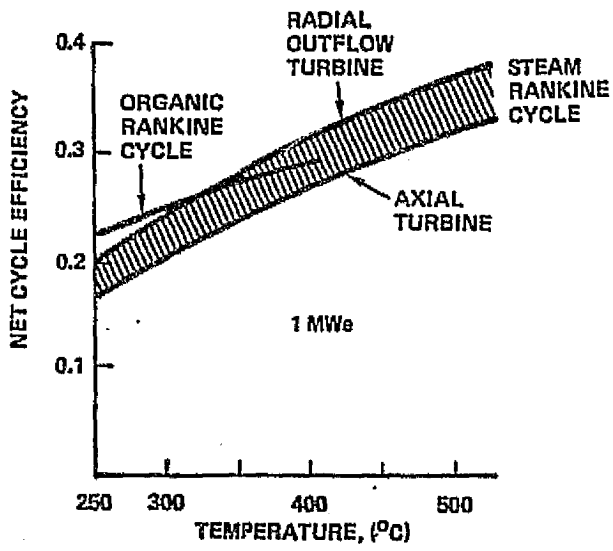


- STEAM RANKINE CYCLE SELECTED

EVALUATION

- ORGANIC RANKINE CYCLE
  - LIMITED TO 400°C (SUPERCRITICAL TOLUENE)
  - POTENTIAL HAZARD
  - LIMITED APPLICATION RANGE (~1 MWe)
  - TURBINE DEVELOPMENT REQUIRED
- STEAM RANKINE CYCLE
  - HIGHER TEMPERATURE CAPABILITY
  - STANDARD TECHNOLOGY/ EQUIPMENT
  - RADIAL OUTFLOW TURBINE DEVELOPMENT DESIRED

Figure 2-4. Selection of Rankine Cycle Working Fluid (Organic vs Steam)

1 MWe turbines. Finally, a turbine development program would be required to produce a 1 MWe supercritical toluene turbine.

The steam Rankine cycle on the other hand has the capability to attain much higher temperatures. Standard technology and equipment can be used for EE No. 1 with efficiencies exceeding the organic unit. In order to provide the improvement in performance noted on the figure, it is desirable to develop a radial outflow turbine. However, this development is not as essential as it is with organic turbines. For all the above reasons, MDAC chose the steam Rankine cycle.

2.4 COLLECTOR FLUID

The next selection was the fluid to be used in the receiver assembly of the collector subsystem. Alternative fluids were evaluated, and their advantages and disadvantages are summarized on Table 2-3. Superheated steam, which is used for the Barstow 10 MWe plant, is current state-of-the-art. Although is difficult to buffer the turbine against insolation transients. Although the resulting operating complexity may be reasonable for a larger plant on a utility grid, such complexity is not suitable for a small community power plant. Additionally, an admission turbine would be required for operation from storage because the regenerated steam is necessarily at lower temperature and pressure. Such turbines are not available in the 1.0 MW range. Consequently, superheated steam is an unattractive candidate. Using saturated steam, a reheat turbine would be required to achieve reasonable efficiency. Such turbines are available in larger sizes, but unavailable at the 1 MW level. Consequently, turbine development would be required. In addition, storing hot saturated water-steam is very expensive because of the high pressure involved. For these reasons, both of the water candidates were omitted.

The organic fluids have the advantage of low vapor pressure and are commercially available. However, their temperature capability is generally limited to around 300°C. This inherent performance limitation is unattractive at 1 MWe, but even more unacceptable when scaled up to the 10 MWe power rating. Also, they require fluid maintenance and makeup. For these reasons, organic collection fluids were eliminated. Syltherm, which replaces the carbon with silicon, has somewhat higher temperature capability. However, cost is very

Table 2-3. Selection of Receiver Collector Fluid

Fluid	Advantages	Disadvantages
Superheated steam	• State-of-the-art	• Difficult to buffer turbine from insolation transients • Dual admission turbine required but not available • Performance penalty when operating from storage
Saturated steam	• Simple system	• Requires reheat turbine • High storage cost
Organics	• Low vapor pressure • Commercial	• Limited temperature • Fluid maintenance • Poor scaleup
Syltherm	• Higher performance capability than organics	• High cost • Limited performance
Hitec/HTS	• Commercial • Temperature capability 500°C+ • Good properties	• Freezing temperature of $\geq$140°C
Liquid sodium	• Best coolant	• High equipment cost • Potential hazards

high and its performance is still limited to 427°C (800°F). Syltherm costs preclude use of the sensible heat of the fluid itself for energy storage. Makeup, even at 400°C, is excessively costly when in contact with candidate solid sensible heat storage materials. As a result, Syltherm was rejected as a receiver coolant.

Liquid sodium was also considered as a heat transfer fluid. It has excellent properties as a coolant; however, associated costs for equipment and auxiliaries are very high. Additionally, sodium is potentially hazardous, especially when used near a water-steam source. Consequently, sodium was rejected.

The use of heat transfer salt (HTS or Hitec) was our selection. The salt is an inorganic material, has good thermal properties, does not decompose at operating temperatures, and requires minimal maintenance or replenishment. These heat transfer salts are used in many commercial applications. Thermal properties are substantially better than the organic fluids. Salt does have the disadvantage of a freezing temperature above 140°C. Based on actual industrial experience with salt, it was determined that this issue could be satisfactorily resolved by the proper use of insulation and thermostatically controlled electric trace heating. For normal 24-hour operations, practically no trace heating is required. The receiver and thermal storage cooldown transients are such that salt temperatures are well above the set point for the heaters when startup is initiated the next morning. Although some trace heating is required to condition the riser and downcomer lines daily, very little energy is required over the 24-hour cycle. Energy for trace heating has been factored into the plant energy balance as a penalty of conversion from thermal to electrical energy. From a trade study between steam trace heating versus electrical, the annual energy usage for electrical heating was so little that the expense of capital equipment for steam tracing could not be justified. For the reasons above, Hitec/HTS was selected as the preferred receiver collector fluid. It has the best overall balance of properties by a large margin.

2.5 ENERGY STORAGE CLASS

The class of energy storage to be used in the plant was the next major element selected. Two classes of energy storage were considered--internal storage of thermal energy versus external storage of work or electricity. The characteristics used for the two system classes are shown on Table 2-4. The thermal (internal) storage candidate used Hitec in a dual medium thermocline storage mode with nominal operating temperatures from 288°C (550°F) to 510°C (950°F). The battery (external) storage candidate used advanced sodium-sulfur batteries, which were assumed to have the capability of 2,500 discharge

Table 2-4. Selection of Energy Storage Class
1 MWe, 0.4 CF (Internal Versus External)

	Thermal (Internal)	Battery (External)
Characteristics	Dual Media Thermocline Hitec 288-510°C	Sodium-sulfur 2,500 discharge cycles 75% efficiency
Contribution to Life-Cycle Energy Costs (Mills/kWhe)		
Capital Cost	7.2	13.2
Replacement	-	12.7
Efficiency	0.6	6.7
Total	7.8	32.6
Evaluation	• Most cost effective • Power conversion need only be sized to plant rating	• No buffering of plant • Could be charged with off-peak grid power

cycles and approximately 75% recovery efficiency of the stored energy. This battery is a development item and would not be available for any of the EE No. 1 programs. However, it is used to represent the future potential of battery storage.

A comparison of the impact of storage to the life-cycle energy costs for a 1 MWe plant with a 0.4 annual capacity factor is also shown on this table. The initial capital cost of the battery storage facility is substantial at this relatively small size. The replacement costs for battery storage are high because the 2,500 discharge cycles are substantially less than required for the plant life of 30 years. Additionally, the cost impact of the recovery efficiency is shown on the table. Since the battery recovers energy at 75% efficiency, more power must be generated to achieve a 0.4 annual capacity factor. On the other hand, thermal storage losses are small, and full system capacity and efficiency are available when operating from storage. This results in an

advantage of over a factor of four in favor of thermal storage as opposed to batteries. This advantage would be even greater if current lead-acid batteries (required for EE No. 1) were compared with even the simplest two-tank thermal storage designs proposed for the shorter EE No. 1 programs.

Another very important factor is that the power conversion unit using thermal storage need only to be sized at the plant rating, since the storage subsystem stores thermal energy. The battery system, on the other hand, stores electricity so that the power conversion subsystem rating must be much higher (typically 1.8 to 2 times the nominal plant rating) for a 0.4 annual capacity factor. This effect is not included on the table. Finally, the battery provides no buffering of plant operation to insolation transients while thermal storage between the collector and the power conversion subsystems provides a complete buffer.

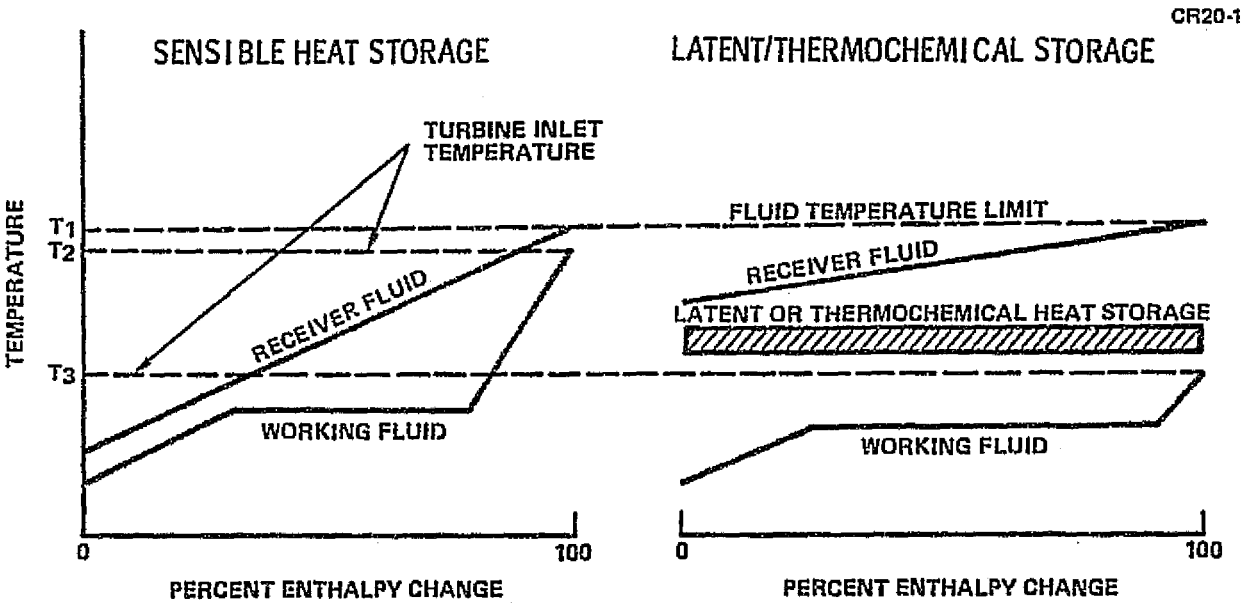
In addition to the reasons above, if an efficient, cost-effective battery system were available, there should be much less interest in small solar electric systems. The battery system itself could be charged with off-peak power rather than with solar. Since we are grid-connected throughout the country, it would be an excellent load-leveling device and appropriate for small community, dispersed power applications. Use of any external storage device with a solar plant ensures that the plant competes with the cheapest alternative source of electricity in the United States. That is, it competes with the alternative of charging the device with off-peak power from large, baseloaded coal- or nuclear-fueled central station plants.

For all of these reasons, and because considerable battery development is required, MDAC chose thermal storage.

2.6 THERMAL STORAGE

Thermal storage candidates were compared which included sensible heat, latent heat and thermochemical storage. Alternative candidates for both latent heat and thermochemical storage were identified and evaluated. None were found that had the potential for lower costs than sensible heat storage. The major reason for this was that heat transfer surface rather than tankage or storage media was the major cost driver.

However, the system impacts illustrated on Figure 2-5 provided the clinching argument in favor of sensible heat storage. Temperature and enthalpy relationships for the different storage concepts are shown. For sensible heat storage, the receiver fluid was used directly to heat the working fluid for a steam Rankine cycle. A generic curve for the working fluid is shown in which the temperature increases during the liquid preheating phase, then is constant during the latent heat of boiling phase and finally increases as superheat is added to the vapor. With sensible heat storage, this can be closely matched by the receiver or storage fluid as shown on the figure. If, on the other hand, a constant temperature storage is used (which used to be the favored approach), a significant difference in the input and recovery temperature will result. If the temperature of the stored energy is constant, it must be charged at a higher temperature than it can be recovered. So, if a limit were put on exit temperature of the receiver fluid (line T_1), the average temperature in the receiver for latent or thermochemical storage must be elevated, as shown on the figure. This results in much higher thermal losses and more pumping power. Working fluid temperatures and subsystem efficiencies are thus penalized. From our



- EFFICIENT PERFORMANCE
- LOW COST
- NO DEVELOPMENT RISK
- REDUCED HEAT LOSSES

- CYCLE EFFICIENCY DEGRADATION
- COMPLEX AND/OR COSTLY SYSTEM (HEAT TRANSFER SURFACE IS MAJOR COST DRIVER)
- EXTENSIVE DEVELOPMENT COSTS

Figure 2-5. Selection of Thermal Storage Principle

evaluations, these latent heat and advanced thermochemical concepts for thermal storage are not attractive when used in this type of system application. For these reasons, latent and thermochemical storage devices were rejected. Sensible heat was chosen for EE No. 1.

2.7 POWER CONVERSION SUBSYSTEM MODULARITY

The next selection was between redundant and a single prime mover for the power conversion subsystem. The selection criteria supplied by JPL and reproduced on Table 2-2 stated under (1) high operational reliability..." enhancement of reliability through modularity/redundancy should be considered." The potential advantages of achieving greater availability for EE No. 1 by using redundancy were compared with the costs associated with redundant power modules. The results are summarized on Figure 2-6. The availability of full power versus the number of power conversion modules drops significantly as the number of modules is increased for a constant power rating of 1.0 MWe (e.g., 10-100 kWe modules). This is due to the higher probability with multiple units that

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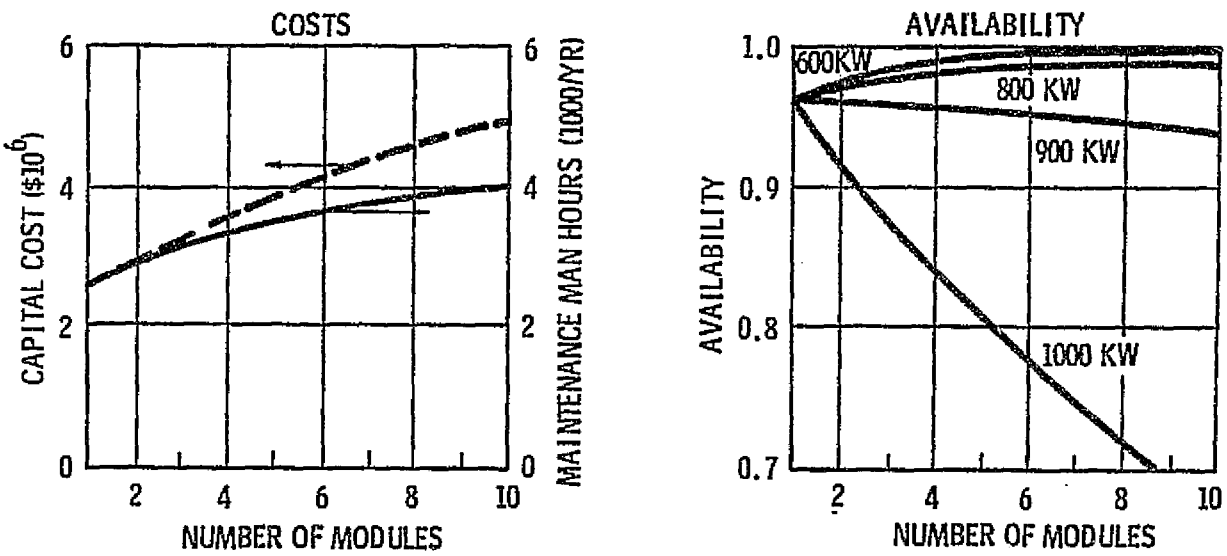

- MODULARITY COSTLY
- NOT EFFECTIVE IN IMPROVING FULL POWER SYSTEM AVAILABILITY

Figure 2-6. Modularity Study Results

one or more of the units will fail. As shown on the figure, the availability of the system to produce 900 kWe with ten 100 kWe modules is slightly less than if only one 1,000 kWe module were used. However, if two of the 100 kWe modules are out, we have increased our availability to deliver 800 kWe. But this means that another 20% excess capacity must be built into the plant to achieve the availability of one 1000 kWe unit. If ten modules are used, it is expected that one of them will be down most of the time.

As shown on the figure, capital and maintenance costs increase with multiple units. Cost/sizing relationships usually favor larger equipment sizes. Thus, capital cost for the multiple units goes up substantially. Also, maintenance manhours and costs increase with multiple units. One can easily visualize the many mechanics out in the field with the power conversion subsystem hoods up, working on them continuously. From this analysis, modularity was found to be too costly with insufficient improvement in system availability to justify it. Consequently, a single power conversion loop was selected.

2.8 PRIME MOVER

With a single prime mover selected for the power conversion subsystem, comparisons were also made between axial flow and radial flow turbines and reciprocating engines. Turbines were preferred over reciprocating engines based on performance and maintenance aspects. The axial turbine was selected for the shorter development programs (3.5- and 4.5-year programs) and the radial outflow turbine was selected for the longer development program (6.5-year program).

2.9 PREFERRED SYSTEMS SELECTED

Final selections for the three preferred systems for the 3.5-, 4.5-, and 6.5-year programs are shown on Table 2-5. Heat transfer salt was selected as the receiver fluid for all cases. Hitec (53% KNO_3, 7% $NaNO_3$, 40% $NaNO_2$) was used for the 3.5- and 4.5-year programs. The binary salt mixture denoted as HTS (54% KNO_3, 46% $NaNO_3$) was selected for the 6.5-year program. This provides a higher temperature capability.

To minimize program risks and costs, lower operating temperature constraints were imposed on the system for the 3.5-year program duration and allowed to increase as more development time was available. Two tanks were selected for thermal storage for the shorter duration programs, whereas a dual-media thermocline was selected for the 6.5-year program. An axial turbine was selected for both the 3.5- and 4.5-year programs. The radial outflow turbine was selected for the 6.5-year program. The preferred systems summarized on Table 2-5 provide the basis for the further conceptual design and analysis conducted in this program and summarized in the following sections.

Table 2-5. Selections for Three Preferred Systems

	3.5 Years	4.5 Years	6.5 Years
Receiver fluid	Hitec	Hitec	HTS
Temperature limit	450°C (842°F)	450-510°C (842-950°F)	510-580°C (950-1076°F)
Thermal storage	2-tank	2-tank	Dual Media Thermocline
Prime mover	Axial turbine	Axial turbine	Radial turbine

Section 3
DESIGN APPROACH

In order to ensure the best design choices for each version of EE No. 1, the system selection criteria from Table 2-2 were expanded into specific requirements for system and subsystem definition. These requirements were then either incorporated into system and subsystem specifications or used as high-level evaluation criteria for trade studies at all levels of system definition. This flowdown from the evaluation criteria to specific requirements is described in the following paragraphs.

3.1 FLOWDOWN FROM RELIABILITY/AVAILABILITY CRITERION

Constraints and guidelines imposed on subsystem design in order to meet the reliability/availability criterion are as follows:

- Use Fully Qualified Hardware
- Select the Most Reliable Components
- Prefer Equipment with Extensive Operating Experience
- Employ Conservative Design Practices
- Seek Design Simplicity
- Utilize Redundancy Where Effective.

The great emphasis placed on this criterion for both the experimental plant and the resulting commercial unit demands a rigorous adherence to the conditions listed. The first three conditions are paramount in selecting plant equipment. The first condition precludes selection of any components not able to be fully qualified for all operating, lifetime, and environmental requirements in the time available. An example of the application of this condition will be to constrain concentrator selection to candidates having substantial prior development and qualification. The second condition can have a major impact on system reliability/availability due to substantial differences in component failure rates. An example of applying this condition would be the selection of an marine-type turbine over a standard industrial design.

Extensive prior operating experience is preferred so that historical failure rate data are available to make reliability/availability predictions with confidence and to avoid any surprises.

The last three conditions relate to design practices to be employed at both the system and subsystem level. Conservative design allows margins for any unforeseen conditions and produces a "forgiving" system. Design simplicity helps achieve system reliability through minimizing both potential sources of failure and "surprises." Redundancy of key elements should be used to reduce single-point failures but only where it is effective. Redundancy inherently complicates the system, conflicting with the simplicity condition above, and imposes additional sources of failure. An example of ineffective redundancy was the full replication of the power conversion equipment described in Section 2 (Figure 2-6).

Strict application of these conditions to EE No. 1 design will produce "an experimental plant which will start up satisfactorily and operate reliably for at least 2 years after startup with minimum forced outages attributable to design deficiencies and hardware failures." Violation of these conditions ensures the opposite.

3.2 FLOWDOWN FROM PROGRAM RISK CRITERION

Minimizing the risk of failure (either technical or schedule) imposes the following conditions on EE No. 1 design:

- Minimize Development Within the EE No. 1 Program
- Utilize Standard Fabrication Techniques and Processes
- Select Materials and Equipment that are Available Without Excessively Long Lead Times
- Provide Schedule Pads for All Activities--Particularly Development and Tests (This Limits Development Objectives)
- Select Equipment with Viable Backups Available Where There Is Any Chance of Failure

These conditions are all self-explanatory but are necessary in order to "provide high confidence that subsystem development can be achieved within Phase II times and that the experiment can be brought on-line at the specified startup times."

3.3 FLOWDOWN FROM COMMERCIALIZATION CRITERION

Although the commercialization criterion strictly applies to the commercial design (described in Volume IV), conditions were imposed on the design of EE No. 1 so that it could logically evolve into a commercially viable system.

Three categories of conditions were developed based on the three sub-elements of the commercialization criterion.

Costs/Performance

Achievement of commercially competitive energy costs imposes the following conditions on the commercial design:

- Low Capital Costs
- Low Maintenance Costs
- Minimum Site Assembly
- Unattended Operation
- High Efficiency.

These conditions were approximated in the EE No. 1 design as closely as consistent with the higher-level criteria described earlier.

Flexibility

This criterion requires that the commercial version be capable of meeting the power needs of different users at different sites with different power demands and duty cycles. This is an extremely important criterion for producing a useful power plant capable of the extensive deployment required to achieve an economic scale of production without excessive "customizing" costs for each installation. Conditions derived from this criterion must be imposed on

the designs generated for EE No. 1 in order to provide a useful experimental plant leading to a commercially viable system. These conditions are:

- Finite Number of Modules to Cover the Power Range of 1 to 10 MWe
- Thermal Storage - This Excludes Battery Storage
- Road-Transportable Modules.

The flexibility to meet differing power level requirements in the 1 to 10 MWe range requires that equipment be designed to cover this range with no more than five (preferably four) discrete modules. These numbers are consistent with common industrial practice, as exemplified by commercial turbines, which are produced to standard frame sizes but which can be applied over a range of power levels up to their maximum rating.

Power demand profiles are not expected to exactly match solar availability. As a consequence, storage must be provided to make the collected energy available when it can be used by the customer. This imposes more storage than the minimum required to meet the annual capacity factor. Although, as an experimental plant, EE No. 1 will be configured with this minimum storage, the storage concept must be selected to provide greater flexibility in the commercial versions--both to meet differing duty cycles and to provide higher annual capacity factors. As shown in Section 2 (Table 2-4), battery storage is far too costly even if the DOE development and cost goals for advanced batteries are achieved. As a result, thermal storage must be employed to meet this criterion.

Widespread deployment of small power systems requires that the system be configured into road-transportable modules. This is particularly important for the concentrator, since it is necessarily large in area. Reasonable costs demand factory preassembly of the majority of the concentrator into road-transportable elements requiring minimum site-assembly operations. This contrasts with large power systems which could amortize site assembly (startup and shutdown) operations over a higher power rating.

Institutional Interface

The two major conditions imposed on subsystem design to meet this criterion are:

- Minimize All Hazards
- Employ Standard Technology to the Greatest Extent Possible.

3.4 FLOWDOWN FROM PROGRAM COST CRITERION

The conditions imposed to meet this criterion are divided into categories according to the two program phases.

Low Costs in Phase II

Conditions imposed to achieve low program costs in Phase II are:

- Minimum Development (Redundant with Condition from Program Risk Criterion)
- Utilize Other DOE Development Programs to the Greatest Extent Possible.

Low Costs in Phase III

Conditions imposed to limit Phase III costs are:

- Use Commercially Available Equipment Wherever Possible
- Use Solar Equipment Being Produced for Other Programs If Possible
- Maximize System Efficiency (Redundant with Condition From Reliability Criterion).

As reviewed above, the general ground rules and selection criteria imposed by JPL were applied rigorously in the overall MDAC design approach. Its specific detailed application will be seen in the balance of these documents. It is therefore no surprise that the MDAC central receiver power plant is the "best" choice for the First Engineering Experiment under the Small Power Systems Program.

Section 4
SYSTEM DESCRIPTION

Conceptual designs were developed for each of the three versions of EE No. 1. The design approach outlined in Section 3 was applied to the three system concepts selected in Section 2 to produce designs that best meet the objectives of the Small Power Systems Program. The top level characteristics for all designs are:

System Electrical Output	1 MW (Net)
System Capacity Factor	0.4
Insolation Model	Barstow 1976

The McDonnell Douglas central receiver plant concept is illustrated in Figure 4-1. The complete system is composed of five major subsystems: the collector, power conversion, energy transport, energy storage, and the plant control subsystems.

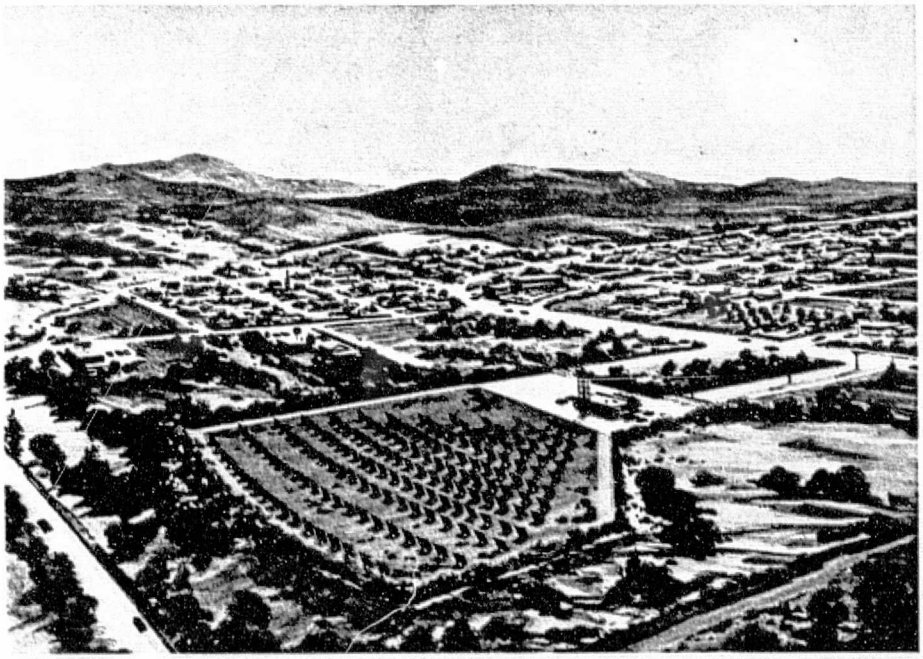

Figure 4-1. The McDonnell Douglas 1 MWe Central Receiver Plant

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The collector subsystem consists of the solar concentrator, receiver, and tower assemblies. The concentrators comprise a field of two-axis tracking heliostats, which reflect and concentrate solar radiation onto a tower-mounted receiver. The heliostat field is located north of the receiver tower.

The power plant layout for the commercial unit is shown on Figure 4-2. Equipment is located on skid-mounted units which are factory assembled, checked out, transported to the site and installed with minimum site assembly operations. The equipment shelter can be as little as a sunshield with removable side panels for some sites. The plant control unit is located in an adjacent trailer. A more substantial Butler-type building is provided for the first experimental plant. Provisions are made for adequate office, laboratory, and bench space to carry out all test and evaluation objectives of the EE No. 1 operations program.

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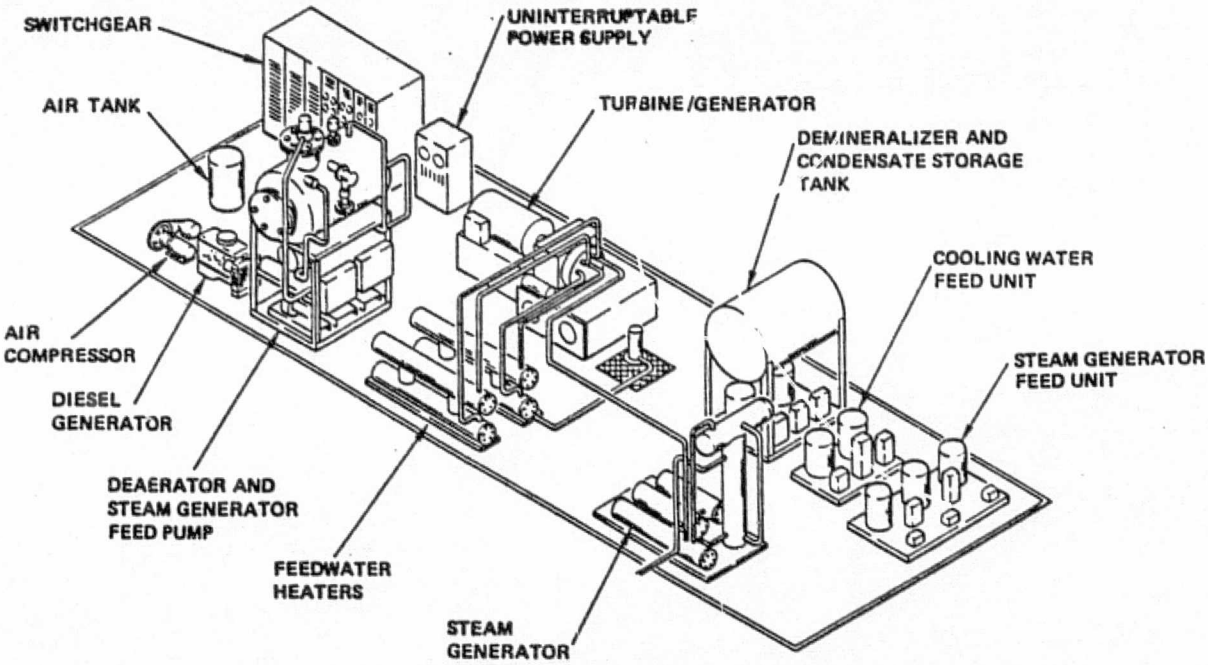

Figure 4-2. Commercial PCS Layout

System schematics for the three versions of EE No. 1 and the commercial system are shown on Figure 4-3. A summary of the design characteristics of each system is given on Table 4-1 together with an indication of the current state-of-the-art. The heliostats, which vary in number from 217 for the 3.5 year EE No. 1 to 133 for the commercial plant, are based on the 10 MWe Barstow plant design. The receiver is a partial cavity-cone, and the fabrication of this unit is fully state-of-the-art.

The energy transport subsystem collects thermal energy from the receiver and transports it to the energy storage subsystem and thence to the power conversion subsystem. Hitec is used as the transport fluid for the 3.5-year and 4.5-year program because of its relatively low melting temperature (142°C) and common use in industrial processes. The binary mixture of 54% KNO_3 and 46% $NaNO_3$, denoted as HTS, is used for the 6.5-year and commercial programs, because it has a higher temperature capability (increasing system performance) and is more economical.

The energy storage subsystem both isolates the power conversion subsystem from the collector subsystem and stores thermal energy for extended operation. For

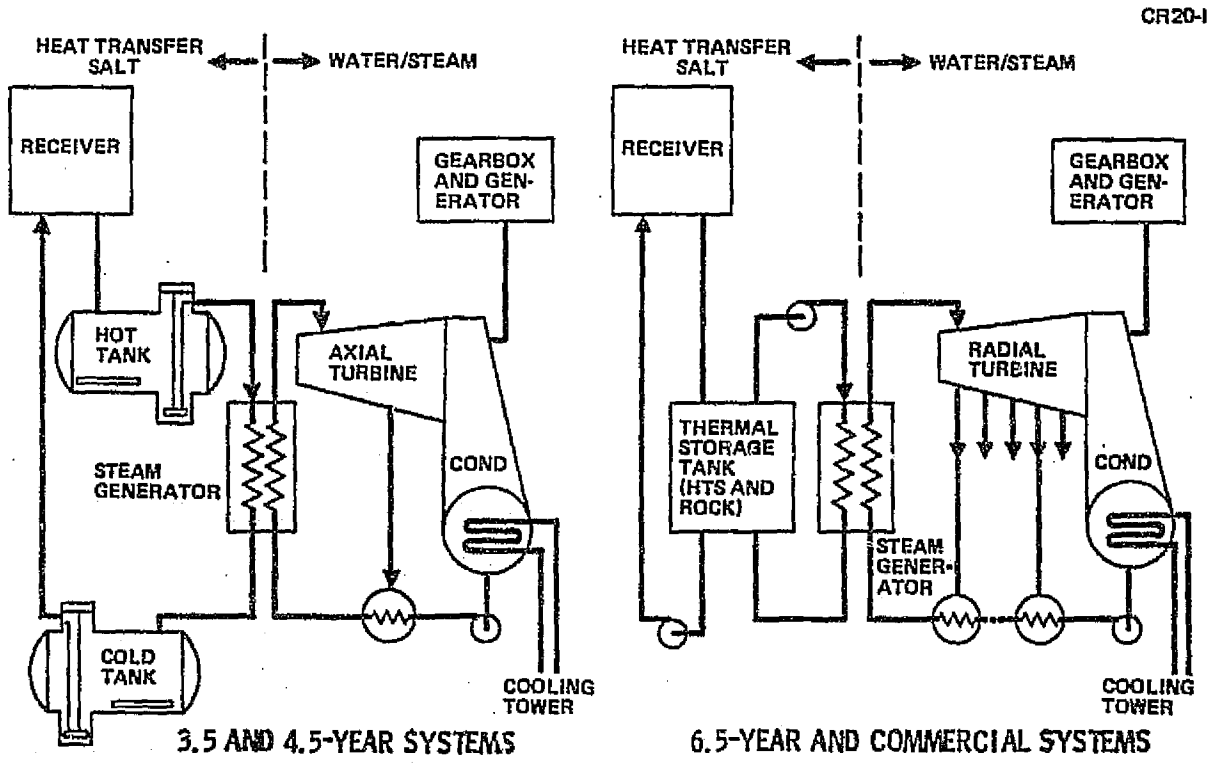

Figure 4-3. Baseline System Configurations

Table 4-1. Systems Summary (1 MWe, 0.4 Capacity Factor)

	3.5 Year	4.5 Year	6.5 Year	Commercial	State-of-the-art
Number of heliostats	217 ($45m^2$)	171 ($49m^2$)	139 ($49m^2$)	133 ($49m^2$)	
Tower height (m)	40	40	40	36	
Receiver type	Partial cavity				Fabrication
Energy transport fluid	Hitec*	Hitec*	HTS**	HTS**	Hitec
Energy storage	Two-tank		Dual media thermocline		Two-tank
Turbine type	Axial	Axial	Radial	Radial	Both
Maximum salt temp (°C)	454	510	538	566	510+
Maximum steam temp (°C)	427	482	510	538	538+
Auxiliary power (kWe)	134	108	82	79	
Overall net efficiency (%)	13.8	16.2	19.8	20.4	

*53% KNO_3, 40% $NaNO_2$, 7% $NaNO_3$
**54% KNO_3, 46% $NaNO_3$

the 3.5- and 4.5-year programs, a simple two-tank configuration is utilized which requires no development. For the 6.5-year and commercial programs, the storage unit consists of a single tank filled with crushed taconite (iron ore). The salt/taconite mixture stores the thermal energy as sensible heat utilizing the thermocline principle with the salt also functioning as the heat transfer medium.

Steam produced from the steam generator drives a steam Rankine cycle turbine which in turn drives an electrical generator to produce electricity. For the 3.5- and 4.5-year programs, an existing axial steam turbine is utilized. For the 6.5-year and commercial programs, a radial outflow turbine currently under development by Energy Technology, Inc. (ETI) is utilized. Waste heat from the turbine is rejected by a wet cooling tower.

All the balance of plant equipment involves state-of-the-art equipment and processes. The technology employed for each EE No. 1 program concept is consistent with the development time available. Further description of EE No. 1 subsystems together with their development status is given in the following section.

In order to determine the requirements and preferences that a utility company might have for a facility such as the one being studied, a number of utilities and communities were visited. The more important conclusions reached are presented below:

- There is a substantial variation in the local grid distribution voltage to which the plant could be connected. In some cases, provisions for interfacing with the grid already exist.
- A preference for wet cooling was indicated since water was not in short supply at most sites.
- A preference for internal (thermal) rather than external (battery) storage was indicated.
- Daily power demand profiles showed that the demand for electricity lags the isolation availability by several hours. The power generation profile can be matched to the demand profile by the use of additional storage beyond the minimum required to meet the specified annual capacity factor. The analysis of utility requirements also indicated that a larger capacity factor of about 0.5 would be preferred to 0.4.

Although the plant is designed to interface with an existing electrical grid, it can be modified to operate as a stand-alone unit in a location not serviced by a grid by making a few alterations.

The capability of supplying the electrical demand 24 hours a day throughout the year can be accomplished by providing either: (1) a diesel generator capable of supplying the plant rated power, or (2) a fossil fuel-fired Hitec heater capable of supplying the heat input necessary for operation of the basic power plant.

The fired heater is the preferred selection with a lower-rated diesel generator utilized for plant auxiliaries and to supply minimum system emergency power requirements.

Additional equipment required in a stand-alone plant would be an electrical resistance bank to serve as a buffer for electrical load transients. This unit would be cooled using the cooling tower water. A slight change in the turbine control system would also be required.

System performance was calculated for each configuration by combining the performance of each of the optimized subsystem designs. The process started with the net annual electrical energy required to meet the plant rating and annual capacity factor and worked "backward" accumulating the various loss factors until the concentrator field was sized. The results are presented graphically on a "waterfall" chart in Figure 4-4. Note that the average annual unavilability of the plant is taken into account in sizing the collector field and specifying plant performance.

The electrical energy produced by the system each month, based on the Barstow insolation data, is presented in Figure 4-5. This profile would be identical for all experimental programs.

Costs for the commercial plant ranged from about $2.5 million at a deployment rate of 100 plants per year to $2.2 million at a rate of 5,000 plants per year. The corresponding energy costs, including operations and maintenance, on an investor-owned utility ranged from 156 to 169 mills/kWhe using the JPL-supplied costing groundrules. The corresponding energy costs on a municipal-owned utility would be less. These costs could be competitive with diesel electric generation in rural areas not connected to a grid. The sensitivity of energy costs to plant rating and annual capacity factor are covered in Section 6.

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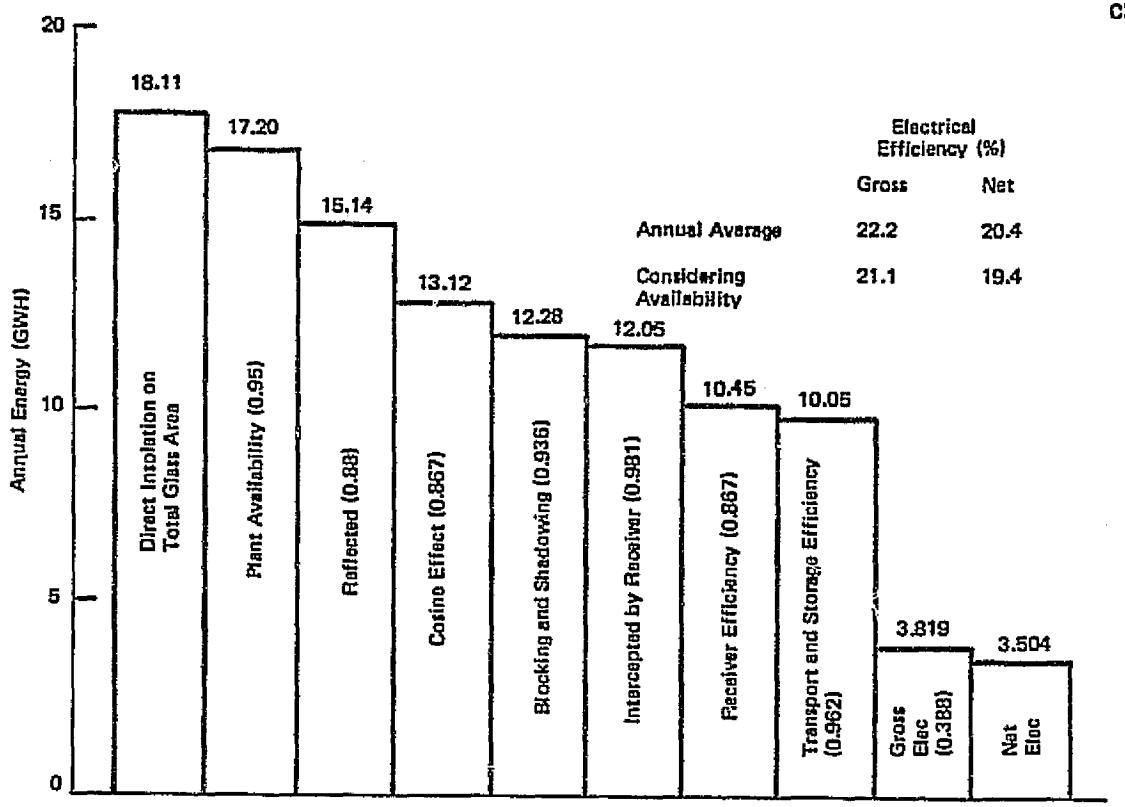

Figure 4-4. Performance Waterfall for Commercial System

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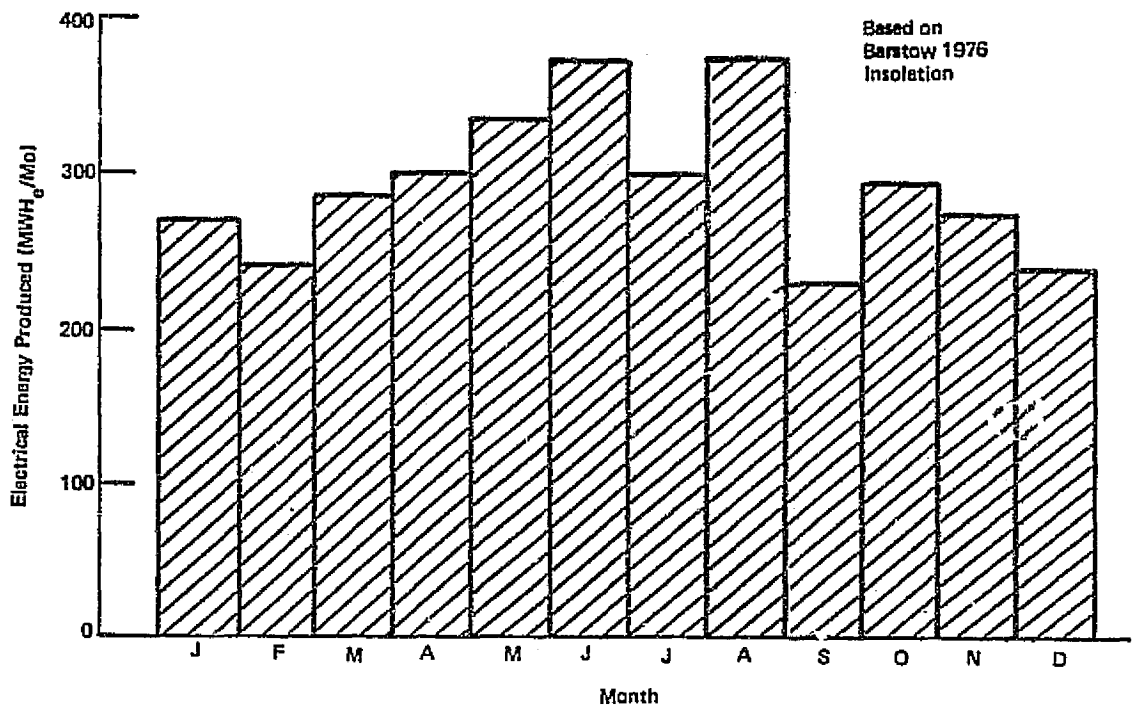

Figure 4-5. Monthly Energy Production

Section 5
SUBSYSTEM STATUS

A summary description of the subsystems selected for each version of EE No. 1 will be given here together with a review of their development status and an evaluation using the selection criteria presented on Table 2-2. It should be kept in mind that the actual process went in the opposite direction--starting with the selection criteria, proceeding through an assessment of development status to arrive at subsystem designs which fully satisfied the selection criteria for each program duration.

The five major subsystems will be described with the collector assemblies (concentrator, receiver, and tower) treated separately because of their distinct characteristics. The energy transport and storage subsystems will be described together because they utilize common technology, equipment, and transport fluid.

5.1 COLLECTOR SUBSYSTEM — CONCENTRATOR ASSEMBLY

The function of the concentrator assembly is to collect, redirect, and focus insolation on the receiver assembly that is mounted south of the field on a tower. The concentrator assembly consists of heliostats plus related controls and the electrical power supply necessary for drive purposes. The heliostats are individually mounted on pedestals and are segmented for easy site assembly.

The heliostats selected for EE No. 1 are shown on Figure 5-1. The 3.5-year program uses the heliostat developed for the Barstow 10 MWe plant with minor modifications. A more advanced second generation heliostat is proposed for the 4.5-year, 6.5-year and commercial designs. This heliostat is similar to the Barstow unit; however, various design changes were incorporated to reduce its costs, particularly in high-volume production.

Both heliostats have four subassemblies: the reflector panels, the drive unit, the pedestal support and foundation, and control. While dimensions and details differ, the description given below generally applies to both units.

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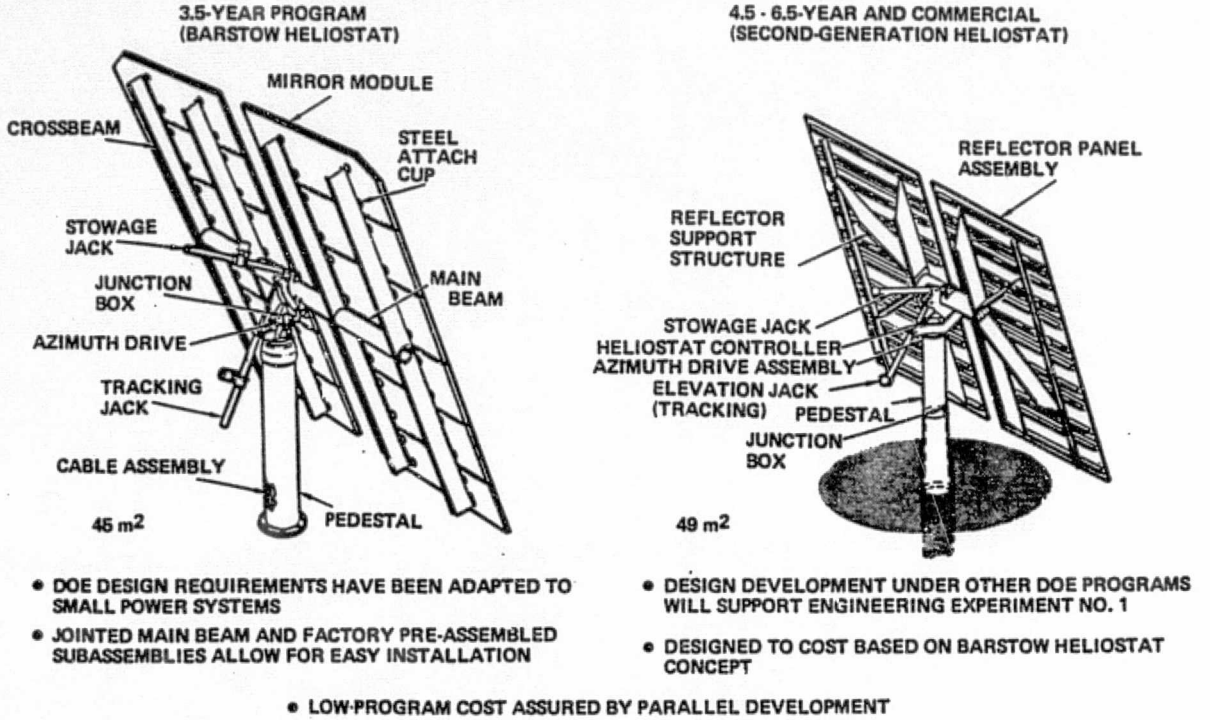


Figure 5-1. Collector Subsystem (Heliostats)

There are two reflector panels per heliostat and each panel is made up of six mirror modules. The mirror modules use second-surface glass mirrors. The modules are attached to a support structure that maintains their alignment and rigidly attaches them to the drive unit. Focusing is achieved by slightly curving the mirror modules during manufacturing, and by shimming the modules to the proper cant angles after attachment to the support structure.

The drive unit incorporates azimuth and elevation drive mechanisms. It is mounted on top of the pedestal and consists of motors, drive transmissions, position feedback sensors, reflector support bearings, and a structural housing. The drive unit positions the reflector during normal operation to redirect the solar radiation to the receiver. The drive unit can also position the heliostat in an inverted stowage position to minimize the risk of damage from severe weather conditions.

The pedestal support and foundation is used to mount the heliostat in the field. The drive unit and reflector panels are mounted on top of the pedestal.

The pedestal is rigidly attached to a precast concrete foundation by bolted flanges (3.5-year design) or slip joint (4.5-, 6.5-year, and commercial designs).

Heliostat control is achieved from the control subassembly. Field controllers calculate the sun's position, direct individual heliostat motions, calculate any errors in position, and direct corrective motions. Heliostat controllers calculate actual heliostat position, compare to the commanded position from the field controller, and drive the motors to correct the errors indicated. Power supply to the drive units and the control function are made through a "serial hookup." This enables remaining heliostats to function normally should one heliostat fail. All heliostat controls have manual override capabilities.

Heliostat development at MDAC is illustrated on Figure 5-2. The Small Power System Program will benefit greatly from the preceding and on-going development of heliostats shown on this figure. Heliostat research was initiated by MDAC in 1973 with the first U.S. heliostat built and tested in 1974 under National Science Foundation (NSF) contract.

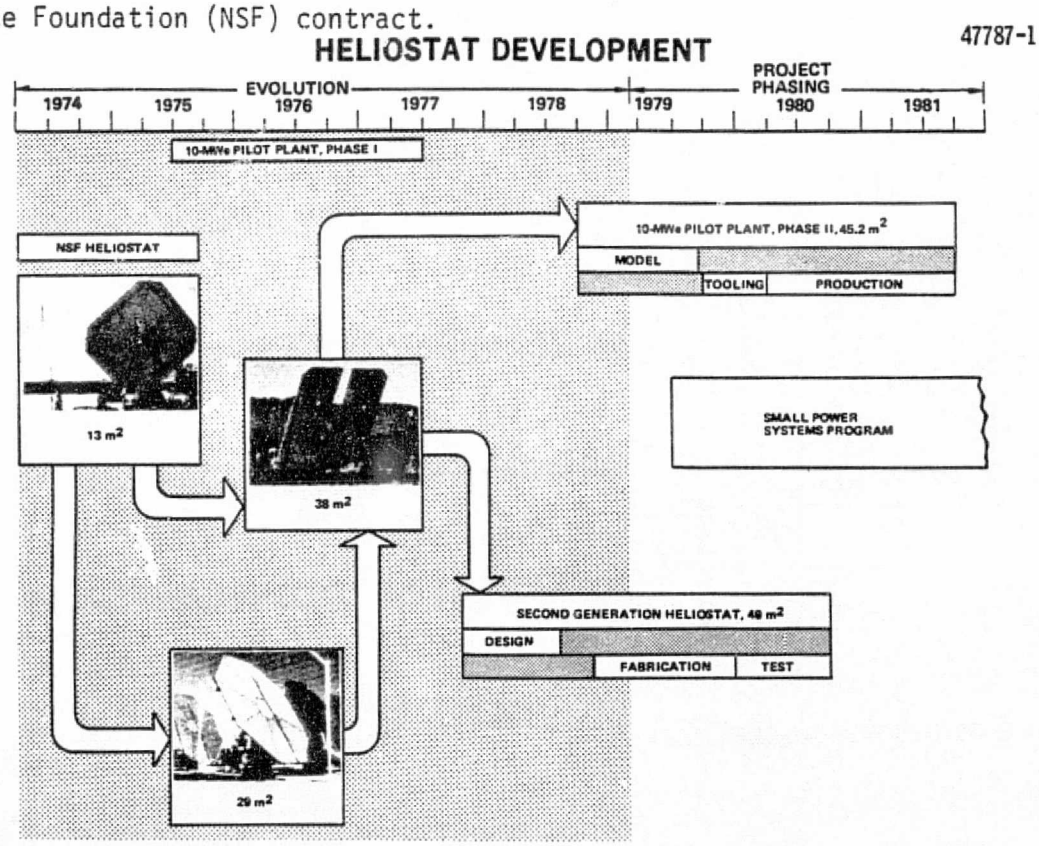


Figure 5-2. Heliostat Development at MDAC

An improved version was built and tested in 1975 as part of the 10 MWe pilot plant Phase I program. Further design improvements formed the basis for a third model built in 1976. This heliostat was tested for performance in the desert at China Lake, California, and was subjected to full structural, lifetime, and environmental testing.

The design of this third model was selected by DOE for the Barstow 10 MWe plant with engineering models now under construction and evaluation. Production of these heliostats is scheduled to start in 1980 with a production rate of approximately 2,000 heliostats per year.

The heliostat design selected for Barstow also became the basis for the MDAC second generation design. This unit is being fabricated, and evaluation tests will be conducted in 1980.

The three factors present in this program which are considered necessary for the successful deployment of solar concentrators in the Small Power Systems Program are:

- A substantial foundation of design, development, and testing
- A significant level of hardware production, and
- An on-going program for product improvement (cost reduction).

The concentrator for EE No. 1 should not be based on a less-solid foundation.

An evaluation of the concentrators for the collector subsystem using the prescribed selection criteria is shown on Table 5-1. With respect to reliability and availability, the hardware has been put through life cycle and environmental tests qualifying it for 30-year operation. Moreover, the heliostat field has inherent redundancy. Program risk is low because there is no development required for the EE No. 1 program--heliostat hardware will be available. From the commercialization standpoint, this heliostat design can produce thermal energy cheaper than any other type of concentrator MDAC has investigated; this is the most cost-effective system concept. Common use of this hardware for both large plants (greater than 10 MW) and small plants, produce economies of production scale. Similarly, the same hardware can be

Table 5-1. Collector Subsystem Evaluation (Heliostat)

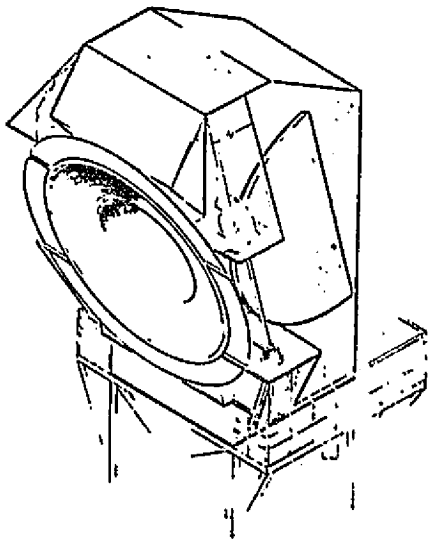
Criterion	Features
Reliability/availability	• Hardware qualified for 30-year life and environmental conditions
	• Inherent redundancy
Program risk	• No development in EE No. 1 program
	• Hardware will be available
Commercialization potential	• Lowest cost ($/GJ) concentrator examined
	• Common hardware for large (>10 MWe) and small (1-10 MWe) systems
	• Common hardware for electricity, thermal, both
	• Designed for transportability
Low program costs	• Development cost charged to earlier programs
	• Volume production available from large central receiver programs

used to produce electricity, to produce steam only, or to produce a combination. Of particular importance, the hardware has been designed for road transportability. The program costs are low because heliostat development was largely amortized on earlier programs. Furthermore, because the Barstow program is on-going with an expected production rate of about 2,000 units a year, a much higher volume base is available than could be provided for EE No. 1 alone.

5.2 COLLECTOR SUBSYSTEM - RECEIVER ASSEMBLY

The receiver assembly is shown on Figure 5-3, together with major characteristics for the three versions of EE No. 1 and the commercial unit. The receiver assembly is composed of an absorber unit, structural assembly (including housing and doors), instrumentation, insulation, and heaters. The receiver faces south with the aperture tilted downward 20° from the vertical.

The absorber is a partial cavity design consisting of spiral tubes with the heat transfer fluid entering at the periphery and exiting at the apex of the cone.



	3.5	4.5	6.5	COMMER.
• CONFIGURATION	— SPIRAL PARTIAL CAVITY —			
• APERTURE DIA (m)	4.5	4.28	4.00	3.5
• ABSORBER TUBE MATERIAL	— 316 CRES —		— INCOLOY 800 —	
• TUBE O.D. (mm)	44.5	44.5	38.1	38.1
• NUMBER OF PARALLEL TUBES	4	4	4	3
• OUTLET TEMPERATURE (°C)	454	510	538	566

Figure 5-3. Collector Subsystem (Receiver)

The edge section contains relatively cool fluid that is exposed to atmospheric cooling. This section is heated with the lower intensity fringe elements of the flux. As the flux builds up closer to the center, the tubes are formed into a much steeper conical cavity and the hot fluid exits at the center. Four parallel tubes are used for EE No. 1, whereas three parallel tubes are used for the commercial unit all with standard size tubing. For the 3.5- and 4.5-year programs, standard 316 CRES is used. The 6.5-year and commercial programs employ Incoloy 800 for the higher allowable design temperatures.

Insulated doors close over the receiver aperture to prevent excessive cool down during periods of no insolation. Trace heaters keep the Hitec/HTS from cooling and solidifying.

The receiver development status is summarized on Figure 5-4. There are two main development issues for the receiver assembly: (1) fabrication and (2) technical verification of performance. A top-down requirement imposed

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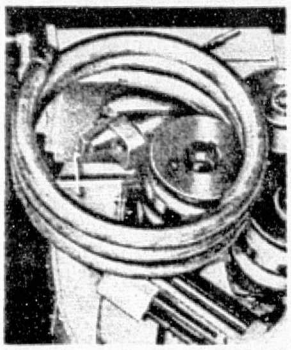


CONVENTIONAL ROLL BENDING EMPLOYED

- STATE OF THE ART

TECHNICAL VERIFICATION

- 3.5-YEAR PROGRAM
  - ANALYSES ONLY
  - BACKED OFF FROM STATE-OF-THE-ART TECHNOLOGY
- 4.5-YEAR PROGRAM
  - CRTF MODEL TEST
  - VERIFY STATE-OF-THE-ART TECHNOLOGY
- 6.5-YEAR PROGRAM
  - LABORATORY TESTS
  - CRTF MODEL TEST
  - EXTEND TECHNOLOGY

Figure 5-4. Receiver Development Status

was that the fabrication utilize standard state-of-the-art processes to minimize development risks and costs. Consequently, the spiral tube approach was selected which can be formed by conventional roll bending techniques, as shown on the figure. Consequently, there is no fabrication development required for this design.

To verify performance, development testing will be required in some cases. MDAC started with the 4.5-year program for which full model testing in the Central Receiver Test Facility (CRTF) was possible. This design was set at the state-of-the-art for heat flux and temperature conditions. Since the 3.5-year program does not have an adequate duration to allow such testing, operating conditions were backed off from the current state-of-the-art so that we can operate with full confidence without experimental verification. For the 6.5-year program, which has a very long development period, the technology was extended in the areas that would be cost effective in the performance of the plant. Both laboratory tests and CRTF testing was included in this program.

An evaluation of this assembly, according to the design criteria, is shown on Table 5-2. From a reliability/availability standpoint, the design is very conservative because it is based on standard boiler codes for 30-year lifetime. Since the abosrber consists of continuous spiral tubes, there are only entrance and exit welds. This greatly enhances equipment reliability. If the receiver required many panels with extensive tube-header welds, there would be many more sources for failure and deployment for the 3.5-year program without verification testing would have been questionable.

Standard fabrication methods were used for all designs. This minimizes potential program risks. For the 3.5-year program, the risk criterion is met by having an extremely conservative technical design. For the 4.5-year program, the risk criterion is met by imposing state-of-the-art conditions and performing verification testing. A development test in the Central Receiver Test Facility (CRTF) is planned, and this becomes the critical path for tracking the program. The Phase II test has a 4-month schedule "pad" which is considered to be acceptable. The duration of the 6.5-year program is so long that there are no schedule constraints whatsoever.

The receiver is designed to be cost effective in large production rates, and it is designed for road transportability. From a cost standpoint, there will be a significant first-unit cost since this is the first-of-a-kind to be built Additionally, in the 4.5- and 6.5-year programs, the test program itself is a major program cost element.

5.3 COLLECTOR SUBSYSTEM — TOWER ASSEMBLY

The primary function of the tower assembly is to provide support for the receiver. It is designed for the most severe wind and seismic conditions expected and also to minimize receiver sway resulting in reflected solar energy missing the receiver aperture. In addition, the tower provides support for the Hitec/HTS riser and downcomer and allows for necessary maintenance functions.

The tower assembly, shown on Figure 5-5, consists of the basic tower structure, supporting guy wires, foundations, working platforms, service elevator and

Table 5-2. Collector Subsystem Evaluation (Receiver)

Criterion		Features
Reliability/Availability		• Designed to ASME boiler code (30-year life) • Minimum tube/manifold welds
Program risk	All programs	• Standard fabrication methods
	3.5-year	• Conservative technical design
	4.5-year	• Phase II test is critical item (4-month schedule pad)
	6.5-year	• No development schedule constraints
Commercialization potential		• Designed for automated production • Designed for transportability
Program cost	All programs	• Significant first-unit costs
	4.5- and 6.5-year	• Model test is major element

ladders, lights, lightning protection, heliostat target device, electric power lines, water lines, and supports for heat transfer fluid lines, nitrogen purge lines, instrumentation and pneumatic lines.

An evaluation of the tower assembly is shown on Table 5-3. From a reliability standpoint, the tower is designed to cope with all operating conditions. Towers of this type have been used for years, and there is no program risk because there are no development issues. From a commercialization standpoint, this size tower uses a low-cost guyed-steel design. The tower is transportable, either in prefabricated sections or as steel members for fabrication at the

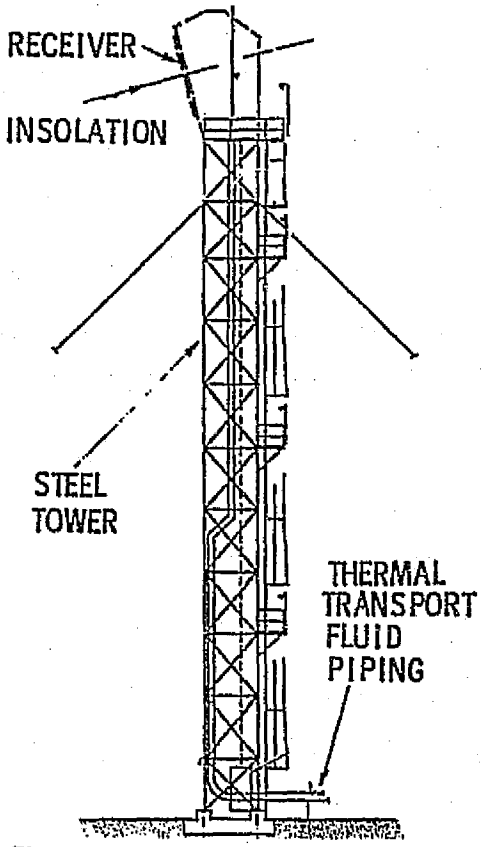


Figure 5-5. Collector Subsystem (Tower)

- HEIGHT: 40 m (131 FT) - EE NO. 1 PLANT
  36 m (112 FT) - COMMERCIAL PLANT
- GUYED STEEL - FOUR 2.5 cm (1 INCH) DIA CABLES
- ASSEMBLED FROM STANDARD STEEL SECTIONS
- CONCRETE BASE - 27.5 m^3 (36 CU YD)
- OPERATING DEFLECTION - 1.5 cm (0.6 IN) IN 16 m/s (36 MPH) WIND
- SERVICE ELEVATOR FOR EE NO. 1

Table 5-3. Collector Subsystem Evaluation (Tower)

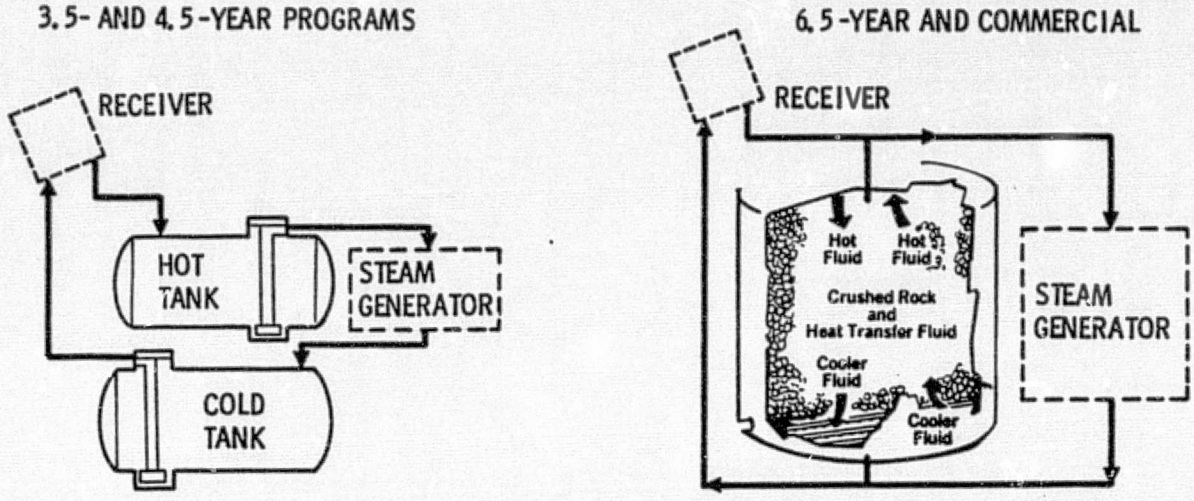
Criterion	Features
Reliability/availability	• Designed to code for all conditions
Program risk	• No development required • Standard construction/erection
Commercialization potential	• Low-cost guy steel design • Transportable, prefabricated tower sections • Painted to be unobtrusive
Program cost	• No development • Low cost for first unit

site. The tower can be painted to be relatively unobtrusive. Program costs will be low since no development is required and, since it is of standard construction, there are no unique high first-unit costs.

5.4 ENERGY TRANSPORT AND STORAGE SUBSYSTEMS

The energy transport and storage subsystems include all necessary Hitec/HTS circulation and control equipment and storage tanks. They are configured to allow independent operation of the receiver and power conversion loops, thus providing operational flexibility by permitting startup, shutdown and normal operation of one loop while the other loop is in a different mode. This is accomplished by the use of two independent circulation circuits, each with its own circulation pump, control valves, isolation valves and sensors. The receiver loop extracts fluid from storage at a low temperature, pumps the fluid to the receiver in a controlled manner to maintain a constant receiver outlet temperature and returns the heated fluid to the storage subsystem. A pump then sends the required quantity of "hot" Hitec/HTS through the second loop to the steam generator and returns the "cold" fluid to storage.

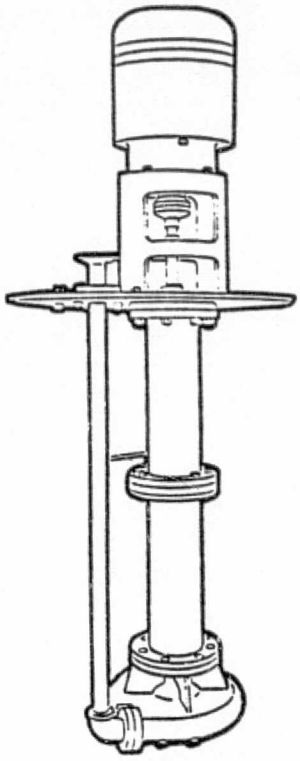
The designs selected for the three versions of EE No. 1 and the commercial plant are shown on Figure 5-6. A simple two-tank configuration is used for the 3.5-year and 4.5-year programs while a single-tank, dual-media thermocline configuration is used for the 6.5-year and commercial designs. Consistent with the general design guidelines discussed earlier, progressively higher operating temperatures are allowed for the longer duration programs.



	3.5-YEAR	4.5-YEAR	6.5-YEAR	COMMERCIAL
FLUID	HITEC	HITEC	HTS	HTS
STORAGE	← 2-TANK →		← DUAL MEDIA THERMOCLINE →	
CAPACITY (MWH)	17.1	14.9	12.5	11.9
MAX TEMPERATURE (^{0}C)	454	510	538	566
PUMPS	← VERTICAL SUBMERGED →		← HORIZONTAL IN-LINE →	

Figure 5-6. Energy Transport and Storage Subsystems

The development status of the energy transport and storage subsystems is summarized on Figure 5-7. Since the 3.5- and 4.5-year programs use Hitec, two separate storage tanks, and qualified vertical submerged pumps, there are no development requirements. All the components are standard and have had extensive application in many systems throughout the world. For the 6.5-year program, HTS is used together with a single dual-media thermocline tank and horizontal in-line pumps. A more complete material compatibility test is needed for the HTS and the solid material (Taconite). Moreover, horizontal, in-line centrifugal pumps for HTS have not been operated for extensive periods at these conditions nor are they in commercial use. The HTS research program presently underway at the Sandia Livermore Laboratory should provide the salt and component technology needed for the 6.5-year design.



3.5- AND 4.5-YEAR PROGRAMS

- ALL COMPONENTS ARE STANDARD ITEMS WITH EXTENSIVE PRIOR APPLICATION

6.5-YEAR PROGRAM

- MATERIAL COMPATIBILITY VERIFICATION FOR DUAL MEDIA
- QUALIFICATION OF IN-LINE PUMPS, OTHER COMPONENTS -USE RESULTS FROM DOE SALT TECHNOLOGY PROGRAM (SANDIA-L)

Figure 5-7. Energy Transport and Storage Development Status

The evaluation of the energy transport and storage subsystems is given on Table 5-4. From a reliability/availability standpoint, the present operating experience with salt energy transport installations is excellent. Existing systems work very well with minimum maintenance or replacement. Advanced components are planned to be used only when fully qualified. For the short duration programs, there is no development required, and consequently, no program risk. For the 6.5-year program, there are no schedule constraints for the necessary development testing. If necessary, conditions can be reduced to the 4.5-year design temperature and configuration for which there is no development required. For commercialization, one of the most important objectives was low-cost storage to match the solar availability to the various user demands. Program costs are expected to be low, primarily because there are no development requirements in the 3.5- and 4.5-year programs and moderate costs in the 6.5-year program. For the shorter duration programs, the equipment is commercially available and in common use, which will result in low first unit costs. However, MDAC does plan to make use of other DOE programs.

Table 5-4. Energy Transport and Storage Evaluation

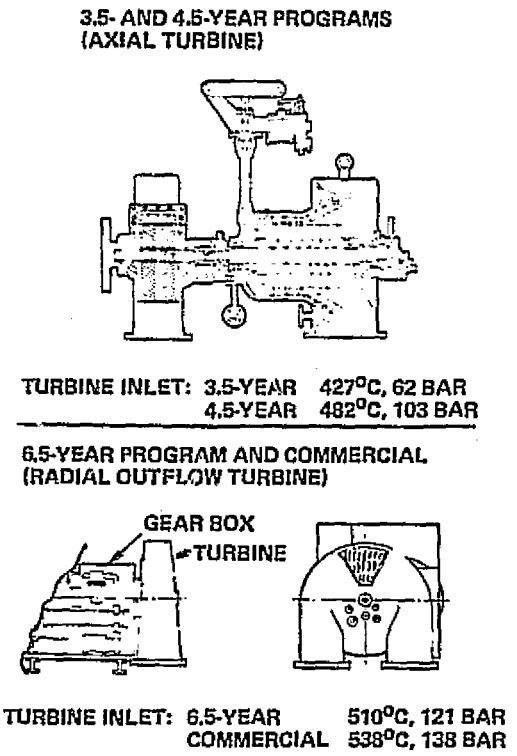
Criterion		Features
Reliability/availability		• Present operating experience is excellent • Advanced components used only when/if fully qualified
Program risk	3.5- and 4.5-year	• No development required
	6.5-year	• No development schedule constraints - 4.5-year design as backup
Commercialization potential		• Low-cost storage to match various demand profiles/ capacity factors
Program cost	3.5- and 4.5-year	• No development costs • Low first-unit costs
	6.5-year	• Moderate cost for dual-media tests • Use of DOE salt technology program results

5.5 POWER CONVERSION SUBSYSTEM

The function of the power conversion subsystem (PCS) is to convert the thermal energy collected and stored in the Hitec/HTS into electricity, to distribute this electrical energy to the electric grid, and to supply the plant's auxiliary (parasitic) power requirements.

The PCS generates power by use of a steam Rankine cycle. The major components of the PCS are listed on Figure 5-8.

The selection of the steam turbine is the most critical element in the design of the PCS. The 3.5-year and 4.5-year programs will utilize conventional



MAJOR COMPONENTS
(PACKAGED AS SKID-MOUNTED MODULES)

- TURBOGENERATOR AND ANCILLARY EQUIPMENT
- STEAM GENERATOR
- FEEDWATER HEATERS AND PIPING
- PUMPS
- CONDENSER AND AIR REMOVAL EQUIPMENT
- HEAT REJECTION EQUIPMENT
- WATER TREATMENT
- AUXILIARY POWER UNIT
- INSTRUMENTATION AND CONTROL VALVES
- SWITCHGEAR AND PLANT ELECTRICAL NETWORK

Figure 5-8. Power Conversion Subsystem

marine turbines. The radial outflow turbine, as developed by Energy Technology, Inc. (ETI), will be the prime mover in the 6.5-year and commercial programs. This turbine offers significant performance advantages due to improved expansion efficiency and the ability to provide up to five extraction ports for feedwater heating. These two configurations are shown on Figure 5-8.

The steam generator consists of a separate preheater, natural recirculation boiler and superheater sections connected in series. Heat rejection is accomplished with a wet cooling tower. Piping is carbon steel or admiralty alloy throughout. The water/steam loop will be blanketed with nitrogen at night to prevent oxidation and corrosion.

All elements of the PCS have been selected for maximum reliability and are standard equipment requiring no major development effort with the exception of the turbine for the 6.5-year program. Development status of the PCS is summarized on Table 5-5.

Table 5-5. Power Conversion Subsystem Development

Steam Turbine Is Only Development Item
• 3.5-Year program -- Standard axial marine turbine (100's in service)
• 4.5-Year program -- Slightly uprated axial marine turbine (standard 3.5-year design as backup)
• 6.5-Year program -- Full development/qualification of optimized radial outflow turbine

An evaluation of the power conversion subsystem, is summarized on Table 5-6. All the EE No. 1 programs utilize a natural recirculation boiler to enhance the reliability of the power conversion loop. The 3.5- and 4.5-year programs use high reliability axial marine turbines. The reliability/availability values obtained from several of the manufacturers of these marine units are outstanding. For the 6.5-year program, the ETI design for the radial outflow turbine is an inherently reliable one.

There is no development risk in the shorter programs, since there is no development required. For the 6.5-year program, the development period is very adequate. The radial outflow trubine could also be developed for the 4.5-year program, however, only at some schedule risk. The high cycle efficiency of this turbine greatly enhances its commercialization potential. The radial turbine is designed for automated manufacture and should be a relatively low cost hardware item. All power conversion subsystem elements are designed to be transportable as skid mounted assemblies. The single prime mover and generator provides good commercialization potential compared with multiple power conversion modules as reviewed in Section 2.

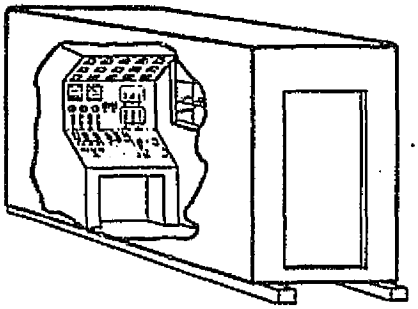
Table 5-6. Power Conversion Subsystem Evaluation

Criterion		Features
Reliability/availability	All programs	• Natural recirculation boiler
	3.5- and 4.5-year	• High reliability marine turbine
	6.5-year	• High reliability design
Program risk	3.5- and 4.5-year	• No development required
	6.5-year	• Substantial "pad" in development schedule
Commercialization potential		• High cycle efficiency
		• Turbine designed for automated manufacture
		• Transportable, skid-mounted equipment
		• Single prime mover/generator
Program cost	3.5- and 4.5-year	• No development costs
		• First unit employs standard equipment
	6.5-year	• Turbine development is major element

Program costs for the shorter programs are minimal since there are no development requirements. The first unit costs are relatively low since standard equipment is utilized. For the 6.5-year program, development of the radial outflow turbine is a major cost element.

5.6 PLANT CONTROL SUBSYSTEM

The plant control subsystems for the three EE No. 1 programs and the commercial plant are summarized on Figure 5-9. This subsystem includes all command and control equipment, sensors, and display and recording of plant status. For the commercial system, the equipment is trailer mounted as illustrated on the figure. Control equipment addresses two prime areas; the concentrator and



- COMMAND AND CONTROL SUBSYSTEMS
- SENSE SUBSYSTEM OPERATIONS
- DISPLAY/RECORD PLANT STATUS
- TRAILER-MOUNTED (COMMERCIAL UNIT)

	3.5-YEAR	4.5-YEAR	6.5-YEAR	COMMERCIAL
COLLECTOR/ CONCENTRATOR	THREE-ELEMENT FROM 10 MWe	COMBINED INTO TWO ELEMENTS →		
DEGREE OF AUTOMATION	• MODE TRANSITIONS	• LOOP WARMUP AND SHUTDOWN	• TURBINE STARTUP AND SHUTDOWN • OTHER PLANT OPERATIONS	• ALL SYSTEMS • FULL REDUNDANCY
OPERATIONAL MODES:	• MANUAL • SEMIAUTOMATIC • AUTOMATIC	→	• SEMIAUTOMATIC • AUTOMATIC • MANUAL	• AUTOMATIC (UNATTENDED) • SEMIAUTOMATIC • MANUAL

Figure 5-9. Plant Control Subsystem

the entire plant. For the 3.5-year program, concentrator control is exactly the same as for the Barstow 10 MWe plant, which uses three prime control elements. These are: the heliostat controller (HC), the heliostat field controller (HFC), and the heliostat array controller (HAC). For the longer programs, these controls are reduced to two elements which are more cost effective for a small plant. Fully automated plant operation is required for the commercial unit. In the 3.5-year program, only mode transitions are automated. Greater amounts of automation are utilized for the longer programs. Full realization of automated control, including full control redundancy, is not achieved until the commercial unit. One of the three experimental programs would be used to gain the experience and confidence required to fully develop automated control. Operating modes for the 3.5- and 4.5-year programs will have manual control as a basic operating mode backed up with semiautomatic and limited automatic operation. The 6.5-year program uses semiautomatic control with automatic and manual backup.

Plant control development requirements are summarized on Table 5-7. As reviewed above, no development is required for the 3.5-year program. Equipment similar to the 10 MWe Barstow plant will be used. The plant processor, as a ong-lead item, will have to be procured during Phase II. This same equipment will be used for the 4.5-year program except that field control will be incorporated into the central plant control--the field controller will be eliminated. Also, additional automated techniques will be incorporated. More extensive automated control will be used for the 6.5-year program.

Table 5-7. Plant Control Development

- 3.5-Year Program
  - No development required
  - Order plant processor during Phase II (Long-lead procurement)
  - Automation tools available for testing
- 4.5-Year Program
  - Eliminate field controller
  - 3.5-year system hardware configuration
  - Add additional automated techniques
- 6.5-Year Program
  - Extensive automation developed

An evaluation of the plant control subsystem is given on Table 5-8. Reliability and availability are enhanced with the three control level options (manual, semiautomatic, automatic). Also, the plant processor is redundant in all configurations. For the commercial unit, full redundancy of the subsystem is proposed which ensures virtually no unavailability. Program risk is very low for all cases. For the 3.5-year program, commercial hardware is used throughout--there is no development required whatsoever. On the other two programs, the development objectives are matched to the available time. Plant control development is extended as far as practical in meeting this criterion and in being cost effective. There is minimal risk with this program flexibility.

For commercialization, automated operation is key to achieving competitive power costs. Consequently, automation is one of our major goals leading to commercialization. In addition, the transportability criterion is met by the trailer mounted control unit. This is important in order to have access to virtually any remote site where the plant may be deployed. Since commercial hardware is used for all programs, there are no development costs for the 3.5-year program, and only moderate development costs to incorporate progressive automation features for the 4.5-and 6.5-year programs. Full realization of the automated operation is considered to be outside the scope of the EE No. 1 program.

Table 5-8. Plant Control Evaluation

Reliability/availability		• Three-Level control options • Redundant plant processor • Full redundancy (commercial unit)
Program risk	All programs 3.5- year 4.5- and 6.5-year	• Commercial hardware • No development required • Development matched to avail-ble time • Less automation as backup
Commercialization potential		• Automated operation • Transportable trailer-mounted unit
Program costs	All programs 3.5-year 4.5- and 6.5 year	• Commercial hardware used • No development costs • Moderate development costs • Full realization outside scope of EE No. 1 programs

Section 6
SENSITIVITY TO POWER LEVEL AND STORAGE CAPACITY

Sensitivity to changes in power rating and annual capacity factor was determined. The power rating was varied from 0.5 to 10.0 MWe at a constant capacity factor of 0.4. Likewise, the capacity factor was varied from no storage to 0.7 at constant rated power of 1.0 MWe.

For the 10 MWe power rating, both a partial cavity receiver with a north field, and a cylindrical receiver with a 360° surrounding field were investigated. From the results of trade studies, the north field/partial cavity receiver was selected for the 10 MWe power rating because the more effective field performance and higher receiver efficiency produced a lower overall cost of energy.

For the no-storage case, a small two-tank energy storage subsystem was retained to isolate the power conversion subsystem from insolation transients caused by intermittent cloud passage. These buffer tanks were sized for 10 minutes of full-power operation. The corresponding heliostat field was optimized to produce 1 MWe at 750 W/m^2. Consequently, the "no-storage" case has a capacity factor of 0.275.

Results are shown on Figure 6-1, which presents energy costs relative to the baseline plant at 1.0 MWe and 0.7 capacity factor. Energy costs for the baseline plant were given in Section 4 as a function of annual deployment rate. The lower curves represent the cost contribution of capital equipment. The upper curve represents the total costs of capital equipment and operations and maintenance (O&M). As can be noted from the figure, energy costs increase rapidly for plant ratings below 1.0 MWe. Above 1.0 MWe the costs decline in a more gradual manner. An interesting observation that can be made from this analyses is that even with automated operation, the O&M costs make a very large contribution to the energy costs.

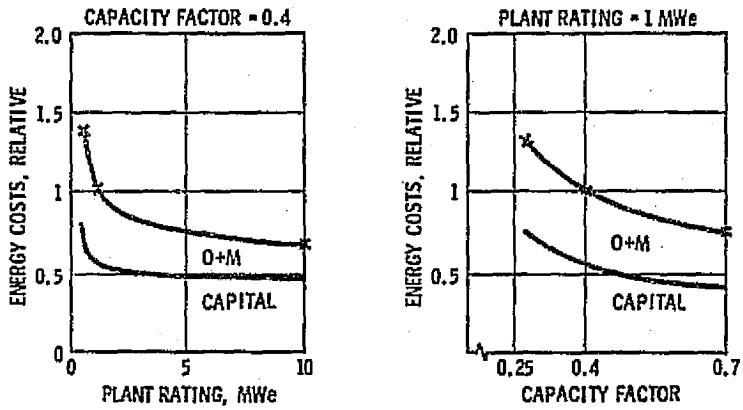


Figure 6-1. Sensitivity Results

For capacity factor variations, a more gradual behavior is apparent. However, energy costs are lower for plants with larger annual capacity factors. For these relatively small plants, the power conversion equipment is a major contributor to captial costs. Higher capacity factors amortize this cost over more annual energy; thus reducing energy costs.

From these results it can be seen that more competitive energy costs would be produced by plants with ratings above 2 MWe and anuual capacity factors above 0.4.

Section 7
OVERALL EVALUATION

An overall evaluation of the final system designs was made based on the major selection and evaluation criteria previously reviewed.

High operational reliability is the first evaluation criterion. To meet this requirement, selected system concepts should lead to: (1) an experimental plant that will start up satisfactorily and operate reliably for at least 2 years after startup with minimum forced outage attributable to design deficiencies and hardware failures, and (2) a commercial plant that will operate with high reliability during its lifetime (typically 30 years). In addition, enhancement of reliability through modularity/redundancy should be considered.

The corresponding system reliability evaluation is given on Table 7-1. All of the concepts proposed by MDAC have a predicted availability of 0.95 or better.

Table 7-1. System Evaluation--Reliability/Availability

- Predicted Plant Availability 0.95 (All Designs)
  - Full life qualification of heliostats
  - Conservative receiver design conditions - Reliable design
  - Balance of equipment conventional (historical failure data available)
  - Redundancy where appropriate
- Full Redundancy of Power Conversion Not Justified
  - High capital cost
  - High maintenance cost
  - Reduced availability of full capacity

Fully qualified heliostats from other programs will be used. Conservative receiver design conditions have been selected and state-of-the-art fabrication techniques used. The balance of the plant utilizes conventional equipment with historical failure rate data that have been used for the reliability predictions. Selected redundancy has been employed where appropriate; however, full redundancy of the power conversion unit was not justified due to higher capital costs, high maintenance costs, and reduced availability of full capacity. Based on these design and operating approaches, the proposed experimental and commercial systems will meet these reliability criteria better than any alternative solar thermal electric concept.

Minimum risk of failure is the next major criterion to be evaluated. The selected concepts were to minimize development risk and thereby provide high confidence that subsystem development can be achieved within Phase II times and that the experiment can be brought on-line at the specified startup times. A system summary relative to program risk is given on Table 7-2. By design, all the proposed programs have minimum technical and minimum schedule risks. No collector development is required. This would normally be a major risk

Table 7-2. System Evaluation--Program Risk

All Programs Have Minimum Technical and Schedule Risk

- No collector development required
- Receiver fabrication methods are conventional
- Standard equipment used exclusively in 3.5- and 4.5-year programs--available within schedules
- All development schedules have substantial "pads"

element to any solar power program. Receiver fabrication methods and operational conditions have been selected to minimize development risks. Standard equipment is used exclusively for the 3.5- and 4.5-year programs and all equipment is available within the prescribed schedules. Finally, the design and development schedules have substantial pads to accommodate unforeseen occurrences. The tightest schedule constraint is a 4-month pad in the 4.5-year program for incorporating receiver test results into the final design.

The next major evaluation criterion is commercialization potential. The selected concepts should use or contribute directly to the eventual systems that are likely to achieve commercial success in the late 1980's. To meet this requirement, commercialization has been reflected in terms of cost/performance, flexibility, and the institutional interface aspects. An evaluation of the MDAC systems is summarized on Table 7-3. Energy costs of the small solar power plant in favorable locations will be competitive with diesel electric plants in this size range in the post-1985 period. In addition, this system should be superior to any of the alternative solar options in the 1 to 10 MWe size range.

To satisfy flexibility needs, it was concluded that four modules can reasonably cover the 1 to 10 MWe size range. Customer power demand profiles can be economically matched by the low-cost thermal storage design selected. Operating flexibility is enhanced further by the segregation of the power generation loop from the power conversion loop. Additionally the desired annual capacity factor for small communities was typically 0.5, which is greater than the baseline 0.4. Again, the value of low-cost storage is important. Stand-alone capability is also possible for use in regions remote from the grid. All equipment is designed for road transportability to achieve flexibility of plant siting. Finally, the same plant can provide thermal energy which increases its potential areas of application.

Minimum unique developments or operational procedures are required for this plant. This makes maximum use of the existing infrastructures avoiding the costs of extensive new industrial development. In addition, the plant is a

Table 7-3. System Evaluation--Commercialization

- Energy Costs
  - Competitive with diesel electric plants in favorable locations--Post-1985
  - Superior to alternative solar plants in 1 to 10 MWe size range
- Flexibility
  - Four modules cover 1-10 MWe range effectively
  - Economically match solar availability to demand
    - Low cost thermal storage
    - Power generation separated from energy collection
  - Stand-alone capability
  - Road transportable for siting flexibility
  - Thermal energy option available from same basic plant
- Institutional Interface
  - Matches existing infrastructure
  - "Good Neighbor"--No unique hazards

"good neighbor." There are no unique hazards from explosions or toxicity nor significant chemical or noise polution.

This proposed small power system should become a genuine commercial product.

The final evaluation criterion is low program costs. Concepts should be selected to minimize the estimated development and capital costs of Phases II and III. An evaluation with respect to this criterion is summarized on Table 7-4.

Phase II development costs have been minimized for the three EE No. 1 systems. Existing concentrators with minimum modifications are used, and thus, concentrator development is not required. The design and operations of other

Table 7-4. System Evaluation--Program Cost

- Phase II Costs Minimized in All Systems
  - Concentrator development not required
  - Other development minimized (none for 3.5 year)
  - Short duration design phases
  - Adequate schedule time for development programs (where required)
- Phase III Costs Minimized in All Systems
  - Low cost designs selected
  - Volume production of concentrator
  - Most other hardware is "off-the-shelf"

subsystems and components have been selected to minimize development requirements. There are no development tests at all for the 3.5-year program. Short duration design phases have been scheduled to minimize engineering costs. Adequate development time has been scheduled for those few components, where required.

Phase III development costs, which include the first experimental unit costs, have also been minimized. In all cases, low cost designs and operational procedures have been selected. The concentrators will be obtained from the volume production lines established for the Barstow 10 MWe solar electric plant. Most other hardware is "off-the-shelf."

In conclusion, all three systems proposed by MDAC fully satisfy the selection criteria specified by DOE/JPL for the First Small Power System Experiment (Engineering Experiment No. 1). Early deployment of one of these experimental plants will provide the operational experience needed for the design of the final commercial version. This plant could significantly reduce our country's dependence on imported oil for energy.