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CLOSED BRAYTON CYCLE ADVANCED CENTRAL RECEIVER SOLAR-ELECTRIC POWER SYSTEM

Volume III: Development Plan for a Commercial-Scale Closed Brayton Cycle Advanced Central Receiver Power Plant with Coupled Sensible Heat Storage

Final Report

By
Keith W. Halvorson

November 1978

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KEITH W. HALVORSON

NOVEMBER, 1978

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PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
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UNDER CONTRACT EG-77-C-03-1726

ABSTRACT

A development plan is presented to advance the closed Brayton cycle, storage-coupled, Advanced Central Receiver Power Plant conceptual design to an initial commercial-scale operational plant in 1985. The plan describes the development approach utilized, the major program elements in the development path, and the technology items which must be improved and/or verified. The plan covers three sequential program phases. Phase II provides for technology development by Subsystem Research Experiments, analyses and test; the preliminary design of the initial 50 MW_e plant; and refinements to the Phase I conceptual design, costs, and schedules. Phase III provides the design phase for the 50 MW_e plant and the necessary permits and certifications. Construction, checkout, and operation of the 50 MW_e plant, and detailed design of the preferred 150 MW_e plant will occupy Phase IV. Program schedules and costs are estimated for the development phases.

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SECTION 1
INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The availability of an economically viable, technically acceptable Advanced Central Receiver Power System (ACRPS) to the United States utilities requires an orderly progression from the conceptual design described in Volume II to a commercial-scale demonstration plant. This volume describes a plan for such development.

Paragraph 1.2 presents a summary of the development plan to be detailed in subsequent sections. Section 2.0 describes the development approach used to arrive at an acceptable plan. Section 3.0 details the major program elements which are key milestones in the development of the ACRPS. The plan also describes those areas where technology must be improved and/or verified; these are discussed in Section 4.0. Finally, the development plan is broken into sequential phases which are described in Section 5.0. The activities in each phase are identified and scheduled, and the resultant costs are estimated.

1.2 SUMMARY

A development plan for the closed Brayton cycle ACRPS has been formulated which is consistent with known DOE schedules, and has the concurrence of the Utility Advisory Board used in Phase I by BEC. The plan shows an orderly advance of the technology and design for a storage-coupled system to an acceptable commercial-scale module. The plan's path is simple, direct, and cost-effective: it moves from subsystem research experiments (SRE's) and a critical experiment in Phase II, to a full size plant which could be operational late in fiscal year 1985.

The development plan is summarized in Figure 1.2-1. The major DOE milestones are shown at the top, with the planned ACRPS development path immediately below. The major features of the plan consist of a critical experiment in Phase II; the proposed Electric Power Research Institute (EPRI) Experimental Plant paralleling Phase III; and the construction and operation of a 50 MW_e, single-module plant in Phase IV.

A small critical experiment will be performed during Phase II to confirm operation of the Brayton cycle receiver heat exchanger tubes. This experiment will be an extension of an earlier SRE where the direct solar flux impinges on the tubes. Air pressure for the critical experiment would be increased to 3.45 MPa (500 psia). The panel SRE and the critical experiment with direct heat flux also support the proposed EPRI Experimental Plant since this technique is a departure from previous EPRI tests.

The EPRI Experimental Plant will provide system verification of Brayton cycle operation. It need not be repeated by construction of a separate pilot plant, nor by simulation techniques.

An alternate development path independent of the EPRI planned Brayton cycle plant is shown in Figure 1.2-1 which, if followed, would necessitate a larger, more inclusive critical experiment in Phase III. This would consist of a solar receiver tubed to

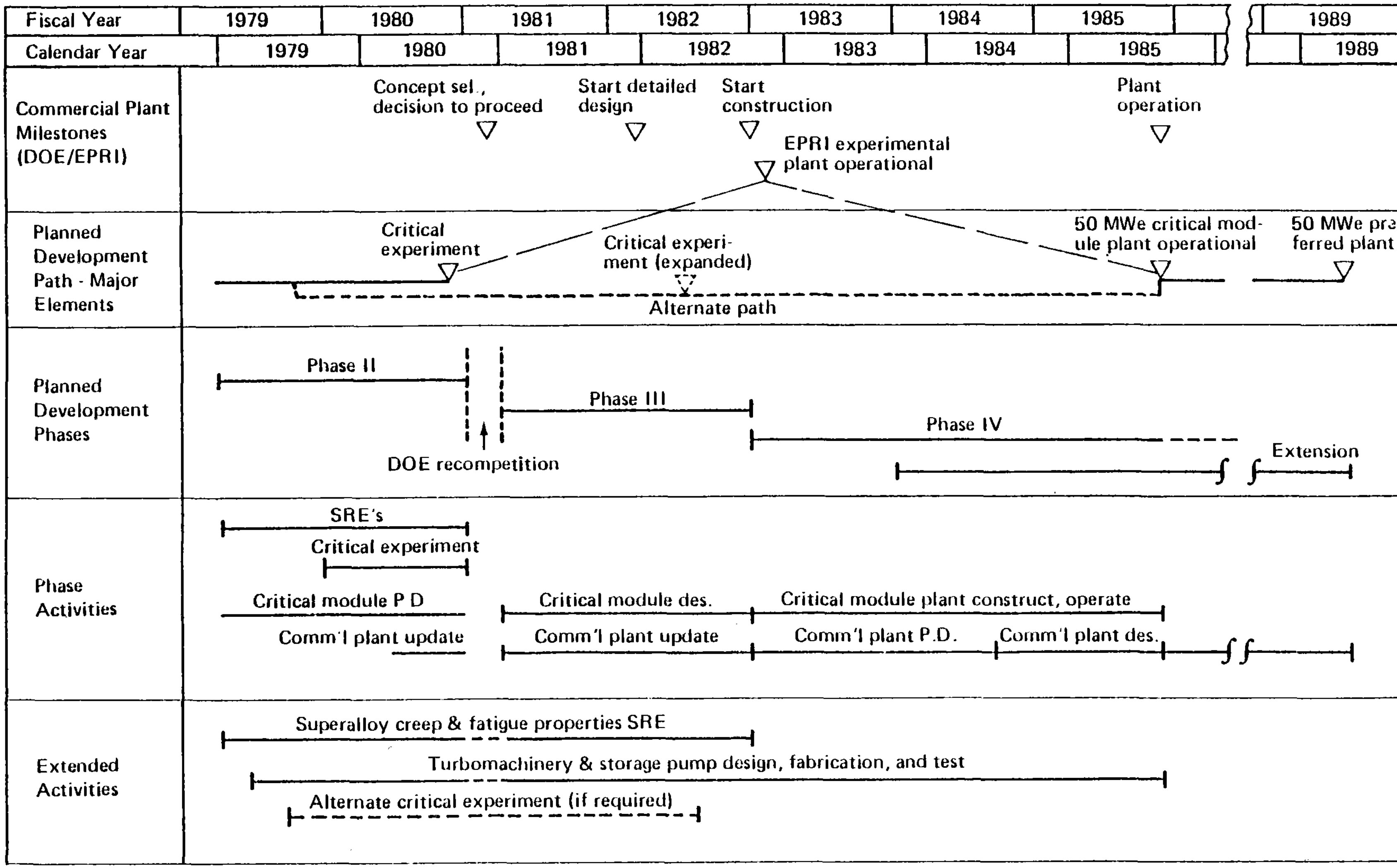


Figure 1.2-1. ACR Power System Summary Development Plan

receive the entire heat flux at the Solar Thermal Test Facility (STTF) and use of active turbomachinery. Either of these paths, along with the concurrent design work, will provide the confidence for construction of the 50 MW_e critical module to be operational in 1985. The preferred ACRPS plant of 150 MW_e (described in Volume II) would be constructed after the 50 MW_e module is operational.

The planned development phases and their schedule are also shown on Figure 1.2-1. Phases II and III are approximately 21 months in duration while the construction/checkout/operational Phase IV is about three years. Activities within each phase are shown on the next lower tier. Some low risk, time consuming activities, notably the turbomachinery development, encompass more than one phase; these are noted at the bottom of the schedule.

The development path for major program elements is shown again on Figure 1.2-2. The timing and sequence of contributing elements outside of the ACRPS program, such as the EPRI Bench Model Solar Receiver, the EPRI Experimental Plant, and the 10 MW_e Barstow pilot plant, are also shown. Each of these non-ACRPS elements will provide a contribution which the ACRPS development program need not duplicate.

Certain of the key subsystem research experiments to be executed in Phase II to fill technology voids or verify concepts in the design are also included in Figure 1.2-2. Specifically (1) the convective heat loss SRE will answer fundamental questions in cavity design; and (2) the panel direct heat flux, downcomer (high temperature line from tower top to the turbine), and sensible heat storage SRE's will verify designs presented in Volume II. Phase II will also provide answers on material

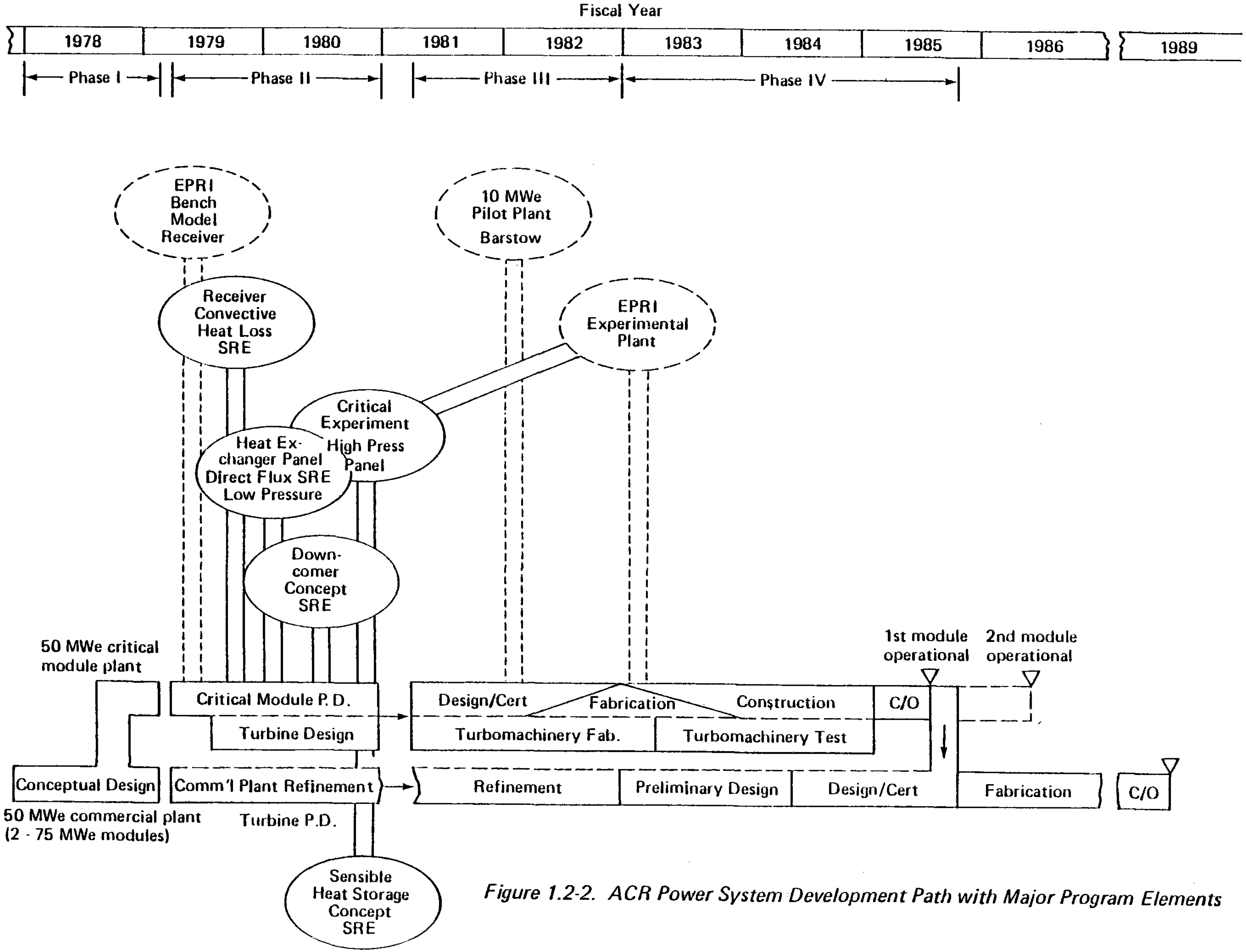


Figure 1.2-2. ACR Power System Development Path with Major Program Elements

behavior at high temperature. Other major activities in Phase II include preliminary design of the 50 MW_e critical module to be made operational in Phase IV, and the selection and preliminary design of turbomachinery applicable to both the 50 MW_e critical module and the 150 MW_e commercial ACRPS plant (2-75 MW_e) modules).

Phase III continues the development of the critical module into the detail design phase. Because of the lead time requirements, this phase also includes initiation of turbomachinery fabrication and superalloy heat exchange material acquisition. Other Phase III activities planned are the acquisition of all necessary plant construction certificates, and the refinement of the preferred 150 MW_e plant design.

Phase IV would cover the construction, checkout and opertional use of the 50 MW_e plant and the detailed design of the 150 MW_e plant.

The total development program encompassing the three phases would cost an estimated $165 million dollars.

SECTION 2

DEVELOPMENT APPROACH

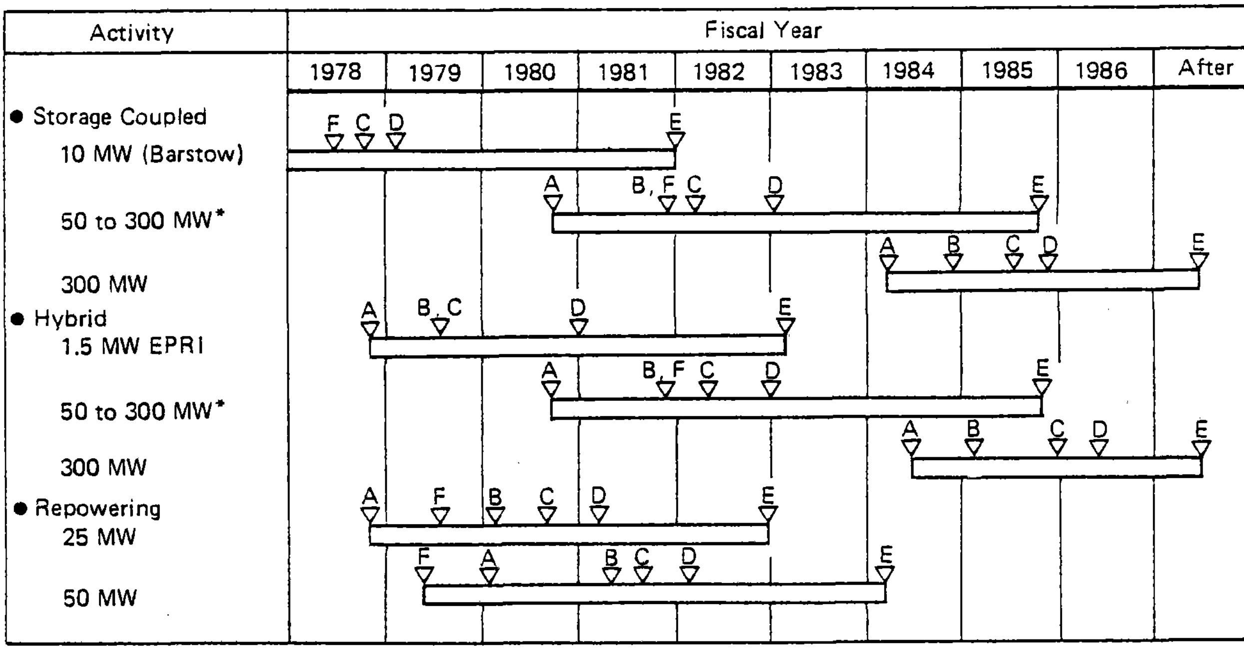
The development plan summarized in Section 1.2 has been formulated based on requirements and features BEC believes to be of major importance to the DOE. An acceptable commercial-scale module will be produced by a development approach which:

a. Is consistent with known DOE schedules;
b. Matures the technology in a progressively and timely manner;
c. Fully utilizes existing and planned solar technology and facilities;
d. Minimizes total cost and cost expenditure levels;
e. Enhances utility acceptance of the commercial plant; and,
f. Is adaptable to subsequent DOE decisions on plant type and technology.

These requirements and features are amplified in the following sections.

2.1 DEVELOPMENT SCHEDULES

The pertinent DOE schedules, excerpted from Reference 2.1-1, are shown on Figure 2.1-1. The schedule for the EPRI Experimental Plant has been included because of its relevance to central station solar electric power system planning, even though this program may not be approved by EPRI until Phase II is underway. As can be seen, the 50 to 300 MW_e ACR solar plant (storage-coupled), and an alternative 50 to 300 MW_e hybrid plant are shown with identical operational schedules leading to a late FY 1985 operational date. Thus, it is necessary to have these two alternate programs at the same state of development in 1982 to provide decision makers with well-defined alternatives.



A - Select utility partner
B - Select concept
C - Start detailed design
D - Start construction
E - Operational
F - Decision to proceed

* Alternative projects

Figure 2.1-1. Central Power Systems Program Milestones

Phase II for the storage-coupled ACR plant program has been specified by the DOE (Reference 2.1-2) as a 21 to 24 month period for subsystem research, pilot plant preliminary design and refinement of the commercial-scale plant design. BEC has selected a 21 month Phase II as appropriate and sufficient to carry out the necessary activities for the ACRPS. Phase II would begin in January, 1979, and be completed in October, 1980 (start of FY 1981). The indication from Reference 2.1-3 is that Phase II of the Solar Hybrid Program has been scheduled to be complete at about the same time to allow the DOE to select either (or both) of these concepts for continuation; and within the selected plant type(s), to make a technology selection (e.g., Brayton, Rankine, combined cycle, etc.) on the awards to Phase III subcontractors. The only apparent inconsistency as seen on Figure 2.1-1 are the 'B' and 'F' milestones which occur late in FY 1981 instead of at the start of FY 1981 after the completion of Phase II. If these milestones are to be applied only to the commercial-scale plant, this problem is resolved.

Phase III of the ACRPS program was shown in Reference 2.1-4 as a period to finalize pilot plant design and to construct and operate such a facility, and to prepare a preliminary design and project plan for a commercial scale plant. The time span of Phase III was not specified in Reference 2.1-4, except that the initial commercial operation of the pilot plant should be expected in the mid-1980's time frame. For the solar hybrid plant, Reference 2.1-5 states that Phase III should be a two-year period. Requirements for the Phase III solar hybrid program are identical to those for the ACRPS program with the exception that it is primarily concerned with a "Critical Experiment" instead of a "Pilot Plant". Because this later reference is more in line with the Figure 2.1-1 schedules, the BEC Phase III ACRPS activities would occupy a two-year time frame (FY 1981, 1982). Two years is insufficient to design, construct, operate, and evaluate a pilot plant so one is not recommended. However, other activities satisfy this requirement.

The EPRI 1.5 MW_e Experimental Plant, as proposed by BEC to EPRI, will allow demonstration of Brayton cycle technology and overall plant design and operation during the Phase III period. If the EPRI plan is implemented (a decision scheduled for early in Phase II), the requirement for an alternative STTF test of the BEC cavity-type receiver would be eliminated. (The critical experiment to be run in Phase II would provide confirmation of the closed-loop high pressure operation of the heat exchanger to be used in commercial plant receivers.) Other activities during Phase III would be to initiate design of the initial commercial scale module; establish manufacturing and procurement plans, start major component manufacturing; and complete siting studies, environmental impact and certifications for the initial commercial-scale module.

Phase IV of the ACRPS program would be a 3-year period to construct and put into operation the initial commercial-scale module. As currently planned, this module would produce 50 MW_e and will be defined as the "Critical Plant Module" to differentiate it from the optimized 75 MW_e commercial plant module described in Volume II. To be consistent with Figure 15 of Reference 2.1-1, two such modules would be required to produce the 100 MW_e suggested for late FY 1985 completion. The rationale for the 50 MW_e size is contained in Section 3.0. Other Phase IV activities would relate to the design of the preferred ACRPS 75 MW_e modules and obtaining the required plant certification.

2.2 TECHNOLOGY DEVELOPMENT

Another major feature of the development plan is the orderly development of the required technology. Data obtained as part of this development may be utilized to refine the design of major downstream program elements such as the critical experiment, the EPRI Experimental Plant (as applicable), and the critical plant module. The 21-month Phase II ACR Power System Program is structured to obtain necessary technical data and subsystem experimental verification as early as possible. Table 2.2-1 identifies the technology items by category, describes how each item will be satisfied, and indicates their intended use.

Table 2.2-1. Technology Development

Technical Requirements Category	Items	Phase II Plans	End Usage
Basic data	Superalloy properties	SRE (continue into Phase III)	Tube design data, vendor specifications, maintenance schedule/ procedures
	Insulation	SRE (continue into Phase III if required)	Receiver insulation selection, vendor specifications, maintenance schedule/ procedures
	Convective heat loss test	SRE	Define receiver heat losses and receiver efficiency. Design apertures
Concept Verification	Heat exchanger panel direct flux impingement	SRE	Commercial plant refinement, critical plant module design, EPRI exp. plant usage
	Downcomer design concept	SRE	Commercial plant refinement, critical plant module design
	Sensible heat storage concept	SRE	Commercial plant refinement, critical plant module design
Long Lead Equipment	High pressure equipment	Survey, design	Critical experiment
	Turbomachinery	Preliminary design	Critical plant module, commercial plant
	Storage pump	Preliminary design	Critical plant module, commercial plant
System Studies	Plant operation strategy	Analysis	Critical plant module, commercial plant
	Plant acoustics survey	Analysis	Critical plant module, commercial plant

A flow of these technology items is summarized on Figure 1.2-2. The detailed description of each item with supporting rationale for its inclusion is contained in Section 4, Technology Requirements.

2.3 USAGE OF EXISTING/PLANNED TECHNOLOGY AND FACILITIES

The ACRPS development plan makes use of existing and planned solar technology activities and available facilities. This applies to the major program development items and to the technology SRE's initiated during Phase II.

Maximum advantage will be taken of the 1 MW_t Bench Model Solar Receiver (BMSR) and the air supply system (compressors, recuperator, piping, etc.) for the test, both built by BEC and under test at STTF. Figure 2.3-1 shows the BMSR and the recuperator skid in the configuration used at the STTF 140 ft. level; the top portion of the receiver is removed for the photo. The air compressors are located at the base of the STTF tower.

The 1 MW_t Brayton-cycle receiver will furnish data which are directly applicable to tube design[1], air flow rates, receiver heat losses, and structural integrity which can be applied directly to subsequent ACRPS design. The fabrication of the receiver and the superalloy (Inconel 617) heat exchangers have already provided much transferable information on welding, insulation layup, scheduling, and costing. The only critical experiment which needs to be performed in the ACRPS development program is to test a receiver or panel at higher pressure to confirm closed cycle operation, inventory control, and tube temperature gradient control. The subsequent use of the Bench Model Solar Receiver for this purpose after the current test is being explored.

Section 2.1 described the utilization of the proposed EPRI 1.5 MW_e Experimental Plant as a demonstration of the Brayton cycle system technology and plant operation. Such use would obviate the necessity of a separate "Pilot Plant" test. This planned activity, coincident with ACRPS Phases II and III, preserves the DOE schedule for a commercial-scale critical plant module, and it reduces program cost. The EPRI Experimental Plant, as proposed by BEC, is described briefly in Section 3.0.

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[1] The heat exchanger tubes have been designed for 2.1 MPA (300psia) pressure. Either this receiver or a specially built panel could be used at STTF for this purpose.

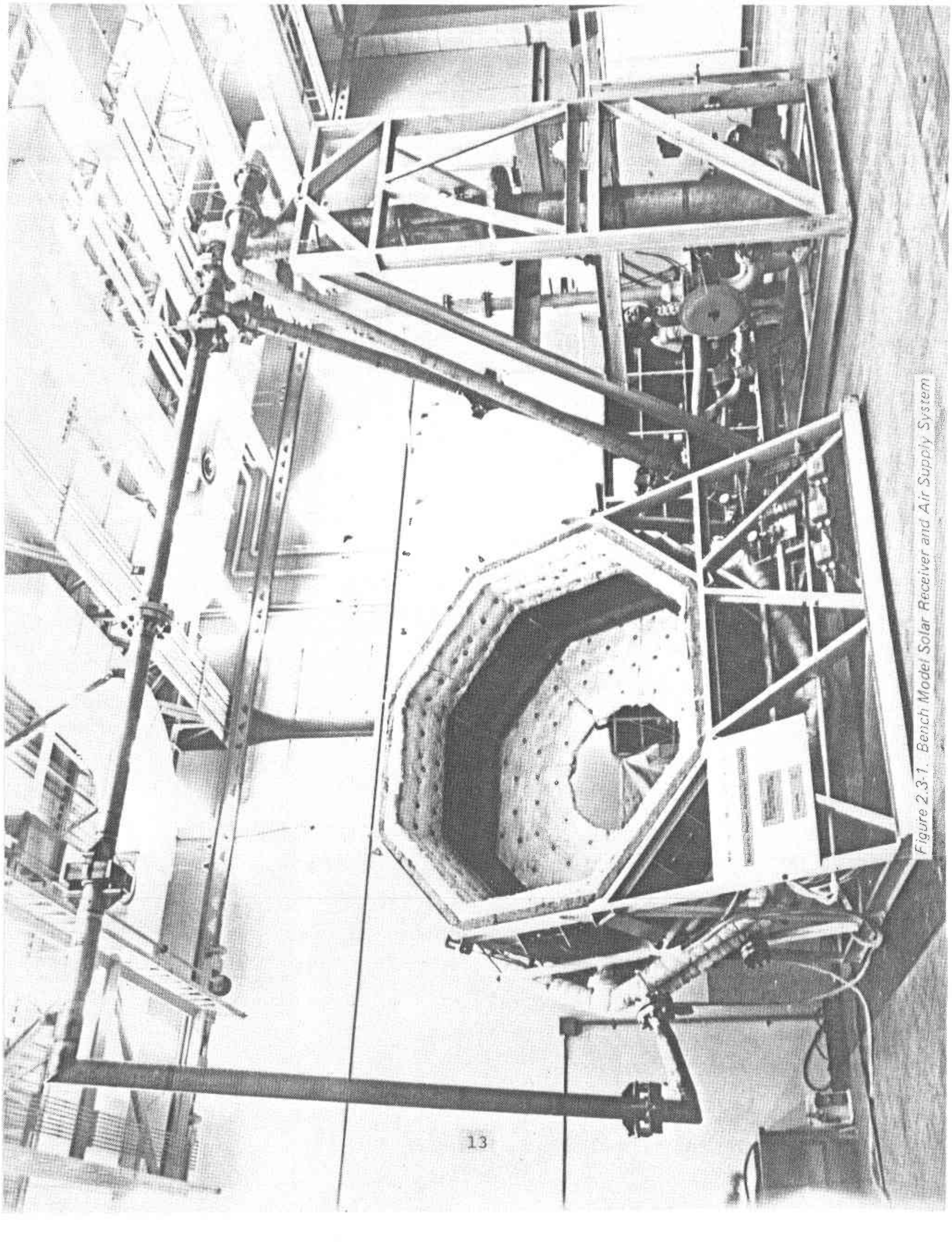


Figure 2.3.1. Bench Model Solar Receiver and Air Supply System

All the SRE's listed in Table 2.2-1 (except for the sensible heat storage test) make use of existing facilities, some of which are privately owned. The testing of superalloys (Inconel 617 and Haynes 188) for creep rupture and fatigue properties will be subcontracted to a suitably equipped testing firm. A receiver insulation test at sustained high temperature for long-term material effects and optical properties is planned for the Boeing Aerospace Company's Solar Radiation High Flux Facility.

A heat exchanger panel will be constructed early in Phase II to test the direct impingement of solar heat flux in the distribution expected in the larger size ACRPS receivers and in the EPRI Experimental Plant which uses the same concept. The testing would be performed at STTF. The tube/panel size is such that the existing air supply system built for the EPRI Bench Model Solar Receiver could be used directly in the test.

The BEC concept[2] for the long piping runs between the receiver and the turbine will be tested as an SRE by a firm with the facilities and experience to perform flow tests at 816°C (1500°F) on large scale models.

2.4 COST EFFECTIVENESS

The development approach selected will minimize the ACRPS development program total cost and the cost-expenditure level by fiscal year while obtaining the necessary technical data. Estimated costs are discussed in Section 6.0.

The use of existing and planned facilities discussed in Section 2.3 do much to minimize program costs. The use of the proposed EPRI Experimental Plant for Brayton concept system operation eliminates the necessity of a separate

[2] The BEC piping concept is discussed in detail in Section 5.3.3, Volume II, and also in Section 4 of this Volume.

receiver/field test at STTF. The availability of the air supply system for the initial low-pressure testing of a directly-impinged heat exchanger panel at STTF also provides a saving of approximately $500,000.

A critical plant module of 50 MW_e offers a cost savings of approximately $50 million over the optimized 75 MW_e commercial-scale plant module.

2.5 UTILITY ACCEPTANCE

The valuable assistance provided to BEC by a utility advisory board during Phase I of the ACRPS program will be continued into Phase II. This board, identified in Section 1.4, Volume II, has met with BEC prior to each DOE review and provided insights and suggestions for utility integration, plant operation, and costs. They have also participated in the commercial system assessment detailed in Section 6 of Volume II. When the critical module site selection and program planning is initiated, this board will be a valuable asset.

The combined DOE/EPRI participation in the planned EPRI Experimental Plant will improve utility acceptance of the Brayton cycle concept. The major factor in commercial plant acceptance is the extrapolation from 1.5 MW_e (10 MW_e for Barstow) to a plant of 50-75 MW_e module size. There are two significant concerns which must be considered in using the closed Brayton cycle for intermediate load plants; high capital costs, and new technology areas. The former item is true for all solar plants: thus, an aggressive cost reduction effort must be instituted in Phase II to bring capital costs down. BEC will re-examine each element of commercial plant costs to isolate major cost drivers and recommend economies. The technical focus of the ACRPS development program will alleviate the second concern by providing experience under operating pressure, temperature and heat flux conditions. At the same time, feasible alternative technological solutions and processes will be examined to ensure a cost-effective commercial system. Thus, the closed cycle high pressure Brayton cycle operation will be confirmed in the United States, extending the current high temperature gas technology and the West Germany[3] closed Brayton cycle utility experiences. Lower system pressure alternatives with less efficient but available turbomachinery will be reviewed and priced to provide utilities with the proper cost and risk perspective for an alternative ACRPS plant.

2.6 ADAPTATIONS TO DOE CENTRAL POWER SYSTEMS DECISIONS

The DOE plans to make a decision after the conclusion of Phase II of the ACRPS and Hybrid Power System programs, choosing either one or both plant types for subsequent Phase III and IV activities. It is expected that the final selection will be made by competitive contractor evaluations of closed Brayton cycle, liquid sodium and molten salt thermal loops combined with advanced Rankine cycle systems.

BEC is committed to a hot-gas receiver system because of its simplicity, response, high efficiency, control capabilities, cost-effectiveness, and safety. It is also adaptable without major unproven changes to : (1) use as a hybrid plant both with and without a Rankine bottoming cycle: and (2) use with open cycle turbomachinery with and without a bottoming cycle.

[3] The closed Brayton cycle is used by utilities in the Federal Republic of Germany. Typical operating conditions are 760°C (1400°F) and 2.76 MPa (400 psia).

A Brayton cycle adaptation being considered for the critical plant module is the use of off-the-shelf open cycle machinery with a closed cycle receiver/storage loop. The two loops are connected by a heat exchanger. Such a cycle with storage is shown in Figure 2.6-1.

The cycle efficiency of the system shown in Figure 2.6-1 is decreased because of a lower turbine inlet temperature; the adaptation to sensible heat storage is also somewhat more cumbersome. The advantages to be gained, however, are decreased lead time for the turbomachinery with no development costs, and very efficient heat transfer characteristics in the receiver heat exchanger and the storage device. Note also that no cooling tower per se is required. Depending on DOE decisions for Phase III and IV developments, such a plant could be adapted to fossil firing and/or a bottoming cycle. These options are shown within the borders of the dashed blocks within Figure 2.6-1, the upper block showing a hybrid option, the lower right block showing extension to a bottoming cycle. Other Brayton cycle usages which have been studied are discussed in Appendix A.

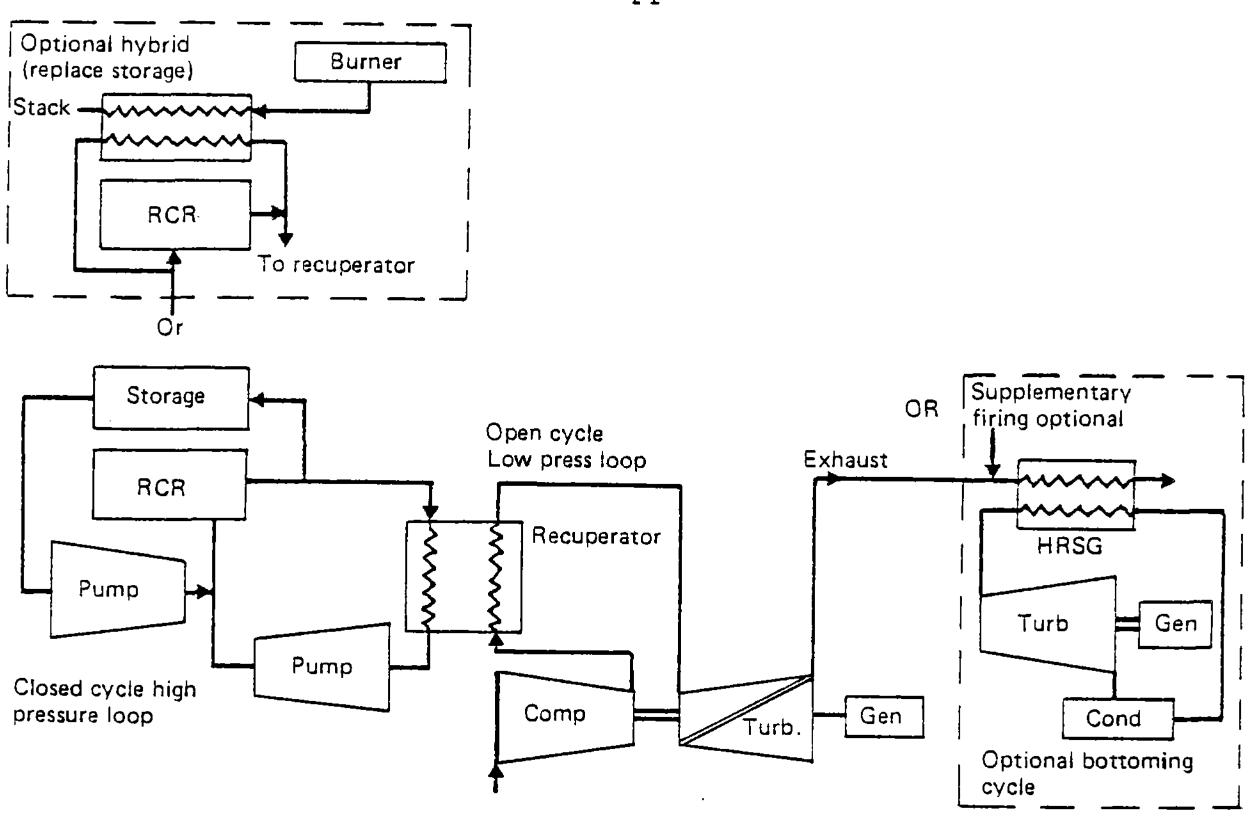


Figure 2.6-1. Dual Loop Solar Plant with Options

SECTION 3

MAJOR PROGRAM ELEMENTS

There are certain major program elements which must be included in the development plan to achieve a commercial-scale plant in the late 1980's. Included are a critical experiment, a proposed experimental plant (EPRI), a critical plant module, and the detailed design of the full scale commercial ACRPS plant.

3.1 CRITICAL EXPERIMENT

A critical experiment is one of the primary sources of test and demonstration data required to ensure technical success of the development program and utility acceptance of the results and projections. Such an experiment must be carefully designed and executed to minimize cost and meet program schedule constraints.

3.1.1 Rationale for a Critical Experiment

The need for a critical experiment may be derived from Table 3.1-1. It lists the important ACRPS features and verifications available up to and through the critical plant module (50 MW_e). Utility acceptance of the closed Brayton cycle ACRPS will be enhanced if there is at least one verification of each major feature prior to the decision to begin construction of the critical plant module.

Examining Table 3.1-1 shows that the following areas require such verification:

a. Receiver heat exchanger direct flux;[4]

[4] Due to changed temperature gradients and stress levels in the receiver heat exchanger tubes.

Table 3.1-1. ACR Power System Verification

Brayton Cycle Feature	ACR Power System Feature	Verification: Prior Event(1)	Verification: ØII SRE	Verification: EPRI Exp. Plant(2)	Verification: Critical Module
Receiver					
- Cavity operation	X	BMSR	N/A	X	X
- H/X high temperature	X	BMSR	X	X	X
- H/X direct flux	X	None	X	X	X
- H/X low pressure operation		BMSR(3)	X	X	N/A
- H/X high pressure operation	X	None		N/A	X
Piping concept					
- High temperature operation	X	None	X	N/A	X
- High pressure operation	X	Gas reactors	X	N/A	X
Turbomachinery					
- Open cycle	(4)	Industry use	N/A	X	N/A(4)
- Closed cycle air	X	Limited use	None	N/A	X
- Closed cycle helium	(5)	Oberhausen	None	N/A	(5)
Sensible heat storage					
- High temperature operation	X	Industry use	X	N/A	X
- High pressure operation	X	None	X	N/A	X
- Pump concept	X	None	X(6)	N/A	X
System					
- Low pressure operation		BMSR	N/A	X	N/A(4)
- High pressure operation (air)	X	None	N/A	N/A	X
- High pressure operation (helium)	(5)	Industry use	(5)	N/A	(5)
- Inventory control (air)	X	None		N/A	X

NOTES: (1) As of January, 1979
(2) Proposed
(3) Limited laboratory tests
(4) Potential variation - see Figure 2.6-1
(5) Helium is a potential flow medium
(6) Availability must be determined

b. Receiver heat exchanger tube high pressure operation;

c. Turbomachinery closed-cycle operation; and

d. System inventory control

In the above list, the turbomachinery items appears to be of least concern based on experience with closed cycle turbomachinery (both air and helium) at Oberhausen, West Germany[5], the gas reactor programs, and the many combustion

---

[5] Design and operation of a closed-cycle helium system is a more severe problem than a comparable air system due to increased containment requirements (seals, valves, etc.).

turbines in world-wide operation. The remaining items can be designed into ACRPS critical experiment at relatively low cost.

3.1.2 Critical Experiment Options

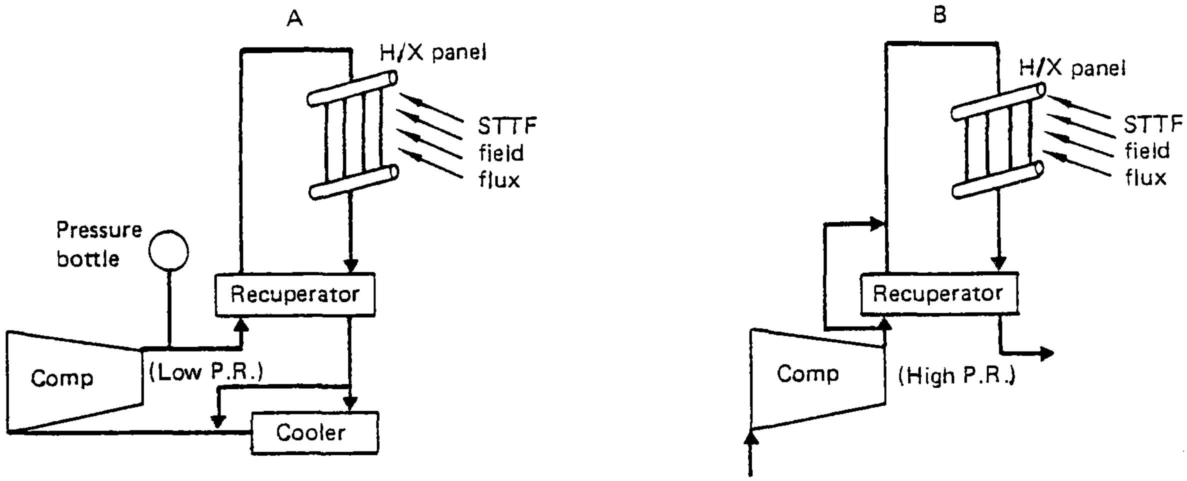
Short of developing a fully or partially-tubed receiver for solar flux testing at STTF, the most viable option is to test a heat exchanger panel at STTF. In such a test, the STTF heliostats would be programmed to provide the flux distribution range on the tubes. The primary question for experimental design is how to achieve the 300-500 psia pressures necessary for verification; feasible options are: (1) a high pressure bottle for initial pressurization, with a compressor used during operation to produce the necessary velocities and to make up pressure losses; or (2) use an open air compressor with a high pressure ratio. These options are schematically shown in Figure 3.1.2-1. These two options will be examined during the early part of the ACRPS Phase II, with design and test of the selected option made during the balance of Phase II. The heat exchanger panel might be the same panel used in an earlier SRE testing direct flux on tubes at lower pressure (see Section 4.2.1).

3.2 EXPERIMENTAL POWER PLANT

In paragraph 2.1, it was noted that a pilot plant similar to the 10 MW_e Barstow activity would not be included in the ACRPS development plant. The reasons are:

a. Inordinate expense for the amount of power produced;

b. A significant schedule delay in arriving at a commercial-scale power plant;



Advantages:

Tests high pressure
Tests direct flux on tubes
Tests inventory control

Disadvantages:

Low inlet temperature with recuperator
High cooling requirements without

Advantages:

Tests fairly high pressure
Tests direct flux on tubes
Inlet temperature at design value
No cooling requirements (except last compressor stage(s))

Disadvantages:

Limited pressure ~300 psia
Does not allow inventory options
Compressor availability

Figure 3.1.2-1. Heat Exchanger Panel Critical Experiment Options

c. The Barstow Pilot Plant will prove out the collector field and controls;

d. The proposed EPRI Experimental Plant parallels the DOE ACRPS program phasing;

e. The proposed EPRI Experimental Plant in conjuction with the planned ACRPS Phase II SRE's and critical experiment provide all the technical verifications required prior to commitment to the 50 MW_e critical plant module; and,

f. A development path which includes the EPRI Experimental Plant will generate wider acceptance by the electric utility community.

3.2.1 The EPRI Experimental Power Plant

This section describes the EPRI 1.5 MW_e Experimental Power Plant as proposed by BEC. The description should be considered very preliminary because of the continuing system efforts in this area.

3.2.1.1 General Description

The BEC proposed EPRI Experimental Power Plant would produce a nominal 1.5 MW_e of electrical power. The plant would be a solar thermal power plant of the central receiver type utilizing an open air Brayton cycle for power conversion. A fossil fuel heater would be included to produce power during non-insolation hours and to smooth out electrical production during periods of solar insolation dropouts. Plant performance and operation have been projected using Gila Bend, Arizona, as a reference site.

3.2.1.2 Receiver Description

The proposed central receiver would be a cavity-type receiver similar to that of the Advanced Central Receiver described in Volume II of this Final Report. It would have one active aperture with potentially three inactive apertures. Reflected solar flux from a north collector field would pass through the active aperture and impinge directly on straight (single pass) heat exchanger tubes mounted off the opposite interior cavity wall. The interior of the cavity would be tubed over approximately half of the receiver's interior surface. Receiver heat exchanger tubes would be of Inconel 617 or Haynes 188. Maximum tube temperatures would be held at or below 871°C (1600°F). Tubes would use the same constant-design-life tube[6] concept proposed for the commercial ACRPS.

3.2.1.3 System Description

The schematic of the BEC proposed system is shown in

[6] See paragraph 3.2.5 of Volume II for a detailed description of the tube design concept.

Figure 3.2.1.3-1. The proposed design has the receiver and fossil fuel burner in a parallel configuration. The thermodynamic cycle incorporates a recuperator to recover heat from the exhaust gas stream to pre-heat the air to the receiver. Air is raised to 816°C (1500°F) in the receiver and/or the fossil fuel burner and flows through the turbine to drive the compressor and produce power. Air enters the receiver and/or fossil fuel burner between 400°C (750°F) and 427°C (800°F). System operation is at approximately 0.76 MPa (110 psia). System thermodynamic efficiency is approximately 25%. The turbomachinery would be located at the tower top to shorten high temperature tubing runs to the turbine.

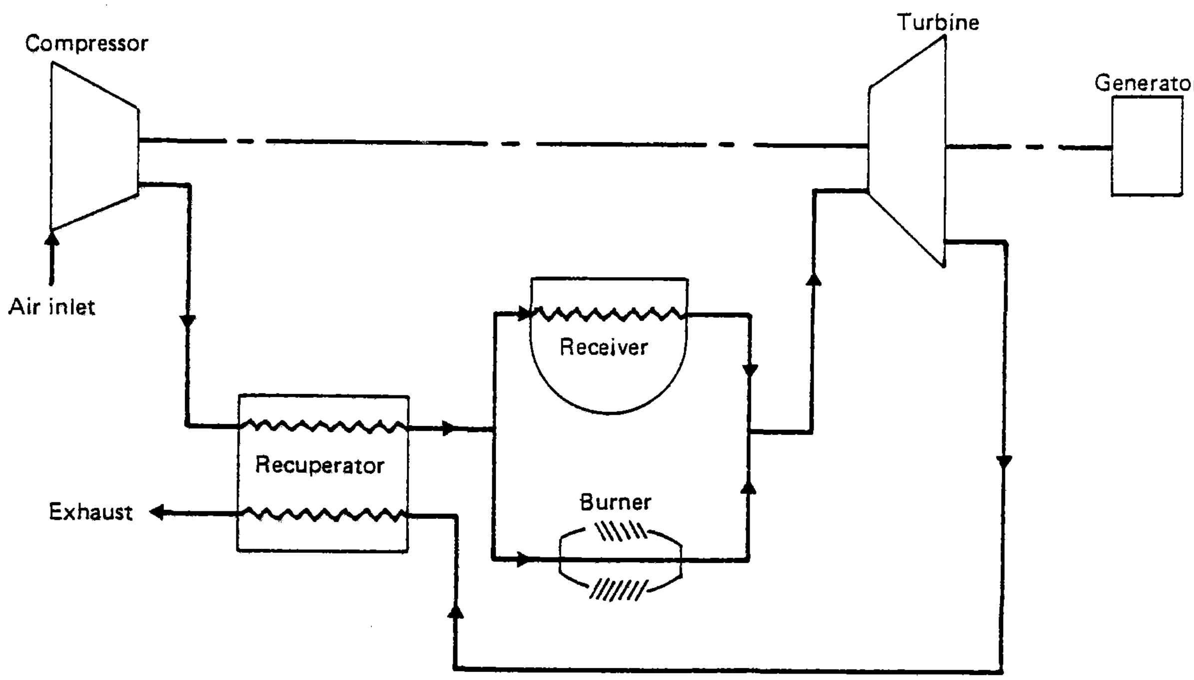


Figure 3.2.1.3-1. EPRI Experimental Plant System Schematic

3.2.2 Alternative Experimental Power Plant

If for any reason, the plans for the EPRI plant do not proceed, an alternative plan will be followed[7]. The alternative would consist of a receiver configured with four apertures to accept the entire 5.5 MW_t flux from the STTF field. The receiver would be mounted at the top of the facility tower. Again, straight tube (single pass) heat exchanger panels would be used within the cavity, but would cover the entire interior surface of the receiver.

In this alternative plan, the critical experiment described in Section 3.1 would be incorporated into the new system. An examination would be made in Phase II to determine whether active turbomachinery can be included in the experiment. This would be accomplished by using an open cycle machine modified to provide the 2.07 MPa (300 psia) to 3.45 MPa (500 psia) pressure required. If turbomachinery usage were inappropriate due to cost, schedule, or STTF integration factors; the air supply options shown on Figure 3.1.2.1 could be utilized. This alternative to the EPRI Plant would also provide all the remaining required verifications of the Brayton closed air cycle prior to commitment to the 50 MW_e Critical Plant Module.

3.3 CRITICAL PLANT MODULE

The critical module is planned as a 50 MW_e power plant rather than the 75 MW_e preferred ACRPS commercial-scale module described in Volume II. The size was selected to satisfy utility requirements for a module reasonably close to the 75 MW_e size, while achieving the objective of cost-effectiveness. In addition, such a size provides experimental flexibility and permits a greater range of

[7]A decision on the EPRI plant is expected early in Phase II of the ACRPS development program.

module build-up possibilities. It would be substantially the same as the ACRPS 75 MW_e module system in performance and operation as described in Volume II.

3.3.1 Critical Module Conceptual Design

A conceptual design of the critical module has been performed. A summary of the pertinent design features is contained in the subsequent paragraphs.

3.3.1.1 Receiver Subsystem

The receiver for the 50 MW_e critical module is mounted on a 163 m (535 ft.) tower. The receiver/tower profile is shown on Figure 3.3.1-1. The tower would be of slip formed reinforced concrete with construction similar to that proposed for the 75 MW_e modules (see Volume II). Tower/receiver design conforms to the soil conditions, wind loading and seismic loading specified in the ACR system specification (Reference 2.1-4).

Receiver dimensions are as shown on Figure 3.3.1-2. The weight of the receiver is 2000 metric tons. The receiver center of gravity is located 37.3 m (122.3ft) from the receiver base. Receiver moments are displayed on Figure 3.3.1-3, and load factors are shown on Figure 3.3.1-4.

The receiver contains vertical single-pass heat exchanger tubes which are 21.9 m (71.8 ft.) long and spaced away from the insulated wall as shown on Figure 3.3.1-2. The inlet air enters the tubes at the bottom. Tube length was arrived at using the scale relationship:

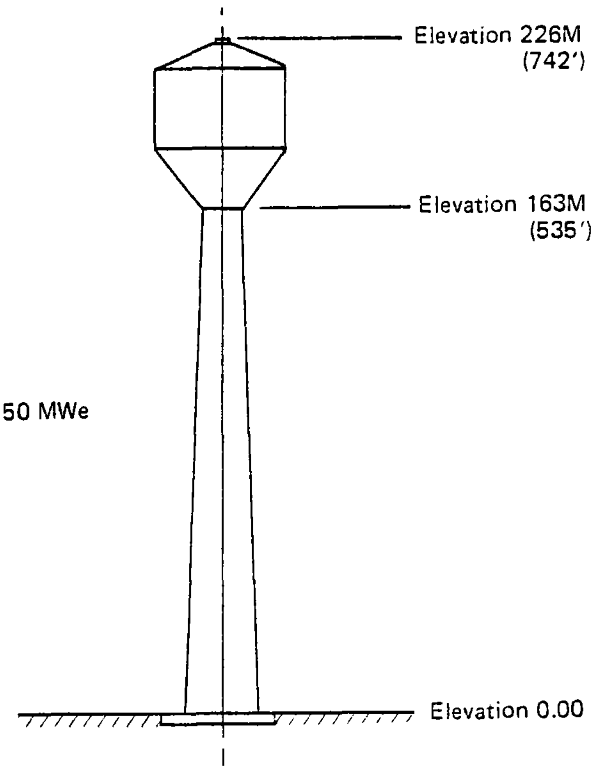
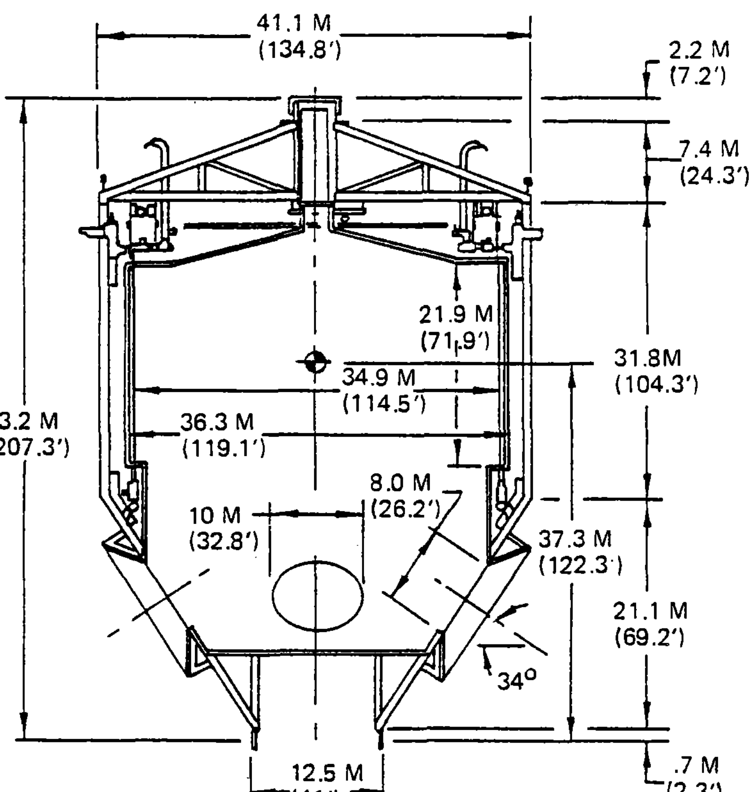


Figure 3.3.1-1. Receiver Tower Geometry - 50 MW_E Critical Module



Weight
2,003 metric tons
(2,208 short tons)

Figure 3.3.1-2. Critical Module Receiver Configuration

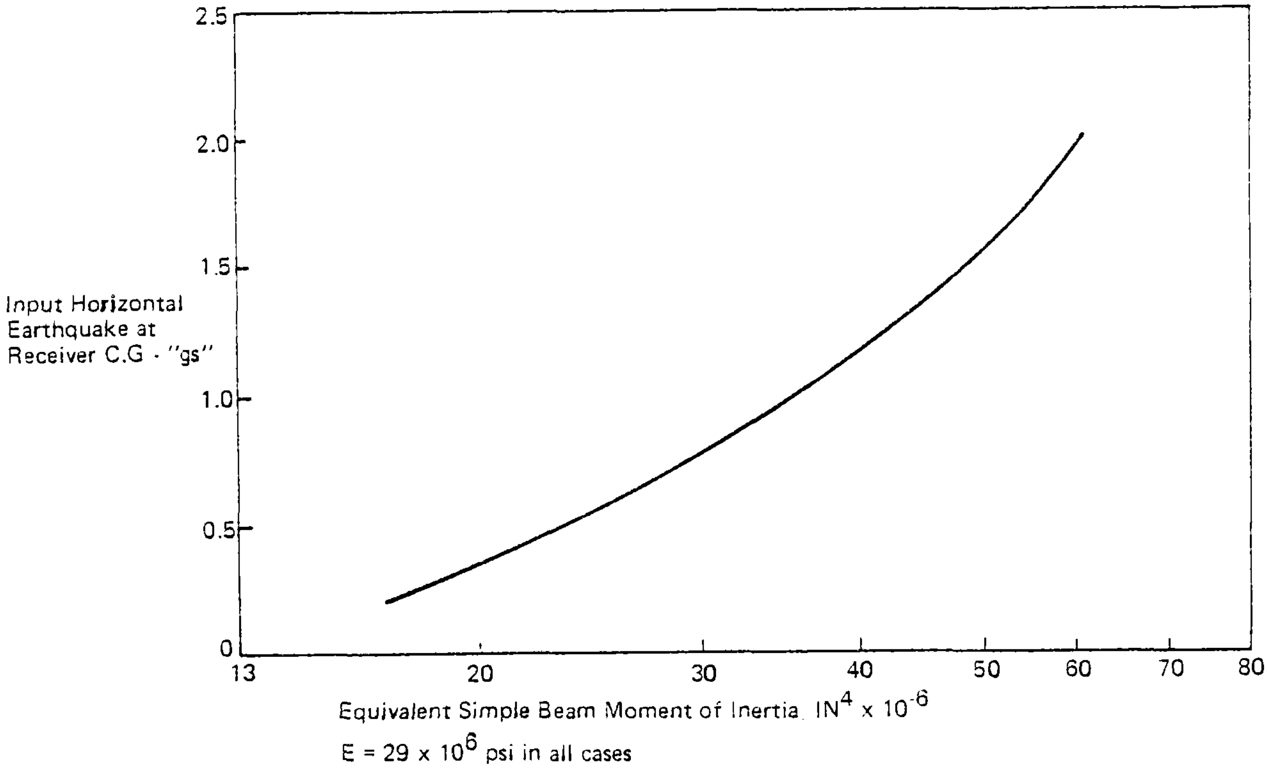


Figure 3.3.1-3. Receiver Elasticity

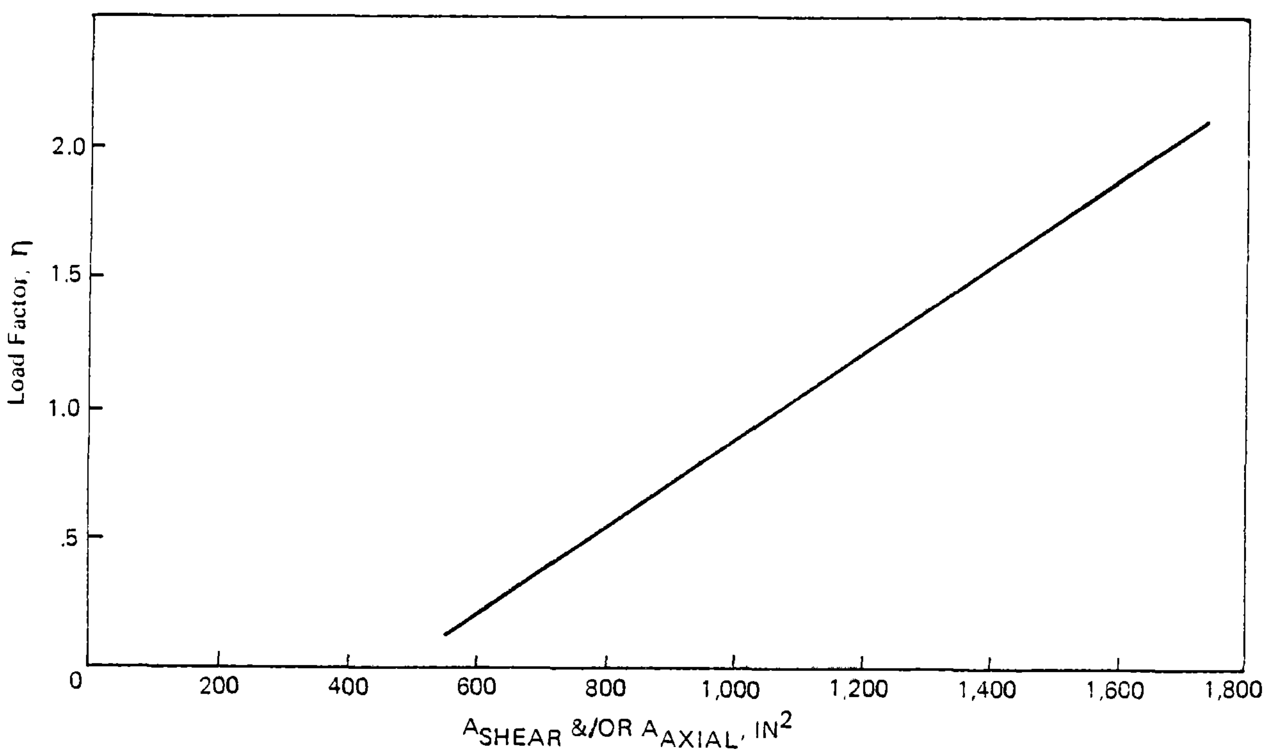


Figure 3.3.1-4. 50 MW_e Receiver Load Factors

$$\frac{Q_{\text{Critical Module}}}{Q_{\text{ACRPS COMM'L Module}}} = \left(\frac{L_{\text{Critical Module}}}{L_{\text{ACRPS COMM'L Module}}}\right)^2 \text{ which gives}$$

$$L_{\text{Critical Module}} = (L_{\text{ACRPS COMM'L Module}})(\sqrt{2/3}) = 71.8 \text{ feet.}$$

The tube diameter and wall thickness were retained at the ACR heat exchanger tube dimensions. Using the same 3-foot standoff from the wall, the 948 tubes required have a pitch of 3.2.

The receiver utilizes four apertures mounted 45° off the cardinal points similar to the 75 MW_e ACRPS modules described in Volume II. Dimensions of the apertures are exactly the same being ellipses of 10 m (32.8 ft.) on the major axis and 8 m (26.2 ft.) on the minor axis.

3.3.1.2 Piping

The one riser and one downcomer located in the tower and used to contain air moving between the receiver and the EPGS/storage subsystem are each 1.5 m (4.9 ft.) outside diameter. The downcomer is designed with a vented super-alloy inner liner separated from an outer steel pressure pipe by insulation. This concept is the same as the ACRPS 75 MW_e module and is further described in Section 4.2.2. Pipe size for the lines to the storage subsystem are 1.3 m (4.3 ft.) outside diameter, while those for the EPGS are 1.1 m (3.6 ft.)

3.3.1.3 Collector Subsystem

The collector field contains 6,950 heliostats arranged in a field shape similar to the 75 MW_e ACR plant module. This shape is shown on Figure 3.3.1-5. Field dimensions are approximately 1300 m x 1175m.

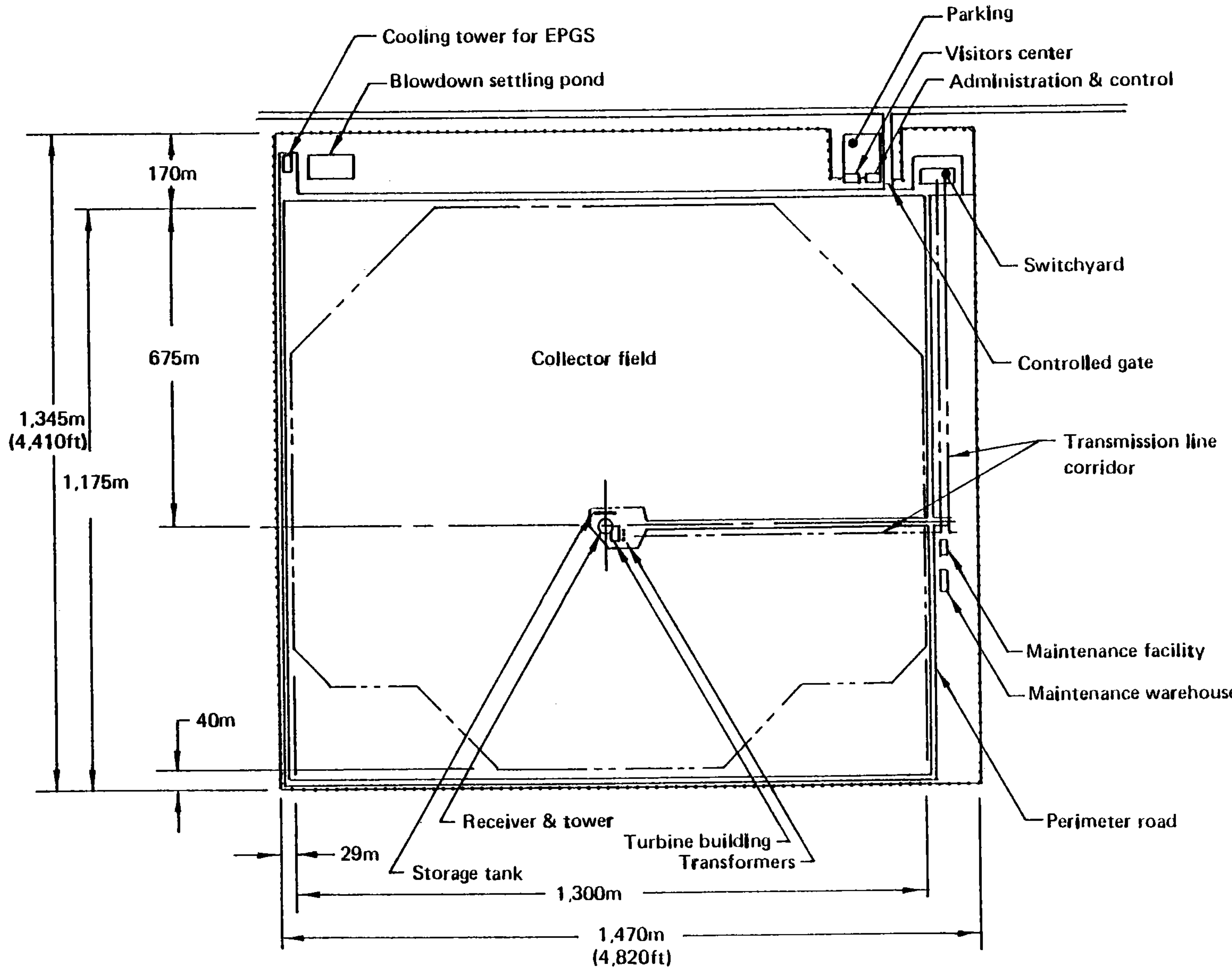


Figure 3.3.1-5. Plant Layout 50 MW_e Critical Module

3.3.1.4 Storage Subsystem

The storage subsystem uses alumina (Al_2O_3) bricks to store and discharge sensible heat. The bricks are of a Freyn type configuration and are located in a single cylindrical tank with hemispherical ends. The tank shell is 33.5 m (110 ft.) long in the straight (brick) section and is 6.23 m (20.4 ft.) in diameter. Total weight of the system is approximatley 4080 metric tons. Section 5.3.5 of Volume II describes the conceptual design layup of the bricks within the shell. Figure 4.2.3.1-1 of this volume shows the same configuration for a sensible heat storage SRE.

3.3.1.5 Electric Power Generation Subsystem (EPGS)

The dimensions and weights of the turbomachinery equipment (compressor, turbine, generator) will be established when the design and development path has been determined early in Phase II. Turbomachinery has to be planned which meets the requirements of the 50 MW_e critical module and the longer term 75 MW_e preferred commercial plant modules described in Volume II.

Two options exist to meet this challenge of supplying machinery without incurring the cost of two separate development schedules. The first option is to use an existing turbine for the 50 MW_e critical module and initiate the direct development of a 75 MW_e machine for the full-size 150 MW_e plant. The existing turbine could be configured into the plant as shown on Figure 2.6-1. Some drop in efficiency from the 42% efficiency of the total closed Brayton cycle system would occur because of the lower temperature and lower pressure in the open cycle turbine loop.

A much preferrable second option is to develop the $75\ MW_e$ machine to operate at both the $50\ MW_e$ and $75\ MW_e$ conditions. The advantage of the closed Brayton cycle with inventory control of pressure and mass flow makes this a very realizable objective. It is planned to initiate a competition between major engine manufacturers at the initiation of Phase II to achieve this commonality at the least overall development cost. Because of the size of other Brayton cycle usages outside the ACRPS program (e.g., $1.5\ MW_e$ for the EPRI Experimental Plant), DOE funding is required if there is to be any large scale Brayton cycle plant operational in the near future.

Other EPGS components sized for the $50\ MW_e$ critical module used with the second option described above are listed below:

Recuperator	Length:	20.4 m (67')
	Diameter:	2.8 m (9.1')
	Weight:	158.1 metric tons (173.9 short tons)
Precooler	Length:	8.4 m (27.4')
	Diameter:	2.2 m (7.2')
	Weight:	33.1 metric tons (36.4 short tons)
Intercooler	Length:	7.5 m (24.6')
	Diameter:	1.5 m (4.8')
	Weight:	15 metric tons
Inventory Storage	20 tanks, 5 per tier, 4 tiers	
	Lgth/Tank:	7.6 m (25')
	Tank O.D. =	.6 m (2')
	Wgt/Tank:	5 metric tons (6 short tons)

3.3.1.6 System Schematics

The system schematic for the 50 MW_e critical modules major components and piping is shown on Figure 3.3.1-6. This system is similar in all aspects to that of the 75 MW_e preferred plant modules described in Volume II. The collector field cable layout is shown schematically on Figure 3.3.1-7. The single line plant power schematic is shown on Figure 3.3.1-8 and the field power arrangement by Figure 3.3.1-9.

3.3.2 Critical Module Development Plan

Development of the 50 MW_e ARC Power System plant module is the primary thrust of the overall development plan. As such, it constitutes a substantial portion of all program development phases (II, III, and IV) and a large portion of the overall development program costs. The important siting, schedule and cost aspects of the ACRPS critical module development are discussed in this section.

3.3.2.1 Siting

The actual geographical location of the proposed plant is not expected to be known until the initiation of Phase III in FY 1981. The site will probably result from a DOE cost-sharing competition between states and utilities, similar to that used to select the system for the 10 MW_e Barstow plant. When the site is known, actual insolation values and environmental conditions can be used for performance and design studies, and the various environmental reports and certifications, (local, state, Federal) can then be undertaken with the aid of the sponsoring utility. The transmission grid to be used and load center to be supplied will also be known so that the plant operation

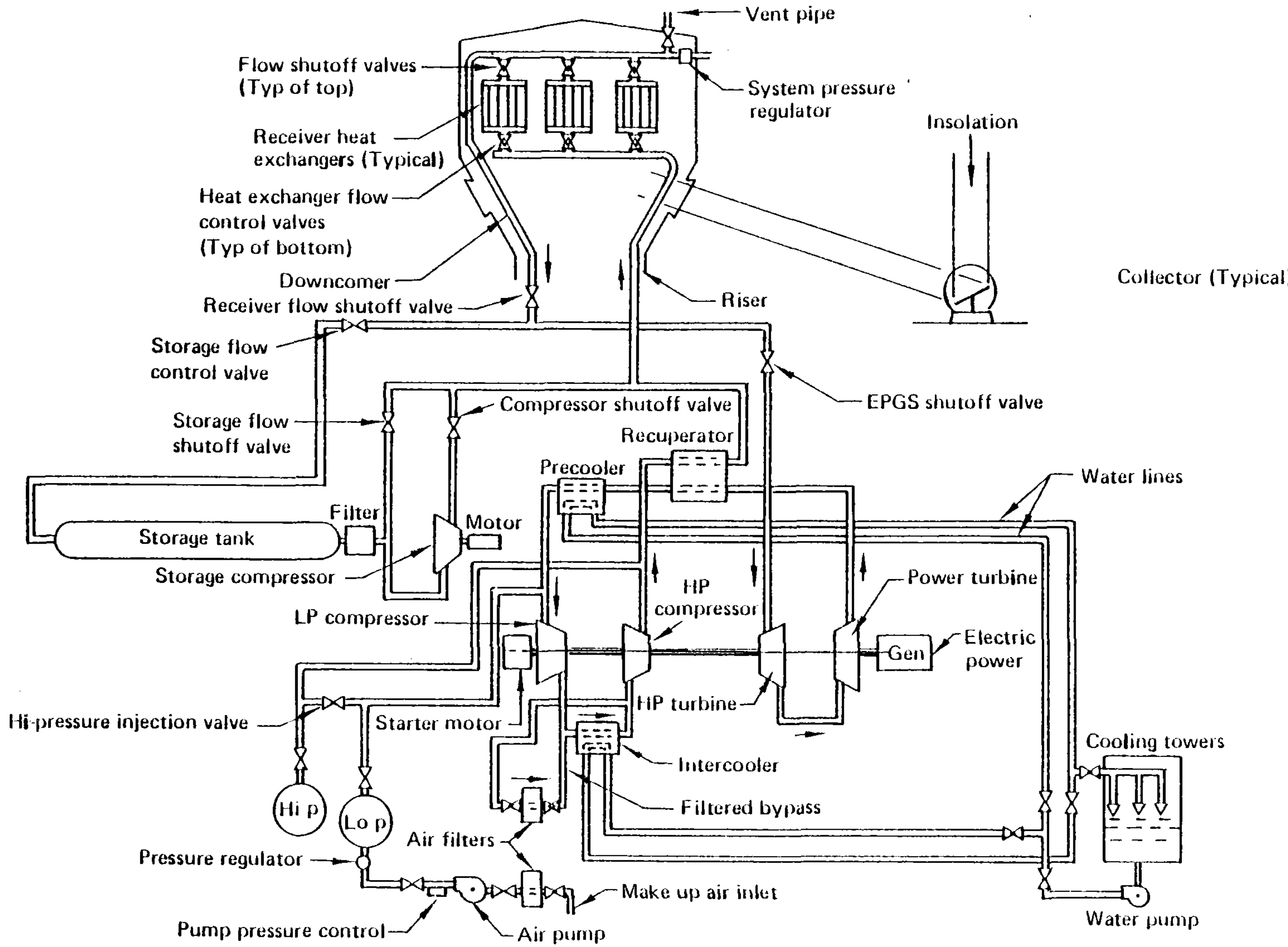


Figure 3.3.1-6. 50 MWe ACR Solar Power System Schematic

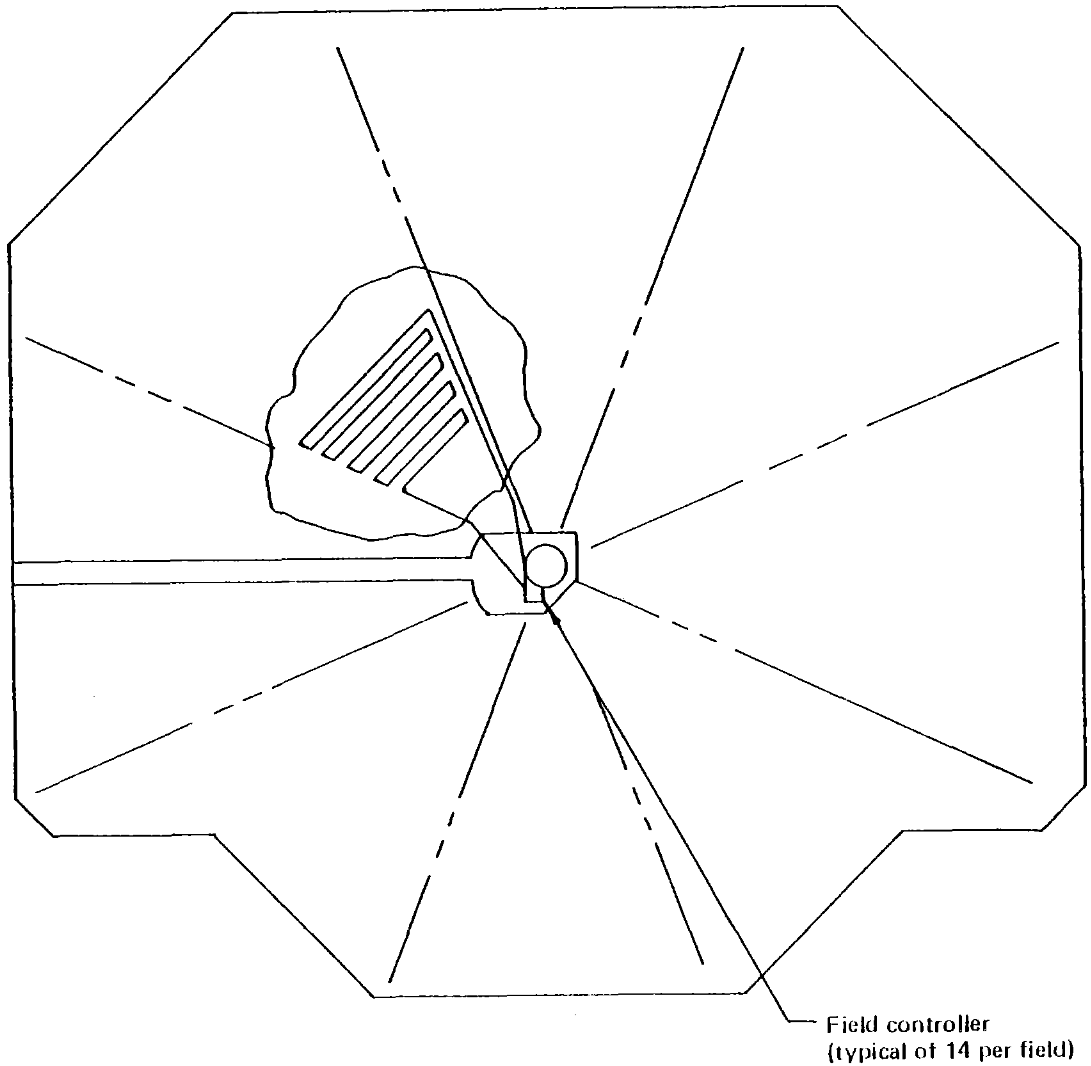


Figure 3.3.1-7. Collector Field Control Cable Layout

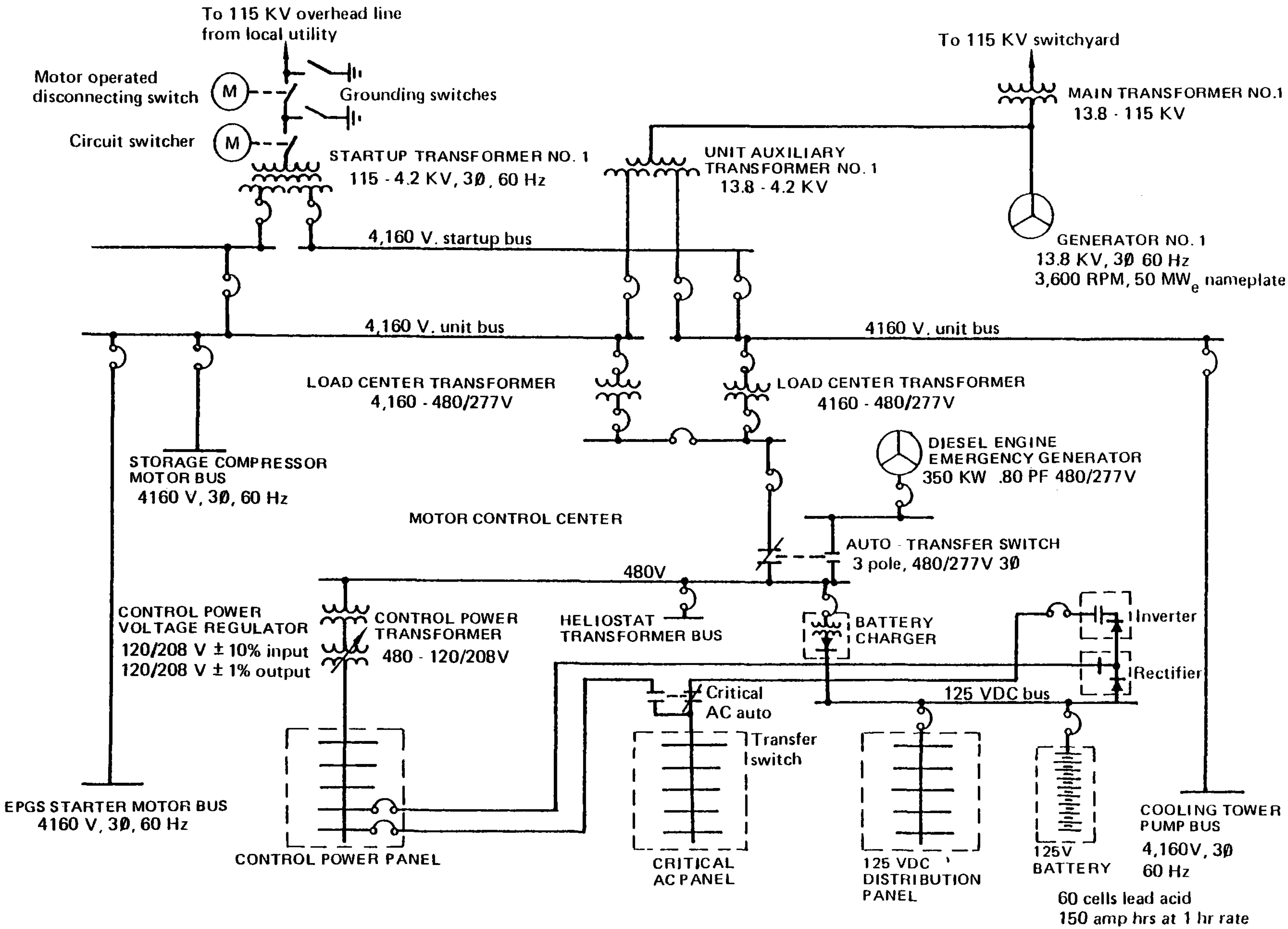


Figure 3.3.1-8. Single Line Plant Power Schematic

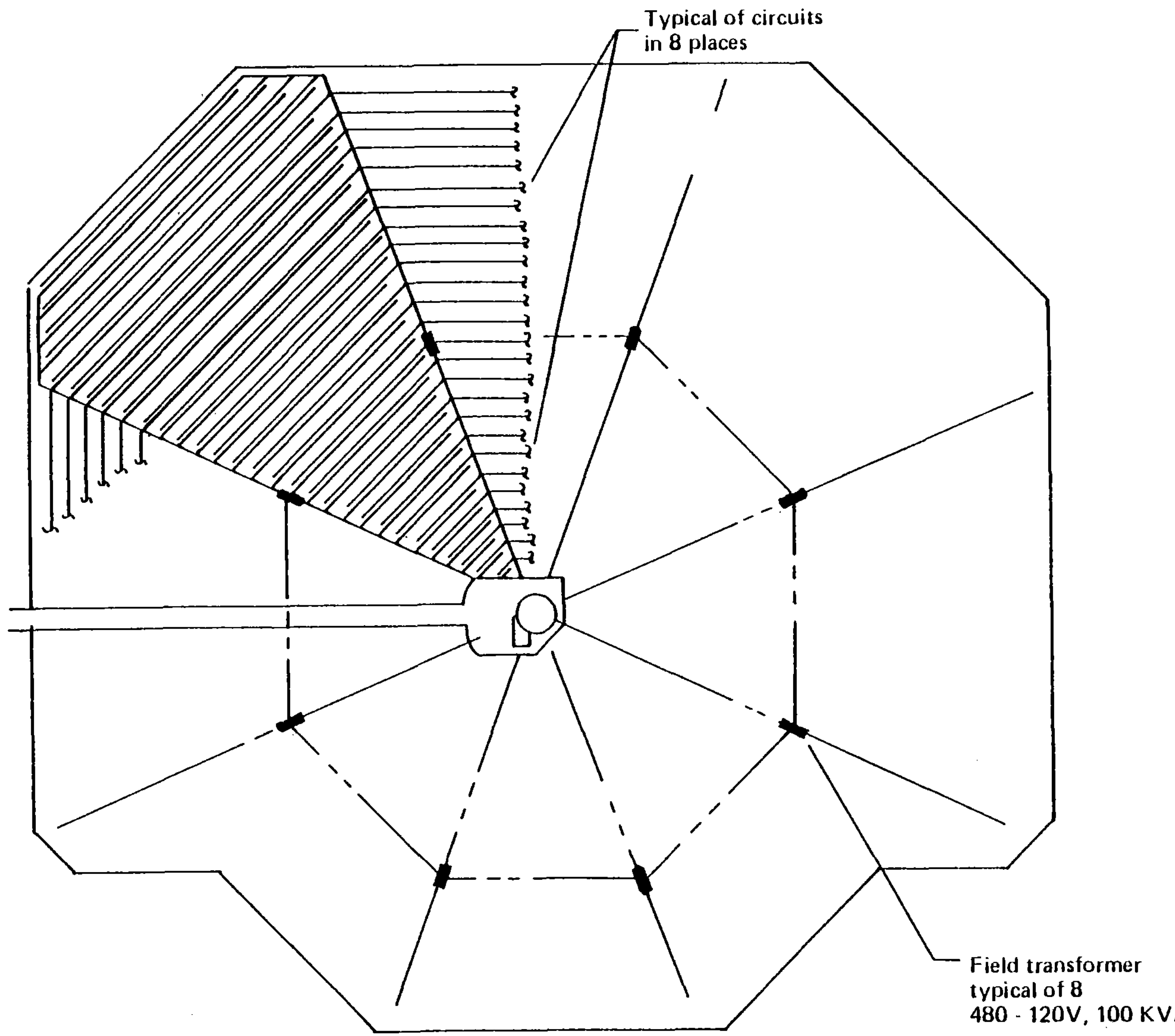


Figure 3.3.1-9. Single Line Field Power Arrangement

strategy can be optimized. Seismic and soil conditions, and water availability are also important inputs to design and construction which can only be determined after site selection. For example, the "soft" tower foundation concept explored during Phase I provides a method of constructing the receiver tower in an active seismic zone without undue cost. This concept would be employed if the site is seismic zone 4 or greater.

3.3.2.2 Schedule

An overall schedule for critical module development has been summarized on Figure 1.2-1. Separate schedules for Phases II, III, and IV are presented in Section 5 as Figures 5.1.2-1, 5.2.2-1, and 5.3.2-1, respectively.

3.3.2.3 Cost

The bulk of the critical module development costs are in the design and construction Phases III and IV. The total cost through all phases is estimated at approximately $150 million, without counting contributing SRE costs from Phase II.

SECTION 4

TECHNOLOGY REQUIREMENTS

Certain areas of technology for the ACRPS need to be improved prior to full commercialization. To achieve this improvement, subsystem and component research experiments (SRE's) and analyses are planned during Phase III (see Table 2.2-1).

4.1 BASIC DATA REQUIREMENTS

4.1.1 Superalloy Properties

Heat exchanger tubes used in the ACRPS receiver are to withstand the sustained high temperatures and pressures of solar operation and the daily thermal/pressure cycling associated with the 30-year lifetime requirement. Studies have shown it is more cost-effective to design the receiver for the full 30-year plant operating life than to schedule replacements at convenient intervals. Under EPRI Contract RP377-1 (Reference 4.1-1), 10,000 thermal cycles (simulating the 30-year lifetime) were performed on Inconel 617 and Hayne H-188 alloys without any deleterious effects. Temperatures were varied from 482°C (900°F) to 829°C (1525°F) under sustained 3.45 MPa (500 psia) helium pressure. However, the accumulated time at high temperature and pressure was very small and no data were accumulated on effects of cyclic loads. Because the ACRPS receiver tubes must be designed for approximately 100,000 hours of operation at high temperature, and be capable of withstanding daily temperature and pressure cycles, data must be accumulated on the creep and fatigue behavior of the tube materials. These data will be used both for the design of the commercial ACRPS, and to establish code specifications for material procurements.[7]

The current concept of ACRPS heat exchanger tube design, described in paragraph 3.2.2.2 of Volume II, is for a constant life along their length while subjected to direct solar flux impingement. The current approach for a 30-year life tube is to use stress values at 2/3 the ASME boiler code. This procedure may be too conservative and costly considering the amount of tubing required for the large-size receivers. Performance of both base-metal and welded materials must be determined.

Accordingly, an SRE to obtain creep, tensile strength, stress-rupture, and fatigue data is planned for the 21-month Phase II program. It is strongly recommended that this SRE be continued well beyond Phase II. It will be performed by a well qualified testing laboratory under subcontract to BEC[8]. Sections 4.1.1.1 and 4.1.1.2 describe the tasks the subcontractor would perform.

4.1.1.1 Long-Term Creep and Stress-Rupture of Superalloys

Test specimens of Inconel 617 and Haynes 188 are to be prepared and tested at sustained temperature levels of 816°C (1500°F), 817°C (1600°F), and 927°C (1700°F). Data

7 If the data obtained show that higher receiver operating temperatures are permissible, this will allow an increase in turbine inlet temperature with a corresponding increase in thermodynamic cycle conversion efficiency above the 42% expected at the 816°C (1500°F) turbine air inlet temperature.

8 BEC has already issued requests for proposals to several firms for this testing. Cost estimates will be discussed in the Phase II proposal submitted under separate cover.

are to be obtained periodically on creep rates, tensile strength, and stress-rupture properties. Forms of the materials shall be in the as-annealed and as-welded condition. This testing will be performed throughout the 21-month Phase II program, with recommended extension beyond this period. The data will be used to develop design allowable stresses as a function of both lifetime and temperature.

The feasibility of operating at substantially higher temperatures will be determined. The cycle efficiency of 42% at 816°C (1500 °F) turbine inlet temperature can be raised approximately 2% for every 56°C (100°F) elevation in temperature. This has a significant effect on plant costs. A subcontractor will assist BEC in developing tube procurement specifications relating to acceptable grain size, chemical composition limits, surface defect limits, and other tube properties.

4.1.1.2 Fatigue Testing of Superalloys

A family of S-N curves for Inconel 617 and Haynes 188 will be developed to characterize the materials in its various forms and service temperatures. The necessity for obtaining cyclic load data to measure fatigue is accentuated by the fact there are no existing data for these materials. Without such data, the receiver design will have to be very conservative, and hence expensive, to satisfy applicable codes. Figure 4.1.1.2-1 is an example of the type of curves desired at each temperature.

Temperature levels will be at 816°C (1500°F), 817°C (1600°F), and 927°C (1700°F). Test specimens will consist of base metal and weldments. The test duration shall be as required to accumulate the data.

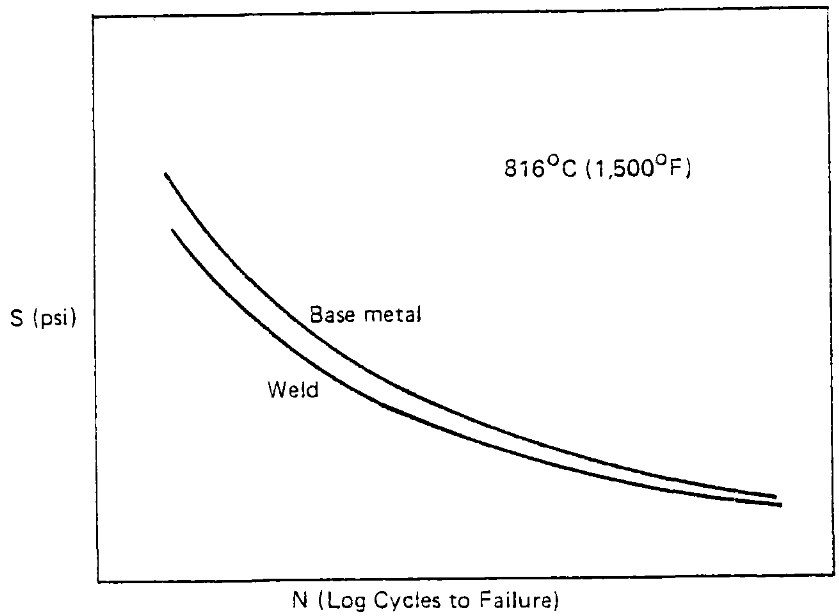


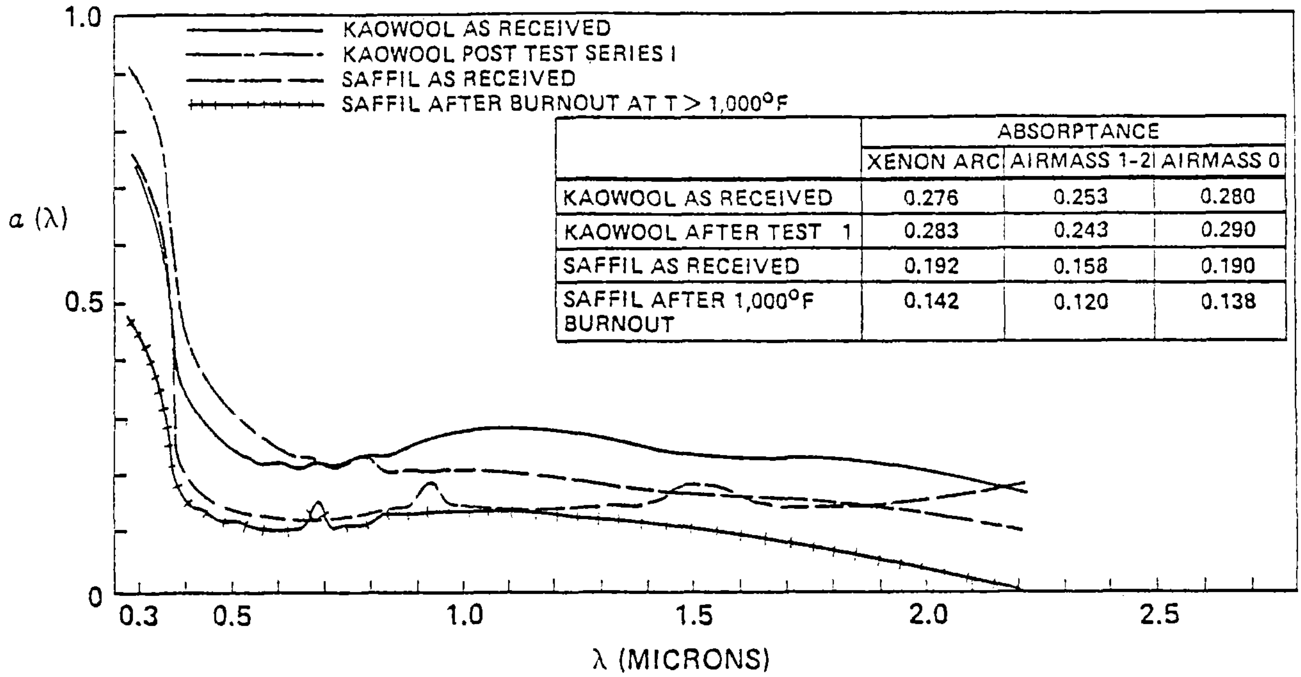
Figure 4.1.1.2-1. Material Fatigue Characterization

4.1.2 Insulation Properties

Large quantities of lightweight insulation materials are required to line the cavity interior. The insulation is used to control the heat distribution within the receiver and prevent substantial conduction loss. This requires that the optical properties of the material and the surface characteristics remain constant under the sustained high heat flux within the cavity. Current insulation candidates are Kaowool^{R} [1] and Saffil ^{R} [1]. These materials have been exposed to solar fluxes in excess of anticipated levels with no detectable short-term degradation. Spectral characteristics for both materials are shown on Figure 4.1.2-1. Long term tests are required to confirm that there is no long term degradation

[1] Kaowool^{R} and Saffil ^{R} are registered trandemarks of insulations marketed by Babcock and Wilcox.

Solar Absorptance
Kaowool and Saffil Samples



	ABSORPTANCE		
	XENON ARC	AIRMASS 1-2	AIRMASS 0
KAOWOOL AS RECEIVED	0.276	0.253	0.280
KAOWOOL AFTER TEST 1	0.283	0.243	0.290
SAFFIL AS RECEIVED	0.192	0.158	0.190
SAFFIL AFTER 1,000°F BURNOUT	0.142	0.120	0.138

Emittance
Kaowool and Saffil Samples

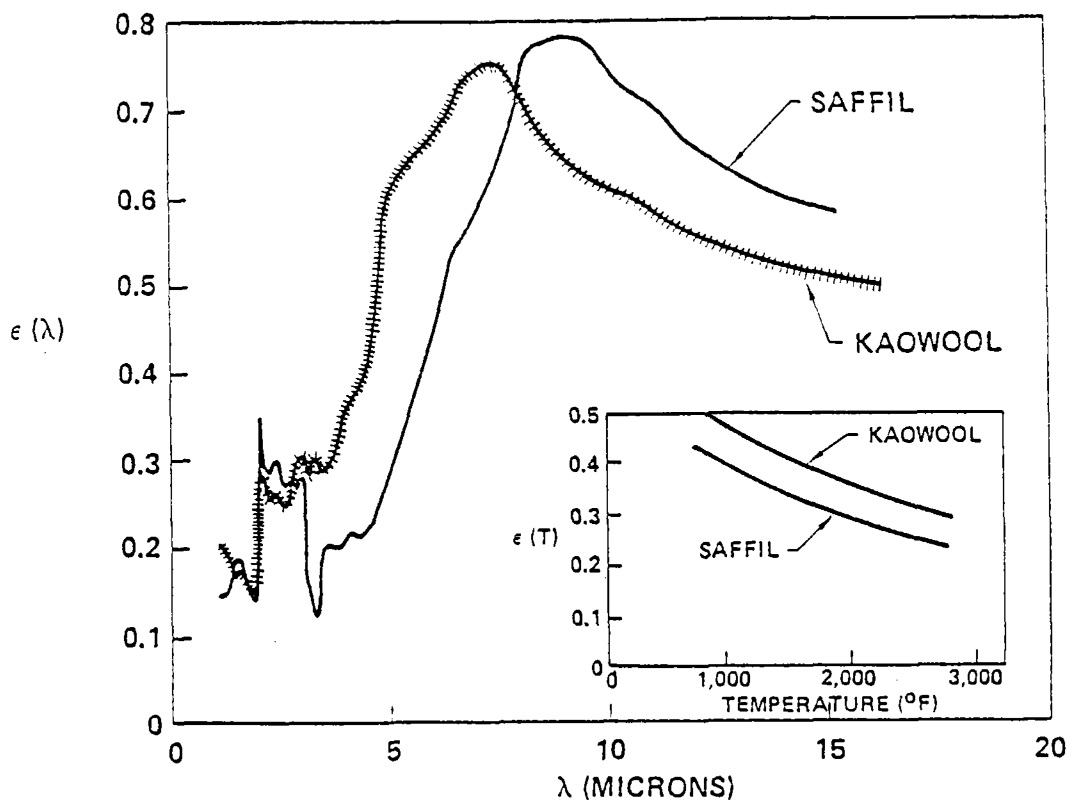


Figure 4.1.2-1. Spectral Characteristics of Selected Insulations

either in optical properties or surface charactristics which materially affect insulation/receiver operations.

An SRE to examine the effects of long term solar flux exposure (up to 5000 hours) on insulation blanket materials will be performed at Boeing in the Solar Radiation Laboratory. The high solar flux facility is shown schematically on Figure 4.1.2-2. The facility consists of two A-7000 solar simulator source modules. The high flux is focused on the test plane and provides a uniform irradiance up to 50 watts/cm^2 on the removable black wall. The two different test materials are placed at the test plane. The uniformity of irradiance on the test plane is shown in Figure 4.1.2-3. Flux levels up to 50w/cm^2 can be achieved. Approximately 40 w/cm^2 is required to achieve the desired 1093^{o}C (2000^{o}F) on the test samples.

The two materials to be evaluated will be mounted in the test box as shown in Figure 4.1.2-2 such that half of the illuminated area will expose each material. Two removable samples for each material will also be cut and mounted at the test plane for simultaneous tests. The removable samples will have the solar absorptivity from 0.25 through 2.5 microns and infrared emittance from 2.5 through 25.0 micron periodically measured at the target temperature.

4.1.2.1 Test Plan

The removable samples will be made to fit the test box and two additional samples will be cut from the as-received insulation. Solar absorptivity and infrared emittance will be measured.

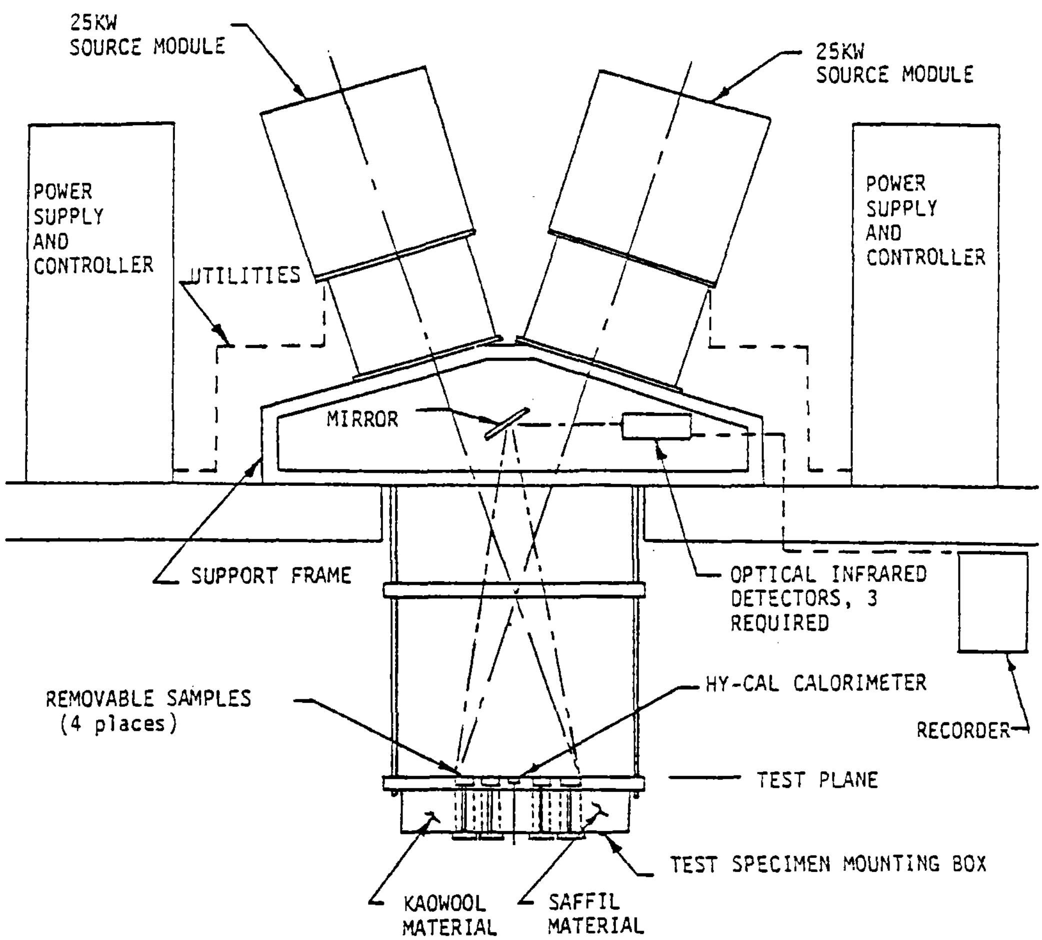


Figure 4.1.2-2. Long Term Exposure Insulation Test Schematic-High Flux Test Facility

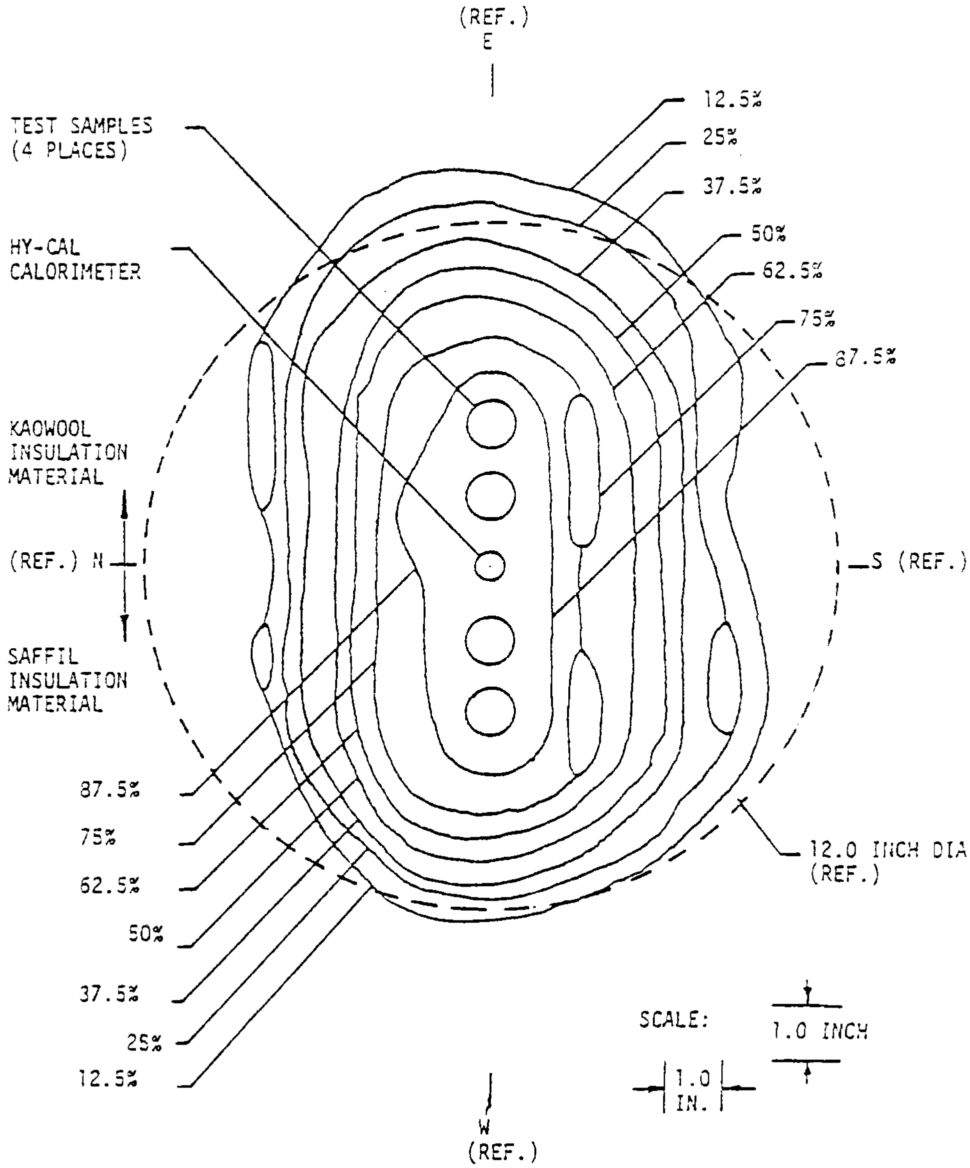


Figure 4.1.2-3. High Solar Flux Facility Uniformity of Irradiance

The removable samples will be installed in the test box and surrounded with the same insulation as shown in Figure 4.1.2-3. From this data, the emissivity of the insulation will be calculated based on an exposure temperature of 1093°C (2000°F). The optical infrared detector will be adjusted for this emissivity, the high solar flux facility started, and the irradiance adjusted to provide this initial temperature. The irradiance will be monitored with a Hy-Cal Calorimeter and maintained throughout 5,000 hours of exposure. The test operation will provide for approximately 100 hours of solar exposure and 60 hours off per week. This is based on a 5-day per week operation and 2-days for weekends. The optical properties of the removable samples will be measured from 0.25 through 25.0 microns afer 100, 500, 1000, 2500, and 5000 hours of exposure. The initial two cut samples will also be measured for reference.

Three optical infrared detectors will be aligned to view the exposed surfaces of the two insulation materials. The spectral response of these detectors are 0.9, 5.5, and 11.0 microns, respectively. The purpose of these instruments is to continuously monitor the reflected and emitted energy from the insulation materials. The response regions were chosen to allow comparative relations to the complete optical property measurements, monitor any changes in the optical properties during exposure, and provide a temperature decay curve of the materials when the solar flux facility is shut down at weekend. For example, the high solar flux facility has no energy available at the 5.5 and 11.0 micron region. All energy in these regions will be emitted by the insulation material. In a similar manner, the insulation materials emit less than 0.4 percent of its energy at 0.9 microns while the high solar flux facility will contain over 50 percent of its energy in the 0.5 to 1.0 micron region. Therefore, the optical infrared detector with the response region of 0.9 microns will be monitoring the refelcted energy and any changes that occur during the long exposure. Likewise, the other two optical infrared detectors will be monitoring the emitted energy in two regions to detect any changes.

The above test will provide data to note the long term exposure effects on the optical properties, changes in the optical properties at temperature, and effects of returning insulation materials to ambient conditions.

4.1.2.2 Test Equipment

To perform the long-term insulation testing, it is anticipated that the equipment listed below will be required. This equipment is either readily available in Boeing's Solar Radiation Laboratory or will be obtained for the test.

High Flux Test Facility (See Figure 4.1.2-2)
Test Specimen Mounting Box
Insulation Samples and Guards
Power Supplies and Controllers
20 kw Xenon Lamp Replacements (16)
Hy-Cal Calorimeter
Optical Infrared Detectors (3)
Recorders

In addition, it is estimated that the two 22-inch aconic collectors in the source modules will have to be refurbished eight times during the course of the testing.

4.1.2.3 Test Results Monitoring

This SRE will be initiated at the beginning of Phase II and continue throughout the period. Insulation properties will be periodically evaluated; if no changes are detected at 5000 hours, no further testing will be recommended. If changes are occurring, recommendations will be made to continue testing either or both materials into Phase III.

4.1.3 Receiver Convective Heat Loss

It is extremely important that the efficiency of the central receiver be as high as possible. Losses from the receiver are by conduction through the walls and radiation, reflection, and convection losses through the receiver apertures. All heat loss mechanisms have been amenable to calculations using the detailed BEC computer models except for convection losses through the aperture. During Phase I the convection losses were estimated at two percent. The DOE has suggested that this loss mechanism merits a more critical evaluation. BEC has examined the two possible modes of testing to determine convective losses: (a) using an active receiver at the level of the STTF tower, and (b) using a ground test model. It has been determined that gound-level testing would offer the greatest potential for quantifying convective losses.

4.1.3.1 Model Configuration

The proposed test model for this SRE would be a 1/14 scale model of the 75 MW_e ACRPS receiver with four apertures. Existing wind-making machines were used to determine the size. Figure 4.1.3.1-1 shows the model dimensions. The model would be fabricated from sheet steel with reinforcing rings at appropriate points, and would be supported by guy wires. The model exterior would be lined with insulating blankets to reduce wall conductive heat loss. The insulation would be covered with netting to prevent wind damage.

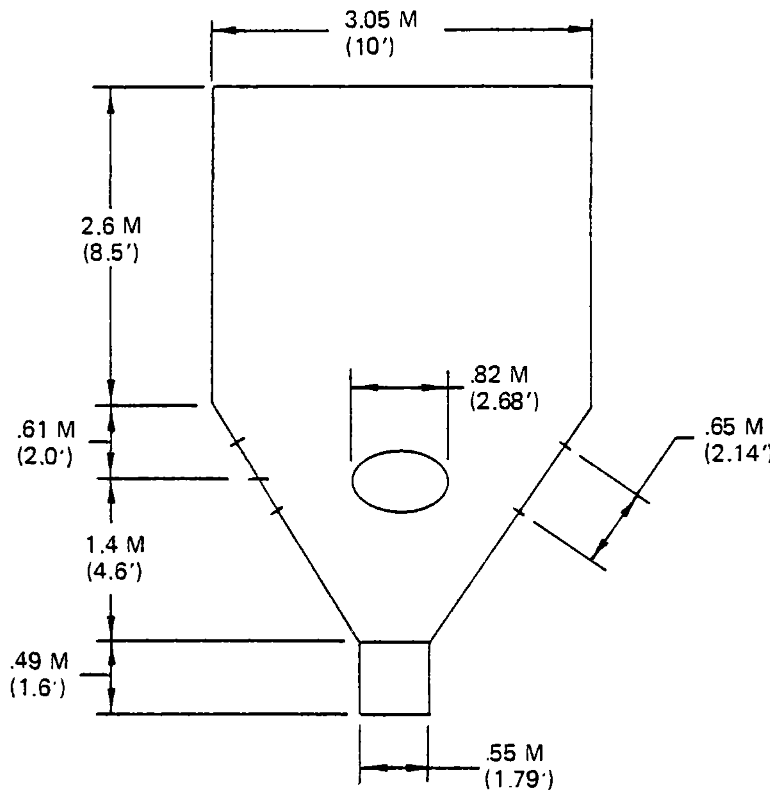


Figure 4.1.3.1-1. Model Receiver for Convective Loss Test

4.1.3.2 Test Plan and Equipment

The test concept is based on determining convective heat loss by measuring the heater power necessary to maintain equilibrium cavity temperatures while forcing air of known velocity across the apertures. The wind would be produced by an available portable wind machine. This machine consists of a 3.65 meter (12 foot) diameter steel duct, 4.9 meter (16 feet) long, with a short bellmouth-shaped inlet on the front end and a honeycomb flow-straightening section on the aft end. The device is powered by an 18 cylinder Pratt and Whitney R-2800-31 engine with a 3.56 meter (11 foot, 8 inch) diameter, 4-bladed variable pitch propeller. The engine is mounted on a pylon made of 0.254 meter (10 inch) pipe. The machine weighs about 7260 Kgm (16,000 pounds) but can be moved by two forklift trucks. Wind speeds to 20 m/s (65 f/s) can be produced. All test speeds used will produce turbulent flow. Heaters and measurement equipment are of sufficient accuracy to determine convective heat losses to an accuracy of about 2%.

To simulate the solar flux within the cavity, a heat source of six 480 volt Inconel finned air heating elements will be provided. Each element will be 9.1 meters (29.83 feet) in length, 3.05 centimeters (1.2 inches) in diameter, configured as a hoop with a radius of 1.37 meters (4.5 feet). The elements will line the inside of the cavity and be staggered at 0.15 meters (6 inches) intervals starting at the ceiling. With these elements the cavity temperature can be raised to 316^{O}C (600^{O}F) assuming a heat loss of 130 KW.

Each of the four apertures will be fitted with removable water-cooled covers, which when used will determine the radiation loss at the aperture planes. Water flow will be controlled by a valve and flow measured with a turbine-flow meter. Thermocouples will sense inlet and outlet water temperatures. A series of four tests will be conducted:

a. Test series #1 will be conducted with apertures covered. Heat will be applied until equilibrium is achieved between the cavity wall and the water-cooled apertures. This test will provide a measure of power required in a no-wind state with free convection inside the cavity and radiation out of the apertures. This will provide data to serve as the baseline for further test comparisons.

b. Test series #2 will be conducted with aperture covers removed. Heat will be applied until the same equilibrium conditions of 316°C(600°F) exist within the cavity. The measured power to achieve the condition will be compared to the baseline power (series 1) to determine the convection losses out of the apertures in a no-wind condition.

c. Test series #3 will consist of a repeat of series #2 with simulated wind. Air will be blown parallel to the ground plane and directed towards one aperture. Power measurements at a variety of wind speeds are used to determine the convective losses when compared to test series #1 and #2.

d. Test series #4 is a repeat of series #3 except the wind vector will be aligned at other angles to the aperture and also between apertures.

Test series #3 and #4 will be run at five different Reynolds numbers which will be attained by varying the wind speed. For each Reynolds number, the corresponding Nusselt number will be found by measuring the power to maintain the temperature of the cavity at 316°C (600°F). The five flow velocities and their corresponding Reynolds numbers are listed below:

Wind Speeds m/sec (ft/sec)	Reynolds Number $\times 10^{-5}$
2.44 (8)	1.15
5.36 (17.6)	2.53
7.62 (25)	3.59
9.14 (30)	4.31
12.2 (49)	5.75

4.1.3.3 Model Data Analysis and Generalization to the ACR

Model Data Analysis

The convection loss $\dot{q}_c$ in the no-wind case (test series 2) can be calculated directly from the additional power required to maintain the same cavity equilibrium conditions as in test series 1 or:

$$\dot{q}_c \text{ (no wind)} = \dot{q} \text{ (heater power 2)} - \dot{q} \text{ (heater power 1)} - \dot{q}_r \text{ (test series 1)} - \text{kilowatts}$$

The same type of equation will be used for the wind tests to determine the convection loss ($\dot{q}_c$) at each Reynolds number and orientation. However, the results only have value if they can be scaled to other situations. Using the horizontal flow directed at one aperture as an example, the procedure for determining the proper scaling law is described below.

For a given Reynolds number and convection heat loss, the heat transfer coefficient (h) can be extracted from:

$$h = \dot{q}_c / A \, (316^\circ - T_{ambient})$$

where A is taken as the area of the apertures.

Then, the Nusselt number is determined from the relationship:

$$Nu = \frac{h\,d}{k}$$

where d = diameter of aperture

k = air thermal conductivity,

The scaling law of interest is the relationship used in heat transfer calculations of

$$Nu = C\, Re^{a}\, Pr^{b}$$

where C, a, and are undetermined constants and $Pr = c_p \mu / k$ = constant.

For each series of Reynolds numbers and calculated Nusselt numbers, a curve such as shown on Figure 4.1.3.3-1 may be drawn.

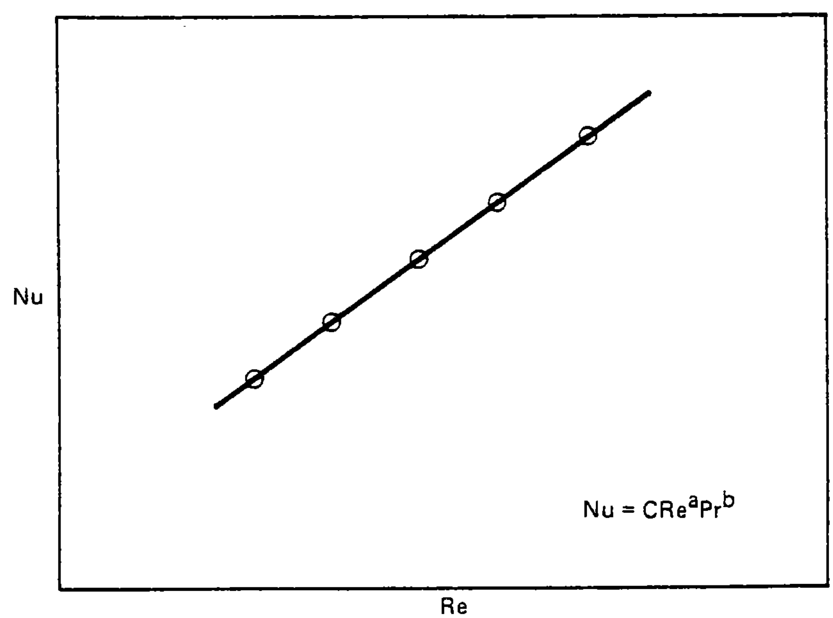


Figure 4.1.3.3-1. Convection Loss Scaling Relationship

Then the constants C, a, and b can be determined to give the useful relation at the given flow orientation. Curves at other wind/aperture orientations would provide other sets of constants. The free convection parameter (Grashoff number) remains constant for the test series.

<u>Generalization to the ACRPS Receiver</u>

At a given flow Reynolds number and flow orientation for the full size receiver, one uses the appropriate formula:

$$Nu = C\, Re^a Pr^b$$

where $Re = Vd\rho/\eta$ and $Nu = hd/k$ are now based on the full size aperture diameter, and c, a, and b are the determined constants

$$h = \frac{Nu\ k}{d}$$

$$\dot{q}_c = h\, A\, (T_{cav} - T_{ambient})$$

where the cavity temperature, T_{cav}., is estimated.

Thus, the convection heat loss of the 4-aperture ACRPS receiver can be determined assuming the same degree of mixing occurs between the more buoyant (less dense) cavity air and the cool external air. The correction should then be made to re-estimate average ACRPS wall temperature with the calculated convection loss to determine new radiant heat loss.

4.1.3.4 Schedule

Because of the importance of obtaining an accurate estimate of the convective heat loss to determine overall receiver efficiency, this SRE would be performed during the first 5 months of the 21-month Phase II program. The first month will involve test system design, analysis and predictions, and test planning. The second and third months would cover test instrumentation design, fabrication, and assembly of the scale model. The last two months will be used for testing, data evaluation, and report preparation.

4.2 ACR CONCEPT VERIFICATION

The next area of technical requirements (Reference Table 2.2-1) involves verification of specific concepts which BEC selected for the preferred ACRPS in Phase I; these are: direct flux impingement on heat exchanger tubes; downcomer/riser design; and sensible heat storage.

4.2.1 Heat Exchanger Panel Direct Flux Impingement

The EPRI/BEC Bench Model Solar Receiver (BMSR) prepared for test at the STTF was designed to prevent direct solar flux impingement on the heat exchanger tubes. This design relies instead on reflected and reradiated flux from the insulated cavity walls. This concept provides a more uniform flux loading on the heat exchangers - a necessity for the two-pass heat exchanger tubes used.

In contrast to the BMSR receiver, the ACRPS receiver concept (described in paragraphs 3.2 and 5.3.2 of Volume II) uses direct flux impingement on the heat exchanger tubes. This flux varies from a maximum of 200 kW/m^2 on the cold (inlet) ends of the tubes to approximately 1/10th of that value at the hot (upper) end. This permits a constant-life tube design, rather than a tube whose life is determined by the minimum life condition which exists at the hot (gas exit) end of the tube. The net result is more heat absorption per tube without exceeding the 30-year lifetime allowables. This concept is a significant departure from previous practice, and significantly reduces the amount of superalloy metal required. The concept will be used for ACRPS commercial plants, and the BEC-proposed EPRI Experimental Plant. Therefore, an SRE is planned which would verify the thermal performance of the concept for the range of fluxes and flux gradients expected in the cavity interior.

4.2.1.1 SRE Model Configuration

The proposed test model would be a straight, single-pass heat exchanger panel configured to accept up to the full 1 MW_t solar flux capability of the STTF's "A" field. The tubes would be of Inconel 617 or Haynes 188 and be approximately 2.54 cm (1 inch) outside diameter; tube pitch would be approximately 2. The tubes would be mounted on an insulated panel, but spaced away from the insulation by several diameters. Headers would be shielded from direct solar flux as is planned in the ACRPS receiver. Figure 4.2.1.1-1 shows the tube/panel test configuration.

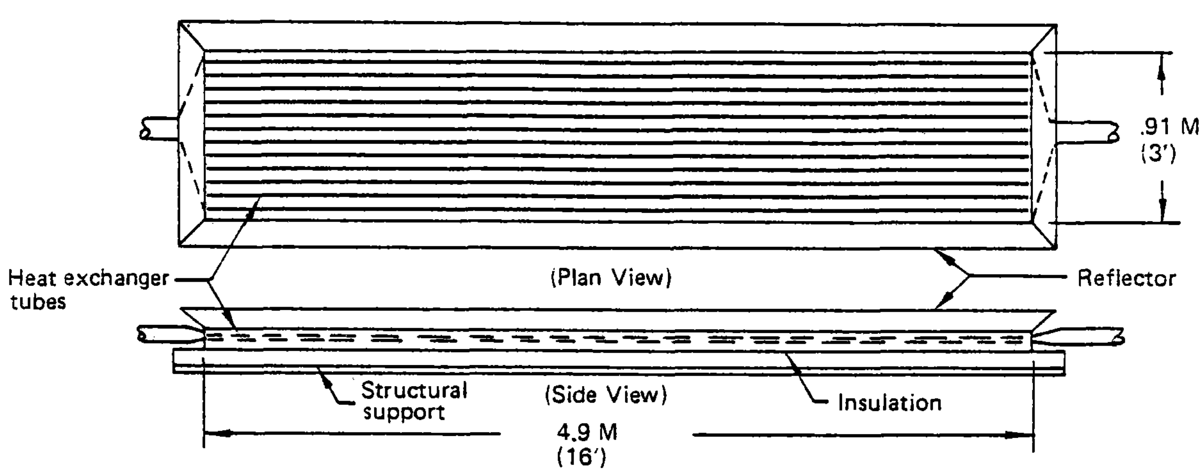


Figure 4.2.1.1-1. Heat Exchanger Panel Configuration

Because of the necessarily reduced size (based on the 1 MW_t solar flux capability), the tubes have been dimensioned to the approximate length required for the EPRI Experimental Plant. The receiver proposed for this plant would be the first usage of the direct flux concept.

4.2.1.2 Test Plan

The test model would be located at the 43m (140 ft) or 49m (160 ft) level of the STTF. The approximate 10 to 1 variation in heat flux along the length of the tubes would be provided by selectively focusing the STTF heliostats at different target areas on the panels. At maximum heat flux acceptance (1 MW_t), the distribution of targets along the panel length would be as shown in Figure 4.2.1.2-1. The distribution of heat flux to be matched is also shown on the figure. The number of targets would be reduced for the lower flux levels to be expected at other circumferential positions within the ACRPS receiver.

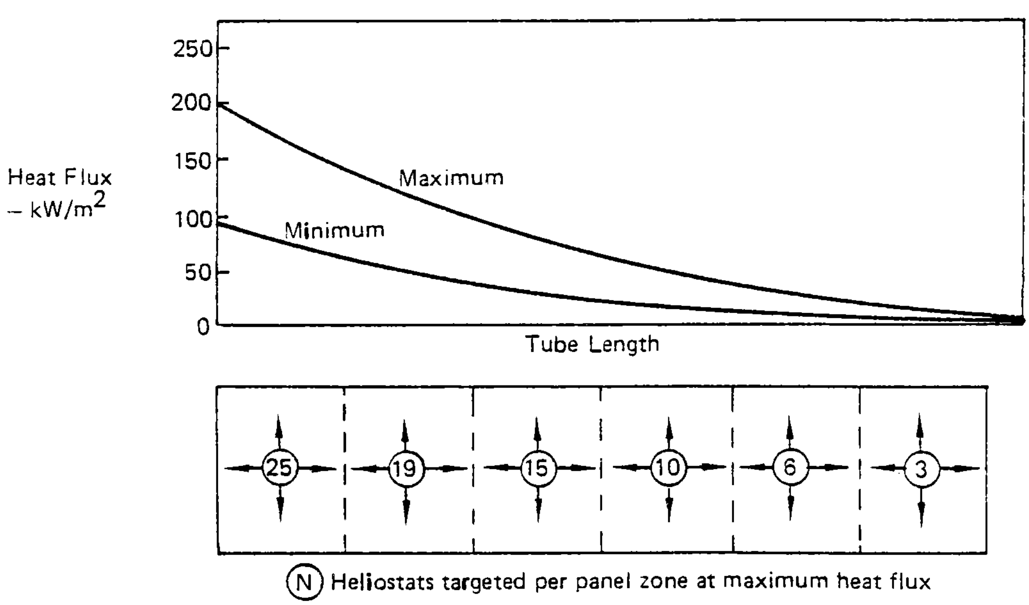


Figure 4.2.1.2-1. Approximate Heliostat Target Areas for Maximum Heat Flux

The heat exchanger panel would be supported horizontally at the selected STTF tower level and tilted downward to receive the STTF flux most directly. A range of flux patterns (heliostat target patterns) will be run in series, beginning with the minimum level and progressing up to the maximum flux levels desired.

4.2.1.3 Test Equipment

The experimental heat exchanger would be sized (number of tubes, length, etc.) within the cooling capability of the air supply system used for the EPRI/BEC BMSR test at STTF. Thus, no new equipment will be required. The BEC air supply system provides up to 2.5 Kg/sec (5.5 lb/sec) of air which can be heated to 538^{o}C (1000^{o}F) for the heat exchanger panel test. This heating is provided by recuperation with the exit air from the tubes of the BSMR. In this experiment, the heat exchanger panel would replace the BMSR shown in Figure 2.3-1. The indicated panel requires an additional length of piping (shown overhead in Figure 2.3-1) for the inlet air supply to the panel. The necessity for additional valving in the inlet supply line for closer flow control will be examined for adequacy, as will the pressure and temperature instrumentation on the existing air supply system. Pressure in the tube panel are expected to be in the 0.86 MPa-(125 psia) to 1.04 MPa (150 psia) range as supplied by the compressors at the STTF ground level. Tubes will be sized to achieve the required pressure drop.

Radiation calorimeters will be mounted on the insulation surface (unblocked by tubes) to give a measure of the incident flux on the tubes at various locations, and to verify flux distribution patterns along the panel. Temperature sensors would be located in the insulation and on selected tubes (front and back) to determine actual temperature distributions. Post-test, metalographic and x-ray measurements can be made to determine presence and distribution of oxide layer build-up on the tubes.

4.2.1.4 Schedule

The heat exchanger panel SRE would be initiated at the beginning of Phase II to allow lead time for superalloy procurement. Fabrication of the tube, headers and the panels are expected to be completed within five months. Assembly, instrumentation, checkout, and shipping would require another 2 months. Testing is expected to be completed within 9 months after initiation of Phase II.

4.2.2 Downcomer Design Concept

A unique design concept has been conceived for the long piping run between the receiver and the ground-based turbo-machinery in the ACRPS. A thin, vented liner of superalloy material backed by insulation is used to separate the high temperature air from an outer steel pressure pipe. This concept promises to be very cost effective compared to the alternative of using a solid superalloy pressure pipe. The concept is shown in Figure 4.2.2-1, and described in more detail in paragraph 5.5.3 of Volume II.

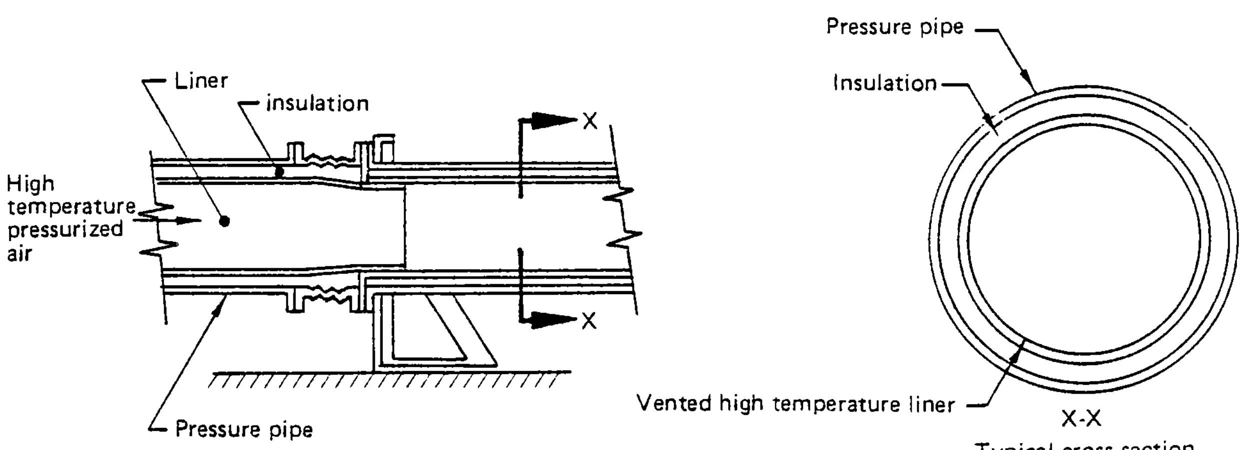


Figure 4.2.2-1. Downcomer Design Concept

The downcomer design concept must be verified prior to usage on the proposed larger-scale ACRPS plants. Of primary concern is the structural integrity of the insulation when subjected to repetitive temperature and pressure cycles. An SRE for this purpose is planned for Phase II and is described below.

4.2.2.1 Model Configuration

The model would be configured as shown in Figure 4.2.2-1, but reduced in scale to an approximate 4.6 meters (15 feet) length and 0.6 meter (2 foot) inside diameter. One or more overlaps of the inner sleeving would be included to demonstrate thermal expansion and contraction, and one or more expansion joints would be designed into the exterior pressure pipe. The non-load bearing insulations to be used in the test will be selected based on low thermal conductivity, low porosity, mechanical integrity of fibers, and resilience under repeated operating cycles. A filter would be added on the downstream side of the pipe to permit determination of insulation loss due to repetitive expansions and contractions.

4.2.2.2 Test Plan

Cold - and hot-flow test series will be sequenced to determine the structural integrity and thermal performance of the piping concept. Cold-flow static tests will determine the insulation capability to withstand sustained pressure and subsequent depressurizations. The pipe will be pressurized, pressure held for a period to time, and then blown down. An internal heater could be placed inside the pipe to give combined temperature and pressure effects. The resilience of the insulation and its ability to retain its shape and mechanical properties in the cavity between the shell and the vented liner will be determined. The specific concern is that if the insulation settles, hot spots will develop in the mild steel pressure pipe.

The piping hot-flow series will be used to determine thermal conduction losses and the operation of the expansion devices (sleeving, bellows). Hot air would be supplied at 816°C (150°F) at atmospheric pressure. The penetration of hot air into the insulation as a factor in increased heat conduction loss or pipe pressure loss will be investigated.

Planned variables in this test series include two or more insulations of differing densities, and two internal alloy sleeves with differing vent patters.

A subcontractor has been found who has the necessary facilities for this SRE and the experience to carry out the proposed work.

4.2.2.3 Test Equipment

This SRE requires a pressurization system capable of obtaining and sustaining 3.45 MPa (500 psi) for the static pressure/blowdown tests, and a heater capable of raising the air temperature to 816°C (1500°F), for the hot flow tests. For the model size described in Section 4.2.2.1 air flow capability required is about 3 Kg/sec (6.5 lb/sec) for the hot flow test series.

Instrumentation requirements are thermocouples for wall, insulation, and gas temperatures; and pressure transducers to determine system pressure and pipe pressure drops. A filter of a size appropriate to catching insulation particles will be required.

The actual model size and instrumentation would be negotiated with a potential subcontractor, and be adapted to his available facilities to do the high temperature, high pressure testing required.

4.2.2.4 Schedule

This test with data analysis is expected to require approximately 12 months of the 21-month ACRPS Phase II program.

4.2.3 Sensible Heat Storage Concept

The preferred ACRPS design uses sensible heat storage in alumina (Al_2O_3) bricks. Rationale for the selection of this concept is described in paragraph 3.3 of Volume II; conceptual design details are described in paragraph 5.3.5 of Volume II.

Sensible heat storage in bricks is not a new concept, as there is widespread use of refractory bricks to store heat in "checkerworks" in the steel industry. These systems operate at high temperature but at fairly low pressures. Steel industry experience is not too helpful because slight spalling and dusting is not a concern for that usage. The effects of brick spalling and dusting could be serious in the ACRPS plants in that airborne particulates could erode turbine casing and blades Thus, inlet and outlet filters have been proposed in the storage subsystem conceptual design. The proposed ARRPS concept combines both high temperature and high pressure conditions. High pressure enhances heat transfer into (during charge) and out of (during discharge) the brick, but the associated effects on brick integrity at high pressure are not known.

Other potential problems are (1) relative motion between bricks caused by non-uniform thermal expansion, (2) sudden decreases in pressure, and (3) thermal shock. An SRE is required to confirm the thermal operation and structural integrity of the concept, determine whether the brick materials is eroded through dusting and spalling, and determine filtering requirements.

4.2.3.1 Model Configuration

The model for the sensible heat storage SRE would be patterned exactly after that of the preferred ACRPS design concept. The same size bricks as those intended for the commercial size plants will be used but will be enclosed in a much smaller cylinder. Figure 4.2.3.1-1 shows the nominal dimensions selected for the SRE; these will be refined during detailed experimental design. The exact size of the cylinder (and the number of bricks required) will be determined based on a search for an appropriate low-cost container, and on analysis of edge-effect losses. Approximately 7,600 alumina bricks are required for the pressure vessel shown on Figure 4.2.3.2-1. This would provide 95 channels for air flow at 2.42 cm (0.95 in) channel diameter. Inlet and exit lines to the pressure vessel would be approximately 25 cm (10 inches) inside diameter. Two inches of insulation would line the interior of the pressure vessel.

4.2.3.2 Test Plan

Testing on the sensible heat storage SRE would be divided into three phases: cold flow tests, hot flow tests, and thermal cycling.

The cold flow test would be operated at 3.45 MPa (500 psia) pressure and be used to determine system pressure loss and

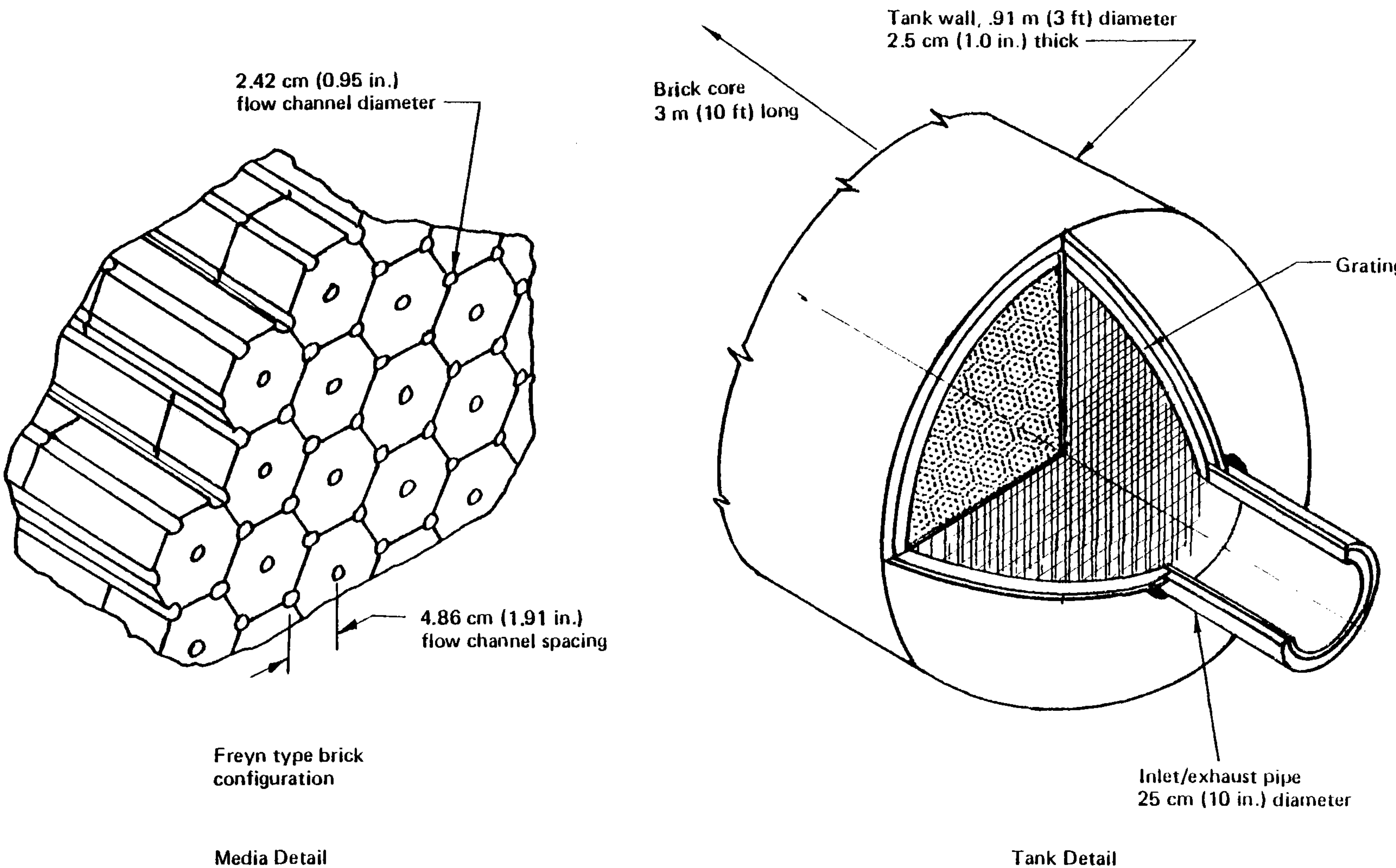


Figure 4.2.3.1-1. Sensible Heat Storage SRE Model Configuration

alumina material loss. For the latter purpose a small size particulate filer will be placed in the downstream exit line. The cold flow tests will also eliminate dust on the bricks as delivered, prior to installing the final test filter.

The hot flow test sequence will use once-through hot air conditioned to 3.45 MPa (500 psia) and at selected temperature levels to an upper limit of 816°C (1500°F). For thermal performance, it is more important to preserve the 300°C (540°F) temperature swing between the hot and cold ends than the actual temperature level. The air will be filtered at high temperature (if suitable filters can be found to operate at test temperatures) or filtering will occur after the exit air has been cooled. Temperature histories will be recorded at the air exit and at selected positions (axially and circumferentially) throughout the brick material. This will provide thermocline data at various charging times. Pressure drops through the media will also be recorded.

The thermal cycling tests will consist of hot charging for a pre-selected interval and then reversing the flow direction to use a cooler air inlet (simulating the recuperator outlet on the preferred ACRPS design). This will permit measurement of heat extracted from storage in the discharge mode.

4.2.3.3 Test Equipment

The SRE requires a pressurization system capable of up to 3.45 MPa (500 psia) and a heater capable of raising the air temperature to 816°C (1500°F). For the model size depicted in Figure 4.2.3.1-1, 50 Kg/sec (112 lb/sec) air flow capability is required for the cold flow test series at pressure. Availability of a heater compatible with the required flow ratio is a modest design problem. Depending on the flows and temperatures achievable with machines available at the test conductor's facilities (see paragraph 4.2.2), this SRE design could be integrated with the piping SRE to achieve a cost reduction. This will be evaluated during SRE detail design.

A range of filter sizes will be used in the cold flow test to determine the particle sizes of alumina brick material lost. The maximum filtration level will be selected based on coordination with turbine manufactures to determine the minimum particle size which will not cause blade erosion.

Additional piping and a segmented air heater will be required to simulate alternate charge and discharge temperatures of the preferred storage system concept. A schematic of the system could be as shown in Figure 4.2.3.3-1.

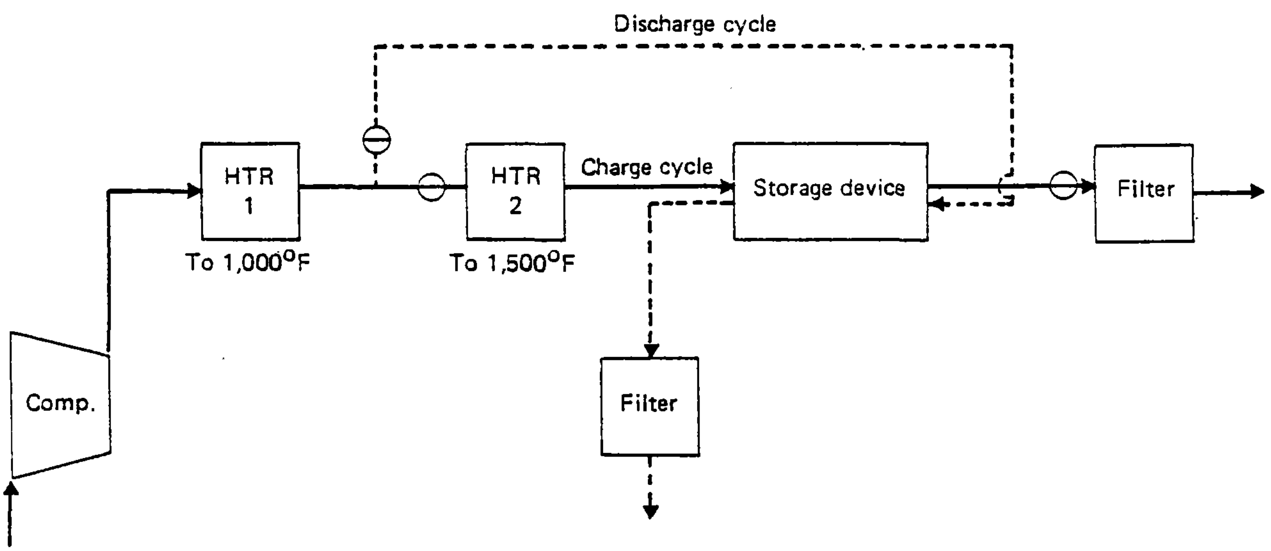


Figure 4.2.3.3-1. Sensible Heat Storage SRE Charge and Discharge Simulator

4.2.3.4 Test Schedule

Planning and detailed design of the storage SRE would begin at the start of Phase II. Test model fabrication and instrumentation would be completed about four months after start. Actual testing would occur during the next six months and be followed by a two month data analysis and SRE report period. Total duration of this SRE is expected to be 12 months.

4.3 LONG LEAD EQUIPMENT

To support the ACRPS technology developement, certain items of equipment must be available on a timely schedule. In this category are the high pressure equipment required for the critical experiment to be performed in Phase II, and the turbomachinery and storage pumps required for the 50 MW_e critical plant and 75 MW_e preferred plant modules.

4.3.1 High Pressure Equipment

The critical experiment described in paragraph 3.1 requires a high pressure test of heat exchanger tubing receiving direct solar flux. This pressure is obtainable by either of the two options shown on Figure 3.1.2-1. The option which comes closest to simulating the actual conditions expected would use pressure bottles for initial pressurization to 3.45 MPa (500 psia), and the low-pressure-ratio compressor to make up pressure lost in the cycle. The other option (which minimizes cooling requirements) would utilize a high-pressure-ratio compressor. Such a compressor would probably require modification of the last compressor stage to handle the resulting temperatures. Work would begin immediately in Phase II to determine the merits, costs, and schedule attainment with either option, to make a selection, and to obtain the necessary equipment.

4.3.2 Turbomachinery

The lead time for closed cycle turbomachinery can vary anywhere from 3 to 7 years depending on the number of components that can be adapted from existing machines. The decision to put a 50 MW_e critical module plant in operation prior to that of the 150 MW_e preferred plant described in Volume II necessitates an early system study, and a turbomachinery recompetition in Phase II. This study is intended to reconcile the 50 MW_e turbomachinery requirement with that of the 75 MW_e turbomachinery required for the modules of the larger commercial plant. Quite clearly, two separate turbomachinery development paths would be prohibitive. The thrust of the study will be to retain the advantages of the closed cycle, namely, the inventory control system, while arriving at a singular turbomachinery development path which can suit both purposes. Section 3.3.1.5 has discussed some of the options available. Assuming 4-5 years to have a tested machine available to support the 50 MW_e critical module, turbine design work must start early in Phase II to match the construction/installation schedule shown in Section 5.3.2 and to support power production late in FY 1985. Production of the first machine would then be initiated in Phase III.

Another turbomachinery development path would be followed if plans for the EPRI 1.5 MW_e experimental plant are not carried forward. In this case, the critical experiment discussed in paragraph 3.1 would be expanded to use a receiver configured to accept the full 5.5 MW_{th} flux from the STTF field. This new critical experiment would be performed in Phase III of the ACRPS program.

Since the same pressure and temperature requirements exist, the need for a complete closed cycle, high pressure system demonstration can best be fulfilled by incorporating active machinery at the STTF test site. An open cycle turbomachine can be modified to produce the 2.07 MPa (300 psia) to 3.45 MPa (500 psia) required. The time available for such modification would be approximatley two years. In any event, this alternative path to turbomachinery or high pressure equipment would have to be vigorously pursued to assure on-schedule availability.

4.3.3 Storage Pump

One of the critical long lead items required for the 50 MW_e critical module is a storage pump. This device makes up pressure loss for the air going through the storage system during charging so that the air recycles to the receiver at the required system pressure. As presently conceived, this pump must handle high pressure, high temperature air at flow rates up to 318 Kg/sec (700 lb/sec). Such a pump is not in the inventory of equipment manufacturers and requires a separate design, development and fabrication schedule which should be initiated in Phase II.

4.4 SYSTEM STUDIES

A number of basic system studies must be completed during the development program to improve its cost effectiveness, and to ensure that the ACRPS design is of maximum value to the electric utilities.

4.4.1 System Operation Strategy

In the BEC ACRPS, storage can be charged and discharged at various times during the day. One mode of operation is to charge as much storage as possible while the insolation level is rising in the early morning. Another mode would use the earliest insolation for system warm-up, then switch to turbine operation, deferring storage charging until later in the day. This system study is intended to evaluate all feasible modes of operation. In close cooperation with electric utility advisors, the optimal modes will be determined for a variety of insolation, system load and other conditions. While these cannot be known in particular until the utility and site is selected in Phase III, certain characteristic patterns for utilities in the Southwestern United States can be used as the basis for evaluation.

For example, if the demand is lower throughout the insolation hours and peaks in the evening, it may be desireable to produce less power directly from solar insolation, putting the excess into storage for use during the evening peak load period. The effect on storage capacity versus predicted grid demand versus time must also be carefully analyzed. BEC will continue to use a utility review board composed of southwestern utility members to provide the necessary expertise in determining optimal operating strategies.

4.4.2 System Acoustics

Another study is required to obtain an estimate of the acoustic properties of the proposed ACRPS plants. This is required not only to determine noise levels for environmental impact analysis and plant certification, but also to estimate the associated vibration and resonance levels which plant equipment and personnel would experience.

The absence of a combustor is a positive advantage in terms of noise levels, but little data are available in the United States on closed Brayton cycle operation. A survey will be made of such turbomachinery usage in Europe to determine sound and noise levels and associated resonance phenomena. When the turbomachinery development path has been established (see 4.4.3) and preliminary turbomachinery determined, the acoustics analysis can be applied to both the 50 MW_e critical module plant and to the 75 MW_e module of the preferred commercial plant.

4.4.3 Cost Effectiveness

Of major concern at the present time is the high initial capital cost of a solar plant. There are economies of design and construction possible which can reduce the capital costs. These range from use of lower temperature materials wherever possible, to larger economies in turbomachinery selection. The assessment task performed late in Phase I indicates other areas where economies can be effected. These will be examined in greater depth for both the 50 MW_e critical module plant and the larger 150 MW_e plant during the course of Phase II when the other SRE's and analyses are essentially complete.

SECTION 5
DEVELOPMENT PLAN BY PHASE

In Sections 3 and 4 the major ACRPS program elements and technology developments were discussed. It is now necessary to integrate these activities into a total program and identify their probable costs. These activities and costs must then be allocated to program phases identified in Reference 2.1-4 and 2.1-5.

The overall DOE Central Power Systems Program for the storage-coupled ACRPS has been presented in Figure 2.1-1. The major program phases of the proposed development plan are also shown.

The planning of the major activities will result in a (1) concentration on technology development, turbomachinery design, critical module PD, and critical experiment execution in Phase II, (2) utilization of Phase III for critical module design and the EPRI Experimental Plant for concept verification; and (3) utilization of Phase IV for the critical plant module construction and initiation of the preferred commercial-scale ACRPS design.

Phase II is a 21-month period beginning in January, 1979, and ending in October, 1980. After a DOE recompetition period in which the technology, plant location, and utility co-sponsors are determined, Phase III would be initiated (as estimated) in January, 1981. It would last approximately 21 months ending in October, 1982. Phase IV would commence immediately thereafter with the first 50 MW_e critical module becoming operational by August, 1985.

Due to extremely short time allowed for construction of the critical module in Phase IV, it is recommended that program funds be released during Phase III to begin fabrication of long-lead components so that the schedule can be maintained.

5.1 PHASE II

5.1.1 Phase II Activities

The major activities of Phase II are listed in Table 5.1.1-1 showing how each will be accomplished and citing the section reference where each is discussed.

Table 5.1.1-1. Phase II Activities

Category	Item	Activity	Section Reference
Technology Development or Verification	Superalloy properties	SRE	4.1.1
	Insulation properties	SRE	4.1.2
	Receiver convective heat loss	SRE	4 1.3
	H/X panel direct flux impingement	SRE	4.2.1
	Downcomer design concept	SRE	4.2.2
	Sensible heat storage concept	SRE	4.2.3
	Plant operations strategy	Analysis	4.4.1
	Plant acoustics	Survey, analysis	4.4.2
Critical Experiment	Panel pressure, direct heat flux confirmation	Design, fabrication, and test	3.1
	High pressure air supply	Design, fabrication, and test	4.3.1
	Alternate critical experiment (if req'd)	Design	3.2.2
	Alternate turbomachinery (if req'd)	Design	3.2.2, 4.3.2
50 MWe Critical Module	System, plant	Preliminary design	3.3
	Capital cost reduction	Analysis	2.4, 4.4.3
	Turbomachinery	Preliminary design	4.3.2
	Storage pump	Preliminary design	4.3.3
Commercial Scale Plant	Conceptual design refinement	Analysis	5.2.1
	Capital cost · reduction	Analysis	2.5
	System alternatives	IR&D	2.6, App.

Note that Table 5.1.1-1 provides for an alternative experiment plant development in case the EPRI Experimental Plant is not constructed or is substantially delayed.

5.1.2 Phase II Schedule

Figure 5.1.2-1 shows the proposed schedule for Phase II activities along with major milestones. Results from the SRE's will be utilized in the preliminary and detail design activities.

5.1.3 Phase II Facilities Requirements

All the Phase II activities can be performed in available facilities. One SRE (heat exchanger panel direct flux impingement), and the critical experiment require use of STTF for two separate 2-month intervals. These would occur during July and August of 1979, and again in July and August of 1980.

5.1.4 Phase II Costs

The estimated total cost of the 21-month ACRPS Phase II program is $3,120,000. Of this amount, $1,290,000 would be required for the 9-month FY 1979 period, and $1,830,000 for FY 1980. Alternate costs for a development path independent of the EPRI Experimental Plant would be approximately the same. This path would result in a more costly Phase III, because of the deferral and increased scope of the critical experiment.

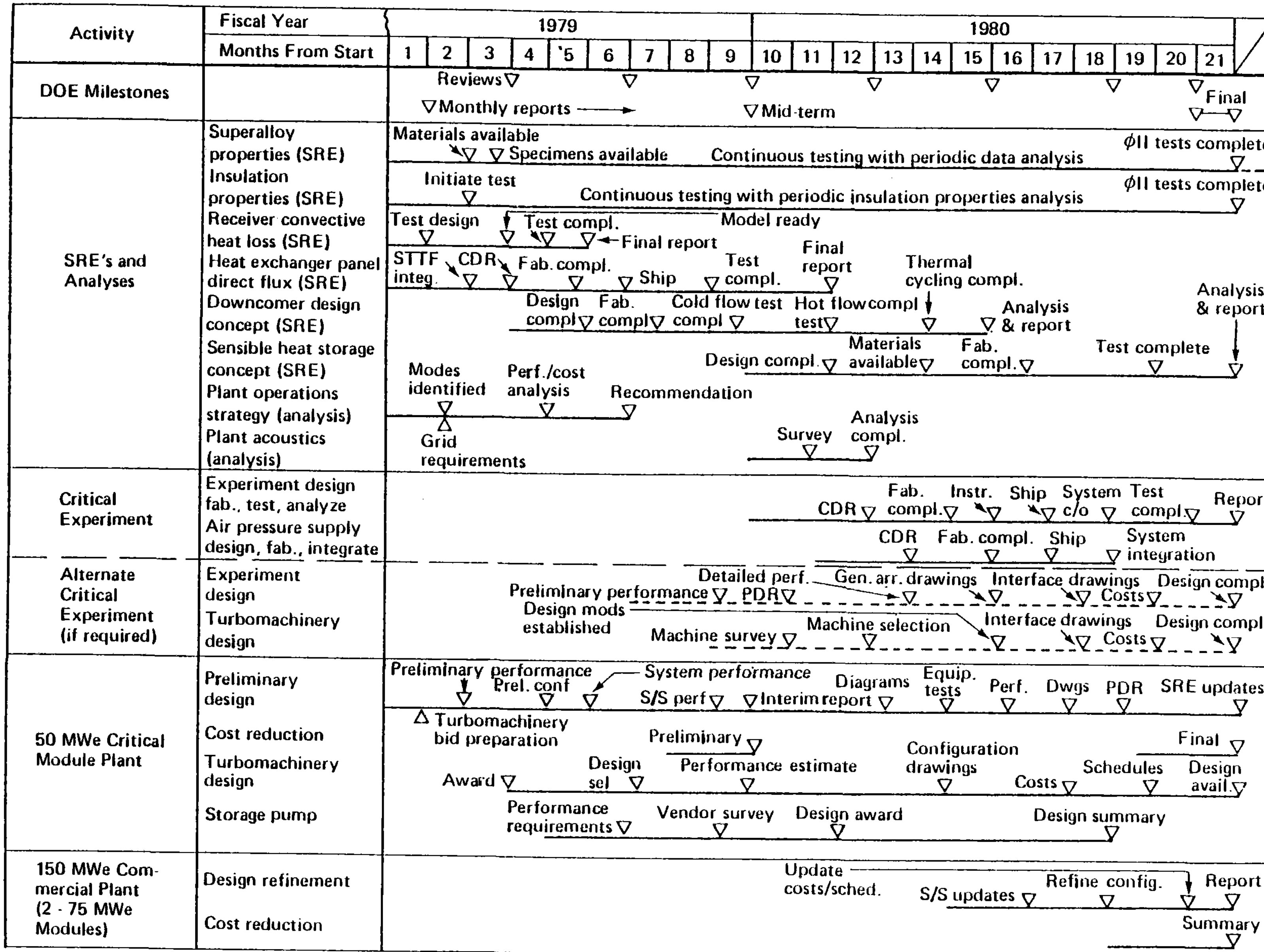


Figure 5.1.2-1. Phase II Activity Schedule

5.2 PHASE III

5.2.1 Phase III Activities

The approximately 21-month Phase III program period would be initiated following a successful DOE re-competition at the conclusion of Phase II activities. Phase III would include:

a. SRE's: Superalloy Properties (continuation from Phase II)

b. 50 MW Critical Module Activities:
   1. Siting analysis;
   2. Utility coordination and interfaces;
   3. EIS and certifications completion;
   4. Fabrication and construction planning;
   5. Critical module design and initial fabrication;
   6. Turbomachinery fabrication; and,
   7. Storage pump development.

c. $75MW_e$ Commercial Scale Plant Module Activities
   1. Plant refinements; and,
   2. Turbomachinery performance and plant integration

5.2.2 Phase III Schedule

The schedule for Phase III is indicated on Figure 5.2.2-1. Actual scheduling will be highly dependent on Phase II activities, particularly as a result of capital cost reduction studies and the selected turbomachinery development path.

5.2.3 Phase III Facility Requirements

All the facility requirements for Phase III are expected to be met by existing facilities at contractor/subcontractor plants.

5.2.4 Phase III Costs

Total costs for Phase III are expected to be approximately 34,000,000 assuming a go-ahead for turbomachinery

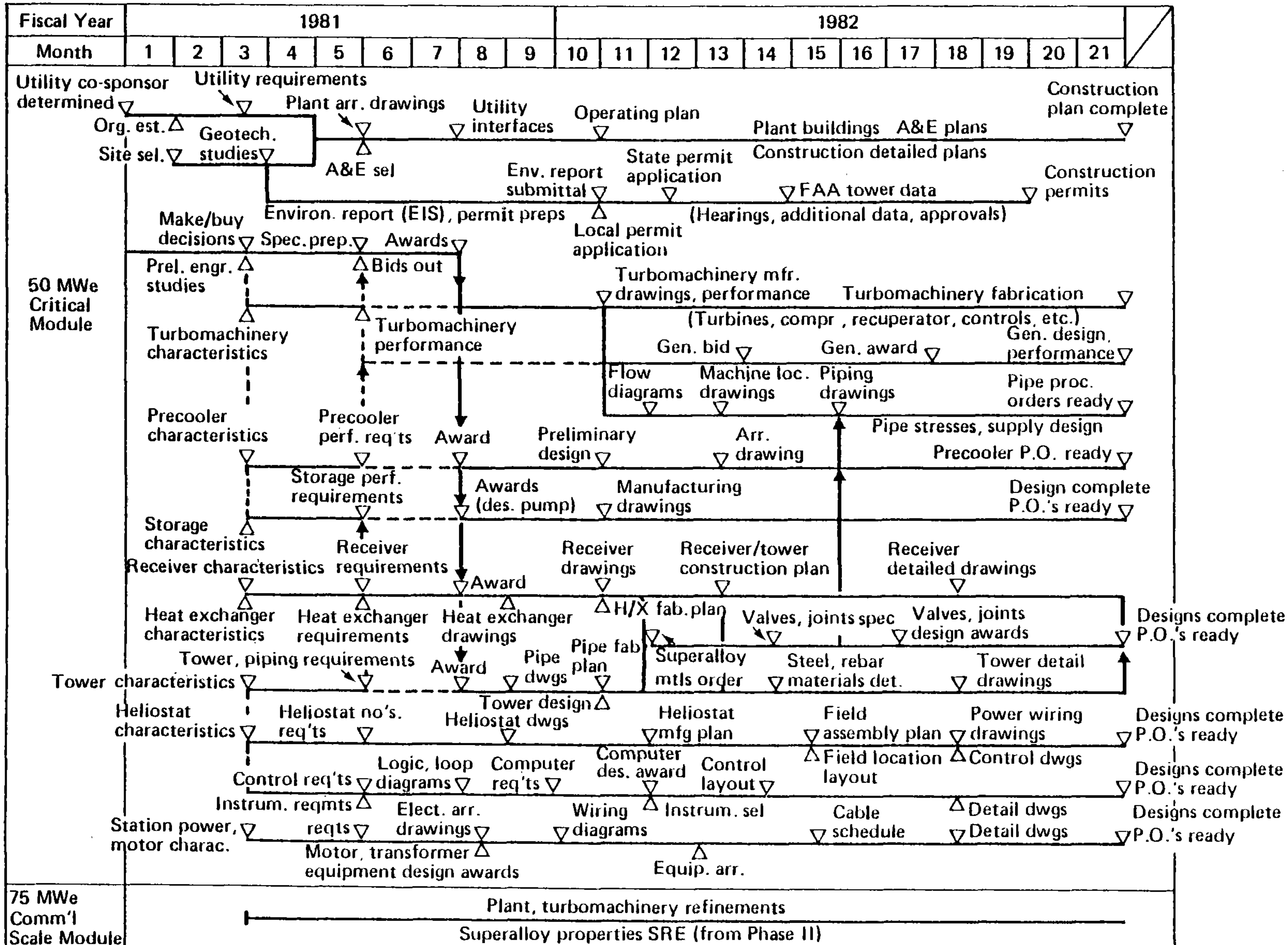


Figure 5.2.2-1. Phase III Activity Schedule

fabrication or modification, and the procurement of superalloy material for the receiver heat exchanger tubing. This cost is partitioned into an estimated $9,000,000 for FY 1981 (9-month period), and $25,000,000 for FY 1982. This funding schedule assumes that the heliostat development program will have matured to the point that adequate heliostats can be made available to the construction/installation schedule of Phase IV.

5.3 Phase IV

5.3.1 Phase IV Activities

Phase IV is approximately 3 years in length; it will include construction, test and checkout, and utility operation of the 50 MW_e Critical Module Plant. The primary activities in this phase are:

a. 50 MW_e Critical Module:

1. Fabrication of Subsystem Components;
2. Site Clearing, Excavation and Trenching;
3. Facility Construction (Receiver Tower, Cooling Tower, Collector Foundations, Turbine Building Administration Building, Visitors Control);
4. Receiver Construction and Piping Installation;
5. Heliostat Installation, Wiring and Alignment;
6. Storage Subsystem Installation;
7. Computer Instrumentation and Controls Installation;
8. Turbomachinery Tests and Installation;
9. System Check-Out and Test; and,
10. Utility Integration and Operation.

b. 75 MW_e commercial-scale plant module:

1. Module Preliminary Design;
2. Module Design; and.
3. Plant Certifications

5.3.2 Phase IV Schedule

Figure 5.3.2-1 shows the Phase IV schedule for the 50 MW_e critical module plant construction, and the design activities for

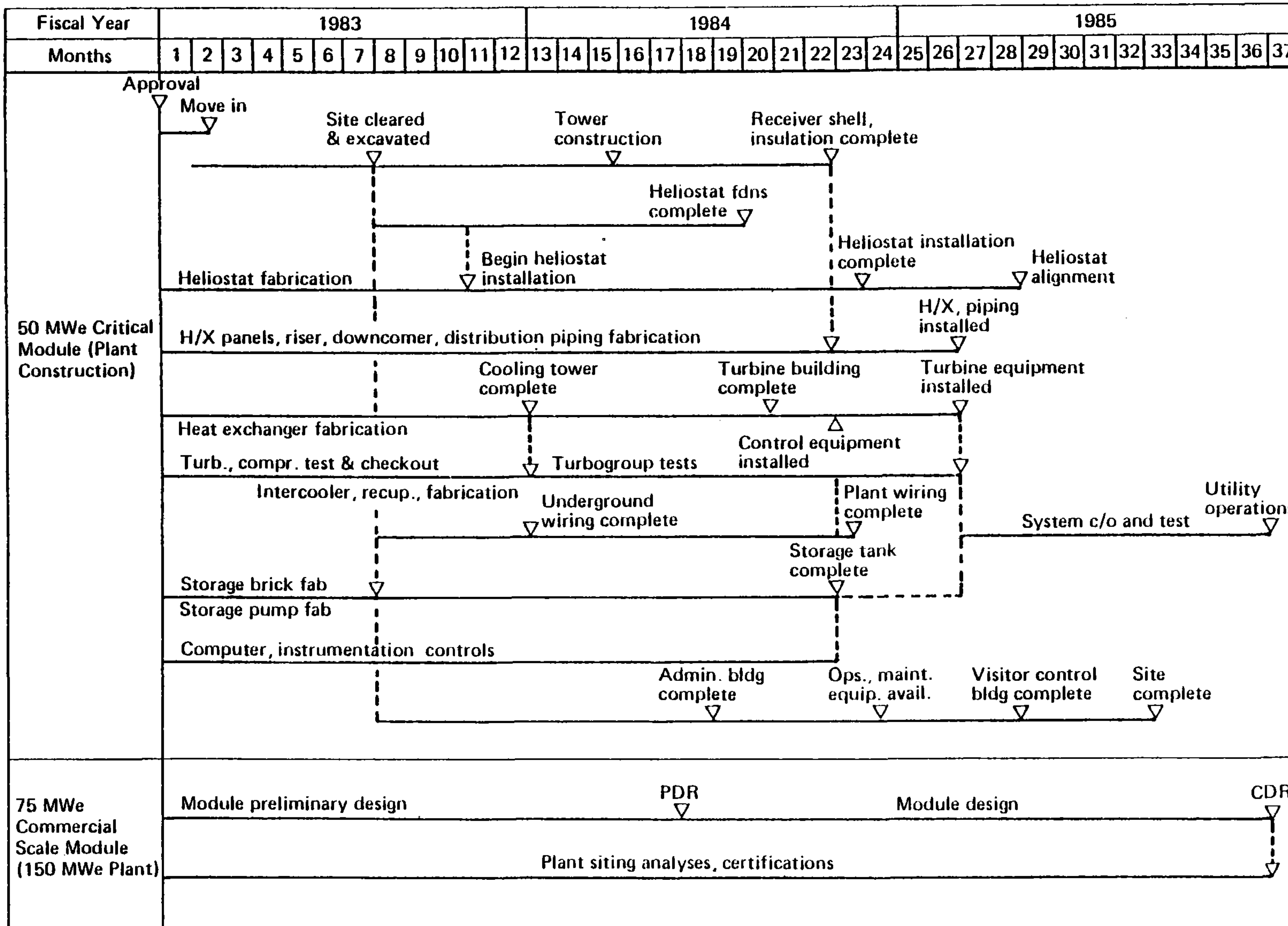


Figure 5.3.2-1. Phase IV Activity Schedule

the 75 MW_e preferred commercial-scale module. Fabrication of the latter plant would commence after utility acceptance of the 50 MW_e critical module at the end of Phase IV; it would be completed in FY 1989. The option exists any time during Phase IV to initiate construction of an adjacent 50 MW_e critical module to have a 100 MW_e ACRPS plant. This could be achieved in approximately 8-12 months after go-ahead by moving crews from one module to the other.

5.3.3 Phase IV Facility Requirements

Facility requirements would be determined during Phase III. The major facility required is a heliostat manufacturing plant and this depends on the choice of heliostats.

5.3.4 Phase IV Costs

The total cost for Phase IV activities is estimated to be $127,000,000. This figure includes $3,000,000 for design work on the 150 MW_e preferred ACRPS commercial plant (2-75 MW_e modules). The 50 MW_e critical module plant is estimated to cost $81,500,000 (direct costs and labor) and $42,500,000 for distributable and indirect costs. These values were pro-rated from the 150 MW_e ACR Power System Commercial Plant account structure furnished by Stone & Webster Engineering Corporation, Denver Operations Center. $14,500,000 of cost has been scheduled for expense in Phase III for turbomachinery fabrication ($13,000,000) and advanced superalloy material purchase ($1,500,000) due to the long-lead requirements. Expenditures by fiscal year as estimated are:

FY 1983	-	$50M
FY 1984	-	$46M
FY 1985	-	$31M

5.4 SUMMARY COST ESTIMATE

The total development program estimated costs as itemized in the previous subsections is $164,300,000. The fiscal year costs are summarized in the table below:

Table 5.4-1: ACRPS DEVELOPMENT PROGRAM EXPENDITURE SCHEDULE

Fiscal Year	Phase	Months		Costs (M)*
1979	II	9		$ 1.3
1980	II	12		1.8
1981	III	9		9.0
1982	III	12		25.0
1983	IV	12		50.0
1984	IV	12		46.0
1985	IV	11		31.0
			TOTAL	$164.1M

*1978 constant $'s

SECTION 5

REFERENCES

The following references are cited by the two-digit section number where they are used in the text.

2.1-1 Robert W. Hughey, "Solar Thermal Power Systems Multi-Year Program Plan", Draft Review Plan of April 14, 1978, to Donald D. Cox, Boeing Engineering and Construction, received August 18, 1978.

2.1-2 Robert Tomihiro, "Alternate (Advanced) Central Receiver Power Systems Program: Instructions for Preparation and Submission of Phase II Technical and Cost Proposals," Department of Energy, San Francisco Operations Office, Letter to E.J. Valley received August 7, 1978.

2.1-3 S. Douglass Elliott, "Preproposal Conference for RFP No. ET-78-R-03-2051, Solar Central Receiver Hybrid Power System," Department of Energy, San Francisco Operations Office, Letter to Boeing Engineering and Construction received May 26, 1978.

2.1-4 "Conceptual Design of Advanced Central Receiver Power Systems", RFP No. EG-77-R-03-1483, U.S. Energy Research and Development Administration, San Francisco Operations Office.

2.1-5 "Solar Central Receiver Hybrid Power System", RFP No. ET-78-R03-2501, Department of Energy, San Francisco Operations Office.

4.1-1 John R. Gintz, "Closed-Cycle, High Temperature Central Receiver Concept for Solar Electric Power", EPRI ER-629, Final Report prepared by Boeing Engineering and Construction, January, 1978.

APPENDIX A

BRAYTON CYCLE ADAPTABILITY

Section 2.6 discussed the advantages and versatility of the Brayton cycle in general terms. This Appendix is intended to show how the Brayton cycle can be adapted to other uses. (DOE decisions after Phase II might eliminate the storage coupled ACRPS from further consideration but retain the Brayton cycle as a viable technology option). Figure 2.6-1 shows one option which combines the advantages of the closed gas cycle for the receiver with use of existing turbomachinery (the dual-loop cycle). Alternate uses as a fossil-fuel hybrid plant and as a combined Brayton/Rankine cycle plant are illustrated on the figure.

The EPRI 1.5 MW_e Experimental Plant discussed in Section 3.2.1 is illustrative of hot gas receiver system used as a hybrid plant. Such an application uses available low-cost turbomachinery in an open-cycle air system, suffering a penalty in efficiency. However, a plant of this size could also be configured as a storage-coupled plant by designing the receiver to accept a higher thermal input, adding more heliostats, and integrating an appropriate storage system.

Another alternative for open cycle systems is to make further use of the stack gas (recuperator exit) to generate steam (or organic vapor) to drive a turbine. Addition of a combined cycle can produce an additional 30 to 75% electrical power. The higher value is obtained by supplementary firing of the exhaust gas. For combined cycles, the efficiency of the gas turbine cyle becomes less important. Efficiencies obtained can be raised to 35-40% over the 25-35% over simple open-cycle gas turbines. Figure A-1 shows unfired and supplementary and supplementary fired versions of an open Brayton cycle solar hybrid plant as it might be used, for example, in repowering an existing steam plant. For a new construction,

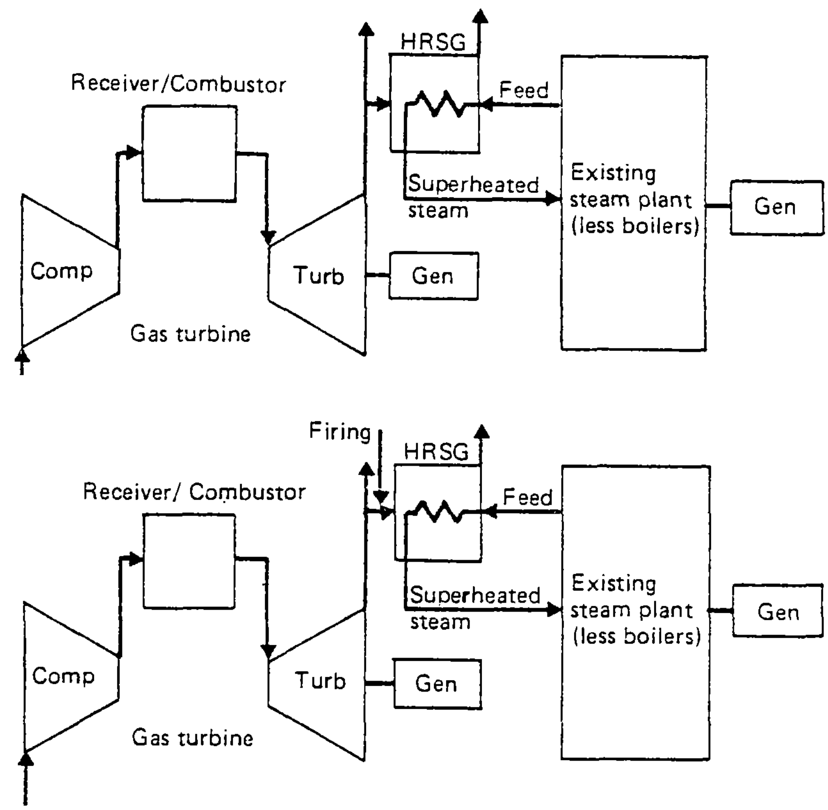


Figure A-1. Unfired and Supplementary-Fired Open Brayton/Steam Combined Cycle Plants

the block titled "Existing Steam Plant (less boiler)", would be replaced by a steam turbine set.

An efficient single cycle solar hybrid plant utilizing the closed Brayton cycle conversion process is shown schematically on Figure A-2. This plant would operate at an efficiency of 40-43% and adapt to firing coal, oil, or gas in the fossil fuel mode.

The closed Brayton cycle also can be easily adapted to use in a combined cycle either as a storage-coupled plant or as a hybrid. Thermodynamic cycle efficiencies obtained would be in the 45-50% range. Figure A-3 shows the schematic of such a hybrid cycle.

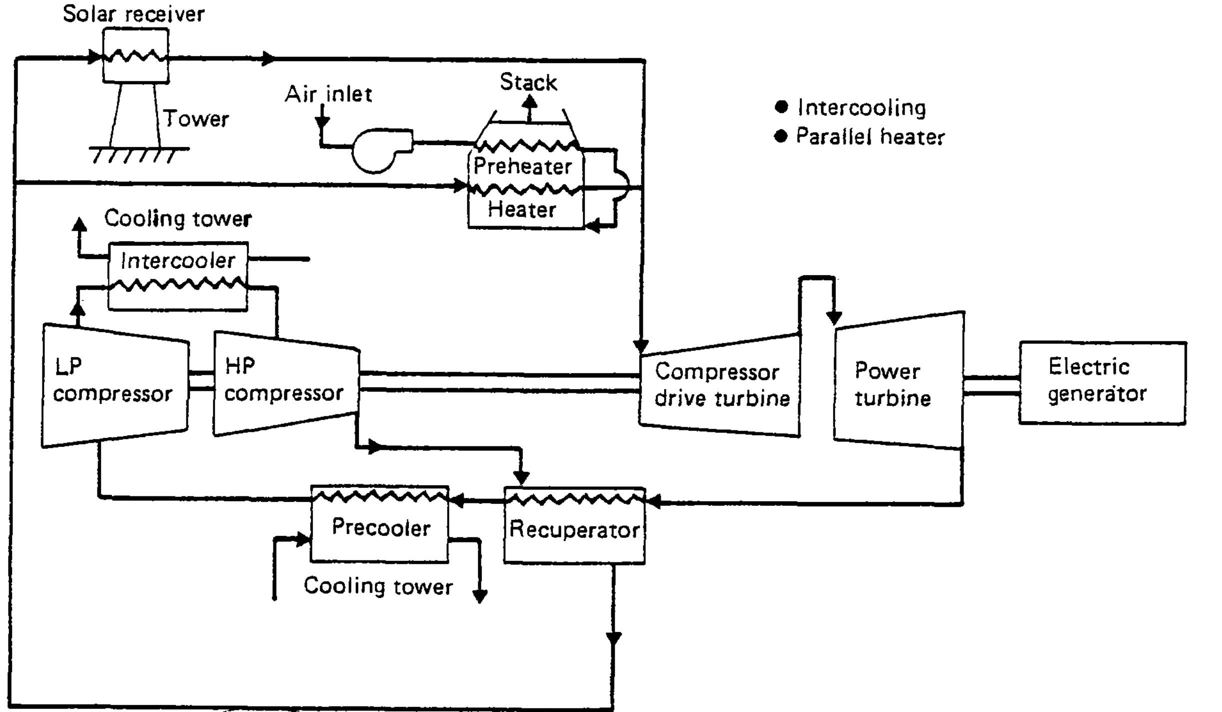


Figure A-2. Baseline Solar Hybrid Power Conversion System

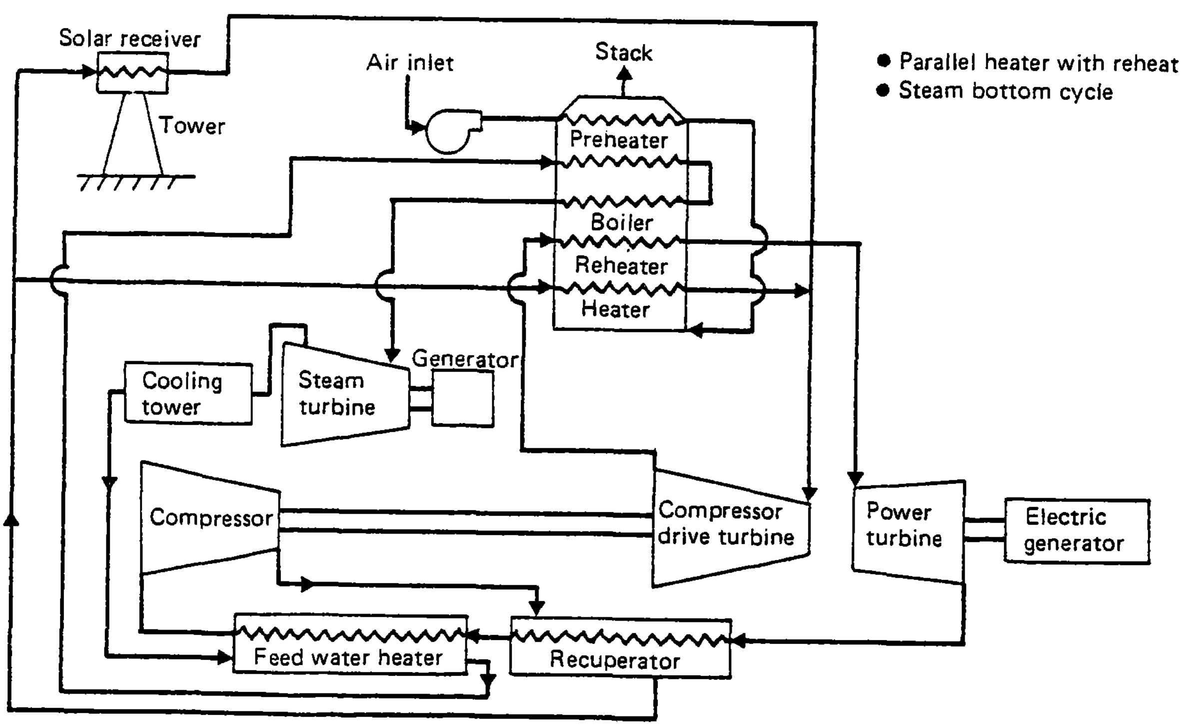


Figure A-3. Closed Brayton Cycle/Steam Combined Cycle Concept

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