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MASTER

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Special Report
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Prepared by
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Santa Clara, California

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ELECTRIC POWER RESEARCH INSTITUTE

PROCEEDINGS OF SEMIANNUAL EPRI SOLAR PROGRAM REVIEW MEETING AND WORKSHOP

EPRI ER-371-SR

Special Report

Falmouth, Massachusetts
October 6-8, 1976

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ABSTRACT

The Electric Power Research Institute has funded an extensive program in solar energy R&D in order to define and develop those solar energy systems which yield the lowest cost, when integrated with utility networks, and to define the impact of solar energy system interactions with these networks. During the week of March 8-12, 1976, EPRI sponsored the first semiannual Program Review Meeting and Workshop in San Diego, California. The second meeting was held in Falmouth, Massachusetts on October 6-8, 1976. The proceedings of the first meeting were published as report EPRI ER-283-SR Volumes I and II. The present report constitutes the proceedings of this second meeting. The first part is concerned primarily with solar heating and cooling and the second part with solar electric power and environmental impact of various solar plants.

TABLE OF CONTENTS

INTRODUCTION

Many if not most solar energy utilization systems being considered at present will have to be connected to the utilities in some way. If solar heating and cooling systems of buildings fail to provide comfort due to extended bad weather, it may be most convenient to use the utilities as a backup power supply. If solar energy is used to produce electrical power, the electric network of the electric power utilities is almost certain to be used to distribute solar electric power produced in central power plants, or as a backup for dispersed local solar electric power systems.

Diurnal and seasonal fluctuations in loads have historically been one of the most troublesome problems facing the electric utilities. One can not invest in a power plant of maximum efficiency if the very high capital cost associated with such a plant is to be useful only for satisfying power peaks existing a small fraction of the time. The most efficient power plants are also not generally suited for peaking service, since they take a long time to bring on line. The plants used for peaking are (except for hydroelectric plants) cheaper to buy but significantly more expensive to operate.

If solar energy systems are designed and implemented in such a way as to reduce the power peaks in the utility network, they will save more fossil fuel, and be more effective in reducing energy costs. If on the other hand solar energy systems are designed in such a way as to reduce the base loads in an electric power network, but to impose enormous power peak requirements in times of some weather conditions, it is quite clear these systems would produce many problems. There is a great incentive to encourage solar energy systems which are preferred in this regard, and to develop a full awareness of the harmful implications of those systems which are not preferred. We are faced with the energy problems of society: if costs are imposed through bad design someone will have to pay them.

The Electric Power Research Institute has a significant research program in solar energy. The objectives of the program are as suggested above: to define and develop those solar energy systems which seem most promising when examined in the light of total economics, and to identify those solar energy systems which will impose serious economic problems. Work is being sponsored both in the Solar Heating and Cooling of Buildings (SHACOB), and in solar electric power production. It should be noted that many regional questions are involved in this program. The climate, the utility customers, and the time schedule and magnitude of power consumption fluctuations all vary from place to place.

The U.S. Government (primarily the Energy Research & Development Administration) has a major program in solar energy R&D aimed at a somewhat different set of questions. There has been a continuing effort to coordinate the EPRI program with the work being sponsored by ERDA.

The EPRI Solar Energy Program started approximately two years ago. During the week of March 8-12, 1976, EPRI sponsored a review meeting and workshop for the Solar Energy Program in San Diego. That was the first semiannual meeting, aimed at reviewing current work, planning future work, and at allowing all the contractors to gain familiarity with and contribute to the overall EPRI Program. The second meeting, of which the present report constitutes the proceedings, was held in Falmouth, Massachusetts, October 6-8, 1977.

The contractors were asked to supply camera-ready copy of their visual aid material, and an accompanying discussion suitable for preparing a set of proceedings of the "landscape" type. The coordination of the meeting and the editing of the proceedings was done under contract by the Altas Corporation.

Questions regarding the work can be directed to the individual authors or to EPRI. Questions regarding future meetings should be directed to EPRI.

OPENING STATEMENT AT THE MEETING, By Piet B. Bos, Manager of the Solar Energy Program of EPRI

Good Morning.

It is a pleasure for me to welcome you to this semiannual EPRI Solar Program Review Meeting and Workshop.

For those of you not familiar with the Electric Power Research Institute, this Institute was established by the electric utility industry in January, 1973, for the purpose of doing electric energy research and development under the sponsorship of the nation's utility industry. Its goal is to develop a broad, coordinated advanced technology program for improving electric power production, transmission, distribution and utilization in an environmentally acceptable manner.

The Electric Power Research Institute budget for 1976 is approximately 130 million dollars with funding provided by voluntary contributions from public and private utilities across the nation. There are more than 500 member organizations supporting the EPRI program. These utilities account for more than 80% of the electric power generating capacity of the nation. The EPRI research programs are closely coordinated with parallel efforts of federal agencies such as the Energy Research and Development Administration, NASA and others.

The EPRI solar energy program is complementary in nature to the ERDA program and emphasizes those aspects of solar energy research and development requiring utility interfacing and for covering such areas that we feel need additional emphasis. The EPRI Solar program parallels the ERDA programs to incorporate research and development in solar heating and cooling of buildings, solar thermal conversion, photo-voltaic energy conversion, wind energy conversion, environmental impact assessment, materials and components testing as well as technical assessment of new and innovative approaches.

The EPRI solar program objectives are to make an independent assessment of solar energy applications; to make a comparative evaluation of alternative concepts; to inform the utility industry of the potential and credibility of solar applications; and to set project priorities for demonstration of preferred systems which have wide geographic applicability. The program thrusts are to establish the preferred roles of alternative solar applications; to establish system requirements and to evaluate the impact on the electric utility industry; to conduct selective subsystem and system experiments of preferred systems; and to develop materials and components performance data necessary for reliable and economic operation of such systems. Furthermore, independent evaluation of the available insolation is to be assessed by a utility network of measurements; and finally the program will incorporate a flexible budget to provide for new and innovative approaches that were not previously identified in the program plan.

Because technical feasibility of many solar energy systems has been demonstrated one could raise the question why so much money is expended on solar energy technology without significant application in the near term. The problem is primarily one of economics and reliability. Even though solar energy is an intriguing and promising alternative to supplement the nation's power generating system because it is virtually inexhaustible, is widely distributed and is not expected to introduce major environmental problems, it has two major drawbacks. The first relates to the diffused nature of solar energy, making solar energy systems capital intensive, requiring long operating lifetimes (15-30 years) for amortization. The second problem is related to the intermittent nature of solar energy, requiring all solar applications to incorporate energy storage. Because of the high cost of energy storage, the amount of storage for solar systems applications is limited, consequently, solar energy systems inherently have a low reliability of operation as compared to conventional power sources.

Conventional power sources, in addition to scheduled outages for maintenance, incur unscheduled outages due to component failures on a statistical basis. Solar energy systems for electric power generation have, in addition to component failures which occur on a statistically random basis, unscheduled outages due to cloud cover which have a high correlation from one power plant to the next. Consequently, when such solar systems are incorporated into a utility grid network, such systems must be backed up by conventional power systems to provide for the same overall high reliability characteristic of the electric power delivery. This reliability criterion is expressed by a loss of load probability (which occurs when the generation capacity is insufficient to meet the electric power demand). When solar energy systems with a highly correlated outage due to cloud cover are incorporated into a utility grid network, the amount of solar capacity is limited to only fifteen to twenty % of the total installed capacity in order to maintain the same reliability as conventional systems. Furthermore, because of the high cost of energy storage, such solar power plants are anticipated to operate only during the daytime hours (intermediate load applications). In summary, a major objective of the EPRI program is thus to develop solar power plants that have capacity displacement in addition to energy displacement.

The solar electric power system requirements, consequently, are to displace scarce energy resources, such as gas and oil, while incorporating sufficient energy storage such that solar power plants have capacity displacement. As such total capital investment is minimized by reducing the requirement for conventional power plant backup. Furthermore, because of the capital intense nature of solar energy systems, long operating lifetimes are required for capital payback, as well as high reliability of operation characteristic of conventional power plants. A final requirement is to minimize the environmental impact due to electric power production, by incorporating solar energy systems.

These requirements are considered for each of the solar energy alternatives for the production of electric power. Within this electric utility framework a summary of the key issues, problems and projected potential for each of the four major solar energy alternatives can be provided.

The reasons for this semi-annual program review and workshop format are to bring together the EPRI contractors, review committees, utility sponsors and invited federal and state representatives for the purpose of:

(1) detailed quarterly review of each EPRI contractor by the review committee in one location to economize on time and travel expenses
(2) to communicate to our utility sponsors the objectives and accomplishments of the EPRI solar program
(3) to inform the federal and state representatives regarding the interests and concerns of the utility industry regarding the potential of solar programs
(4) to exchange information between the various contractors
(5) to meet with the EPRI Solar Program Committee and the Eastern and Western Solar Working Groups.

The format of the meeting is to have formal (mostly one hour) briefings by each of the

EPRI contractors in the morning; and informal detailed quarterly project reviews with individual contractors in the afternoon (as indicated on a separate program schedule).

The latter review meetings will be restricted to the individual project contractor and review panel members to keep the meeting small and effective.

We are interested in your comments and/or suggestions on the meeting, format, location, etc. A form has been provided for this purpose.

In addition, to obtain inputs regarding specific EPRI projects or contracts or the overall EPRI solar energy program from those who are not part of any review or program committee, two types of forms have been provided. The first form can be given to the project manager and the second to the Program Committee Chairman, Dr. Val Finlayson.

I hope that you will find this meeting to be informative and to achieve the objectives that I have set forth, namely:

(1) to communicate the information derived from the various EPRI solar projects and contracts

(2) to effectively interface with our counterparts in the federal and state programs

as well as

(3) to conduct effective quarterly review with our contractors.

SECTION 3

EPRI CONTRACT RP 553

SOLAR HEATING AND COOLING OF BUILDINGS REQUIREMENTS DEFINITION AND IMPACT ANALYSIS

THE AEROSPACE CORPORATION

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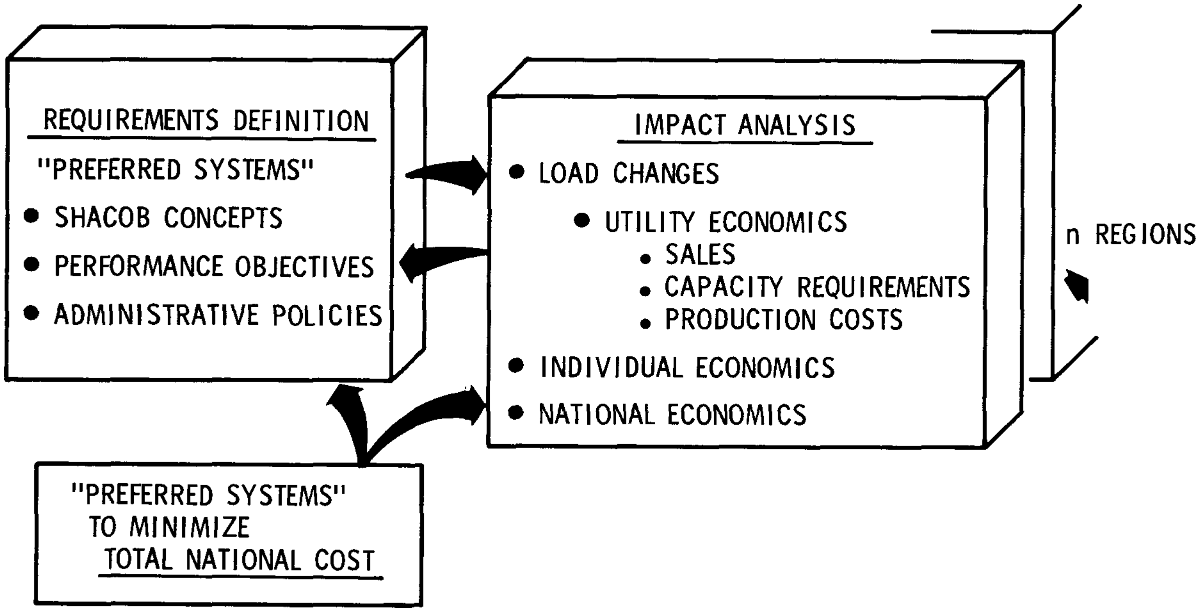
OCTOBER 1976

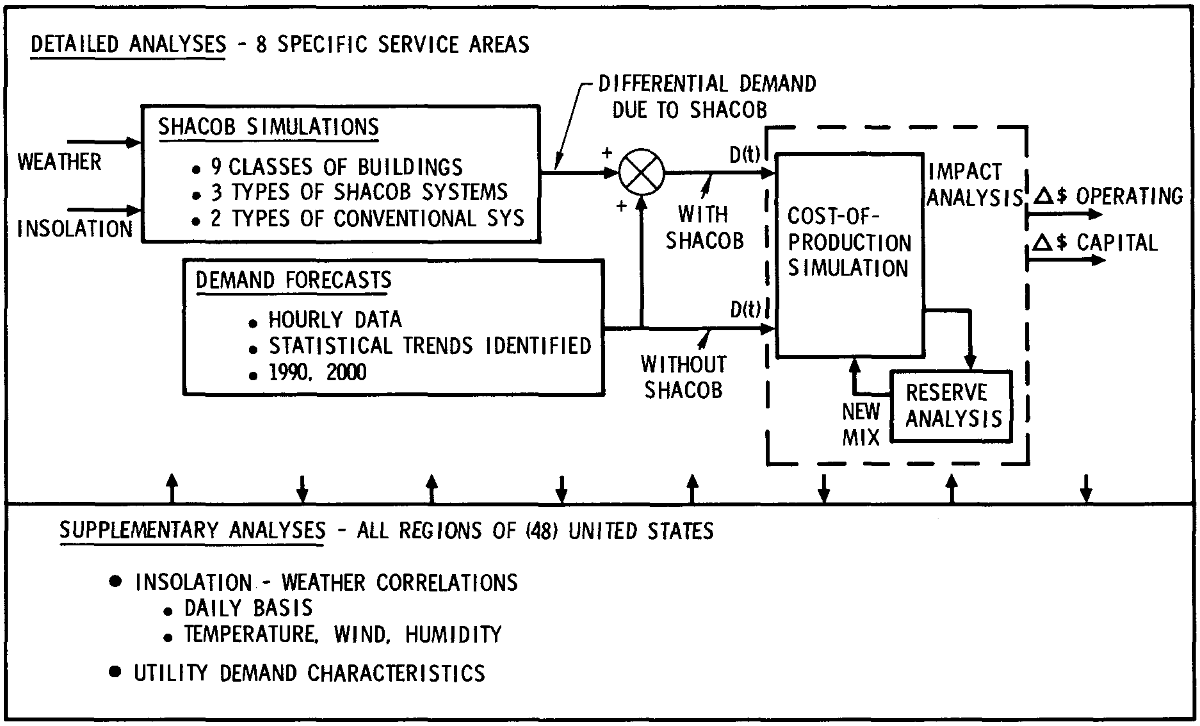
EPRI SOLAR REVIEW MEETING #2



OVERVIEW

There are two main thrusts to this SHACOB study: (1) Defining the preferred SHACOB concepts and their operating performance objectives and nominal design parameter values (a workable concept can have a reverse effect if poorly designed) and (2) analyzing the economic and technical impact on the utilities in particular and the nation in general. The two parts are coupled together, of course. The impact analysis will lead to modifications of the definition of preferred systems. The impact analysis, especially regarding the utility impact, will be done for each region of the country, and is to be predicted out to the years 2000+. There are many fold criteria for the "preferred" systems but the single paramount criterion is that the impact must be minimized in terms of total national cost.

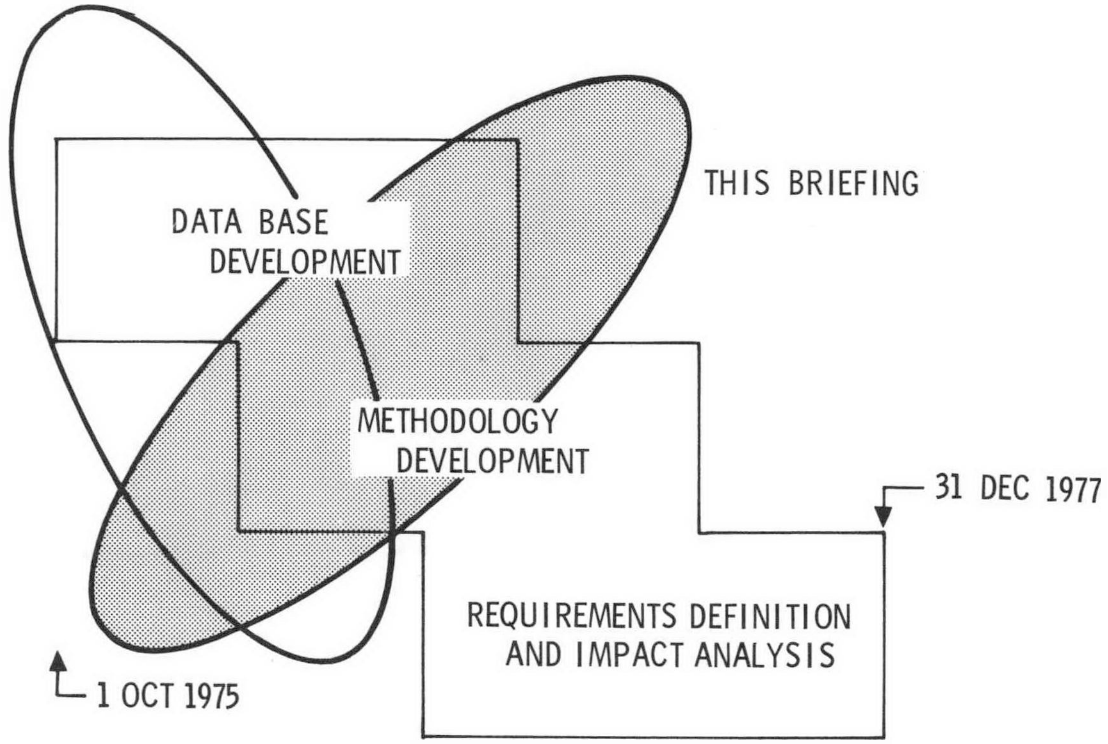
SHACOB
Study Approach



The analysis of the impact of SHAC systems on generating capacity requires detailed calculations on an hourly basis. The changes that occur in the hourly demand due to SHAC systems must first be determined, followed by an analysis of changes in production costs and reserve capacity requirements.

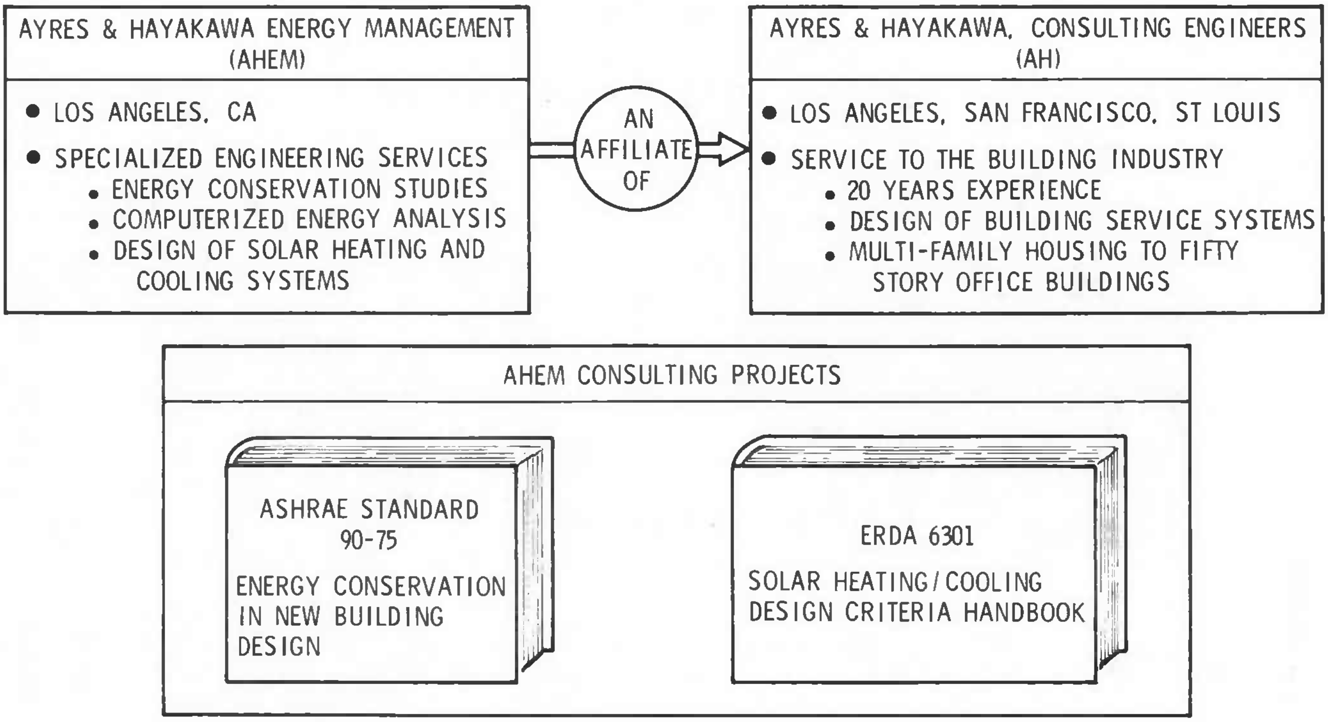
Detailed calculations for at least eight geographic locations around the country are being undertaken for nine basic building types (single family, multiple family, retail store, etc.) three types of SHAC systems (direct solar heating, solar assisted heat pumps, and solar absorption cooling) and both electric resistance and heat pump conventional systems. Subsequently demand forecasting, simulation of dispatching operations, reserve analysis and economic impact analysis will be performed for a specific utility at each geographic location selected.

In addition to these detailed hourly analyses, other parallel analyses of insolation, weather, and demand characteristics are also to be performed to aid in the extrapolation and extension of the detailed analyses to other regions.



The study is technically phased in three sections which overlap somewhat in time: (1) Data Base Development, (2) Methodology Development, and (3) the analysis phase, "Requirements Definition and Impact Analysis," which is the eventual objective of the study as defined on an earlier chart.

These three phases are interrelated, of course. For example, the data base must to some extent reflect the methodology that is developed. The remainder of this report addresses the plans and progress that have been made in the data base development and methodology development areas.



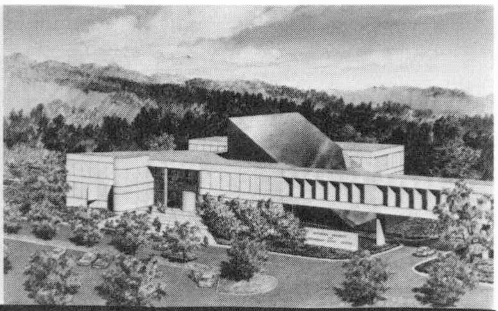
The computation of the change in diurnal load patterns (as a function of geographic region and season) requires the analytic definition of a variety of building types and SHACOB system types in enough detail to produce reasonable accuracy. The definition of the set of buildings in terms of their HVAC parameters, and the nominal selection and definition of their supporting SHACOB and conventional systems will be based on reference systems defined by Ayres and Hayakawa Energy Management under subcontract to the Aerospace Corporation.

Ayres & Hayakawa Energy Management (AHEM) is an affiliate company of Ayres & Hayakawa (AH), a nationally prominent consulting engineering firm specializing in the design of mechanical and electrical building service systems. AHEM was organized as a separate California Corporation in 1974 to offer specialized engineering services in computerized building energy studies, solar heating and cooling of buildings, and the implementation of advanced energy management techniques to conserve management techniques to conserve energy usage in buildings. J. Marx Ayres, President of AHEM, has served as a member and section head of various ASHRAE Research and Technical Committees. Mr. Ayres was also on the panel responsible for the development of the ASHRAE Standard 90-75. Currently, AHEM is a consultant in the preparation of the ERDA 6301 Solar Heating/Cooling Design Criteria Handbook governing the design of ERDA facilities.

SHACOB
AHEM Solar Design Projects

- SOLAR ENERGY COLLECTION & CONVERSION SYSTEM

(Banco Industrial de Cataluna-Barcelona, Spain)

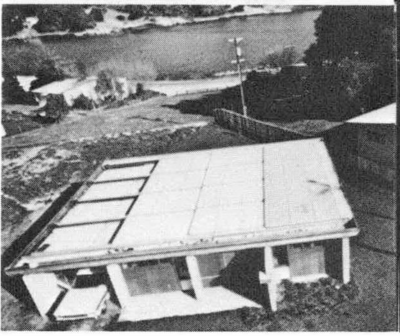


- NATIONAL SECURITY & RESOURCES STUDY CENTER

(Los Alamos Laboratory - Los Alamos, N.M.)

- REHABILITATION & TESTING OF SKYTHERM HOUSE

(ERDA-Atascadero, Ca)



- FOREST SCIENCES LABORATORY

(U.S. Forest Service - Fresno, Ca)

- LABOR TRAINING FACILITY

(Labor Training Fund - Hemet, Ca)

AHEM has participated in a number of major solar design projects in varying levels project responsibility. Representative solar design projects are described below.

The National Security and Resources Study Center is a three story 66,000 sq. ft. building that will serve as a technical library and conference center for the Los Alamos Scientific Laboratory. The solar augmented HVAC system with an 8,000 sq. ft. south facing 35° elevation solar collector, integrated into the roof structure of the building, will provide 87 percent of its annual heating and cooling needs. The AHEM/AH team designed the mechanical electrical systems for the building, and prepared a detailed study of the required instrumentation/data acquisition systems for the project. The fully instrumented project is 90 percent complete and will serve as an ERDA demonstration project on the use of solar energy in large commercial buildings.

AHEM is engineer-architect for the rehabilitation and testing of the Skytherm house in Atascadero, California. This requires the preparation of construction documents and direction of the repair and rehabilitation of this innovative "passive" solar heating and cooling system. The project also includes the conduct of a performance monitoring test to gather data from the instrumented house for comparison with computer models that predict thermal performance.

AHEM designed a solar heating and cooling system to serve as an experimental demonstration project incorporated into the new nine-story office building for the Banco Industrial de Catalina in Barcelona, Spain. The resulting design utilized 3,000 sq. ft. of collector area placed on the southern exposure of the sloping wall areas on the ninth floor of the building. All of the systems are designed to function independently for experimental purposes or augment the main building heating and chilled water plant. A computerized data acquisition system is provided to gather, verify, and record data.

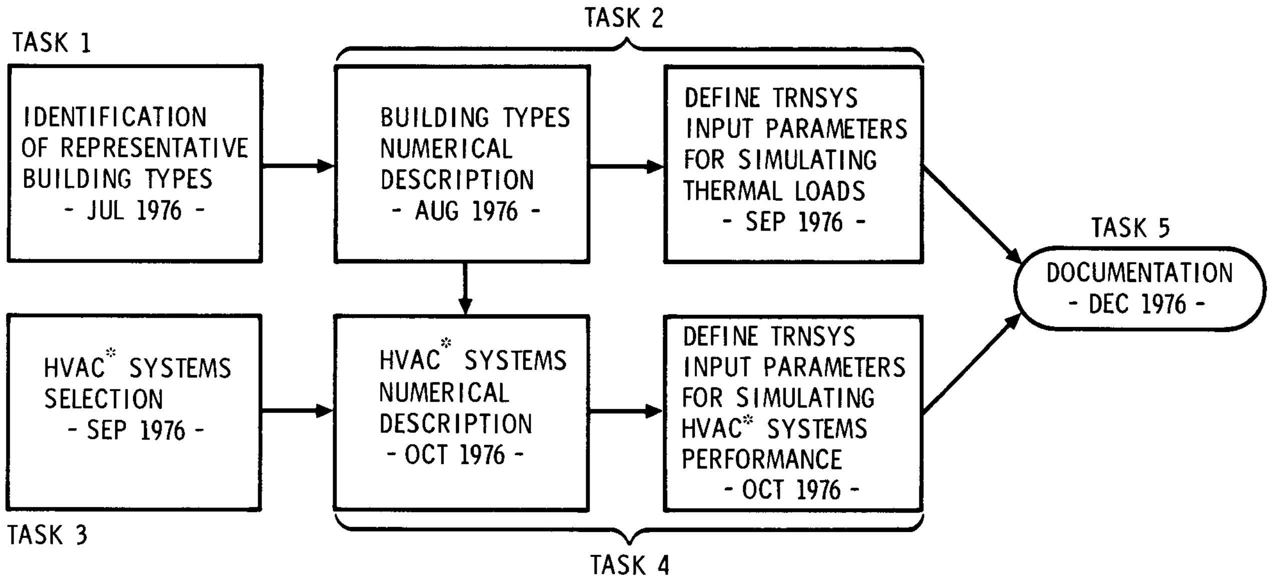
AHEM is also solar systems consultant for the design of the solar heating and cooling system in a 15,000 sq. ft. U.S. Forest Service laboratory in Fresno, California, and a 60,000 sq. ft. labor training complex in Hemet, California.

SHACOB

- SCOPE

IDENTIFY AND QUANTIFY A COMPREHENSIVE MIX OF BUILDINGS AND HVAC* SYSTEMS REPRESENTATIVE OF THE 1990-2000 AD TIME FRAME FOR THE PURPOSE OF ASSESSING THE AGGREGATE UTILITY DEMAND IMPACT

- TASKS



* Solar and conventional

The AHEM study addresses the following tasks:

Task 1: A span of building design types encompassing the nine basic categories will be identified and supported with narrative rationale.

Task 2: Baseline numerical values for the building design parameters will be developed for each building type and climatological region. The span of likely parameter variations about the discrete values selected will also be determined. The parameters defined will be consistent with the input requirements for the simulation of thermal loads using the TRNSYS program.

Task 3: For each of the building types identified above reasonably applicable SHACOB systems will be selected. Hot water systems will be included. Appropriate conventional systems will also be selected.

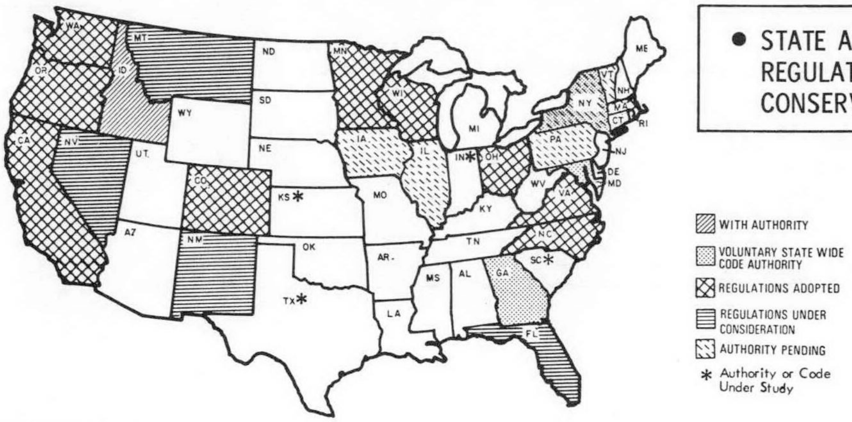
Task 4: Baseline numerical values will be developed for the SHACOB system designs associated with each baseline building design in each climatological region. The span of likely parameters variations about the discrete values selected will be determined. The parameters defined will be consistent with the input requirements for the TRNSYS simulation of heating and cooling systems performance.

Task 5: Presentation, explanation and discussion of all information developed in these tasks will be provided in a formal final report in December 1976.

• ASHRAE 90-75

- ENERGY CONSERVATION DESIGN CRITERIA FOR NEW BUILDINGS
- PRESCRIPTIVE AND PERFORMANCE REQUIREMENTS
- SPECIFIES MAXIMUM THERMAL TRANSMITTANCE VALUE FOR HEATING FOR EXTERIOR WALLS, ROOFS, SLABS & FLOORS
- FOR NON-RESIDENTIAL BUILDINGS SPECIFIES OVERALL THERMAL TRANSFER VALUE FOR COOLING

• STATE AUTHORITY TO REGULATE BUILDING ENERGY CONSERVATION (1976)



ASHRAE Standard 90-75, "Energy Conservation in New Building Design" was produced after over two years of formulation and review effort, by a multi-disipline panel representing the building construction industry. ASHRAE 90-75 is currently being implemented as an ANSI National Standard. Several Federal governmental agencies have incorporated ASHRAE 90-75 in their new construction specifications as a minimum requirement. Both prescriptive and performance requirements are included in ASHRAE 90-75. Over 30 states have already utilized ASHRAE 90-75 as a guideline for the formulation of building energy conservation regulations for new construction.

SHACOB
Key Assumptions for Selecting and Defining Reference Buildings

- BUILDING TYPES AND CHARACTERISTICS
  - NEW CONSTRUCTION WILL CONFORM TO ASHRAE 90-75
  - SHACOB RETROFIT IMPACT ON 1990-2000 AD BUILDING INVENTORY WILL NOT BE SIGNIFICANT
  - SPECTRUM OF AVERAGE BUILDING TYPES WILL BE DETERMINED FOR RESIDENTIAL STRUCTURES
  - AVERAGE BUILDING CONCEPT NOT APPROPRIATE FOR THE HIGHLY DIVERSE TYPES OF NON-RESIDENTIAL STRUCTURES
- REGIONALIZATION
  - BY ANNUAL HEATING DEGREE DAYS FOR ASHRAE 90-75 APPLICATION
  - BY CENSUS AREAS FOR CONSTRUCTION STATISTICS
  - IMPACT ON RESIDENTIAL BUILDING DESIGN WILL BE INCLUDED

The building occupancy categories to be considered include:

- <u>Residential</u>

  Single Family: Detached
  Single Family: Attached
  Multi-Family: Low Rise
  Multi-Family: High Rise

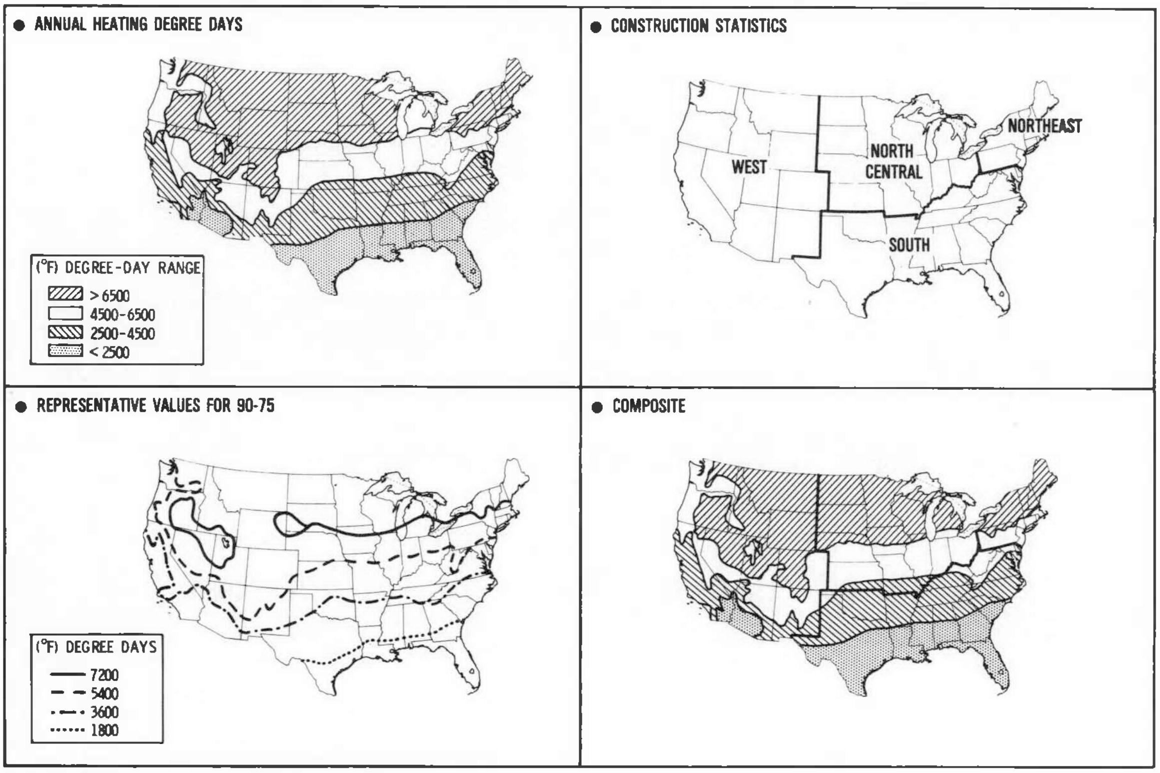
- <u>Non-Residential</u>

  Office
  Retail Store
  Shopping Center
  Schools
  Hospitals
  Motel
  Light Industrial

Certain basic assumptions were made to define a set of reference buildings representative of the various building categories: First, based upon the general acceptance of ASHRAE Standard 90-75, all new construction was assumed to conform with ASHRAE Standard 90-75. Next, an implicit assumption, that the retrofit of existing buildings for space heating and cooling will not have a significant impact on the 1980-2000 building inventory, was made based upon the projected high initial costs associated with retrofit application. However, retrofit application of solar domestic water heating was assumed to be significant during the next 15-25 years.

Sufficient statistical data for residential new construction is available from census tabulations to define a spectrum of average residential buildings. However, a comparable data base does not exist for the diverse types of non-residential buildings. Thus, the average building concept was deemed not appropriate for the non-residential sector and a single representative building was defined for each of the non-residential categories.

SHACOB Regionalization



Since the building insulation requirements of ASHRAE 90-75 are presented as a function of annual heating degree-day value, a degree-day regionalization of the United States was made, based on this parameter, which would also be consistent with the geographic census regions which are used to categorize construction statistics. The U.S. was divided into four annual heating degree-day regions and an average representative value was selected for each degree day region. The following heating degree-day values were used to define (using ASHRAE 90-75 the overall thermal conductance of the reference buildings within each geographic region:

NORTHEAST:	5400, 7200°F degree-day (3000, 4000°C degree-day)
NORTH CENTRAL:	5400, 7200°F degree-day (3000, 4000°C degree-day)
SOUTH:	1800, 3600°F degree-day (1000, 2000°C degree-day)
WEST:	1800, 3600, 5400, 7200°F degree day (1000, 2000, 3000, 4000°C degree-day)

SHACOB
Representative Residential Buildings

• SINGLE FAMILY DETACHED	• SINGLE FAMILY ATTACHED
• ONE STORY, TWO STORY AND SPLIT LEVEL • FOUNDATIONS: HEATED BASEMENT, UNHEATED BASEMENT, SLAB, CRAWL SPACE • FLOOR AREA: 1200, 1600, 2000, 2400 ft^2	• TWO STORY TOWN HOUSE • 4 AND 8 UNIT CONFIGURATIONS • UNIT FLOOR AREAS: 1300, 1500 ft^2
• MULTI-FAMILY LOW RISE	**• MULTI-FAMILY HIGH RISE**
• TWO AND THREE STORY APARTMENTS • BASIC APARTMENT LAYOUT (one exposed wall per unit) • UNIT FLOOR AREA: 900, 1100 ft^2	• FOUR STORY APARTMENT BUILDING • 17,000 GROSS ft^2 • 13 UNITS • UNIT FLOOR AREA: 1100 ft^2

From available construction statistics and other published reference data, a set of single family detached dwellings and multi-family low-rise buildings were defined within each geographic census region. Each set of buildings was selected to represent the general distribution of story height, foundation type, and floor area within the census region. No statistics are available giving the distribution and construction characteristics for single family attached, or multi-family high-rise, buildings over a wide geographic region. In the absence of such data, a town house configuration was selected as representative of the single family, attached category and a four-story apartment building was selected as representative of the multi-family, high rise category. (It should be noted that residential high rise construction is defined as construction greater than three stories in height).

SHACOB
Residential Buildings Definition

- THERMAL PARAMETERS EXAMPLE - NORTHEAST REGION

BUILDING TYPE	FLOOR AREA (ft^2)	NUMBER OF STORIES	FOUNDATION	UA (Btu/hr°F) 5400 DEG DAY REGION (1)	UA (Btu/hr°F) 5400 DEG DAY REGION (2)	UA (Btu/hr°F) 7200 DEG DAY REGION (1)	UA (Btu/hr°F) 7200 DEG DAY REGION (2)	VOLUME (ft^3)
1	1240	1	BASEMENT	429	372	381	338	9,920
2	1640	1	BASEMENT	517	450	460	410	13,120
3	1640	1	SLAB	447	-	394	-	13,120
4	2040	1	BASEMENT	584	519	521	475	16,320
5	1800	2		611	550	537	489	15,300
6	2200	2		681	618	600	551	18,700
7	2600	2		815	689	680	614	22,100
8	2440	1		649	586	580	538	19,250

(1) Heated Basements (2) Unheated Basements

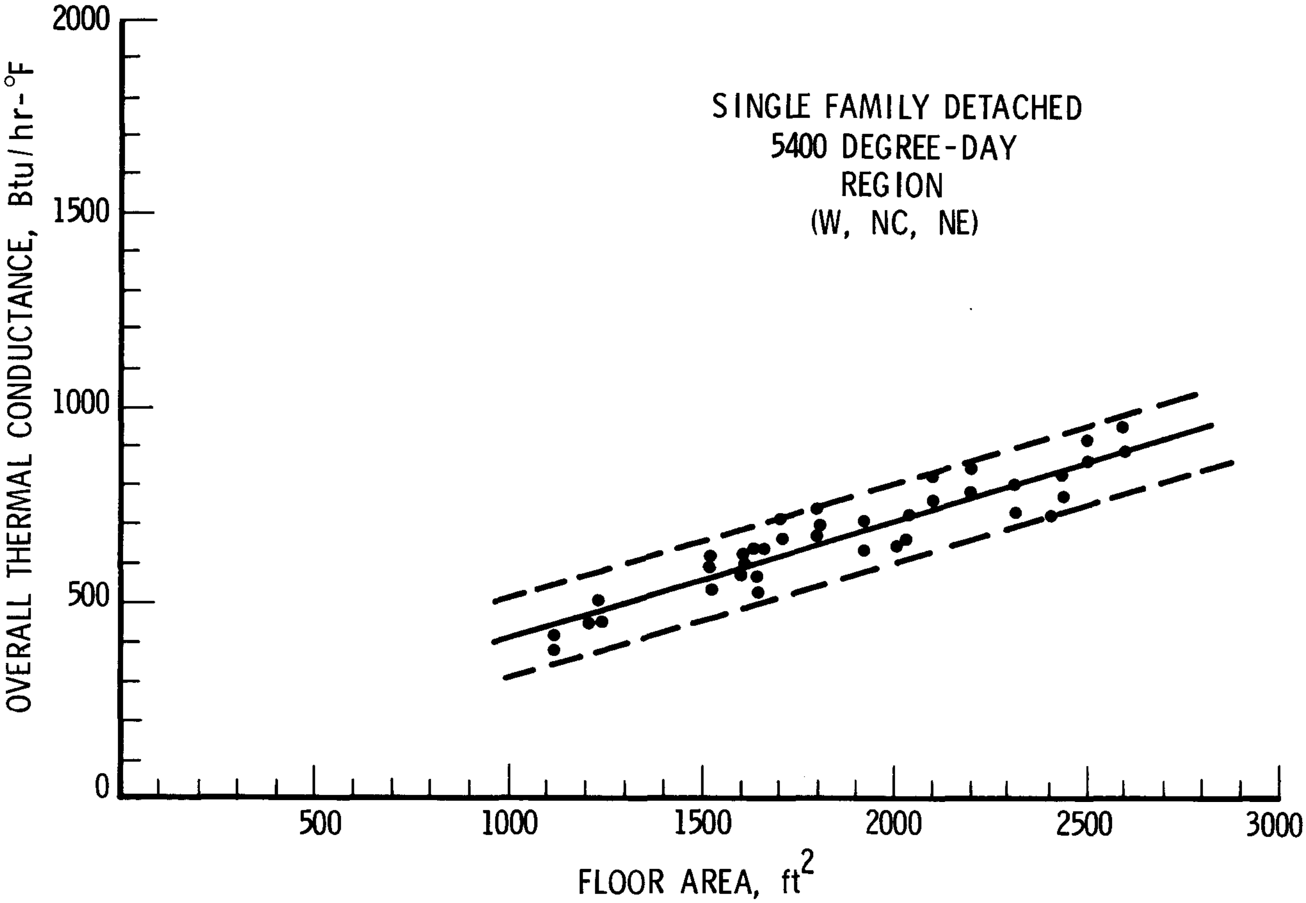
- SUMMARY OF REPRESENTATIVE BUILDINGS

BUILDING TYPE	DEGREE DAY REGION 1800 (W, S)	DEGREE DAY REGION 3600 (W, S)	DEGREE DAY REGION 5400 (W, NC, NE)	DEGREE DAY REGION 7200 (W, NC, NE)	TOTAL
SINGLE FAMILY DETACHED	21	21	40	40	122
SINGLE FAMILY ATTACHED	4	4	4	4	16
MULTI-FAMILY (<3 stories)	12	12	26	26	76
MULTI-FAMILY (>3 stories)	1	1	1	1	4
					218

An example of the set of single family-detached reference buildings defined for the Northeast region is presented in the accompanying table. Floor areas were selected by the distribution of the average floor area ±400, ±800 sq. ft., while the number of stories and foundation was selected to represent the dominant types within the region. The story height for single story dwellings was assumed to be 8 ft. while two-story dwellings were assumed to be 17 ft. in height. Given these descriptive data, the overall thermal conductance UA (a required TRNSYS input parameter) was computed using the ASHRAE 90-75 requirements for allowable heat transmission through walls, roof, and floor. In the absence of pertinent data, 50 percent of the basements were assumed to be heated while 50 percent were assumed to be unheated.

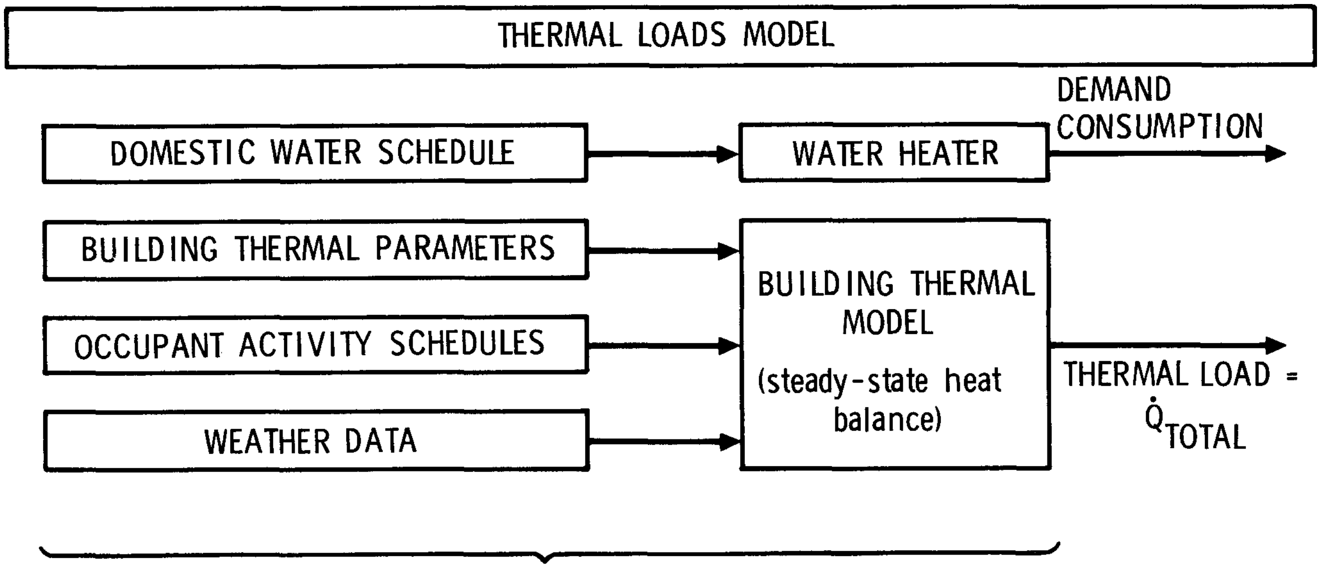
A summary of the representative building set defined for the residential sector is presented in the accompanying table.

SHACOB
Thermal Conductance Sensitivity



With floor area as the independent variable, the thermal conductance, value of each single family, detached, dwelling was plotted using all dwellings defined with the same representative value of heating degree-day. As can be noted from the accompanying figure, an average trend can be identified along with a scatter band which represents the variance of foundation and story height within the geographic regions represented.

SHACOB
Residential Thermal Loads



$$(UA)\ \Delta T + \dot{Q}_{INFILTRATION} + \underset{(glass)}{\dot{Q}_{SOLAR}} + \dot{Q}_{BASEMENT} + \dot{Q}_{LATENT} + \dot{Q}_{INTERNAL} = \dot{Q}_{TOTAL}$$

The residential building thermal model for simulation of time-varying building thermal loads in the steady-state heat balance option of the TRNSYS program. In this option, the thermal inertia of the structure is assumed to be small, the major portion of the building load is computed simply as a function of temperature difference between an assessed constant room temperature and the instantaneous value of the outside air. The total heat flow through the building shell is determined by the thermal conductance, glass solard heat gain and the infiltration rate of outside air including both latent and sensible heat. Internal heat gains are determined from scheduled occupancy and electric baseload.

SHACOB
Non-Residential Buildings Definition

- NON-RESIDENTIAL BUILDINGS ARE EXTREMELY DIVERSE
  - STRUCTURE
  - SIZE
  - GLASS AREA
  - SECONDARY SYSTEMS
- ONE REPRESENTATIVE NON-RESIDENTIAL BUILDING OF EACH TYPE WILL BE DEFINED FOR EACH DEGREE DAY REGION

Due to the wide variance of non-residential building cost allocations and the conceptual interactions between the architect and building owner during the building design process, a wide variance of building structure, size, glass area, and HVAC systems characterize buildings within each of the non-residential categories. Therefore, a single representative building was defined within degree-day region. Other buildings in that category will be assumed to have loads scaling with floor area.

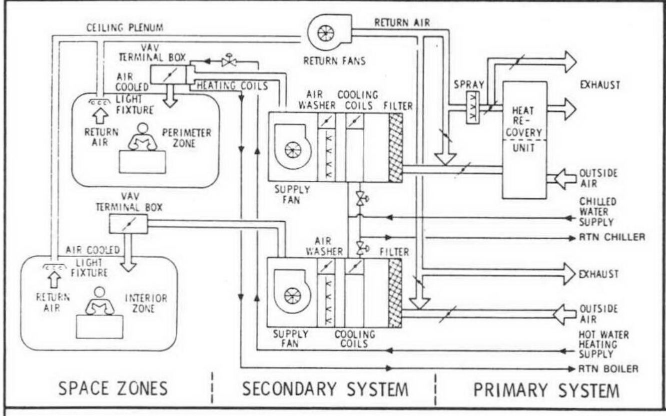
SHACOB
Representative Non-Residential Buildings

- OFFICE BUILDINGS
  - 3 STORY: 40,500 ft^2 (90 ft x 150 ft)
  - 10 STORY: 14,400 ft^2 PER FLOOR
- SHOPPING CENTER
  - 390,000 ft^2, 60% LARGE STORES, 30% SMALL STORES, 10% MALL, 10% GLASS
- HOSPITAL
  - 4 STORY, 60,000 ft^2 (120 beds)
- RETAIL STORE
  - 1 STORY: 40,000 ft^2 (100 ft x 400 ft)
- SCHOOLS
  - 1 STORY: 20,000 ft^2 (elementary, 360 students)
  - 2 STORY: 40,000 ft^2 (high school, 950 students)
- MOTEL
  - 2 STORY: 13,500 ft^2 (32 units)
- LIGHT INDUSTRIAL
  - 142,200 ft^2 (88% factory, 12% mach room)

Outline specifications for each of the basic non-residential building types defined are given in the accompanying chart. Wall, roof, and floor construction for each of these buildings differ within each degree day region. Selection of secondary HVAC systems, occupant schedules, and electric baseload schedules will complete the building definition.

SHACOB
Non-Residential Thermal Loads

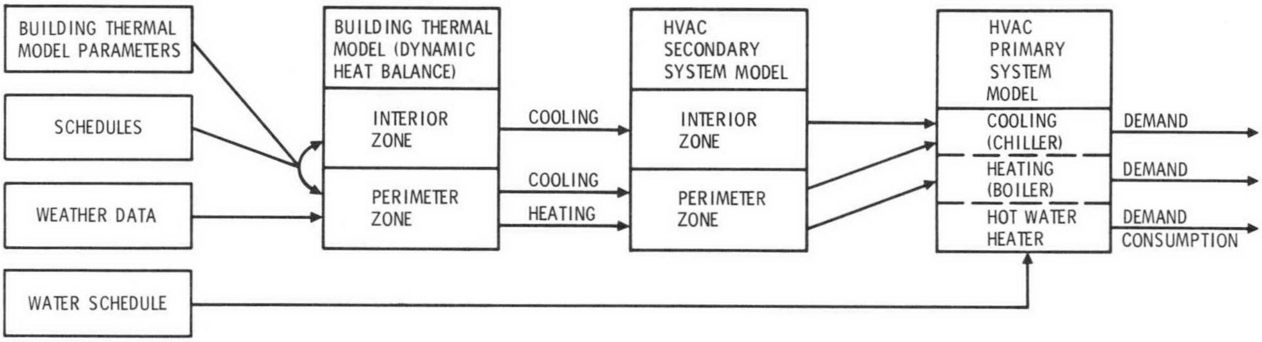
NON-RESIDENTIAL HVAC SYSTEMS



ZONE LOAD COMPONENTS

$$\dot{Q} = \dot{Q}_{SHELL} + \dot{Q}_{VENTILATION} + \underset{\text{(glass)}}{\dot{Q}_{SOLAR}} + \underset{\text{(wall)}}{\dot{Q}_{SOLAR}} + \underset{\text{(roof)}}{\dot{Q}_{SOLAR}} + \dot{Q}_{LATENT} + \dot{Q}_{INTERNAL}$$

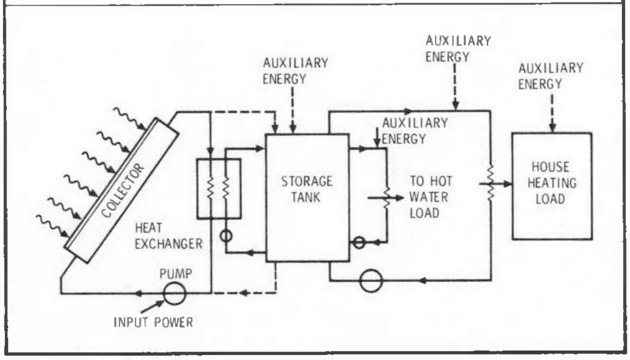
THERMAL LOADS MODEL



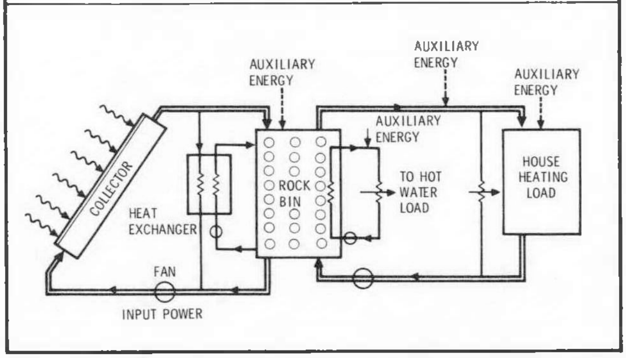
The determination of building thermal loads for non-residential buildings is complicated by secondary HVAC distribution systems and the various control strategies employed. Due to heavier construction, the effects of thermal inertia and solar radiation heat transfer cannot be ignored. Also, the size of the structures create perimeter zones which respond to weather conditions and interior zones which are subject to internal heat gain only. Secondary HVAC systems require additional energy for fans and zone control. Thus the secondary HVAC must be properly simulated if time varying electrical demand loads are to be accurately determined.

SHACOB
Solar Heating and Cooling Systems

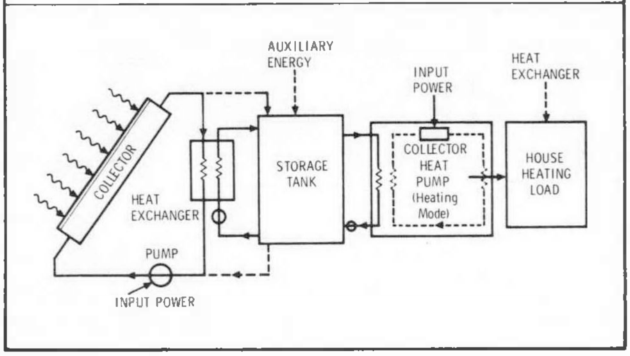
DIRECT SOLAR HEATING SYSTEMS (LIQUID)



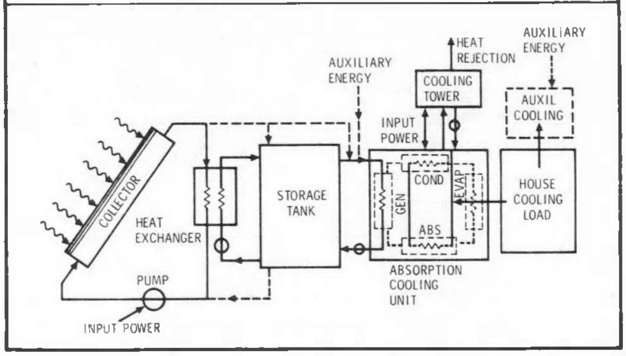
DIRECT SOLAR HEATING SYSTEMS (AIR)



HEAT PUMP/SOLAR SYSTEMS (HEATING)



SOLAR ABSORPTION COOLING SYSTEMS



The basic solar heating and cooling system configurations selected for consideration in the impact assessment are shown in the accompanying figure. Variations of these four configurations are distinguished by the location of the auxiliary input within the system. Since solar systems cannot economically be designed to supply 100% of the heating or cooling requirements of a building, a back-up auxiliary is required. The time variance of electrical demand is dependent upon the point of placement of the auxiliary input within the system. For example, auxiliary input into the storage element allows for use of off-peak power for load management.

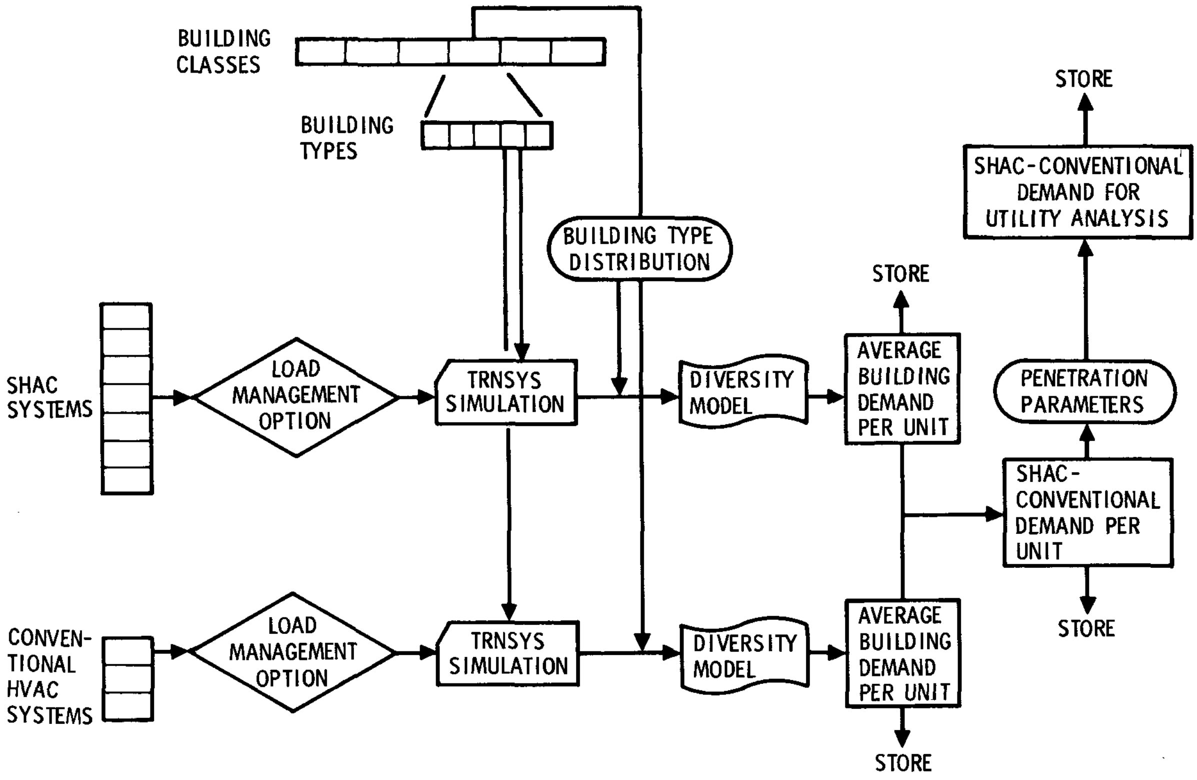
SHACOB
SHAC System Selection and Definition

- WORK IN PROGRESS
  - SHAC SYSTEMS SELECTION
    - REGIONAL FACTORS
    - COMPATIBILITY WITH BUILDING TYPE
    - ENGINEERING AND CONTROL COMPLEXITY
  - SHAC SYSTEMS NUMERICAL DESCRIPTION
    - COLLECTOR/STORAGE SIZING PROCEDURES
    - AVERAGE SYSTEM OPERATING TEMPERATURE
    - HEAT EXCHANGER EFFECTIVENESS
- FINAL REPORT DUE 1 DEC, 1976

The definition of a solar heating (and cooling) system for a specific building depends on the local climatic conditions, peak building thermal load, compatibility with building type, and the engineering/control complexity required to achieve system performance.

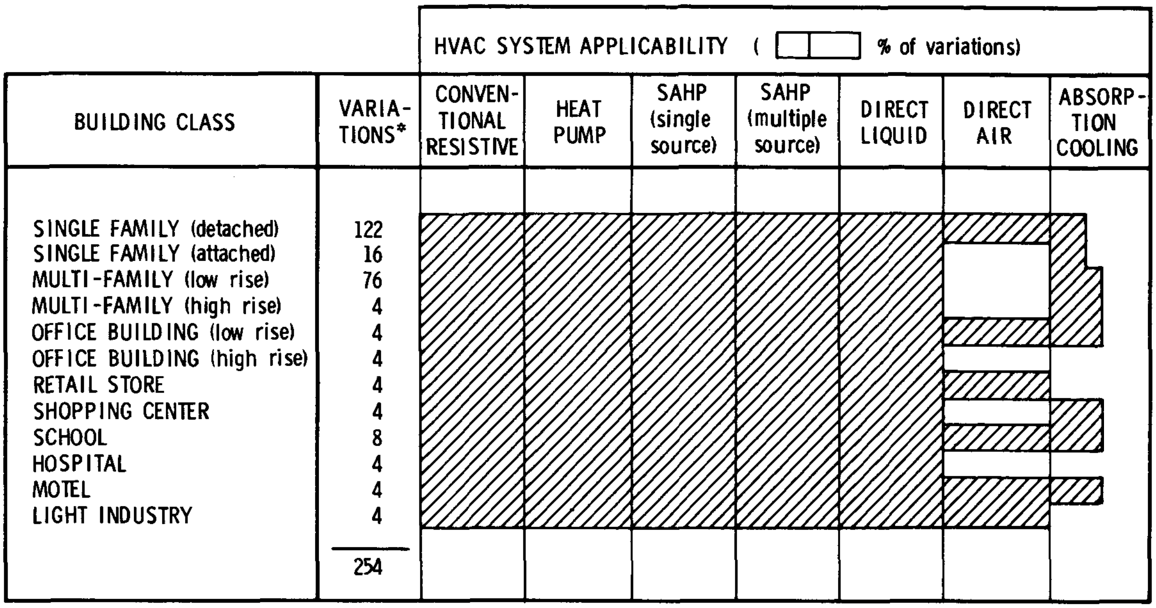
The input parameters required for TRNSYS simulation of SHAC systems are usually normalized functions of collector area, thus making the collector sizing procedure the single most important item in a SHAC system definition. Several simplified sizing procedures have been proposed which are currently being reviewed. Average system operating temperature, is another critical parameter affecting collector (and system) performance. The individual parameters which specify the performance of components such as heat exchangers must be reviewed and the range of possible values defined.

SHACOB
Simulation Analysis Flow Diagram



The overall flow of the demand impact simulation analysis is displayed in the accompanying chart. The building classes and types and the SHAC and conventional HVAC systems are outputs of the AHEM analysis. After a decision is made on whether or not load management is to be exercised in a given case, the TRNSYS program will determine the resulting demand for both SHAC and conventionally equipped residences. The demands for the various building types within a class are then apportioned according to construction statistics. An analytic diversity model accounts for the non-coincidence of energy usage patterns. The resulting average demand per unit is then stored to provide a basis for fossil fuel alternative analysis, if required. For the main analysis, in which only electrical backup auxiliary or primary are considered, the SHAC minus conventional demand can be readily computed. When the appropriate penetration parameters are supplied the total SHAC minus conventional demand can then be added to the total projected utility demand without SHAC to get the total utility demand with SHAC.

SHACOB
Reference Building/SHAC System Configurations



BUILDING CLASS	VARIATIONS*	CONVENTIONAL RESISTIVE	HEAT PUMP	SAHP (single source)	SAHP (multiple source)	DIRECT LIQUID	DIRECT AIR	ABSORPTION COOLING
		HVAC SYSTEM APPLICABILITY (▭ % of variations)						
SINGLE FAMILY (detached)	122	▨	▨	▨	▨	▨	▨	▨
SINGLE FAMILY (attached)	16	▨	▨	▨	▨	▨		▨
MULTI-FAMILY (low rise)	76	▨	▨	▨	▨	▨		▨
MULTI-FAMILY (high rise)	4	▨	▨	▨	▨	▨		▨
OFFICE BUILDING (low rise)	4	▨	▨	▨	▨	▨	▨	▨
OFFICE BUILDING (high rise)	4	▨	▨	▨	▨	▨		
RETAIL STORE	4	▨	▨	▨	▨	▨	▨	
SHOPPING CENTER	4	▨	▨	▨	▨	▨		▨
SCHOOL	8	▨	▨	▨	▨	▨	▨	▨
HOSPITAL	4	▨	▨	▨	▨	▨		
MOTEL	4	▨	▨	▨	▨	▨	▨	▨
LIGHT INDUSTRY	4	▨	▨	▨	▨	▨	▨	
	254							

*Not including load management options, fenestration, or living style variations.

The total number of buildings defined by AHEM comes to 254. Conventional resistance heating, heat pumps, solar assisted heat pumps (SAHP) with single and multiple sources and direct liquid systems can conceivably be applied in all the defined structures. Direct air systems are not likely candidates for buildings in which the volume and weight of rock storage are constraining or there are distribution system limitations. Because of the high initial costs associated with absorption cooling it would only be likely to penetrate in geographic areas where the cooling load dominates and sunshine is abundant.

SHACOB
Truncated Building/SHAC System Simulations

BUILDING CLASS	VARIATIONS*	CONVENTIONAL RESISTIVE	HEAT PUMP	SAHP (single source)	DIRECT LIQUID	TOTAL
SINGLE FAMILY (detached)	128	●	●	●	●	
SINGLE FAMILY (attached)	64	●	●	●	●	
MULTI-FAMILY (low rise)	32	●	●	●	●	
OFFICE BUILDING (low rise)	16	●	●	●	●	
RETAIL STORE	16	●	●	●	●	
TOTAL	256	256	256	256	256	1024

*
- Two collector areas per building class/SHAC system configuration
- Eight utilities

When collector area, load management option, fenestration area and living style patterns are introduced as parameters, the number of cases defined is on the order of tens of thousands for each location analyzed. To bring this down to a tractable number, a number of analysis assumptions will be employed. The resulting truncated matrix represents those cases where extensive analysis is required. Other viable systems will be included through one of the following assumptions:

(1) performance is similar to a system already analyzed (air SHAC system performance from liquid system analysis)

(2) performance can be assessed by perturbation or sensitivity studies, (dual source heat pump performance from single source heat pump analysis)

or

(3) penetration is not expected to be large enough to require extensive analysis (e.g., absorption cooling)

As an example of determining the number of cases to be analyzed, consider single family detached dwellings and conventional resistive heating. Four basic house sizes with two energy usage levels (including fenestration) and at minimum, two collector areas for each of eight utilities results in 128 cases.

SHACOB
SHAC Simulation Computer Program

• SHAC SIMULATION PROGRAM REQUIREMENTS

- STUDY REQUIREMENT: PREDICT AGGREGATE HOURLY DEMAND
- ∴ LARGE NUMBER OF SHACOB SIMULATIONS REQUIRED
- UNCERTAINTY IN INDIVIDUAL SHACOB DEMAND
  - SHAC EQUIPMENT TYPE, FUNCTION, SIZE AND PERFORMANCE
  - USAGE PATTERNS
  - MARKET PENETRATION
- APPROACH:
  (1) FAST-RUNNING SIMULATION
  (2) SACRIFICE SOME ACCURACY

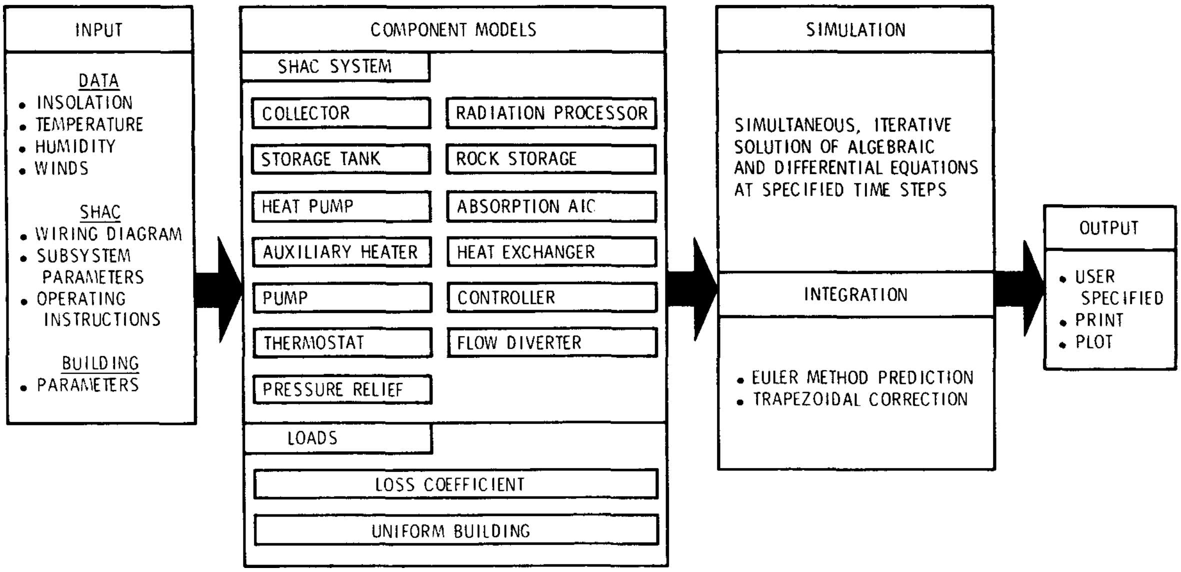
THERMAL LOADS AND SHAC SIMULATION CODE COMPARISONS

CODE	THERMAL LOADS	CONVENTIONAL DEMAND	SHAC DEMAND	RELATIVE ACCURACY	RELATIVE RUN TIME/YR	COMMENTS
NBSLD	YES	RESIDENTIAL ONLY	NO	VERY HIGH	SLOW	RESEARCH TOOL
NECAP	YES	YES	(limited)	HIGH	MODERATE	LIMITED USAGE
AXCESS	YES	YES	NO	HIGH	FAST	DESIGN LOADS INPUT
ECUBE	YES	SIMPLIFIED	NO	MODERATE	FAST	DESIGN LOADS INPUT
SOLSYS	YES	RESIDENTIAL ONLY	YES	MODERATE(?)	FAST(?)	NOT YET AVAILABLE
TRNSYS	YES	RESIDENTIAL ONLY	YES	MODERATE	FAST	IN WIDE USE

The nature of the present study requires the performance analysis of at least a thousand and probably several thousand seasonal simulations to predict the aggregate hourly demand. Furthermore, the inherent uncertainties in predicting aggregate demand removes the requirement for an extremely accurate modeling of a given building/SHAC system combination. It is therefore appropriate to select a fast running simulation program even at the expense of some modeling accuracy.

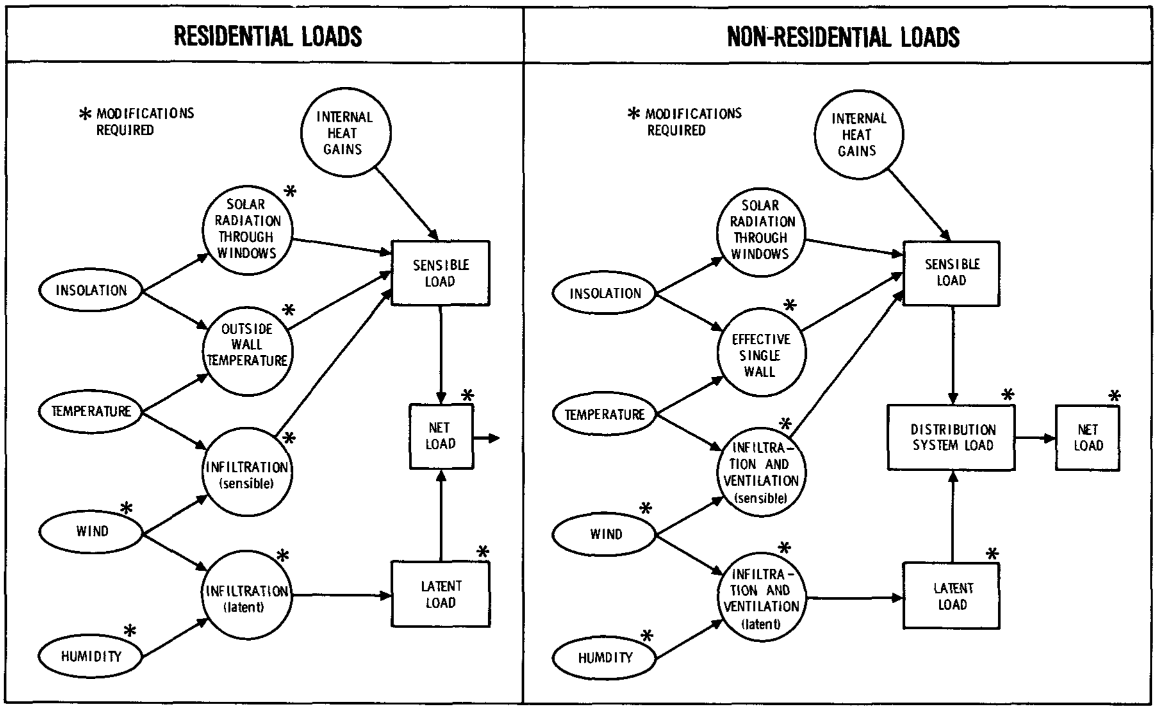
In selecting the SHAC simulation computer program, relevant available codes were reviewed. These range from sophisticated, very accurate and very slow running programs (with little or no SHAC simulation capability) such as NBSLD and NECAP through the AXCESS and ECUBE programs which are reasonably fast running but do not have any SHAC capability to SOLSYS and TRNSYS which are designed for SHAC simulations although primarily for residential applications. TRNSYS being in the most wide usage was therefore selected.

SHACOB
TRNSYS



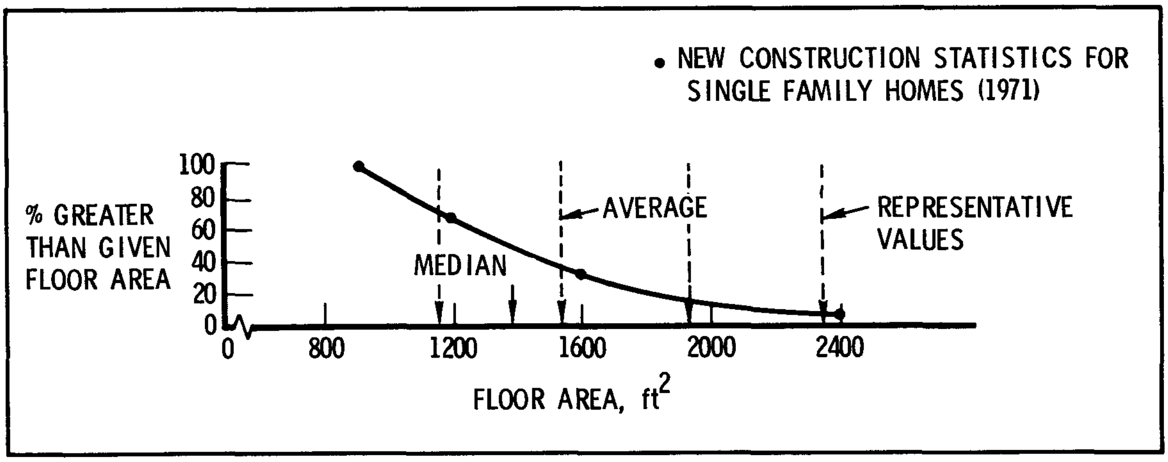
TRNSYS (Transient System Simulation) is a computer code for simulating the dynamic thermal behavior of solar energy heating and cooling systems. It is based on a modular approach which enables users to readily simulate a wide variety of systems. The analyst selects the components and design parameters and specifies the way in which the components are interconnected. When the appropriate insolation and weather data are supplied the time history of system performance is obtained by solving the appropriate algebraic and differential equations.

SHACOB
TRNSYS Modifications



Certain modifications to TRNSYS were required in order to account for all major heat gains and losses. These include the heat gain from solar radiation through the windows, the effect of solar radiation on the outside wall temperature, the determination of sensible heat gains or losses through infiltration and the additional cooling requirements arising from the latent heat gain in infiltrating air. For the non-residential modeling additional modifications were required to approximate the effects of solar energy penetrating the walls, ventilation effects and the losses in the distribution system.

SHACOB
Load Distribution



The distribution of residential sites in terms of floor area will be taken from currently available regional census data similar to that shown (for 1971). The current trend has been toward larger house sizes. However, there will probably be a counter-trend arising from energy conservation awareness and building codes in the future. Therefore, it will be assumed that the distribution for 1990-2000 will be essentially the same as the current distribution. Available data for specific utility areas can always be substituted for the regional distribution.

The AHEM results have shown that the thermal conductance (UA) of a residence is essentially a smooth function of the floor area. It should then be sufficient to select three or four representative values and the corresponding UA's for simulation analysis. The resulting demand profiles can then be summed in proportion to the appropriate distribution factors.

SHACOB
Demand Diversity

- MODEL: $D = \bar{\alpha}\, D_S + \left[1-\alpha(t)\right] \overline{D}_S$
- DEFINITIONS:
  - D = AGGREGATE DEMAND
  - D_S = SIMULATED DEMAND
  - α = 24 hr PERIODIC USAGE FUNCTION
  - $\overline{(\ )}$ = 24 hr AVERAGE OF ( )
- CONSTRAINT: SELECTED FORM FOR $\alpha(t)$ MUST AGREE WITH AVAILABLE AEIC AND UTILITY SPECIFIC DATA

Demand diversity arising from the non-coincidence of individual demand profiles results in a significant lowering of peaks and raising of valleys relative to a typical single profile. Models for this phenomena or extensive data for developing such models are not currently available. However, data does exist giving yearly and monthly diversity factors for peak demand for a number of utilities. For a few utilities, the diversity demand from a group of homes has been tabulated or plotted as a function of time of day and ambient temperature. Even with this data it is difficult to determine relative diversification for simulated cases except where the diversification arises from building or SHAC system parameters as opposed to usage patterns. It is proposed to use the linear model shown to relate simulated demand to diversified demand. Note that this form yields a daily average diversified demand equal to the daily average simulated demand - i.e., the model accounts for different usage patterns but not differing energy consumptions which are accounted for in the simulation models.

The usage function $\alpha(t)$ which is bounded by (1) no diversification and (2) flat demand profile, will be based on available AEIC or utility data when available. At minimum, the form assumed will yield the appropriate coincidence factor at time of peak demand.

SECTION 4

EPRI CONTRACT RP 549

INDIVIDUAL LOAD CENTER-SOLAR HEATING AND COOLING RESIDENTIAL PROJECT

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OCTOBER 1976

EPRI SOLAR REVIEW MEETING #2

INTRODUCTION

The total EPRI Individual Load Center, Solar Heating and Cooling Project is planned for implementation in the following three phases, spanning a period of approximately four years:

FIRST PHASE – System definition study to determine systems for residential solar/load management, space conditioning and domestic hot water system in the Northeast and Southwest regions of the United States. Two utility partners were identified by EPRI to represent the two regions – the Long Island Lighting Company (LILCO) for the Northeast and the Public Service Company of New Mexico (PNM) for the Southwest.

SECOND PHASE – Detailed design of, and preparation of specifications for, ten residential experiments – five for the service area of PNM and five for the service area of LILCO.

THIRD PHASE – Construction, installations, test and evaluation of the ten experiments.

The overall objective of the EPRI project is to provide the electric power industry, through system definition studies and experiments, with a quantitative basis for evaluating the potential impact of residential solar/load management systems on utility load factors, revenues, operating costs and capacity requirements. The impacts can be positive or negative depending upon the characteristics of the particular utility and the design of the particular heating, ventilating and air conditioning (HVAC) system in the single family all-electric residence.

This presentation gives an overview of the Phase 1 system definition study, which was completed August 1, 1976, and a status report of Phase 2, which was initiated at that time and which has a planned duration of 11 months.

An important element of the system definition study was the development of a methodology which relates the performance of various residential HVAC systems to a utility's characteristics in a specific service area (load profile, fuel costs, etc.). With this methodology, it is possible to define HVAC systems that are compatible with utility operations and that minimize the *total* cost of meeting the energy needs for an application – investment in generation capacity at the power plant, fuel costs, and investment at the point of use for energy conservation and HVAC equipment.

A crucial aspect of the system definition approach is the determination of the generic system class – conventional, conventional with addition of load management, solar augmentation or solar with load management – that is most favorable in a given service area for various HVAC functions, viz., (1) hot water, (2) hot water and space heating, and (3) hot water with space heating and cooling. Reference systems were defined, with either heat pumps or electric resistance elements for space heating, from a comprehensive survey of system concepts and screening exercises (addressed in the ADL presentation at the first EPRI Solar Workshop Meeting).

The experimental systems addressed in the Phase 2 effort are designed to:

- Maximize experimental content
- Utilize comprehensive instrumentation for data reduction
- Provide credible system integration in the local residence market
- Implement cost-effective energy conservation.

FIGURE 1
PREFERRED HVAC SYSTEM

DEFINITION

**MINIMIZES TOTAL LIFE-CYCLE COST OF
MEETING HOMEOWNERS' ENERGY NEEDS**

**CONSIDERING: INVESTMENT IN GENERATING CAPACITY
FUEL COSTS
MAINTENANCE, INSURANCE, TAXES, ETC.
HVAC EQUIPMENT AT RESIDENCE
OPERATIONAL REQUIREMENTS**

DESIGN APPROACH

APPROACHES TO PREFERRED SYSTEM

**Building Energy CONSERVATION
Electrical Demand SHIFTS
Energy Resource DISPLACEMENT**

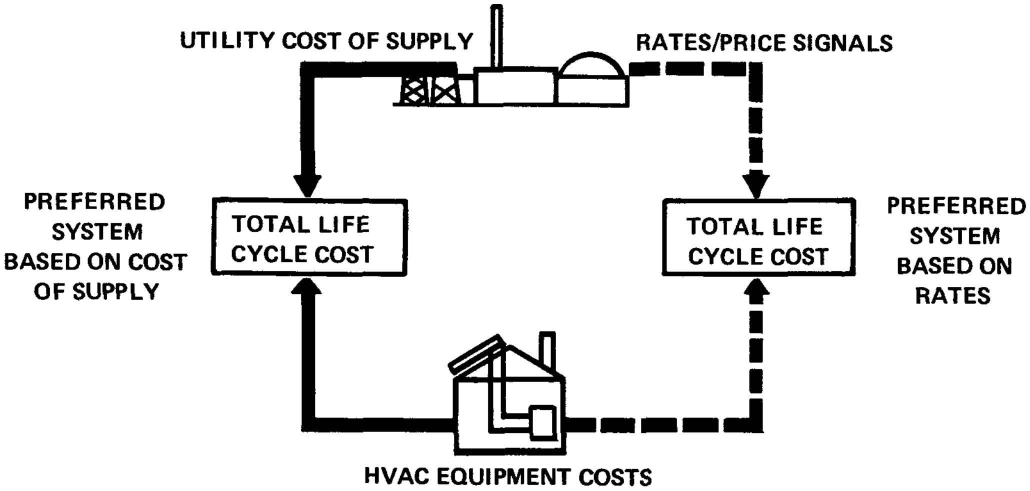
A preferred system, in the context of this work, is one that minimizes the total cost of meeting the energy needs for an application; that is, the cost takes into account all the ingredients, such as investment in generating capacity at the power plant, fuel costs, investment made at the point of use for energy conservation and HVAC equipment and other related costs.

The first step in the design process should be to evaluate cost effective energy conservation measures, applied both in the building structure and in the HVAC equipment. Not only can the energy requirements be reduced at the point of application, but energy conservation can also: (1) reduce peak demand, thereby reducing installed capacity requirements at the utility, and (2) potentially reduce the required capacity of HVAC equipment in a new building.

The next most important step is control of electrical demand by load management techniques, which improve the utilization of existing baseload generation capacity by shifting demand from peak periods. Effective thermal storage and control at the user's site can reduce capacity requirements at the power plant, and thereby provide a "capacity credit" to offset the capital cost associated with the necessary additional load management equipment. In addition, it can also permit a shift from scarce oil and gas to baseload nuclear or coal.

A third option open to the designer is the installation of a solar system for space conditioning. The primary benefit to the user is a net reduction in his energy inputs. However, since the solar system's performance depends on the transient weather conditions, it cannot lead to a dependable savings in generating capacity requirements and could worsen the utility load factor by requiring full backup capacity.

FIGURE 2
PREFERRED SYSTEM DETERMINATION



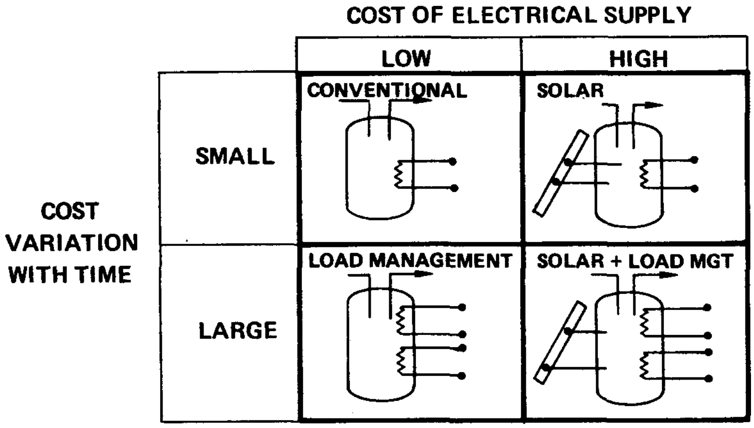
Preferred systems cannot be reliably selected on the basis of existing or historical rate structures for backup electricity. First, some current rate structures do not have allocations for peak load costs experienced by utilities; therefore, they may not be consistent with the actual cost of supply furnished conventionally or as backup for the solar system. Second, the utility may not yet have sufficient performance data to determine the appropriate rate structure for providing backup electricity to solar systems.

One approach to defining preferred systems from an economic standpoint is shown schematically on the left side of the figure, where the total cost is shown as the combination of electrical energy costs (assuming that the utility cost of supply is passed on to the user) plus the costs associated with purchase, installation and maintenance of the HVAC equipment at the residence (including solar components, if applicable). This approach can be used to define systems that minimize the actual total costs of meeting the energy needs at the residence.

As illustrated, the price signals inherent in rates to the user will define systems which appear to be preferred in the marketplace. The rate structures that will actually apply to a given service area will depend upon performance data and information available to utilities, regulatory procedures, and other costs that may be associated with implementing certain rate structures, such as special metering and billing costs.

Although utility rate structures are not meaningful at this time as the sole determinant of preferred systems, they are appropriate for parametric study and comparison of potential revenues and supply costs. If rates in a service area were consistent with the costs of supply, the preferred system determined from price signals would be the same as that defined by the cost-of-supply analysis. On the other hand, if rates were implemented which did not reflect the utility's cost of supply or peak load costs, the preferred system defined on the basis of the price signals would not necessarily represent the most efficient utilization of energy resources and capacity.

FIGURE 3
UTILITY INFLUENCES ON PREFERRED SYSTEMS

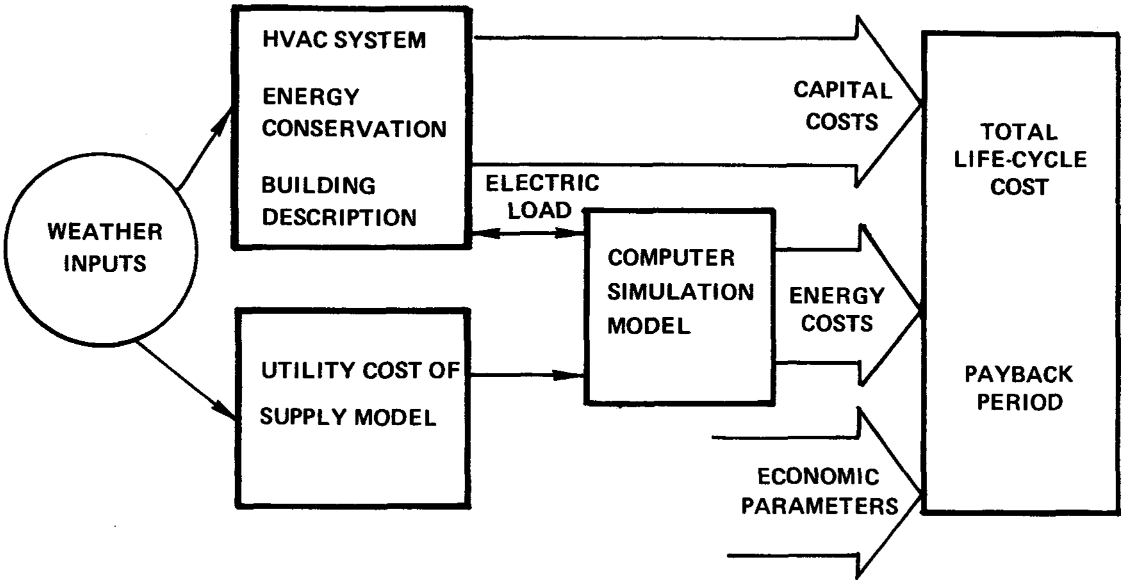


It is useful to define four generic HVAC system options for single family, all-electric residences:

- *Conventional System* – Draws electric energy on demand to satisfy hot water and space conditioning needs. This system would be commonly used in the absence of load management or solar supplement.
- *Load Management System* – Electrical demand is controlled in a manner favorable to utility operation.
- *Solar System* – System displaces energy resources but auxiliary electrical energy is drawn on demand.
- *Solar and Load Management System* – System displaces energy resources, and shifts usage of electrical energy.

Figure 3 summarizes some of the utility influences on preferred systems under bounded or limiting situations. For illustration, the four generic system options are conceptually shown only for the single function of domestic water heating. The cost of electrical supply is indicative of the energy cost component for a specific utility, while the cost variation with time is representative of the temporal use of generation capacity and energy resources. If a utility's cost of supply is low and its cost variation with time is also small, it will be difficult to justify any departures from a conventional system. A high average cost of supply combined with a small cost variation with time could justify consideration of a solar system, but there would be little incentive for a load management function. A low cost of supply, but a large temporal cost variation would favor consideration of a load management function, but not a solar system. Finally, the combination of high cost of supply and large variation in cost with time would justify consideration of systems with both solar and load management features.

FIGURE 4
METHODOLOGY

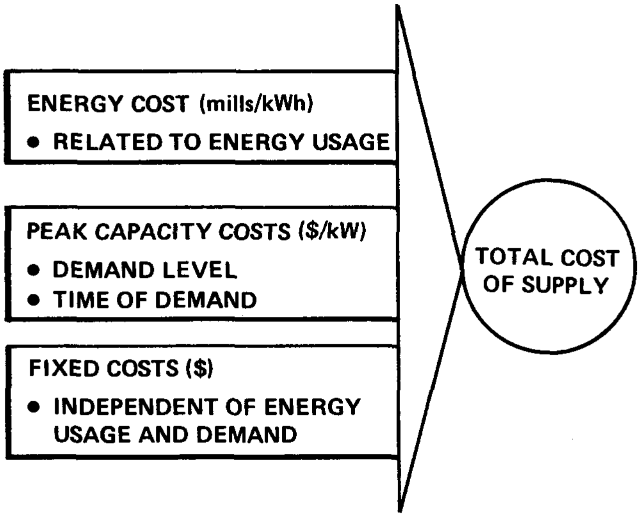


With the cost of supply model and specific utility-related inputs provided by the utility participants, computer simulations were carried out for the reference HVAC systems and single family residences. The computer model determined the hourly electrical demand of the residence to meet its domestic hot water, heating or cooling loads and calculated the utility cost of supply to meet the electrical demand. The simulations were carried out over an entire year of operation and determined the annual costs to the utility to provide the required electrical energy.

The calculations were made on an hour-by-hour basis, by solving appropriate energy balance equations, over the simulated period of performance (normally one year). The computer program computes hourly transient temperatures for each of the elements in the system – including solar/load management system components, as well as the building space whose temperature is being controlled. Analytical models were developed for various system components, e.g., the solar collector, thermal storage subsystem (including auxiliary storage for off-peak energy), heat actuated air conditioning and the system control logic. In addition, the model accounted for the operation of pumps and the dependence of heat exchanger effectiveness on temperature. The model contained control algorithms for actuating the HVAC heating and cooling components including the solar components. The building space conditioning controls were based on thermostat set points (two stage) for both heating and cooling functions.

Actual weather data was used as input to the computer program, including hourly values for dry bulb temperature, wet bulb temperature, wind velocity, humidity ratio, solar vector components, direct and diffuse components, solar flux and the ground reflected flux.

FIGURE 5
CONCEPTUAL ELEMENTS OF COST OF SUPPLY



In discussing the cost of supply for an electric utility, it is convenient to address the following categories:

- *Energy Related Costs* – Associated with fuel and operation of generating equipment;
- *Demand Related Costs* – Associated with the capital requirements for generation capacity, transmission, distribution and other equipment to meet temporal power demands; and
- *Fixed Costs* – Other costs not directly dependent on energy usage or demand patterns.

Energy-related costs derive mainly from the cost of expended fuel. They vary with efficiencies of the generating units used and will usually rise with increasing system-wide load. (The actual energy cost variation with system-wide load may be complex since generating units called to meet the load come in discrete sizes.) System peaks cause the average (as well as incremental) energy-related cost of supply to increase.

Demand-related costs are associated with the capital costs of generation capacity and of transmission and distribution equipment. The demand-related costs are a major component of the total cost of supply, particularly in a utility with a low annual load factor* and with growth in demand during the peaking hours. A demand growth during peaking hours will require large capital expenditures for new peaking equipment with only a minor increase in revenues.

Opinions vary as to the appropriate basis for expressing the cost of supply. One approach would select an incremental basis and consider the cost associated with putting a unit on line to meet the demand added to the existing system total. Another would choose an average basis and consider all generating units on line at a given time to meet the system-wide demand level. This latter method would permit a more meaningful comparison between actual cost of supply and rates since the rate schedules usually reflect average costs for the customer aggregate. On the other hand, evaluating costs on an incremental basis would provide a truer picture of a utility's cost impact when supplying the energy needs of a new customer.

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*Defined as a ratio of the annual average system-wide load to peak annual system-wide load.

FIGURE 6

TEST OF METHODOLOGY

14 ADDITIONAL SERVICE AREAS
CONTAINS MAJOR ELEMENTS
NEEDS MORE OPTIONS FOR ALLOCATING PEAK COSTS
SHOULD BE SIMPLIFIED FOR WIDER USE

BEING ADDRESSED AS SEPARATE EFFORT

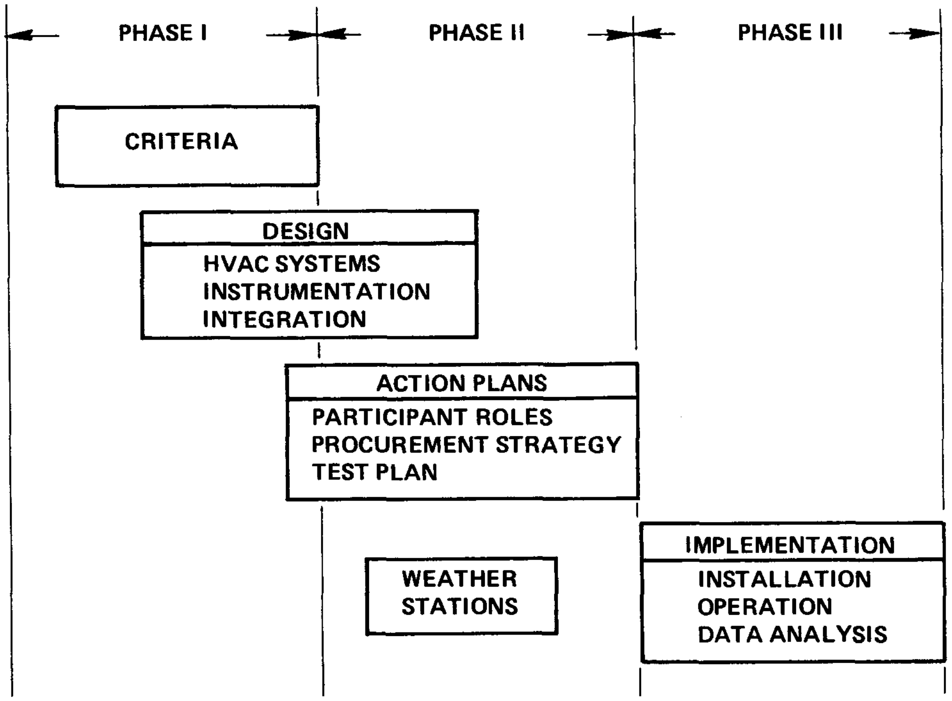
The computer methodology for incorporating utility cost of supply data in system analyses was developed with the primary intent of being compatible with the requirements and preferences of the two utility partners – LILCO and PNM. However, an attempt was made to provide flexibility in the cost accounting procedures so it could be used by other utilities as well.

To test the generality of the methodology and obtain feedback on improvements that could be made, ADL conducted an exercise with 14 additional utilities that represent a diverse mix of geography, generation mix, climate and total generation capacity. Each utility furnished cost-of-supply data for its service area according to the established input formats. Computer runs were made for each utility for each of 15 baseline or reference HVAC systems (considering the generic system classes of conventional; load management; solar; and solar with load management; plus the system functions of domestic hot water, domestic hot water and space heating and domestic hot water, space heating and cooling).

The review of the results with the utility participants showed that the methodology contained all the major elements required for a cost analysis, but more options were required to allow them to conveniently allocate peak costs according to their specific needs and preferences. It was also found that it is very important to have clear definitions for cost of supply elements because items with the same apparent title can have different meanings among utilities. A separate effort is being sponsored by EPRI to make the methodology more flexible to meet the needs of utilities and develop a simpler methodology which can be used by organizations outside the utility industry.

FIGURE 7

OVERALL EXPERIMENTAL PROGRAM



The overall experimental program has elements in all three phases of the EPRI Individual Load Center Solar Heating and Cooling Residential Project.

A prime objective of the first phase is to establish criteria for the experiments, as well as initiate design and integration of the experimental systems and instrumentation.

The second phase will include further detailed design efforts, culminating in action plans that define the roles of the various participants, such as: builder developers, utilities, and equipment suppliers. Details, specifications, and recommendations will be drawn up for the procurement of the various equipment subsystems, and a test plan defining the experimental configuration and sequence of testing will be developed. Also in the second phase, weather stations will be deployed and historical weather data analyzed, utilizing data and equipment available from utilities insofar as it is practicable.

The third phase – which will begin soon after the completion of the second phase – will cover construction, installation, test and evaluation of the ten experiments. The building construction, equipment procurement, installation, and checkout of equipment is expected to be completed within six months from the start of this phase. The duration of the test period is currently planned to be about two years.

FIGURE 8

EXPERIMENTAL CRITERIA

MAXIMUM EXPERIMENTAL CONTENT
COMPREHENSIVE INSTRUMENTATION
CREDIBLE INTEGRATION
COST-EFFECTIVE ENERGY CONSERVATION

Several guidelines have been followed in selecting the residences and solar/load management systems to be used in the third phase of this program. A common element in these guidelines is a desire to fulfill the experimental demands of this residential project and yet do this with credible housing and HVAC equipment. Four principal criteria have been invoked in this selection process.

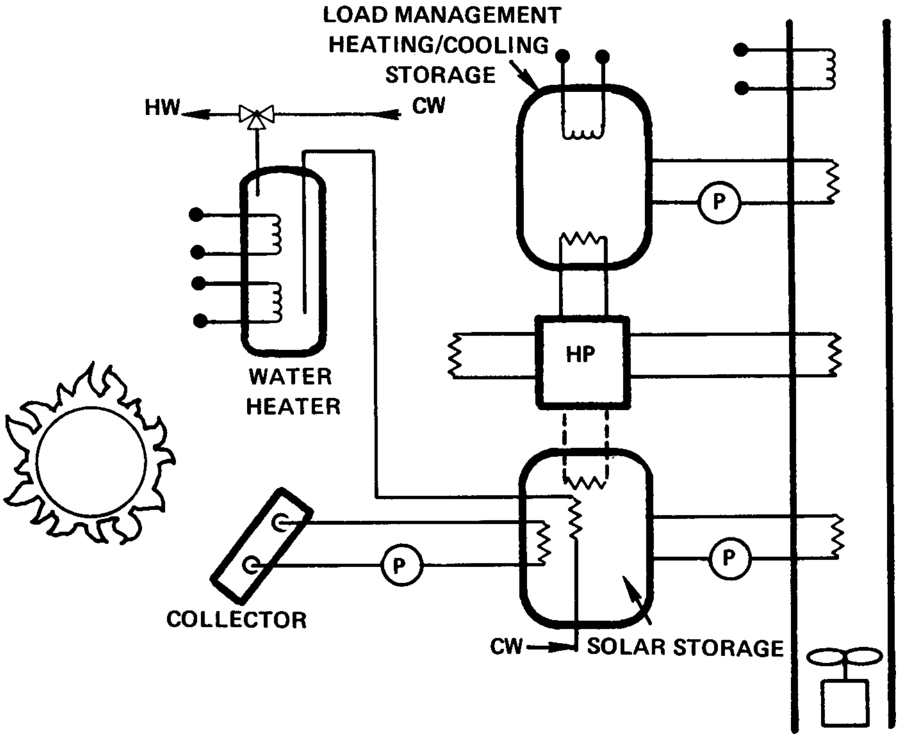
Obtaining maximum information content from the experiments will require that each system operate in several different modes. In one of these modes the system will function as the candidate preferred system; other modes will permit operation in alternative system configurations so that comparisons of the various systems may be made. Major equipment types (e.g., air vs. liquid collectors) as well as variations due to life style and energy conservation measures may be evaluated by making comparisons among the ten installations. Comprehensive, well-conceived instrumentation and data reduction methods will be essential to extracting the maximum useful information from system operation. If the appropriate information is obtained from the system under test, then the performance not only of that system, but of conventional and/or simpler systems may be inferred for similar building energy demands and climatic conditions. This capability allows solar load management and conventional systems to be compared under identical conditions and avoid the uncertainties associated with variations in life style which would arise if the systems were compared in different buildings or at different times.

The experimental systems should demonstrate hardware that can become practical in the near-term (5 to 7 years), serving insofar as possible as a guide for prospective equipment developers and suppliers. The solar load management systems should be integrated with the building construction in such a manner as to minimize adverse aesthetic impact and space requirements for tankage, valves, controls, etc. In particular, they should not present novel architectural features, but rather those which can be adapted with minimum impact to existing styles and living conditions. Satisfying the requirements for credible integration as well as maximum experimental content will involve some trade-offs and possible solutions may include slanting some installations in the direction of high flexibility and others in the direction of being more nearly prototypical of near-term hardware.

The system installations should be characterized by a high degree of energy conservation. Insofar as is practical and compatible with current state-of-the-art installation methods, energy conservation should be brought to the point where further incremental improvements in energy conservation would have paybacks roughly comparable to those of the solar load management systems which are the prime subject of the experimental program.

FIGURE 9

TYPICAL EXPERIMENT SYSTEM



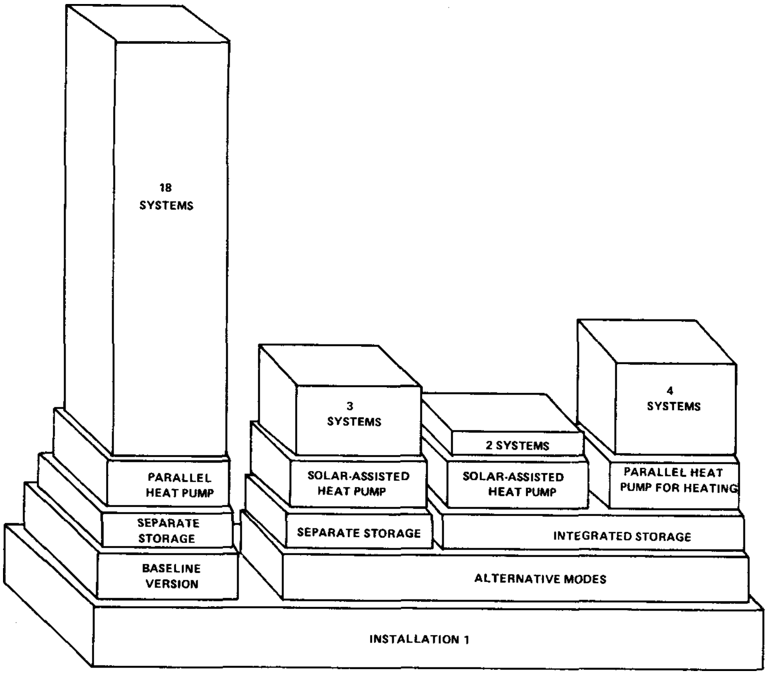
Preliminary designs, instrumentation and test plans were developed for five experiments in Albuquerque and five in Long Island.

One of the more extensive experiments is shown above – a combined heating, cooling and hot water system with load management applied to all three functions and with solar supplement for hot water and space heat. Separate tanks are shown for solar storage and heating and cooling load management storage. An integrated solar load management tank could be simulated experimentally either by providing a flow connection between the tanks or by incorporating an extra electric heating element in the tanks shown for solar storage.

The heat pump system shown here is a very general experimental configuration. It can operate in an air-to-air mode for demand, or in conjunction with either the load management tank, or the solar storage.

This installation can be considered a very general modular representation of a system from which functions or equipment modes may be eliminated if simpler systems are desired. As was indicated earlier, a system of this configuration can produce data for a large number of separate systems when operated with proper instrumentation.

FIGURE 10
EXPERIMENTAL CONTENT



The experimental installations have been designed to allow a wide range of variables to be investigated. The variables fall in four classes:

- Different system arrangements simulated simultaneously with a single installation,
- Different system arrangements achieved in a single installation by relatively minor equipment changes,
- Differences in equipment choices, and
- Differences in building energy conservation features and life style.

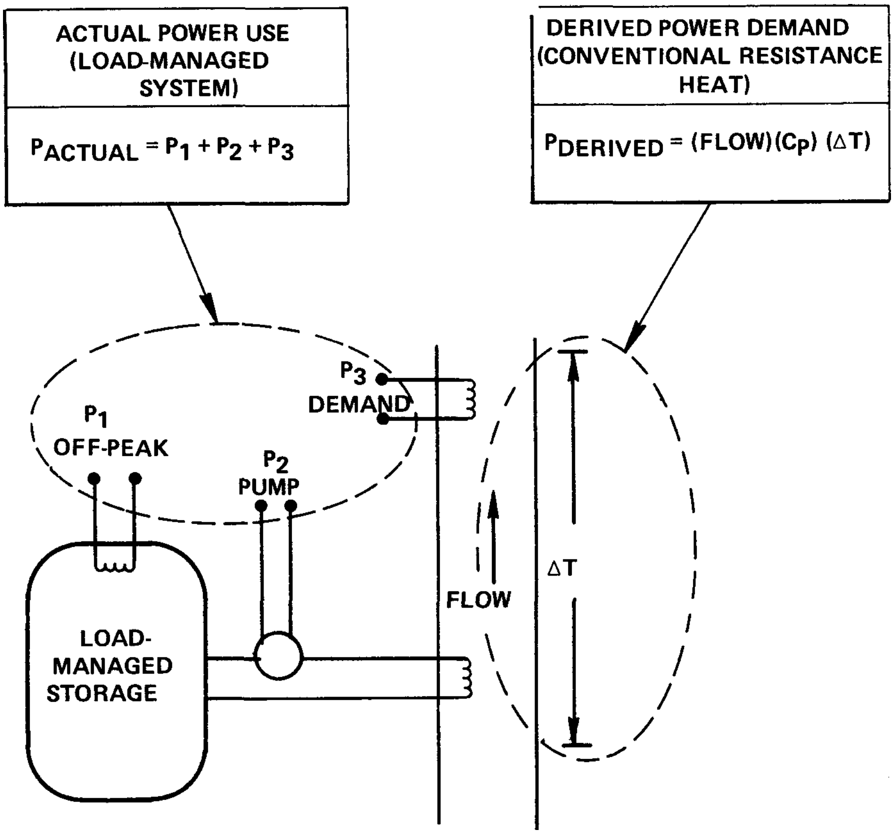
The figure above illustrates the variety of possible systems which are inherent in Installation No. 1, a combined heating, cooling and domestic hot water system with a multi-mode heat pump. For the purpose of this illustration, the installation is considered to have four primary modes of operation:

1) A baseline version,
2) Alternative modes with a solar-assisted heat pump and separate solar and load management storage,
3) Alternative modes with a solar-assisted heat pump and integrated storage, and
4) Alternative modes with a parallel heat pump for heating and integrated storage.

As shown, the baseline arrangement can produce data on 18 baseline systems. Data on 10 of these baseline systems can be derived from data on the parent system without any physical modification to the system. Three alternative system modes can be simulated with the solar-assisted heat pump and dual thermal storage arrangement. By integrating the two thermal storages with an interconnecting pump loop, it is possible to simulate another six system types, two with and four without the solar-assisted heat pump.

FIGURE 11

INFORMATION FOR MULTIPLE SYSTEMS FROM ONE EXPERIMENT



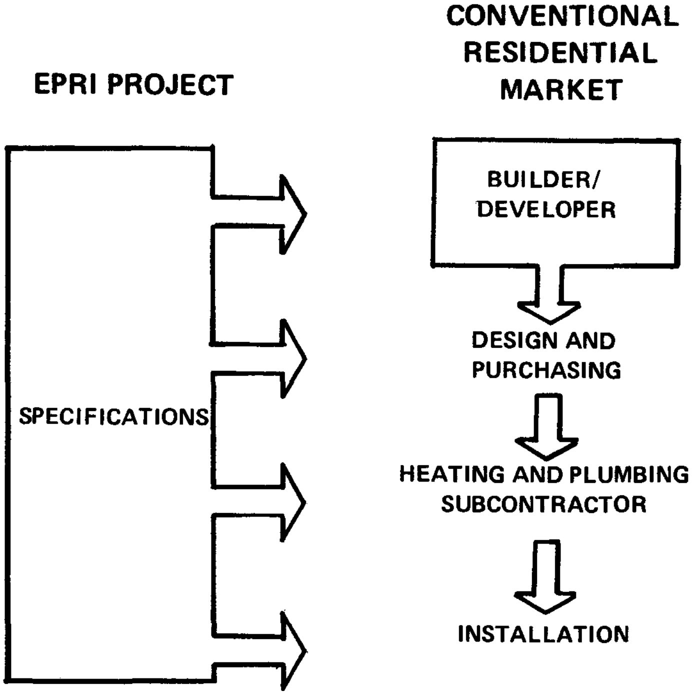
The illustration above shows the technique of deriving information from more than one system from a single set of operating data. For clarity, the technique is illustrated with a simple subsystem, where the instantaneous heating demand is supplied by thermal storage heated at off-peak hours, or with supplementary demand heat as necessary.

For this load management system, the actual electrical demand profile is the sum of the electrical demand profiles for the off-peak heater, the circulating pump, and the demand heater (plus any other ancillary equipment, such as controls). For a conventional system, such as resistance heat on demand, the electrical demand profile which would result from meeting the same building load can be derived solely from the heat added at the air duct. That demand is simply the product of the air flow rate, specific heat and temperature rise across the heating coils.

Over a period of time, the total energy required by both the load-managed system and the conventional, demand-heating system will be nearly the same, except for storage, stand-by heat loss and power supplied to both pumps and ancillary equipment. However, the load-managed system will have a considerably reduced demand during on-peak periods.

FIGURE 12

IMPLEMENTATION APPROACH



Our goal in this project is to adapt as much as possible to the construction process normally used by builder/developers. It is common for builder/developers to have access to architectural design capabilities and a purchasing staff, and to coordinate the installation of equipment provided by other participants, such as heating and plumbing contractors.

We currently have two builder/developer organizations working on our team as consultants – one for the Albuquerque area and one for Long Island. To meet experimental objectives, there will be some unconventional equipment such as solar collectors, advanced heat pumps and sophisticated instrumentation systems which will be new to the established industry participants. Equipment specifications and interface requirements will provide the basis for incorporating equipment in a residence. This can be done by a manufacturer, a local contractor or the builder/developer, as appropriate. In addition to his responsibilities for modifying the house designs, the builder/developer will serve as general contractor.

FIGURE 13

SUBSYSTEM SPECIFICATION APPROACH

PERFORMANCE OVER CONFIGURATION
VENDOR INNOVATION
CREDIBLE NEAR-TERM HARDWARE DESIGN
DEFINED RESPONSIBILITY
INSTALLATION AND START-UP SUPPORT
SERVICE CONTRACT

Conversations with manufacturers and with consultants serve as the basis upon which specifications are being developed for three major subsystems:

- Heat pump subsystems
- Solar subsystem
- Instrumentation subsystem

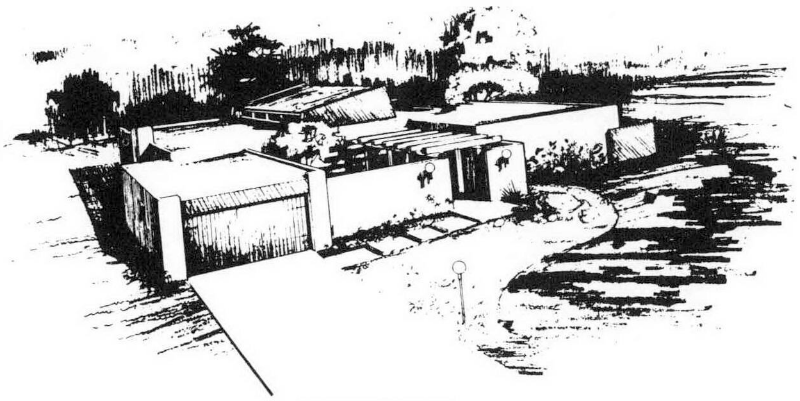
The approach to be followed in preparing specifications will be to place a high degree of responsibility on the subcontractors for the design and integration of these subsystems, including maintenance support during start-up.

Performance requirements rather than configuration details will be stressed as a means of encouraging vendor innovation consistent with the requirements for credible near term hardware design.

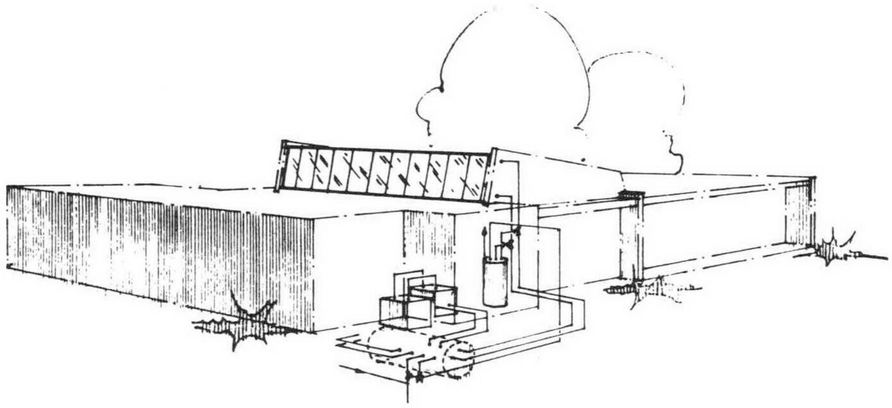
In planning for allocations of responsibility and coordination for the overall effort, the subsystem manufacturer will be required to provide installation and start-up support in close coordination with the builder/developer. The service contract will be a part of the bid document that vendors will respond to.

FIGURE 14

HOUSE ARCHITECTURE AND EQUIPMENT INTEGRATION – ALBUQUERQUE EXPERIMENTS



FRONT VIEW



REAR VIEW

Designs for the five solar/load management experiments have been integrated into home styles being developed by Mossman-Gladden, Inc., our building consultant for the Albuquerque area.

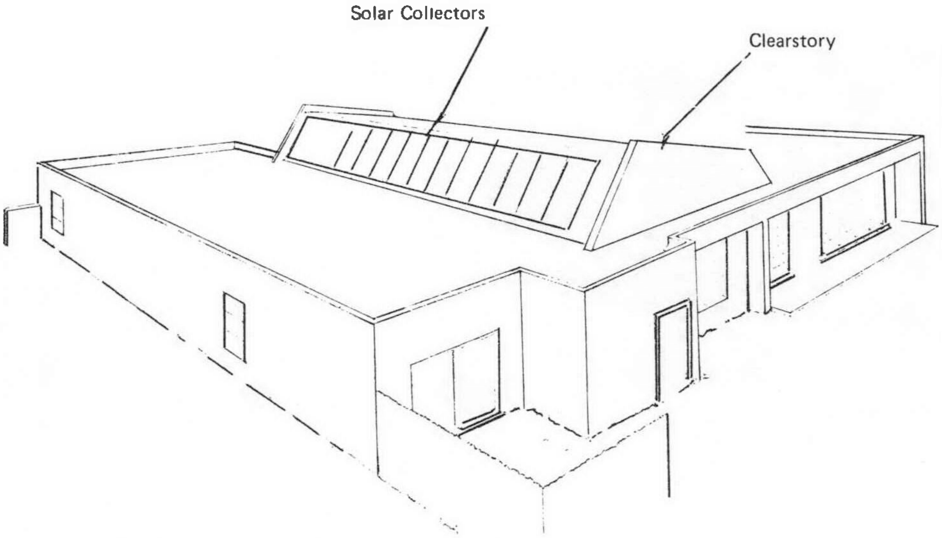
The front-view figure above presents the architectural features of a typical experimental installation while the rear-view figure presents technical features. The architectural features illustration is a perspective rendering of the home, as would be seen from the street servicing the residence. Because the solar collectors have been carefully integrated into the original roof architecture, the street view of the home appears little different than that of a conventional Albuquerque home. More will be said on this on the following pages.

All of the house designs planned for the Albuquerque experiments are flat roofed, single-story homes built on slab foundations. This is the most popular house style in PNM's service area.

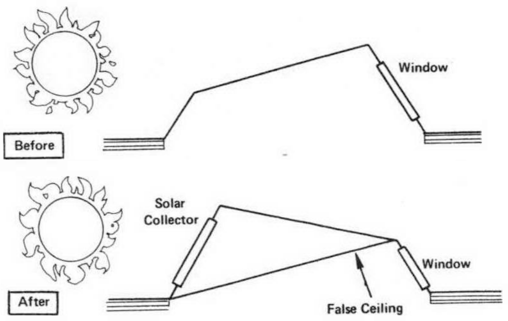
In each installation, plans for standard homes being developed have been modified to include a small HVAC equipment room. This room will house all thermal storage tanks, with the exception of load-management storage tanks, which may be too large for inclusion within the house. These will be buried in the backyard.

FIGURE 15

INTEGRATION OF SOLAR COLLECTORS INTO CLEARSTORY ARCHITECTURE – ALBUQUERQUE EXPERIMENTS



REAR HOUSE VIEW



CLEARSTORY MODIFICATIONS

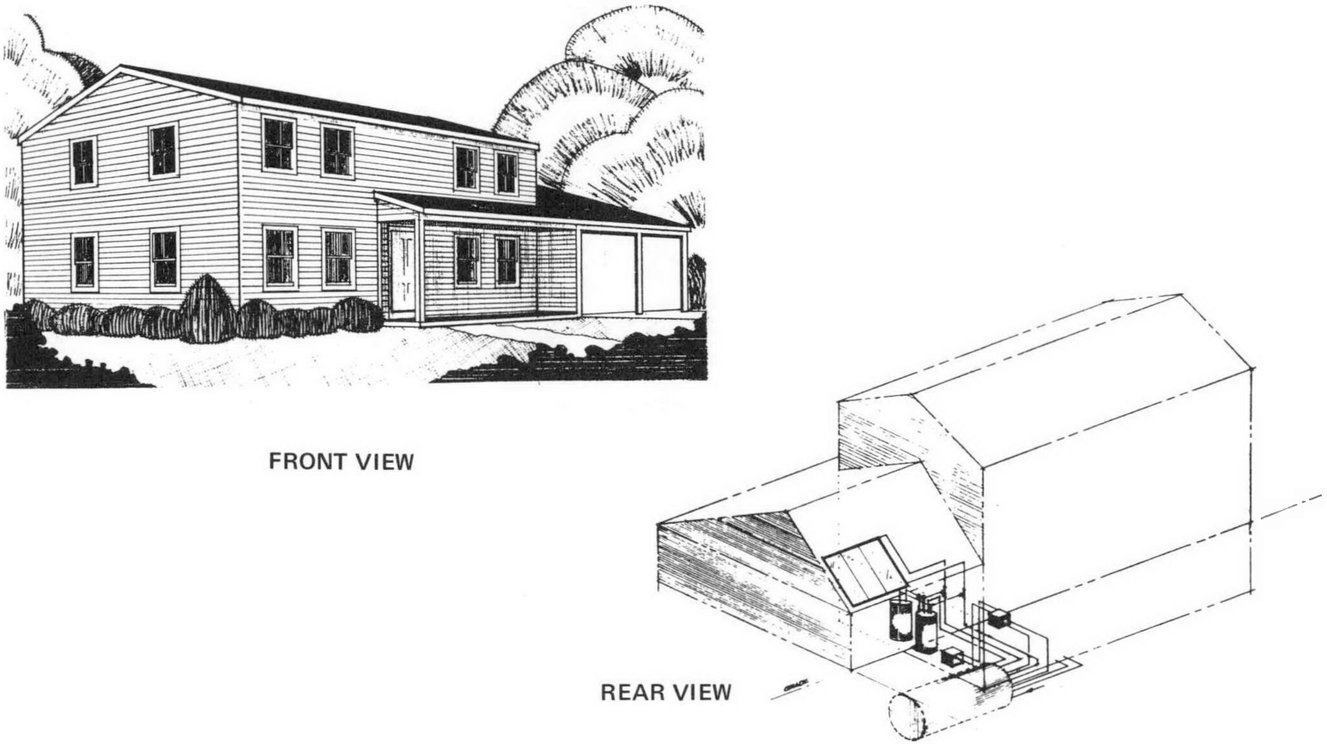
The above house design (same model as shown in Figure 14) was chosen for two of the five experimental installations in Albuquerque. This house has approximately 1,800 square feet of living space.

Integration of solar collector panels into the roof architecture was facilitated by modifying a clearstory which already existed over the living and dining room areas. A clearstory is a partially raised roof which contains windows. Skylights in the north face of the clearstory permit diffuse sunlight to filter down into living spaces below, and the raised ceiling provides an open expansive atmosphere.

As shown by the lower illustration, skylights still will be built into the north wall of the clearstory, with the solar collector panels mounted in the south wall. A false ceiling is an effective way of hiding the solar plumbing and backside of the collector panels.

FIGURE 16

HOUSE ARCHITECTURE AND EQUIPMENT INTEGRATION – LONG ISLAND EXPERIMENTS


FRONT VIEW

REAR VIEW

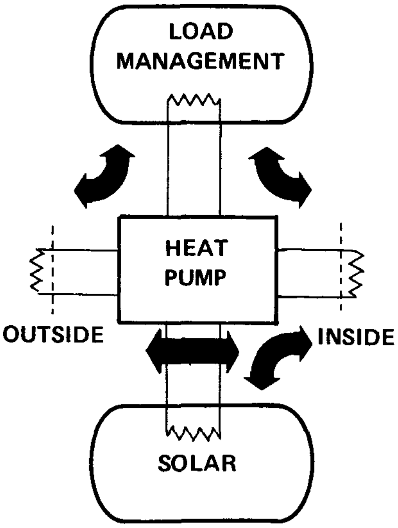
The builder/developer consultant for LILCO's five demonstration homes will be selected in several weeks, based on the performances of two candidate consultants presently participating in a preliminary design exercise. As a result, the illustrations above represent typical designs for Long Island rather than specific house designs from any particular builder's catalog of homes. After exploring the range of potential house designs popular in the Long Island area, a means of equipment integration was defined for two of the more popular styles: the "Cape" and "Long Island Colonial." The colonial is shown above. The cape and colonial house designs provide general vehicles for illustrating methods of integrating solar collector panels into a pitched room structure and of placing thermal storage tanks in the building itself.

The Long Island Colonial house design has about 1,800 square feet of living space, a basement and a two-car garage. The solar collector panels have been integrated into a low roof which is part of the garage structure. To obtain the required roof pitch for collecting solar energy, the peak of this low roof was carried back beyond where it would normally be for equal front and rear roof pitch angles.

Because most Long Island homes normally have basements, it may not be necessary to add on an extra equipment room for housing solar/load management storage tanks. Accordingly, these tanks, plus the indoor unit of a multimode heat pump, have been shown in the basement.

FIGURE 17

HEAT PUMP SUBSYSTEM



Because of the energy conserving potential and the possibilities for integration with solar and load management tanks, great attention was given to heat pump subsystems. The most general type of experimental configuration is shown above, illustrating a heat pump having the capability for direct air-to-air operation, as well as operating in conjunction with either a load management or solar tank. In the direct air-to-air mode, the heat pump will produce heating or cooling on demand. In conjunction with the load management tank, the heat pump can be used either to charge or discharge the load management tank in either the heating or cooling mode – the most promising use in conjunction with the load management tank being that of off-peak cooling. Lastly, in conjunction with the solar tank, the heat pump can operate in the solar-assisted mode, resulting in possibilities for somewhat greater efficiency and operational reliability than if operating in the air-to-air mode.

A preliminary briefing package has been sent to heat pump suppliers to obtain their inputs on the type of equipment that can be supplied.

Multimode capability would be very valuable to the experimental program if such equipment is currently available in a reliable form. If multimode heat pumps are not available, per se, the multimode effect might be achieved, at least in part, with two heat pumps.

Consistent with the availability of equipment, high performance heat pumps are of great interest, both in terms of high efficiency and of relatively high capacity at low ambient temperatures.

The prime focus of this project is not heat pump development. Therefore, selections will be made from equipment which is available or which the manufacturer is willing to develop within the time allowed by the program.

FIGURE 18

INSTRUMENTATION SYSTEM DESIGN ELEMENTS

OBJECTIVES

MEASURE PERFORMANCE:
- SYSTEM UNDER TEST
- RELATED SYSTEMS
- SUBSYSTEMS

PROVIDE CALIBRATION AND CONSISTENCY CHECKS

REQUIREMENTS

DATA SAMPLING RATE AND ACCURACY FOR DETAIL ANALYSIS

KEY SUMMARY PARAMETERS ON DEMAND

ADAPTABLE PROGRAMMING

PERMANENT FILE OF RAW DATA

APPROACH

COMPLETE PACKAGE RESPONSIBILITY
FOR SUBCONTRACTOR
- OVERALL DESIGN
- INSTALLATION AND START-UP
- MAINTENANCE

HIGH RELIABILITY

COST-EFFECTIVE DATA HANDLING

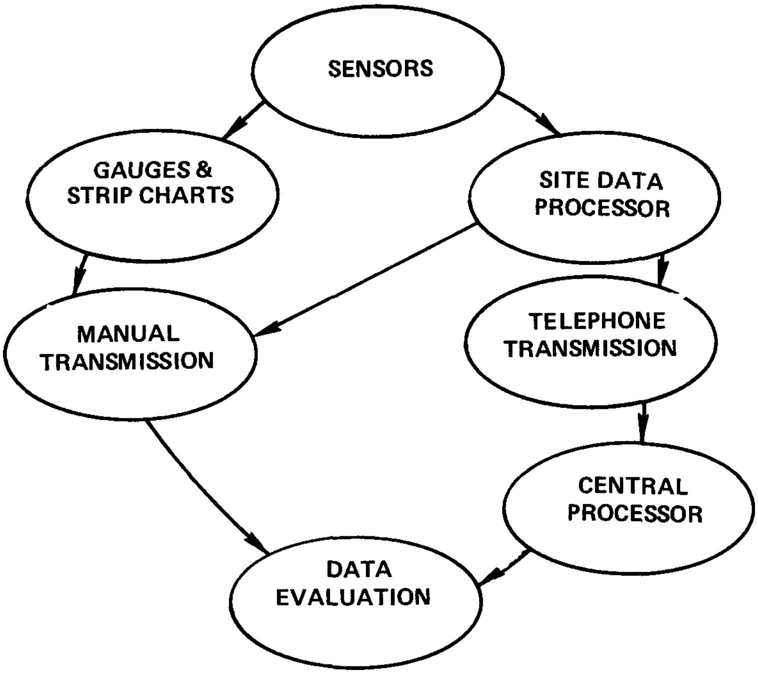
MAXIMUM FEASIBLE UTILITY PARTICIPATION

A major objective in the project is the maximization of experimental information. This objective can only be met with complete, well-documented and operationally flexible data records. The experimental systems thus require a substantial number of measurements. Intermediate translations of these measurements into their correct physical units will allow summary calculations of subsystem performance to be made.

Manufacturers are being sought who can supply complete, packaged ("turn-key") instrumentation subsystems. Procurement would include the manufacture and/or assembly of all necessary hardware, installation, start-up and checkout responsibility and a service and maintenance contract agreement. The hardware would include the measurement sensors, data loggers (with signal conditioning, computational, visual display, printout and data storage equipment) and possibly communications processors.

FIGURE 19

DATA HANDLING OPTIONS



Many options exist for selecting instrumentation equipment and for acquiring, handling, storing, and reducing experimental information. These options are presently being addressed as part of detailed design efforts. System evaluations will include assessments of equipment versatility, cost-effectiveness, reliability and operational information available from similar demonstration projects.

Signals generated by parameter sensors will, in general, first experience sampling and signal conditioning to insure compatibility with a data logger or processor. It may, however, be desirable to acquire some raw data in strip chart form for later diagnostic purposes.

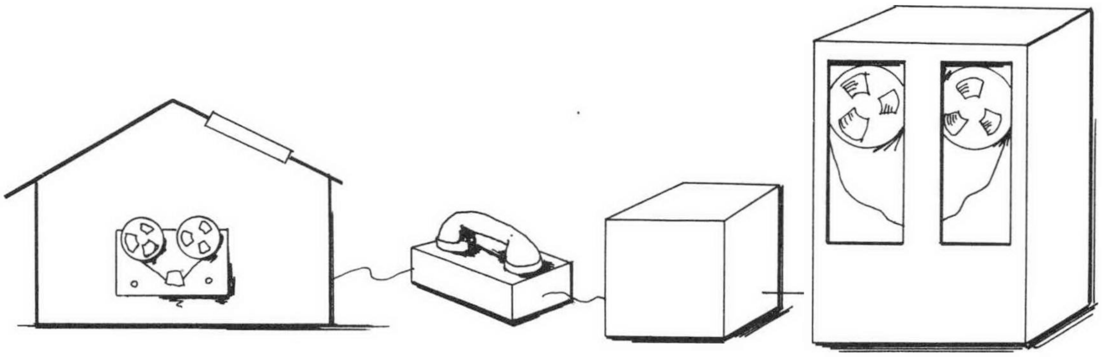
The site data processor can have several configurations. In the simplest arrangement, the site processor could be a data logger which only collects and transmits information. The other end of the spectrum is a site data processor which performs summary calculations such as averages, total energy consumption or maximum electrical demand within a finite period of time.

Experimental data emanating from the site data processor can be treated in many ways. It can be read out at the site in the form of a paper printout or visual display and/or stored on magnetic tape. The information then can be transmitted to a remote computer facility where the final detailed data reduction and analysis would be accomplished.

The data acquisition system may also involve provisions by which a computer terminal operator can query the instrumentation system to retrieve particularly important pieces of information needed prior to a full computer analysis of the data.

FIGURE 20

DATA TRANSMISSION OPTIONS

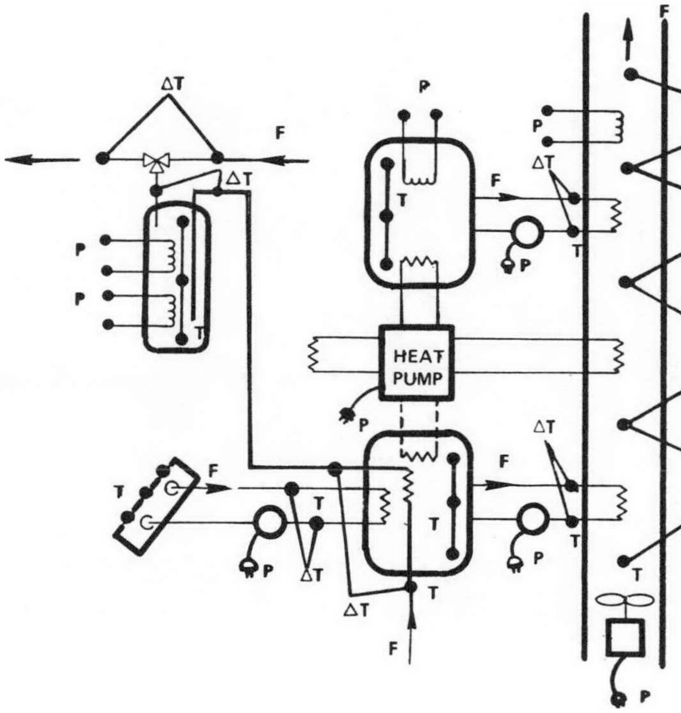


AUTOMATED TRANSMISSION OF DATA RECORDS TO REMOTE COMPUTER CENTER

There are two major modes being considered for transmitting experimental data from the site data processors in the homes to a central data reception facility: 1) automatic data transmission via a telephone line coupling and 2) manual pickup of data tapes at each residence. Automatic data transmission has the obvious advantages of fast and convenient data retrievals without infringing on the living patterns of house occupants. There can, however, be problems with the quality and reliability of telephone equipment when used for automatic data transmission, and there is, of course, the need to guarantee that the communications processing equipment at the receiving end is properly staffed and maintained. However, with so much information from banks, airlines and car rental firms (as several of many possible examples) being sent over telephone lines, control of transmission quality is clearly manageable. Instrumentation subsystem vendors offering fully automatic data transmission systems are being asked to specify the precautions they plan to take to insure the fidelity of transmitted data, and to guarantee that data is not lost if a retransmission is required.

FIGURE 21

TYPICAL MEASUREMENT POINTS



This figure illustrates typical measurement points superimposed on a reference experimental system. The measurements include electrical power consumption, power on-time, temperature, temperature differential and flow. Although not indicated, insolation and other weather measurements will be required.

Typical locations where input electrical power will need to be measured include the:

- Auxiliary space-heating element,
- Load management storage heating element,
- Demand and off-peak water heater resistance elements,
- Heat pump compressor motor,
- Air duct fan motor, and
- Circulating pump motors.

We have a special interest in the cycling characteristics of the heat pump compressor motor so the total time period of operation of this motor will be measured.

Measurements will be made of storage tank temperatures (and stratification), solar collector temperatures, inlet domestic water temperature, heat exchanger inlet temperatures and inlet room temperatures. Some measurements, such as storage tank temperatures, will have a prime part in data reduction and energy balances; others such as solar collector temperatures may be required for diagnostic purposes.

Flow and temperature difference measurements are also required to determine energy exchange in various heat transfer loops. [Heat flow = (fluid flow) x (specific heat) x (temperature difference).]

SECTION 5

EPRI CONTRACT RP-551-1

ENVIRONMENTAL ASSESSMENT OF SOLAR ENERGY POWER PLANTS

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OCTOBER 1976

EPRI SOLAR REVIEW MEETING #2

INTRODUCTION

The National Environmental Policy Act (NEPA) of 1969 established new obligations affecting Federal projects. NEPA requires that for any major Federal action significantly affecting the quality of the human environment, a detailed statement of the impacts associated with that action must be prepared. The significance of this requirement has emerged over the last 6 years to yield the Environmental Impact Statement process that exists today.

Construction of central station solar energy power plants may involve major Federal actions requiring preparation of an Environmental Impact Statement. In addition, many states have adopted legislation imposing requirements similar to the NEPA requirements upon state agencies and individuals.

In the light of these anticipated requirements, it is appropriate to examine solar energy power plants in relation to the National Environmental Policy Act. That is the objective of this Program.

The specific objectives of the Program are as follows.

- Develop a basis for assessment of solar energy alternatives in relation to other types of power plants as required by the National Environmental Policy Act (NEPA) of 1969.
- Anticipate environmental problems which could be associated with solar energy systems, particularly problems with major lead times or monetary implications.

The following five solar energy concepts are being considered.

- Solar Thermal
- Photovoltaic
- Wind
- Ocean Thermal
- Photoproduction

The work is organized around the following 10 major technical tasks.

1.0 Methodology Development
2.0 Reference System Plant Designs
3.0 Reference System Plant Site Selection
4.0 Environmental Data Base
5.0 Environmental Impact Assessments
6.0 Impact Assessment Generalization
7.0 Industrial Implications
8.0 Cost Effectiveness Comparisons
9.0 Basis for "Alternatives" Statement
10.0 Solar Power Plant EIS Framework

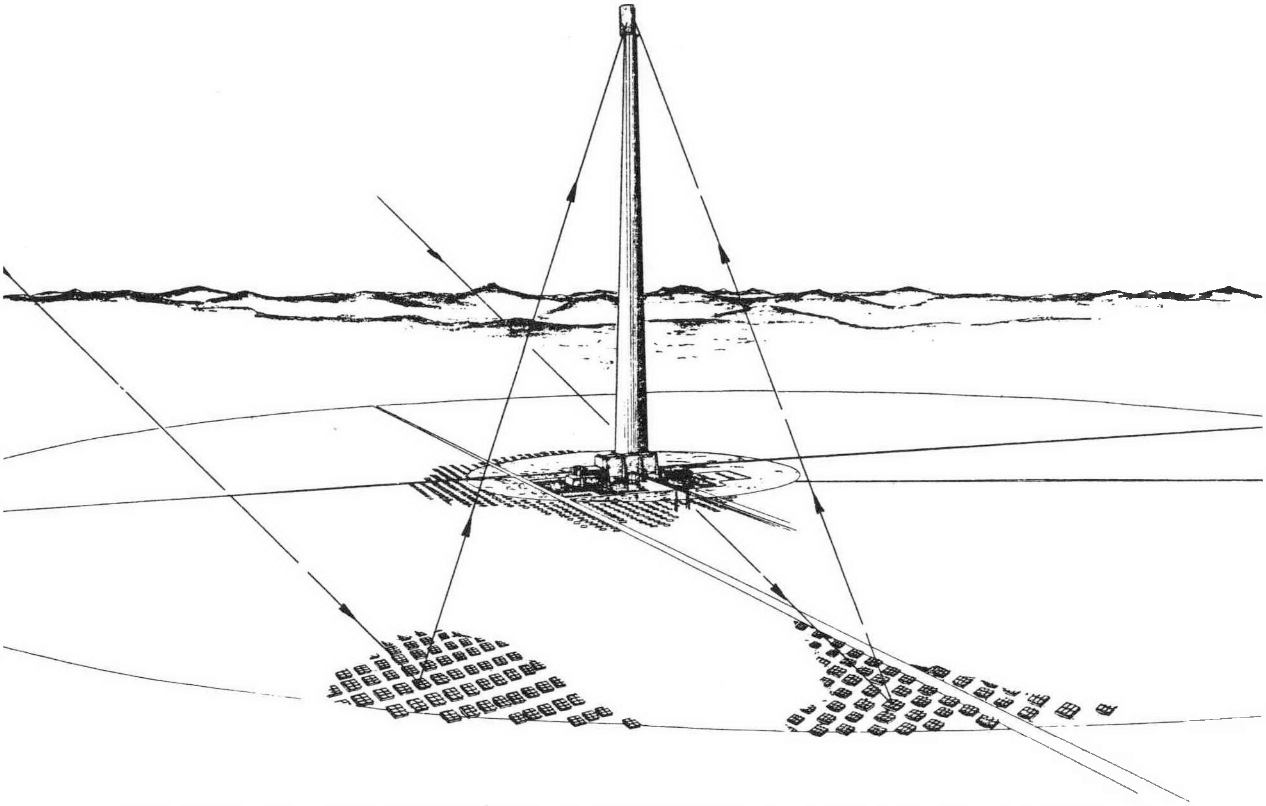
This report will address the following four topics.

- Reference Plant Designs
- Reference Site Selection
- Solar Thermal Environmental Assessment
- Cost-Effectiveness Analysis

SOLAR THERMAL REFERENCE SYSTEMS

- 50 MW_e AND 200 MW_e
- AIR COOLED (BRAYTON CYCLE)
- WATER/STEAM (RANKINE CYCLE)
- SOUTHWESTERN
- NORTHERN PLAINS

Figure 1 Solar thermal reference systems under consideration have 50 MWe and 200 MWe rated capacities. The prime movers in the plants will be either an air-cooled open cycle gas turbine (Brayton cycle) or a conventional water/steam turbine system (Rankine cycle). Water cooled (wet) heat rejection systems are being considered at the site in the Northern Plains siting region. Air-cooled (dry) heat rejection systems are being considered at the site in the Southwestern States siting region.



CONCEPTUAL VIEW OF CENTRAL RECEIVER SOLAR ELECTRIC GENERATING FACILITY

Figure 2 All of the solar thermal reference plant designs are based upon the central receiver concept.

50 MW_e SOLAR THERMAL PLANTS

	STEAM TURBINE	GAS TURBINE
NUMBER OF HELIOSTATS	16,000	6,200
MIRROR AREA – KM^2	0.58	0.23
GROUND AREA – KM^2	1.42	0.42
AVERAGE GROUND COVER RATIO	0.42	0.56
MAXIMUM FIELD RADIUS – M	1,040	460
TOWER/RECEIVER HEIGHT – M	323	198
GENERATOR GROSS – MW_e	59	51
MAKEUP WATER – L/DAY		
WET TOWERS	3,450,000	–
DRY TOWERS	–	–
HEAT REJECTION – MW_t	–	86
WET TOWERS	116	–
DRY TOWERS	125	–
ENERGY STORAGE – MWH_t	1,020	UNLIMITED
OVERALL CONVERSION EFFICIENCY – %	14	17

Figure 3 The solar thermal reference plants are based upon 50 MWe modules. The 200 MWe plants are comprised of four of the modules. This table summarizes characteristics of the 50 MWe modules. Each reference plant includes thermal energy storage for at least 6 hours operation.

PHOTOVOLTAIC REFERENCE SYSTEMS

- 50 MW_e AND 200 MW_e
- SILICON
- CADMIUM SULFIDE
- GALLIUM ARSENIDE
- SOUTHWESTERN
- EASTERN

Figure 4 Photovoltaic reference systems under consideration have rated capacities of 50 MWe and 200 MWe. Three types of cells with efficiencies ranging from 5 to 20 per cent are being considered as are two siting regions.

ELECTRICAL NETWORK

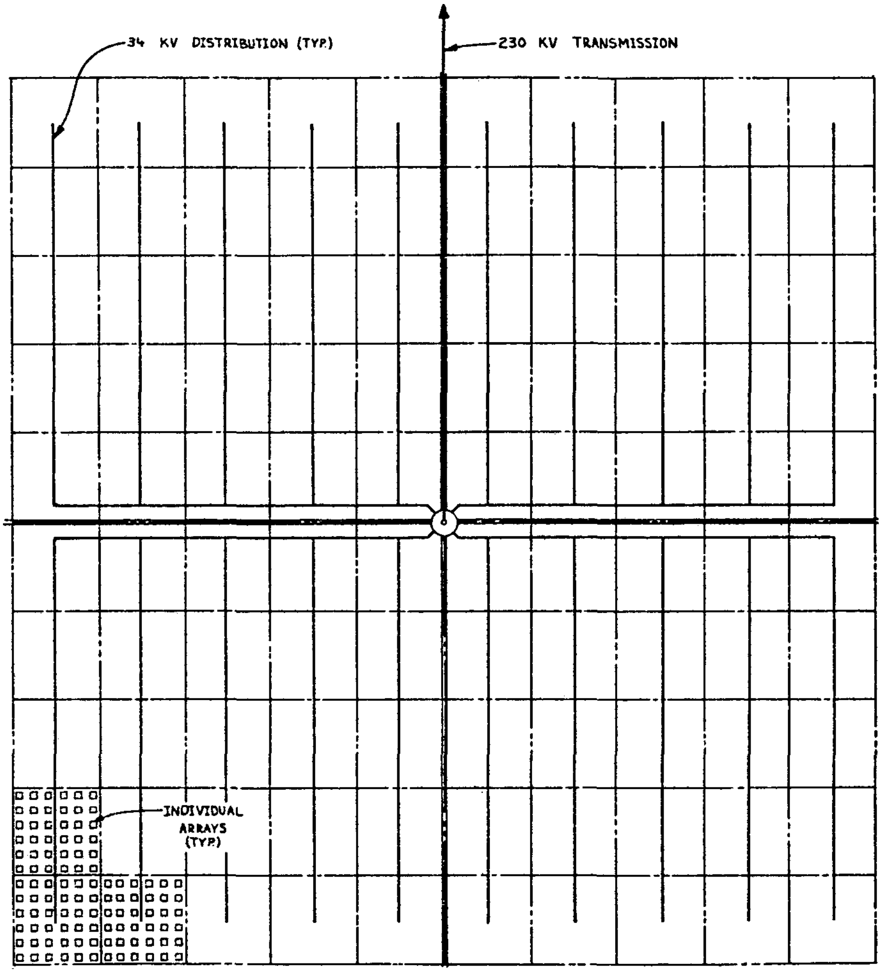
2500 VOLT DIRECT CURRENT BUS
34 KV DISTRIBUTION
34 KV/230 KV SWITCHYARD
230 KV TRANSMISSION LINE

Figure 5 The electrical network of the photovoltaic plants is similar for all three cell types. Array output is collected at 2500 VDC and ultimately delivered to the grid at 230 kVAC.

POWER CONDITIONING AND STORAGE

2.0 MW POWER CONDITIONING MODULES
AC/DC INVERTER
REGULATOR
BATTERIES

Figure 6 Power conditioning modules are distributed throughout the field. Lithium/sulfur batteries are being considered for energy storage.



200 MW PHOTOVOLTAIC STANDARD PLANT

Figure 7 The photovoltaic reference plants have a square arrangement. The physical size of the plant will depend upon cell efficiency but the basic arrangement remains the same. This figure illustrates a 200 MWe arrangement. The 50 MWe plants are equivalent to one quadrant of this plant.

200 MW$_e$ PHOTOVOLTAIC PLANTS

	EASTERN LOCATION				SOUTHWESTERN LOCATION					
CELL MATERIAL	CdS	CdS	Si	Si	CdS	CdS	Si	Si	Si	GaAs
CELL MODULE EFFICIENCY – %	5	10	10	20	5	10	10	20	15/20	20
PLANT EFFICIENCY – %	3.9	7.9	7.9	15.8	3.9	7.9	7.9	15.8	10.0	13.3
CONCENTRATION	–	–	–	–	–	–	–	–	20	500
SOLAR ARRAY AREA – KM^2	11.1	5.6	5.6	2.8	10.9	5.4	5.4	2.7	0.2	0.006
PLANT APERTURE – KM^2	11.1	5.6	5.6	2.8	10.9	5.4	5.4	2.7	4.0	3.0
PLANT AREA – KM^2	27.8	13.9	13.9	6.9	27.2	13.6	13.6	6.8	20.0	14.8

Figure 8 This table summarizes characteristics of 200 MWe photovoltaic reference systems under consideration. These plants include the additional array area necessary to provide energy storage for 6 hours operation at rated capacity.

WIND ENERGY REFERENCE SYSTEMS

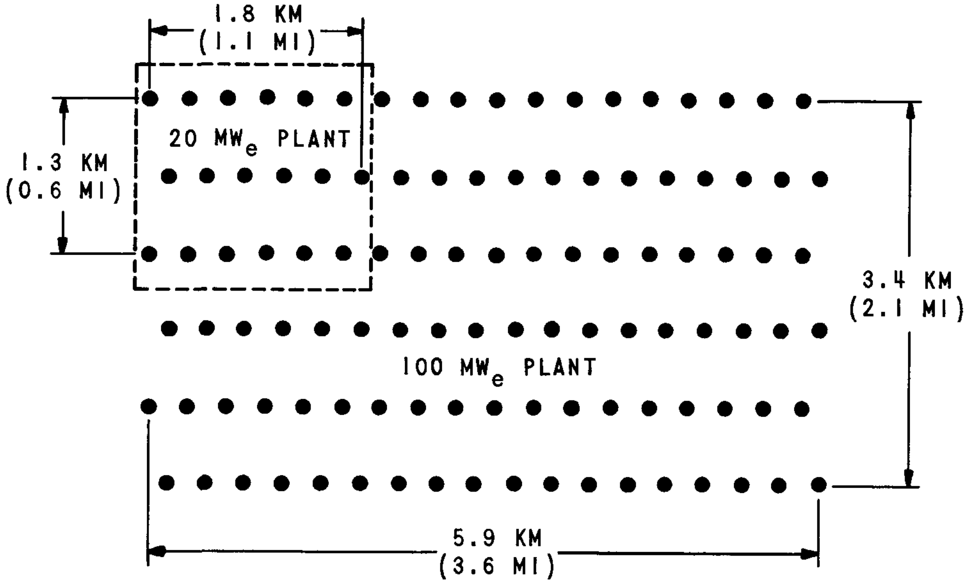
- 20 MW$_e$ AND 100 MW$_e$
- HORIZONTAL AXIS 2.0 MW$_e$ MACHINES
- GREAT PLAINS
- GREAT LAKES
- NORTHEASTERN

Figure 9 Wind energy reference systems under consideration have rated capacities of 20 MWe and 100 MWe, consisting of groups of 2.0 MWe standard wind turbine units. These reference systems will be sited in regions identified as the Great Plains, Great Lakes, and Northeastern States.

STANDARD 2.0 MW_e WIND TURBINE

- ROTOR DIAMETER – 67 M
- CUT-IN VELOCITY – 6.2 M/S
- RATED VELOCITY – 13.4 M/S
- ROTOR SPEED – 32 RPM
- GEARBOX RATIO – 56: 1
- GENERATOR – 4200 V
  3 PHASE
  60 HERTZ
  1800 RPM
- TOWER – 52 M
- OVERALL EFFICIENCY – 38.5%

Figure 10 The characteristics of the standard 2.0 MWe wind turbine units are summarized in this table.



WIND ENERGY PLANT LAYOUTS

Figure 11 The 20 MWe and 100 MWe wind energy reference systems consist of 18 and 108 standard wind turbine units, respectively. The gross area containing these systems is approximately 2.3 and 20.0 square kilometers, although, assuming joint land use, the net land requirements for the wind turbine units is about 0.2 and 0.9 square kilometers. Each wind energy reference plant includes electrical energy storage for 6 hours operation at rated capacity.

OCEAN THERMAL REFERENCE SYSTEMS

100 MW AND 400 MW
FLORIDA

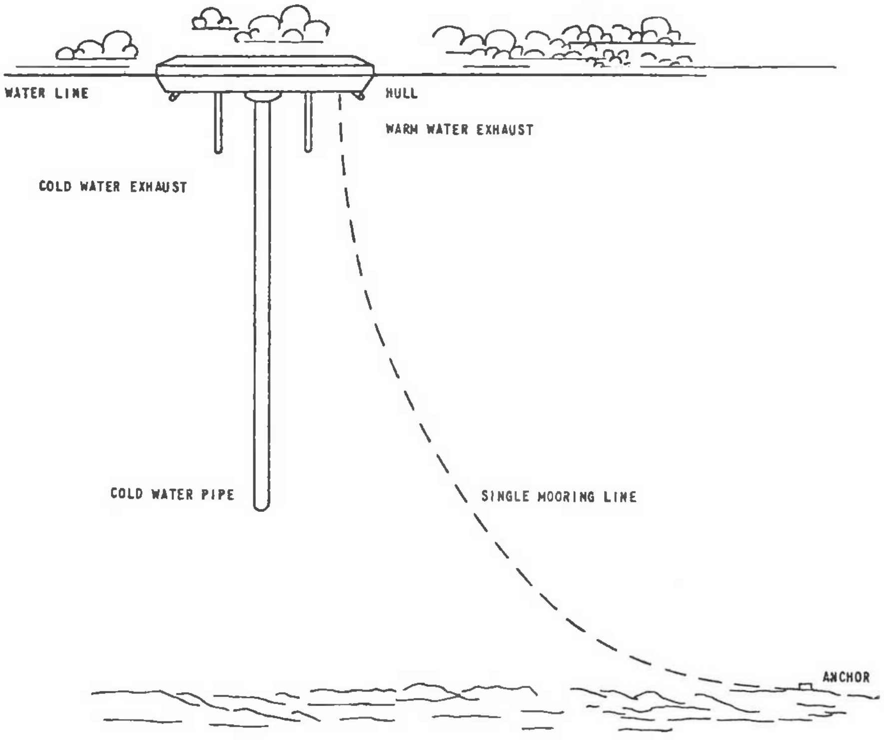
Figure 12 Ocean thermal reference systems under consideration have rated capacities of 120 MWe and 480 MWe. These systems are sited off the eastern coast of Florida.

OCEAN THERMAL REFERENCE PLANTS

	120 MW PLANT	480 MW PLANT
POWER MODULES 30 MWe (GROSS)		
NUMBER PER REFERENCE PLANT	4	16
HULL CONFIGURATION		
GEOMETRY	– RECTANGULAR –	
LENGTH – M	241	268
WIDTH – M	45	183
DEPTH – M	30	38
DRAFT – M	18	24
MATERIAL TYPE	– CONCRETE –	
MATERIAL VOLUME – M^3	49,400	198,000
MOORING		
MOORING LINE TYPE	– LINKED CYLINDRICAL SHELLS –	
ANCHOR WEIGHT – TONS	1,130	2,160
TRANSMISSION		
VOLTAGE	– 138 KV-AC –	
SUBMARINE CABLE TYPE	– ALUMINUM, LEAD SHEATH, OIL-PAPER INSULATION, STEEL WIRE ARMOR –	
CONDUCTOR SIZE – MCM	1,500	1,500
NUMBER CONDUCTORS PER PHASE	1	2
*MAXIMUM CONDUCTOR LENGTH – MI	20	16
EVAPORATORS		
SHELL MATERIAL	–CARBON STEEL –	
TUBE MATERIAL	– TITANIUM –	
TUBE SIZE		
DIAMETER – CM	– 3.8 –	
WALL THICKNESS – CM	– 0.94 –	
LENGTH – M	– 13.1 –	
NUMBER TUBES	303,600	1,214,400
WORKING FLUID	– AMMONIA –	
THERMAL LOAD – MW	3,984	15,936
TURBINE GENERATORS		
NUMBER PER PLANT	4	16
RATED CAPACITY – KVA	141,200	564,800
CONDENSORS		
SHELL MATERIAL	– CARBON STEEL –	
TUBE MATERIAL	– TITANIUM –	
TUBE SIZE		
DIAMETER – CM	– 3.8 –	
WALL THICKNESS – CM	– 0.81 –	
LENGTH – M	– 13.1 –	
NUMBER TUBES	261,600	1,046,000
THERMAL LOAD	3,868	15,472

*DC–AC BREAKEVEN DISTANCE

Figure 13 This table summarizes the characteristics of the ocean thermal reference plants.



CONCEPTUAL VIEW OF OCEAN THERMAL ENERGY
CONVERSION FACILITY

Figure 14 Conceptual view of the ocean thermal conversion reference system.

PHOTOPRODUCTION REFERENCE SYSTEMS

- 100 MW_e AND 500 MW_e
- TREES
- SORGHUM
- SOUTHWESTERN
- SOUTHEASTERN

Figure 15 Two photoproduction reference systems are under consideration. These systems are power plants with a rated capacity of 100 MWe on a site in the Southeastern States utilizing trees for fuel and on a site in the Southwestern States utilizing a sorghum for fuel.

100 MW_e PHOTOPRODUCTION PLANTS

	TREE PRODUCTION	SORGHUM PRODUCTION
FUEL SPECIES	SYCAMORE	SORGHUM/SUDAN GRASS
HEATING VALUE – BTU/LB	4,000	6,800
MOISTURE (AS FIRED) – %	50	20
PRODUCTION YIELD – TONS/AC-YR	8	24
HARVESTED FORM	WOOD CHIPS	CHOPPED
HARVESTING FREQUENCY – PER YR	0.5	3
METHOD OF DRYING	ROTARY DRYER	FIELD
ANNUAL FUEL REQUIREMENTS – TONS	1,200,000	700,000
MINIMUM LAND REQUIREMENT – MI^2	250	50
NET PLANT HEAT RATE – BTU/KWH	13,600	13,600
ASH GENERATION – TONS/YR	24,000	14,000
FLUE GAS TREATMENT	MULTITUBE CYCLONE COLLECTOR PLUS LOW ENERGY IMPINGEMENT SCRUBBER	
HEAT REJECTION METHOD	WET COOLING TOWERS	
PLANT WATER REQUIREMENTS – AC-FT/YR	1,900	1,850

Figure 16 The characteristics of the 100 MWe photoproduction reference plants are summarized in this table.

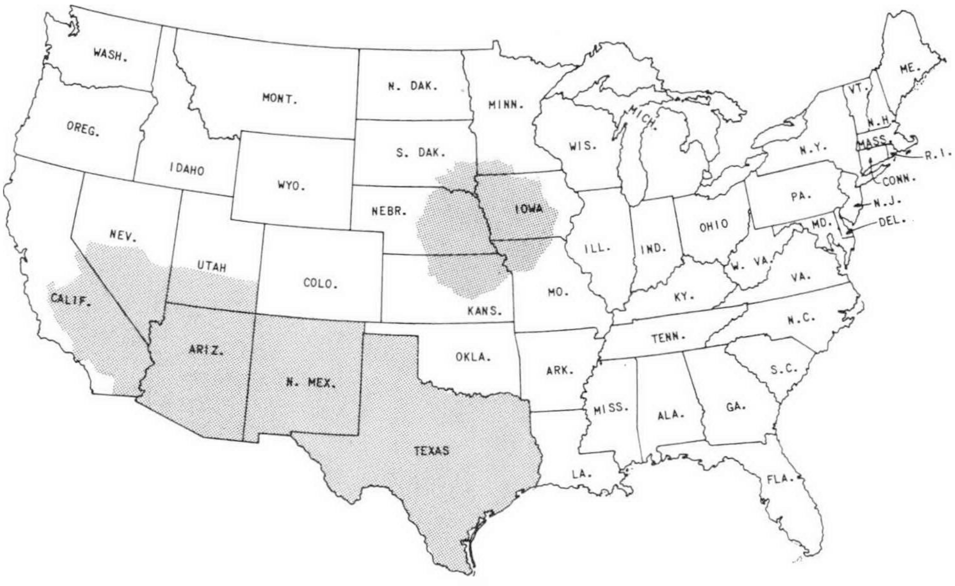


Figure 17 Solar Thermal siting regions.

Figure 18 Photovoltaic siting regions.

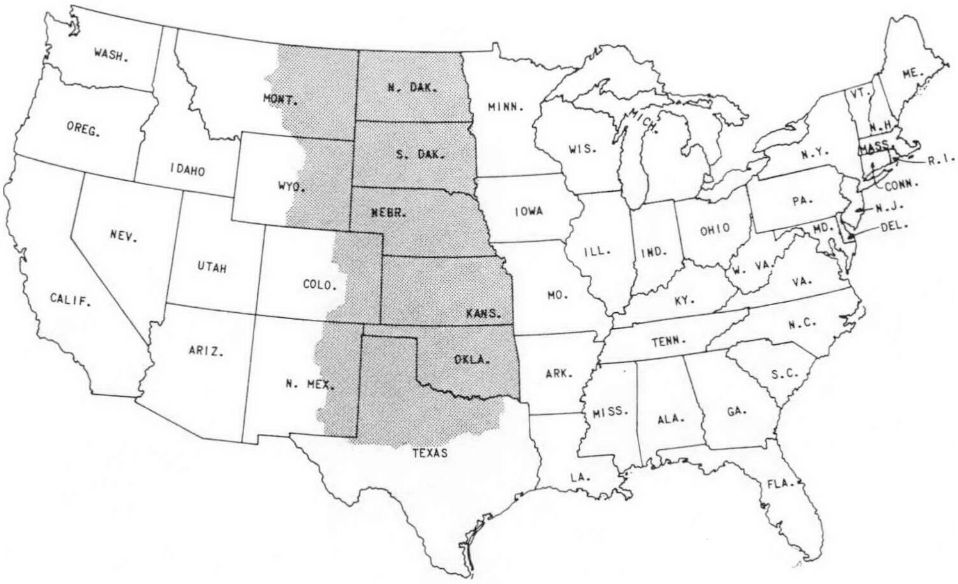


Figure 19 Wind Energy Siting regions.

Figure 20 Photoproduction siting region.

Figure 21 Ocean Thermal siting region.

SITE SELECTION CRITERIA

- GENERAL EXCLUSION CRITERIA
- DETAILED EXCLUSION CRITERIA
- DETAILED SELECTION CRITERIA
- DETAILED EVALUATION CRITERIA

Figure 22 Selection of Reference Sites within the siting regions was accomplished by application of four levels of criteria.

General Exclusion Criteria delineate Candidate Counties within the Siting Region.

Detailed Exclusion Criteria delineate candidate areas within Candidate Counties.

Detailed Selection Criteria delineate Candidate Sites.

Detailed Evaluation Criteria enable Reference Site selection.

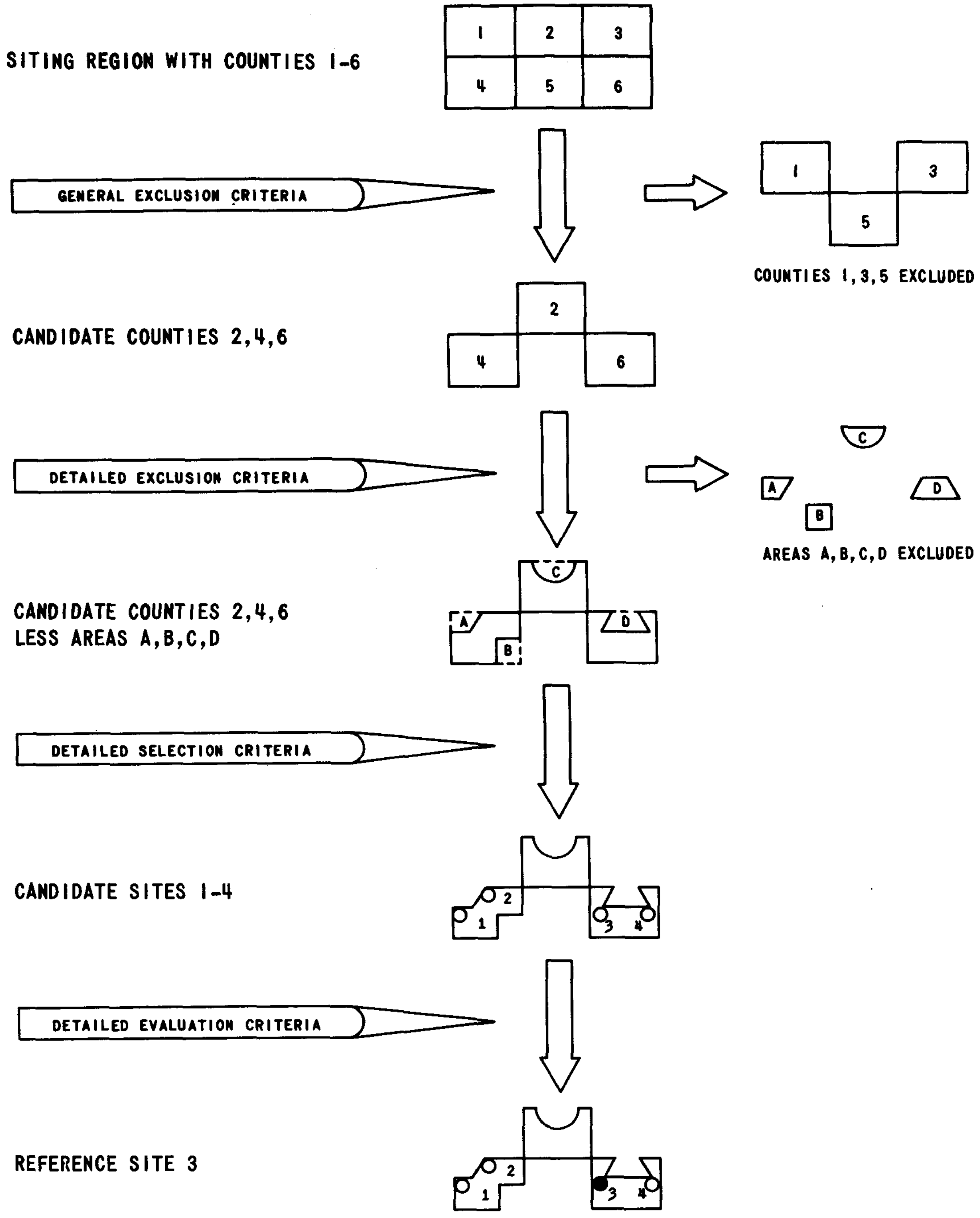


Figure 23 Illustrates the site selection process.

REFERENCE SITE,
KERN COUNTY,
CALIFORNIA

Figure 24 The solar thermal Reference Site in the Southwestern States Siting Region is in Kern County, California. This site is also the Photovoltaic Reference Site in this Siting Region.

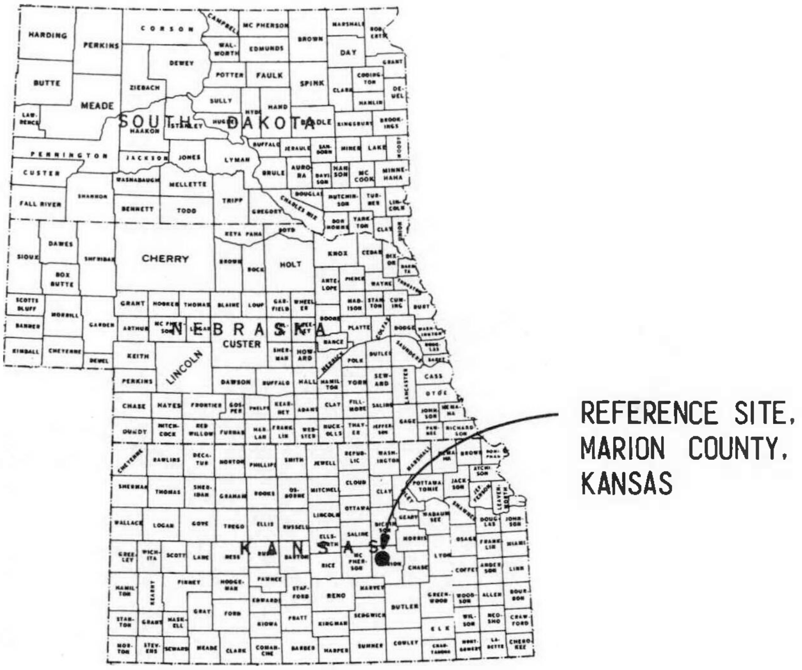


Figure 25 The solar thermal Reference Site in the Northern Plains Region is in Marion County, Kansas.

REFERENCE SITE,
SALEM COUNTY,
NEW JERSEY

Figure 26 The photovoltaic Reference Site in the Eastern States Siting Region is in Salem County, New Jersey.

Figure 27 The wind energy Reference Site in the Great Plains Siting Region is in Carson County, Texas.

Figure 28 The wind energy Reference Site in the Great Lakes Siting Region is in Allegan County, Michigan.

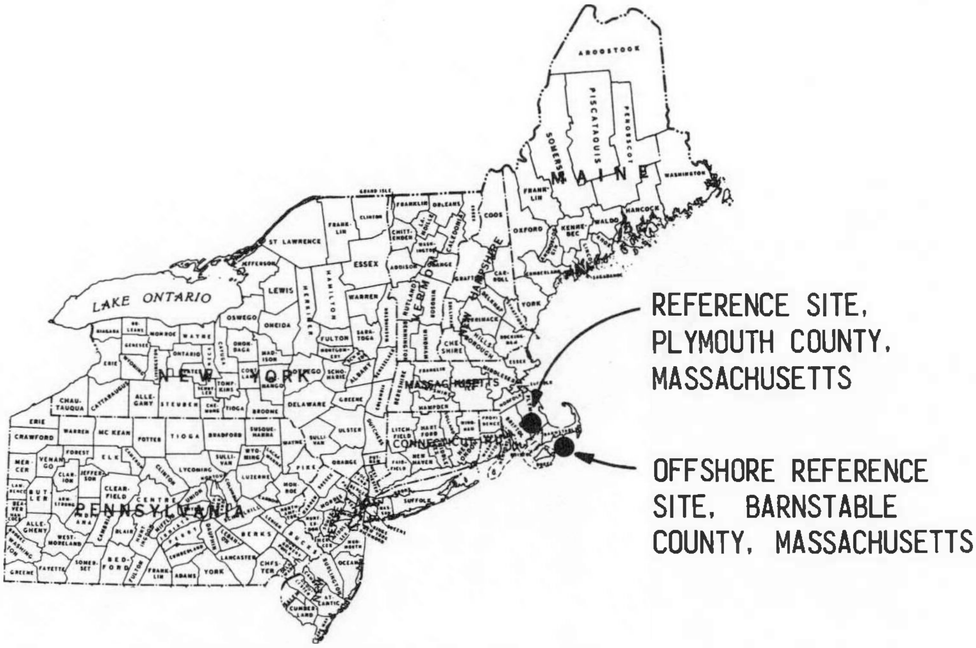
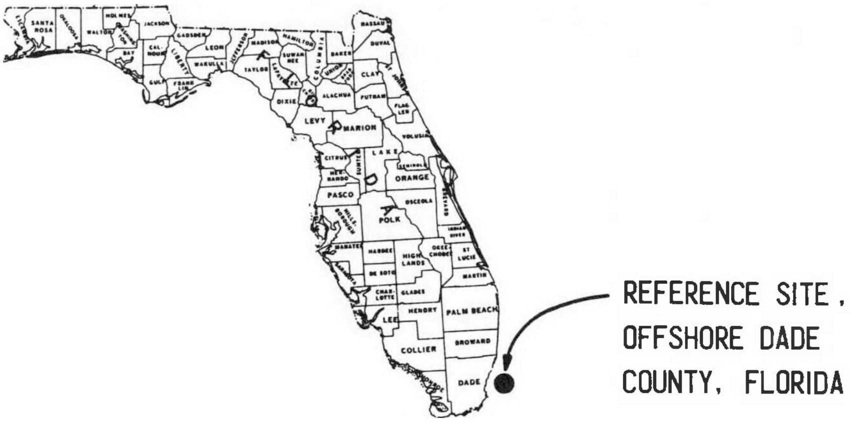


Figure 29 The wind energy Reference Site in the Northeastern States Siting Region is in Plymouth County, Massachusetts. The offshore Reference Site is off the coast of Barnstable County, Massachusetts.



REFERENCE SITE, OFFSHORE DADE COUNTY, FLORIDA

Figure 30 The ocean thermal Reference Site is off the coast of Dade County, Florida.

REFERENCE SITE,
MILAM AND ROBERTSON
COUNTIES, TEXAS

Figure 31 The photoproduction Reference Site in the Southwestern States Siting Region is in Milam and Robertson Counties, Texas.

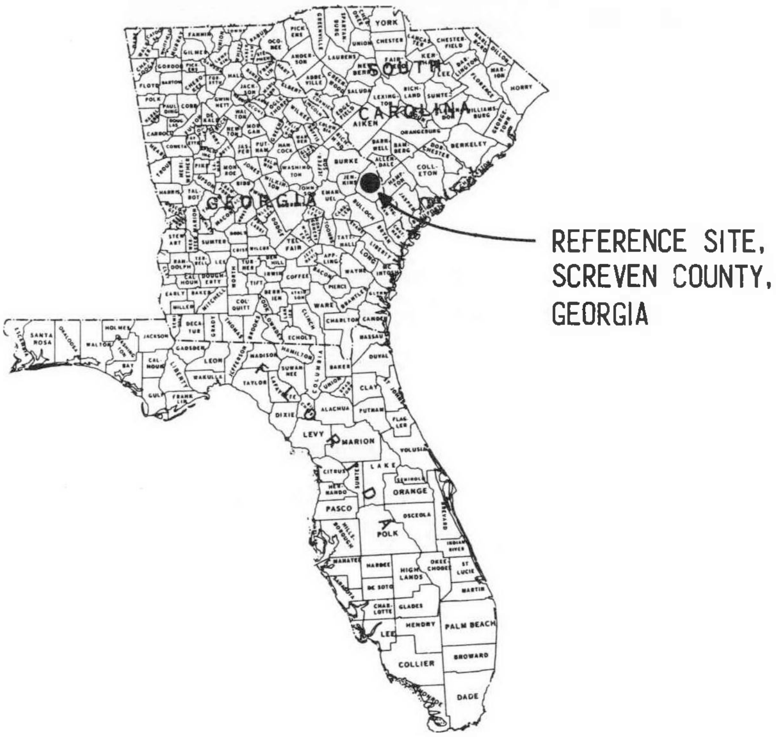


Figure 32 The photoproduction Reference Site in the Southeastern States Region is in Screven County, Georgia.

ENVIRONMENTAL ASSESSMENT
METHODOLOGY

INCORPORATES FEDERAL AGENCY ASSESSMENT PROCEDURES FOR CONVENTIONAL POWER PLANTS BASED ON NATIONAL ENVIRONMENTAL POLICY ACT OF 1969

- PLANT DESCRIPTION
- SITE AND REGION DESCRIPTION
- CONSTRUCTION IMPACT ASSESSMENT
- OPERATION IMPACT ASSESSMENT

Figure 33 The environmental assessments for solar energy power plants are based upon the methodology for preparation of Environmental Impact Statements for coal and nuclear fueled power plants as a consequence of the National Environmental Policy Act.

ENVIRONMENTAL ASSESSMENT
SCOPE

- EACH REFERENCE SYSTEM
- CONSTRUCTION AND OPERATION
- PRIMARY AND SECONDARY EFFECTS
- BENEFICIAL AND ADVERSE EFFECTS
- MITIGATIVE MEASURES
- REGIONAL GENERALIZATIONS OF EFFECTS

Figure 34 The assessments for solar energy power plants have the scope shown in this figure.

ENVIRONMENTAL ASSESSMENT
GENERAL PROCEDURE

STEP 1 – PERFORM GENERIC ASSESSMENT
STEP 2 – PREPARE REFERENCE SITE AND REGIONAL DESCRIPTIONS
STEP 3 – PERFORM REFERENCE SITE ASSESSMENT
STEP 4 – PERFORM REGIONAL GENERALIZATION ASSESSMENT

Figure 35 Four general logical steps are associated with the performance of an environmental assessment for each reference system.

STEP 1 – PERFORM GENERIC ASSESSMENT

- IDENTIFY POSSIBLE SOURCES AND TYPES OF EFFECTS AND WHETHER THEY ARE UNIQUE, SIMILAR OR SUBSTANTIALLY DIFFERENT FROM THOSE OF CONVENTIONAL POWER PLANTS
- CHARACTERIZE SOURCES, AFFECTED ENVIRONMENTAL ELEMENTS, AND OTHER FACTORS DETERMINING INTERACTIONS
- CONSIDER THE POTENTIAL RANGE IN FREQUENCY, MAGNITUDE AND SIGNIFICANCE OF EFFECTS
- IDENTIFY AND EVALUATE MITIGATIVE MEASURES

Figure 36 The generic assessment considers the potential range of environmental impacts from a very broad point of view including identification of impacts of minor significance or improbable occurrence.

SOLAR THERMAL CONSTRUCTION
SOURCES OF EFFECTS

- SITE CLEARING AND EARTHWORK
- FUGITIVE DUST
- NOISE
- ACCIDENTAL CHEMICAL RELEASES
- SOLID WASTE DISPOSAL
- CHEMICAL AND SANITARY WASTE DISPOSAL
- WATER APPROPRIATION
- CONSTRUCTION WORKFORCE
  - EMPLOYMENT
  - TRAFFIC
  - LOCAL EXPENDITURES
  - DEMAND FOR HOUSING AND SERVICES
- TAX AND OTHER PAYMENTS TO GOVERNMENT

Figure 37 These examples illustrate sources of effects during construction.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
GENERIC ASSESSMENT EXAMPLE

- SOURCE – SITE CLEARING AND EARTHWORK
- EFFECTS
  - DISPLACEMENT OF EXISTING SITE LAND USES
  - DESTRUCTION OF HISTORIC OR CULTURAL FEATURES
  - DESTRUCTION OF TERRESTRIAL OR AQUATIC ECOSYSTEMS
  - EROSION
  - SILTATION AND SEDIMENTATION OF SURFACE WATER
- UNIQUENESS
  - EFFECTS ARE SIMILAR TO CONVENTIONAL POWER PLANTS

Figure 38 Considering the first source noted in Figure 37, these are examples of potential effects.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
GENERIC ASSESSMENT EXAMPLE (Continued)

- DISPLACEMENT OF EXISTING SITE LAND USE
  - SOURCE CHARACTERISTICS
    - LAND AREA ACQUIRED/DISTURBED
      200 MWe STEAM TURBINE PLANT – 2560/1400 ACRES
      200 MWe GAS TURBINE PLANT – 640/400 ACRES
- ENVIRONMENTAL ELEMENT CHARACTERISTICS
  - SITE LAND USE
    RESIDENTIAL
    AGRICULTURAL
    TRANSPORTATION
    OTHER

Figure 39 Considering further the generic assessment and the first effect noted in Figure 38, the source characteristics and the characteristics of the affected environmental elements are shown in this figure.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
GENERIC ASSESSMENT EXAMPLE (Continued)

- DISPLACEMENT OF EXISTING SITE LAND USE
  - FREQUENCY OF EFFECT
    - MINIMUM – PLANT OPERATING LIFE
  - MAGNITUDE OF EFFECT
    - RESIDENTIAL – RESIDENTS AFFECTED
    - AGRICULTURAL – ACREAGE AFFECTED
    - TRANSPORTATION – MILES AFFECTED
  - MITIGATIVE MEASURES
    - SITE SELECTION CRITERIA

Figure 40 The frequency and magnitude of the displacement of existing land use can be described. The effects could be mitigated by site selection.

STEP 2 – PREPARE REFERENCE SITE AND REGIONAL DESCRIPTIONS

- DEMOGRAPHY AND LAND USE
- HISTORIC, CULTURAL AND NATURAL FEATURES
- LANDFORMS, SOILS AND MINERALS
- METEOROLOGY
- HYDROLOGY AND WATER USE
- ECOLOGY

Figure 41 Regional and reference site descriptions summarize the characteristics of the site and region. These descriptions are based upon government publications and the technical literature.

STEP 3 – PERFORM REFERENCE SITE ASSESSMENT

- IDENTIFY SPECIFIC SOURCES AND TYPES OF EFFECTS ON REFERENCE SITE AND ENVIRONS
- ESTIMATE THE FREQUENCY, MAGNITUDE AND SIGNIFICANCE OF POTENTIAL EFFECTS
- DETERMINE THE APPLICABILITY AND EFFECTIVENESS OF MITIGATIVE MEASURES

Figure 42 The reference site assessment is designed to determine the qualitative or quantitative significance of the potential impacts, identified generally by the generic assessment, at a specific site.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
REFERENCE SITE ASSESSMENT – EXAMPLE
200 MWe STEAM TURBINE PLANT
MARION COUNTY, KANSAS

- SOURCE – SITE CLEARING AND EARTHWORK
- EFFECT – DISPLACEMENT OF EXISTING SITE LAND USE
- FREQUENCY
  - MINIMUM – 30 YEARS
- MAGNITUDE
  - RESIDENTIAL
    23 RESIDENTS DISPLACED
  - AGRICULTURAL
    2500 ACRES OF CROPLAND ELIMINATED WHAT AND SORGHUM
  - TRANSPORTATION
    6 MILES OF COUNTY ROAD ELIMINATED

Figure 43 Considering the specific Marion County, Kansas solar thermal reference site, the generic assessment of site clearing and earthwork summarized in Figure 40 yields the reference site assessment summarized in this figure.

STEP 4 – PERFORM REGIONAL GENERALIZATION ASSESSMENT

- IDENTIFY THE RANGE OF SOURCES AND TYPES OF EFFECTS EXPECTED FROM REFERENCE PLANT SITING AT VARIOUS SUITABLE LOCATIONS IN REGION
- ESTIMATE THE RANGE IN FREQUENCY, MAGNITUDE AND SIGNIFICANCE OF EFFECTS THROUGHOUT THE REGION
- DETERMINE THE APPLICABILITY AND RANGE IN EFFECTIVENESS OF MITIGATIVE MEASURES

Figure 44 The regional generalization expresses the range of effects throughout the region where candidate sites were identified utilizing information summarized in the regional description.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
REGIONAL GENERALIZATION ASSESSMENT – EXAMPLE
200 MWe STEAM TURBINE PLANT
NORTHERN PLAINS SITING REGION

- SOURCE – SITE CLEARING AND EARTHWORK
- EFFECT – DISPLACEMENT OF EXISTING LAND USE
- FREQUENCY
  - THE MINIMUM 30 YEAR DISPLACEMENT FREQUENCY WOULD OCCUR AT ANY LOCATION WITHIN THE REGION
- MAGNITUDE
  - RESIDENTIAL
    - 6 TO 50 RESIDENTS DISPLACED
  - AGRICULTURAL
    - 2500 ACRES ELIMINATED
    - CROPLAND OR PASTURELAND
  - TRANSPORTATION
    - 4 TO 6 MILES OF ROAD ELIMINATED

Figure 45 Generalization of the reference site assessment summarized in Figure 43 through the range of candidate sites in the Northern Plains solar thermal siting region yields the range of potential effects summarized in this figure.

SOLAR THERMAL OPERATION
SOURCES OF EFFECTS

- COLLECTOR/CONCENTRATOR SUBSYSTEM
  - HELIOSTAT FIELD SURFACE TREATMENT
  - HELIOSTAT REFLECTIONS
  - HELIOSTAT SHADING
  - HELIOSTAT AIR FLOW DEFLECTIONS
  - HELIOSTAT PRECIPITATION INTERCEPTION
  - HELIOSTAT CLEANING WASTES
- RECEIVER/HEAT TRANSFER SUBSYSTEM
  - TOWER AIRSPACE OBSTRUCTION
  - TOWER EXTERIOR FEATURES
  - TOWER SHIELDING AND RECEIVER HOT SURFACES
  - SOLAR RADIATION FLUX NEAR RECEIVER
  - HEAT TRANSFER TUBING CLEANING WASTES
- ELECTRIC POWER GENERATION SUBSYSTEM
  - TURBINE AND GENERATOR NOISE
  - STEAM CYCLE BLOWDOWN WASTEWATER
  - STEAM CYCLE MAKEUP WATER
  - HOT AIR/COMBUSTION GAS RELEASES
- HEAT REJECTION SUBSYSTEM (COOLING TOWER)
  - NOISE
  - HEAT RELEASES
  - WATER VAPOR RELEASES
  - DRIFT
  - BLOWDOWN WASTEWATER
  - MAKEUP WATER APPROPRIATION

Figure 46 A generic assessment of solar thermal power plant operation yields these examples of sources of effects.

SOLAR THERMAL ENVIRONMENT ASSESSMENT
GENERIC ASSESSMENT EXAMPLE

- SOURCE – COLLECTOR/CONCENTRATOR SUBSYSTEM
  - HELIOSTAT REFLECTIONS
- EFFECTS
  - MATERIAL DAMAGE AND FIRE HAZARD
  - VEGETATION FIRE HAZARD
  - WILDLIFE BURN HAZARD
  - HUMAN SKIN BURN HAZARD
  - HUMAN CORNEA BURN HAZARD
  - HUMAN RETINA BURN HAZARD
- UNIQUENESS
  - EFFECTS ARE UNIQUE TO SOLAR THERMAL PLANTS

Figure 47 Considering as an example heliostat reflections, potential effects are noted in this figure.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
GENERIC ASSESSMENT EXAMPLE (Continued)

- SKIN BURN HAZARD
  - SOURCE CHARACTERISTICS
    - HELIOSTAT MIRROR AREA – 37 M^2
    - MIRROR REFLECTIVITY – 0.85
    - HELIOSTAT FOCAL LENGTH
      210 M TO 500 M IN GAS TURBINE PLANT
      305 M to 1,050 M IN STEAM TURBINE PLANT
    - HELIOSTAT AIMING AND MOVEMENT
    - NUMBER OF COINCIDENT REFLECTIONS
  - ENVIRONMENTAL ELEMENT CHARACTERISTICS
    - PERSON'S POSITION WITH RESPECT TO HELIOSTATS
    - BURN THRESHOLD INTENSITY AND DURATION
    - BEHAVIORAL RESPONSES TO EXPOSURE
  - OTHER FACTORS
    - SUN POSITION
    - SOLAR RADIATION INTENSITY
    - OBSTACLES BLOCKING REFLECTIONS

Figure 48 Pursuing the generic assessment example, the skin burn hazard can be characterized as shown in this figure.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
GENERIC ASSESSMENT EXAMPLE (CONT'D)

- SKIN BURN HAZARD – SIMPLEST CASE
  - HELIOSTAT WITH SHORTEST FOCAL LENGTH (210 M)
  - HELIOSTAT IS AIMED AT PERSON
  - PERSON IS AT FOCUS, FACING HELIOSTAT
  - SOLAR RADIATION ANGLE OF INCIDENCE SMALL (O DEG)
  - SOLAR RADIATION INTENSITY IS MAXIMUM (1 KW/M^2)
  - FOCAL RADIATION INTENSITY ON SKIN IS 8KW/M^2
  - FOCAL SPOT WIDTH IS ABOUT 2M

Figure 49 The simplest case of the skin burn hazard occurs under these conditions. Referring to the burn threshold characteristics shown in Figure 50, it can be concluded that an exposure of 15 to 35 seconds is required for a first degree burn to occur.

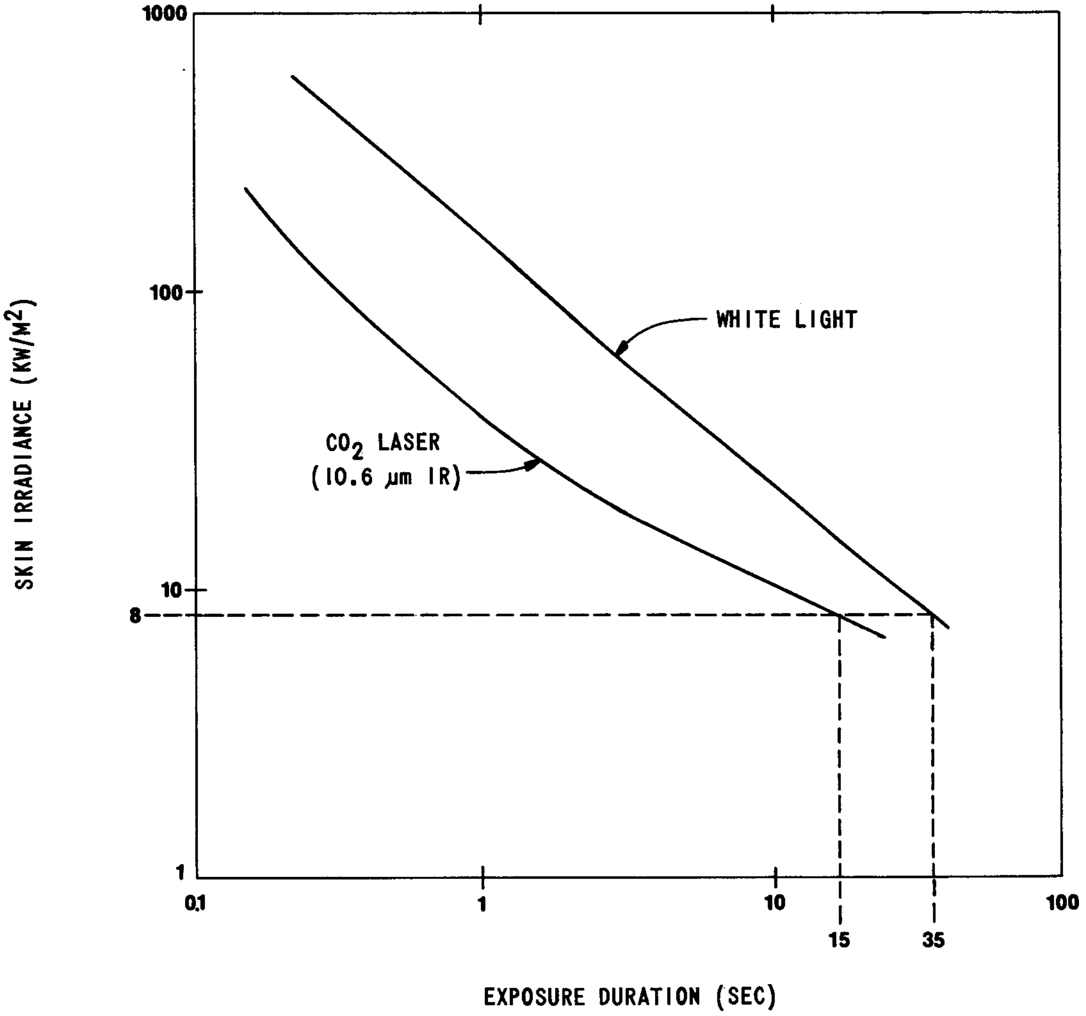


Figure 50 First degree skin burn thresholds.

SOLAR THERMAL ENVIRONMENTAL ASSESSMENT
GENERIC ASSESSMENT EXAMPLE (CONT'D)

- SKIN BURN HAZARD – SIMPLEST CASE (CONT'D)
  - SKIN BURN THRESHOLD IRRADIANCE – DURATION
    - FIRST-DEGREE SKIN BURN THRESHOLD EXPOSURE DURATION IS BETWEEN 15 AND 35 SECONDS
    - SECOND-DEGREE SKIN BURN THRESHOLD EXPOSURE DURATION IS BETWEEN 30 AND 70 SECONDS FOR SKIN IRRADIANCE OF 8 KW/M^2
  - CONCLUSION
    - NO FIRST-DEGREE SKIN BURN WOULD BE ANTICIPATED UNLESS NORMAL AVOIDANCE RESPONSE DOES NOT OCCUR OR RESPONSE TIME IS 3 TO 7 TIMES SLOWER THAN NORMAL

Figure 51 Recognizing a normal response time of about 5 seconds, a conclusion can be drawn concerning the skin burn hazard.

COST-EFFECTIVENESS ANALYSIS FEATURES

- CAPITAL COSTS
- OPERATING COSTS
- MAINTENANCE COSTS
- LEVELIZED BUS BAR ENERGY COSTS
- MID-1975 COST LEVELS
- ELECTRIC UTILITY PRACTICES

Figure 52 The cost effectiveness analysis is designed to consider all of the costs of construction, ownership, and operation for the life of each reference system. This cost analysis is designed to reflect normal utility accounting practices. All of these costs are stated in terms of cost per kilowatt hour of energy.

COST-EFFECTIVENESS ANALYSIS
REFERENCE PLANT
ESTIMATED CAPITAL COSTS
1975 DOLLARS
SUBSYSTEM X

	PESSIMISTIC $1000	BEST GUESS $1000	OPTIMISTIC $1000
COMPONENT NO. 1*	10,000	5,000	1,000
COMPONENT NO. 2	1,000	1,000	1,000
COMPONENT NO. 3	1,000	1,000	1,000
COMPONENT NO. 4	1,000	1,000	1,000
COMPONENT NO. 5	1,000	1,000	1,000
TOTAL SUBSYSTEM X	14,000	9,000	5,000

* HIGH LEVERAGE COST COMPONENT –
DESIGN FEATURES UNCERTAIN

Figure 53 For each reference plant, costs are being estimated for component categories.

The high cost components are being identified and, where there are uncertainties concerning these high cost components, ranges of cost are being estimated.

COST-EFFECTIVENESS ANALYSIS
100 MW$_e$ REFERENCE PLANT
SUMMARY OF ESTIMATED CAPITAL COSTS
(1975 DOLLARS)

	PESSIMISTIC	BEST GUESS	OPTIMISTIC
	$1,000	$1,000	$1,000
SUBSYSTEM X*	14,000	9,000	5,000
SUBSYSTEM Y	500	500	500
SUBSYSTEM Z	500	500	500
	15,000	10,000	6,000
SPARE PARTS – 2%	300	200	120
CONTINGENCY – 10%	1,500	1,000	600
TOTAL DIRECT COST	16,800	11,200	6,720
INDIRECT COST – 20%	3,360	2,240	1,344
TOTAL COST	20,160	13,440	8,064

* INCLUDES HIGH LEVERAGE COST COMPONENT

Figure 54 Subsystem costs are aggregated to determine total costs. Spare parts, contingency, and indirect costs are added as normal utility system burdens on capital expenses. The result of this approach is a uniform procedure for development of capital costs for each reference plant.

ECONOMIC FACTORS

	NOMINAL VALUE
SYSTEM OPERATING LIFETIME	30 YEARS
ANNUAL OTHER TAXES	0.02
ANNUAL INSURANCE PREMIUMS	0.0025
EFFECTIVE INCOME TAX RATE	0.40
RATIO OF DEBT TO TOTAL CAPITALIZATION	0.50
RATIO OF COMMON STOCK TO TOTAL CAPITALIZATION	0.40
RATIO OF PREFERRED STOCK TO TOTAL CAPITALIZATION	0.10
ANNUAL RATE OF RETURN ON DEBT	0.08
ANNUAL RATE OF RETURN ON COMMON STOCK	0.12
ANNUAL RATE OF RETURN ON PREFERRED STOCK	0.08
RATE OF GENERAL INFLATION	0.05
ESCALATION RATE FOR CAPITAL COSTS	0.05
ESCALATION RATE FOR OPERATING COSTS	0.06
ESCALATION RATE FOR MAINTENANCE COSTS	0.06
BASE YEAR FOR CONSTANT DOLLARS	1975
COST OF CAPITAL TO A TYPICAL UTILITY	0.08
CAPITAL RECOVERY FACTOR (8%, 30 YEARS)	0.0888
TYPICAL ANNUALIZED FIXED CHARGE RATE	0.1483

Figure 55 The method used to develop the levelized cost per kilowatt hour for energy from each reference system is The Cost of Energy From Utility-Owned Solar Electric Systems, A Required Revenue Methodology for ERDA/EPRI Evaluations, Jet Propulsion Laboratory, June 1976. The economic factors listed in this figure are part of that methodology.

SECTION 6

EPRI CONTRACT RP 551-2

ENVIRONMENTAL ASSESSMENT METHODOLOGY AND SOLAR PLANT APPLICATIONS

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OCTOBER 1976

EPRI SOLAR REVIEW MEETING #2

Woodward-Clyde Consultants was awarded a 19-month contract to develop a generic methodology for environmental impact assessment and to show an application of the methodology for solar power plants. The basis for this methodology is decision analysis, which provides a framework for quantifying and comparing environmental impacts.

The project is divided into five tasks. The first four deal with developing the methodology, applying it to selected sites for solar power plants, and generalizing the results for different site and plant characteristics. The last task is an independent assessment of the state of the art and the probable degree of market penetration in various regions of the nation for certain solar systems.

ENVIRONMENTAL ASSESSMENT OF SOLAR ENERGY POWER PLANTS: OUTLINE OF OBJECTIVES

1. METHODOLOGY
2. DATA BASE
3. ENVIRONMENTAL IMPACT ASSESSMENT
4. IMPACT GENERALIZATION
5. BASIS FOR ALTERNATIVES

Figure 1 Shows the five task elements of the project. Task 1 develops an innovative methodology for environmental impact assessment. Task 2 develops an environmental data base for solar thermal and wind-powered sites selected by EPRI. Task 3 illustrates the methodology through impact assessments of the selected sites. Task 4 generalizes the assessment as a function of plant and site characteristics. Task 5 develops an independent assessment of the state of the art and the probable degree of market penetration for solar thermal and wind-powered systems. This presentation focuses on Tasks 2 and 3. The previous review meeting of March 1976 focused on Task 1 and part of Task 2. The Task 1 methodology is illustrated in this presentation when the environmental assessment is described.

ENVIRONMENTAL DATA BASE

- CLASSIFICATION CATEGORIES
- LITERATURE SEARCH
- ANALYSIS FOR ANNOTATION OF LITERATURE
- EXTRACTION OF DATA FOR ENVIRONMENTAL IMPACT ASSESSMENT

Figure 2 Outlines the procedure followed in Task 2 of the project to an environmental data base for solar-thermal and wind-powered sites selected by EPRI. Data for each site is collected and organized in a manner which allows it to be used effectively within the environmental impact assessment methodology. The figures which follow illustrate the type of information available in the data base.

DATA BASE SITES

KERN COUNTY, CALIFORNIA	(solar thermal)
MARION COUNTY, KANSAS	(solar thermal)
CARSON COUNTY, TEXAS	(wind)

Figure 3 States the three areas selected as data base sites. The Kern County, California, site is located in the Mojave Desert near the towns of Inyokern and Ridgecrest. The Marion County, Kansas, site is in an area of agricultural use and tall-grass prairie approximately 50 miles north of Wichita. The Carson County, Texas, site is in an area of agricultural use and short-grass prairie approximately 30 miles east of Amarillo.

DATA BASE SUBJECT MATTER

MAJOR DISCIPLINE CATEGORIES

ECOLOGY, SOCIOECONOMICS, METEOROLOGY, WATER QUALITY, etc.

SUBDIVISIONS FOR MAJOR CATEGORIES (examples)

I. ECOLOGY
    A. TERRESTRIAL
        1. WILDLIFE
            a. BIG GAME
            b. SMALL MAMMALS
        2. VEGETATION
            a. SHRUBS
            b. GRASSES

Figure 4 Illustrates the classification categories which form the organizational structure and indicate the subject matter of the data base. These categories provide identifying keywords which can be used to help retrieve specific kinds of data.

DATA SOURCES

LITERATURE SEARCH

- COMPUTERIZED DATA BASES - (e.g., SCISEARCH)
- ABSTRACTING JOURNALS - (e.g., SCIENCE CITATION INDEX)
- OTHER VALUABLE LITERATURE

DATA PREVIOUSLY COLLECTED NEAR SITE (examples)

- BLM PLANNING UNITS
- GAS PIPELINE STUDIES
- TRANSMISSION LINE STUDIES

LIMITED SITE RECONNAISSANCE

Figure 5 Mentions some of the data sources used in developing the data base. These included various types of literature, previous environmental impact studies, and brief site visits by a team of ecologists.

INFORMATION INCLUDED WITH EACH CITATION

AUTHOR, TITLE, DATE, PUBLISHER, JOURNAL

KEY IDENTIFYING WORDS (e.g., Species Name, Subdivision Topic)

ABSTRACT (if available)

IMPACT OR ATTRIBUTE INFORMATION (QUANTITATIVE)

Figure 6 Notes the information involved in annotating the literature citations. The important aspect of an environmental data base geared to a decision analysis approach is the organization of data into meaningful measures which can be used by the decision maker in evaluating alternatives. To this end, quantitative information found in the literature (e.g., lists of species in the area of the site, etc.) is organized into measures called attributes (e.g., species diversity, number of a rare or protected species, etc.) which can be used in subsequent analyses. In this way, the data is processed and summarized in a useful form. This makes it possible to avoid reams and reams of environmental detail which must be handled a second time by anyone evaluating the site.

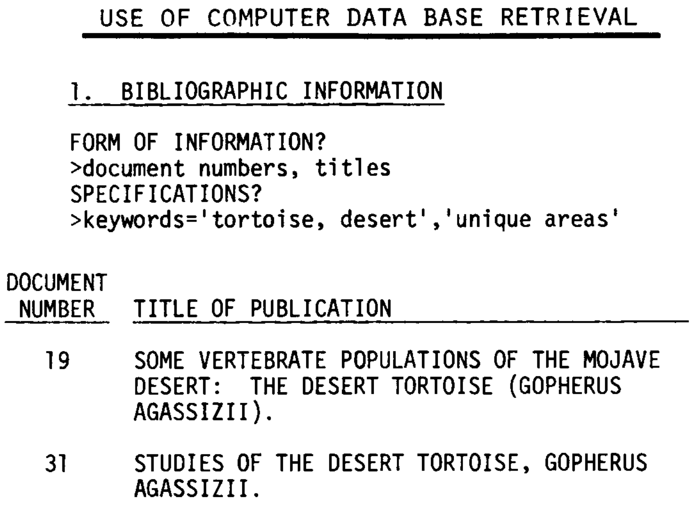
ORGANIZATION AND USE OF DATA BASE

I. EACH CITATION GIVEN A DOCUMENT NUMBER

II. RETRIEVAL OF INFORMATION THROUGH AUTHOR OR KEYWORD SPECIFICATION MATCHING TO DOCUMENT NUMBERS

III. CHOICE OF RETRIEVAL SYSTEMS
  A. MANUAL
    1. AUTHOR CATALOG FILE
    2. KEYWORD CATALOG FILE
  B. COMPUTER

Figure 7 Outlines how the data base can be used to extract information for environmental impact assessment. Particular information is retrieved by describing the desired subject matter using keywords, authors, and document numbers. The retrieval system can be a manual card file indicating the documents containing the appropriate information. These documents may be on file or in libraries. The retrieval system can also be computer implemented. The next few figures will illustrate some computer data base retrieval methods.



```
              USE OF COMPUTER DATA BASE RETRIEVAL

           1.  BIBLIOGRAPHIC INFORMATION

           FORM OF INFORMATION?
           >document numbers, titles
           SPECIFICATIONS?
           >keywords='tortoise, desert','unique areas'

      DOCUMENT
       NUMBER   TITLE OF PUBLICATION

         19     SOME VERTEBRATE POPULATIONS OF THE MOJAVE
                DESERT:  THE DESERT TORTOISE (GOPHERUS
                AGASSIZII).

         31     STUDIES OF THE DESERT TORTOISE, GOPHERUS
                AGASSIZII.
```

Figure 8 Shows an example of one kind of information retrieval from the data base. Suppose one wants to see the document numbers and titles available for references dealing with both "desert tortoises" and "unique areas." When the appropriate specifications are typed in, the computer prints out the relevant information. Thus, very specific documents can be selected for further inquiry. In this way, extracting the desired information from the correct documents is made more efficient.

USE OF COMPUTER DATA BASE RETRIEVAL

2. NUMERICAL INFORMATION

```
FORM OF INFORMATION?
>grid point number
SPECIFICATIONS?
>big horn sheep ge 40.0 and desert tortoise le 50.0

     GRID POINT        BIG HORN        DESERT
       NUMBER            SHEEP        TORTOISE

        17.0             125.0           0.0
        26.0              40.0           1.0
        37.0              40.0           4.0
        47.0              50.0           1.0
```

Figure 9 Shows an example of retrieving and processing quantitative information. If the study area has been divided into a number of grid points, the computer can select those points satisfying certain criteria, such as the number of bighorn sheep greater than or equal to 40 and the number of desert tortoises less than or equal to 50. Thus, the data base can be used as a screening tool to select grid points that satisfy various criteria. An important element of such a capability is to have measures defined which are appropriate for organizing data. The decision analysis methodology is geared to providing such measures.

USE OF COMPUTER DATA BASE RETRIEVAL

3. NUMERICAL INFORMATION

```
FORM OF INFORMATION?
>means, standard devation
'DEVATION' NOT FOUND POSSIBLE MISS-SPELLING?
>deviation
SPECIFICATION?
>big horn sheep, desert tortoise, plant diversity

                                        STANDARD
                               MEAN     DEVIATION

BIG HORN SHEEP                 19.9      31.265
DESERT TORTOISE                 1.5       1.806
PLANT DIVERSITY                 6.8       3.236
```

Figure 10 Shows another example of how numerical information about a study area can be processed. The computer-user dialogue illustrates how simply such a system can be used even when errors in typing are made. (In this case, neither the computer nor the ecologist could spell properly.) The example shows how some global quantitative information could be acquired about a study area which may be made up of several data points.

SOME GENERAL SITE CHARACTERISTICS

TOPIC	INYOKERN, CALIFORNIA	MARION, KANSAS	CARSON, TEXAS
TOPOGRAPHY	FLAT	FLAT	FLAT
LAND USE	GRAZING	3/4 AGRICULTURE 1/4 GRAZING	3/4 AGRICULTURE 1/4 GRAZING
VEGETATION	CREOSOTE BUSH DESERT	TALL-GRASS PRAIRIE	SHORT-GRASS PRAIRIE
DOMINANT WILDLIFE	RODENTS; SMALL BIRDS	RODENTS, RABBITS; SMALL BIRDS; UPLAND GAME BIRDS	RODENTS; SMALL BIRDS

Figure 11 Lists some summary characteristics of the three data base sites. In the subsequent figures, data base information for two of these sites will be used in an illustration of the environmental impact assessment methodology.

APPLICATION OF DECISION ANALYSIS METHODOLOGY TO SPECIFIC SITES

INYOKERN, CALIFORNIA
VS.
MARION COUNTY, KANSAS

Figure 12 Introduces the application of the decision analysis methodology to an environmental impact assessment problem. The application chosen is a comparison of two sites for a 100-MW central solar thermal facility. The problem is to decide, on the basis of environmental impact (in this example, cost of the system is not considered), which site is preferred. Many environmental impact assessments consist of choosing between alternatives. Sometimes, it is the "build" versus "no-build" situation. Here, we are defining a problem involving a choice between sites.

SOME ISSUES IN ENVIRONMENTAL IMPACT ASSESSMENT

- SUBJECTIVE IMPACTS
- MULTIPLE OBJECTIVES REQUIRING VALUE TRADEOFFS
- UNCERTAINTY
- MANY IMPACTED GROUPS

Figure 13 Is a reminder of some issues which make environmental impact assessment a difficult task. It provides the motivation for a formal analysis of the problem. The issues of multiple objectives and uncertainty make an informal analysis very difficult both in terms of making a rational choice and of explaining the choice to others.

EIA METHODOLOGY

1. STRUCTURING THE PROBLEM
2. ASSESSING IMPACTS
3. DETERMINING PREFERENCES FOR IMPACTS
4. EVALUATING ALTERNATIVES

Figure 14 Outlines the environmental impact assessment methodology as a series of four steps. These steps represent the common-sense way of choosing between the alternatives. They correspond directly to the basic questions of what the impacts will be and what the preferences for these impacts will be.

- DEVELOPMENT OF QUANTITATIVE MEASURES FOR VARIOUS ENVIRONMENTAL IMPACTS
- DEVELOPMENT OF PREFERENCE FUNCTIONS FOR THE MEASURES

Figure 15 Notes the distinguishing features of the decision analysis approach that make it a theoretically sound and systematic way of tackling the problem. Environmental impacts are quantified using measures and probabilities, while preferences are quantified using models called utility functions. These formal mechanisms will be discussed in subsequent figures.

STRUCTURING THE PROBLEM

- DEFINING PROBLEM SCOPE
- ESTABLISHING OBJECTIVES AND MEASURES OF EFFECTIVENESS
- IDENTIFYING DECISION MAKERS AND AFFECTED PARTIES

Figure 16 Begins to explore in more detail the first step of the approach, which is structuring the problem. The key formal element of this step is defining explicit quantitative measures for environmental impacts that can measure how well environmental objectives are being met. The problem scope has already been limited to choosing between alternative sites. The decision makers for this example will be a team of ecologists who will make recommendations on the basis of their preferences. Establishing objectives and measures requires a comprehensive overview of possible impacts. We must then focus on those which are of importance in choosing between sites.

SOME AREAS OF ENVIRONMENTAL IMPACT

HEALTH AND SAFETY	SOCIO-CULTURAL	BIOLOGICAL
POLLUTION EFFECTS (AIR, WATER, THERMAL, NOISE, CHEMICAL) ACCIDENT EFFECTS	AESTHETICS SOCIOECONOMICS LAND USE WATER RESOURCES WEATHER MODIFICATION	EFFECTS ON FLORA AND FAUNA THREATENED SPECIES

Figure 17 Shows some areas which are expected to be affected by the building and operation of a solar thermal power plant. Some of the potential impacts will be negligible or identical for both alternatives. This application concentrates on two areas which are expected to show significant differences in impact depending on the site chosen. These areas are socioeconomic impact and terrestrial biotic impact.

TERRESTRIAL BIOTIC IMPACT CONSIDERATIONS

ISSUE	CONSIDERATIONS	MEASURES
IMPACT ON FLORA AND FAUNA DUE TO LAND REQUIREMENTS	• HABITAT AFFECTED	• ACRES OF TALL-GRASS PRAIRIE • ACRES OF CREOSOTE BUSH SCRUB DESERT • ACRES OF AGRICULTURAL LAND
	• RARE ANIMALS	• NUMBER OF ANIMALS LOST

Figure 18 Shows how a general issue can be subdivided into more specific considerations. The considerations are terrestrial biotic impacts. For each concern, a measure or attribute quantitatively describing the impact is shown. These measures can be "objective," such as number of acres of a particular kind of habitat. They may also be subjective, as will be illustrated shortly. The quantitative measure serves to make the description as explicit as possible. The methodology allows for objective and subjective measures. The latter are often necessary and quite appropriate in assessing environmental impacts.

SOCIOECONOMIC IMPACT CONSIDERATIONS

ISSUE	CONSIDERATIONS	MEASURES
IMPACT ON TOWN DUE TO SUDDEN DEMAND FOR SERVICE FACILITIES	DEGRADATION OF SERVICE AND FISCAL IMPAIRMENT DUE TO NEW DEMAND	• PERCENT INCREASE IN POPULATION BEYOND PLANNING OF THE TOWN • NUMBER OF PEOPLE IMPACTED

Figure 19 Is a second illustration of the process for developing quantitative measures. In this figure, two measures are needed to describe the degree of socioeconomic impact due to the influx of construction workers on nearby towns. The first measure uses a scale which requires some subjective judgment in analyzing impacts. What constitutes an increase in population beyond a town's planning capability is difficult to measure. The socioeconomic impact is quite complex, involving effects such as overcrowding in schools, pressure on housing availability, competition for goods (which forces up prices), and many others. A town can cope well with these effects if it has good planning and adequate resources. The measure is meant to enable a knowledgeable person to express and utilize his judgments about the socioeconomic impact in a quantitative manner. The second measure needs to be used in conjunction with the first. This is because the number of people affected is important as well as the effect per capita reflected in the first measure.

DEFINITION OF MEASURES (ATTRIBUTES)

	ATTRIBUTE	BEST IMPACT	WORST IMPACT
x_1	x_{1a} - ACRES CREOSOTE BUSH	0	1,000
	x_{1b} - AVERAGE NUMBER OF DESERT TORTOISES	0	100
	x_2 - ACRES TALL-GRASS PRAIRIE	0	1,000
	x_3 - ACRES AGRICULTURE	0	1,000
x_4	x_{4a} - PERCENT INCREASE IN POPULATION	0	50%
	x_{4b} - NUMBER OF PEOPLE AFFECTED	0	40,000

Figure 20 Shows the final step in defining quantitative measures or attributes. For each attribute, a range is defined within which impacts are expected to fall. The best impact values for the biological attributes are those which reflect little or no impact. This occurs when there are few acres of habitat for natural flora or fauna in the affected land area. The worst impact values are those which show a lot of habitat and/or protected animals in the affected area. Similar considerations apply to the socioeconomic impact. The methodology requires explicit and specific definitions of measures. This requirement gives the procedure the capability for being systematic and consistent. Each measure is given a symbolic notation or variable to facilitate its use in analytical expressions which will come later. Variables x_{1a} and x_{1b} are so labeled because they are connected in characterizing desert habitat. Variables x_{4a} and x_{4b} are connected (as was mentioned in Figure 19) in characterizing the socioeconomic impact.

SUMMARY OF ASSESSMENT

I. STRUCTURING THE PROBLEM

Alternatives: INYOKERN VS. MARION

Measures: ENVIRONMENTAL ATTRIBUTES $X_1, X_2, \ldots$

Advisors: TEAM OF ECOLOGISTS

Figure 21 Summarizes the first step in the decision analysis methodology. The key element has been the formulation of attributes that can measure in an explicit and specific manner how well environmental objectives (i.e., minimizing specific adverse impacts) are being met.

ESTIMATING CONSEQUENCES AND LIKELIHOODS

ANALYTICAL MODELS

SOCIOECONOMICS : WORKER ALLOCATIONS AMONG NEARBY TOWNS

DATA

SITE VISITS : BIOLOGICAL SAMPLING

SUBJECTIVE JUDGMENT

DEGREE OF UNCERTAINTY IN SOCIOECONOMIC MODELS
ABSORPTIVE CAPACITY OF COMMUNITIES

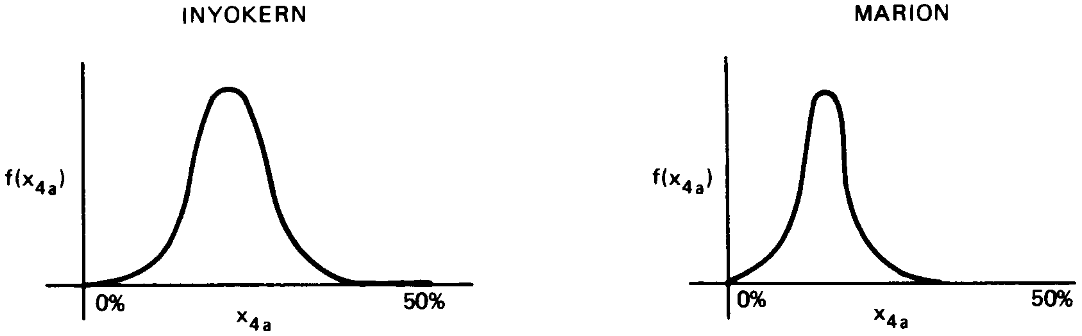
Figure 22 Introduces the second step of the procedure, which is estimating the impacts that will occur at the different sites. The framework for assessing these impacts is the set of quantitative measures developed in the first step. Figure 22 shows techniques which are available for evaluating the magnitude and likelihood of particular consequences. With new technologies, the judgment of professionals is often the only basis available for estimating consequences. Decision analysis can incorporate subjective judgments in the form of probability distributions. The end result is the specification of the magnitude and likelihood of impacts.

SPECIFYING ALTERNATIVES (POINT ESTIMATES)

INYOKERN		MARION
$x_{1a} = 715$	ACRES OF CREOSOTE BUSH	$x_1 = 0$
$x_{1b} = 50$	AVERAGE NUMBER OF TORTOISES	$x_2 = 0$
$x_2 = 0$	ACRES OF PRAIRIE	$x_3 = 179$
$x_3 = 0$	ACRES OF AGRICULTURE	$x_4 = 536$
$x_{4a} = 20\%$	PERCENT INCREASE IN POPULATION	$x_5 = 10\%$
$x_{4b} = 20{,}000$	NUMBER OF PEOPLE AFFECTED	$x_6 = 30{,}000$

Figure 23 Shows how each alternative can be characterized by values assigned to each attribute variable. In the figure, point estimates have been made for each of the attributes. Building at Inyokern, in this instance, involves blading and clearing 715 acres of creosote bush habitat, eliminating fifty protected desert tortoises, and causing a 20% increase beyond the normal planning capability of the nearby towns, affecting a local population of 20,000. For this problem, the alternatives have thus been concisely characterized in terms of the relevant decision-making variables.

PROBABILITY DISTRIBUTIONS



UNCERTAINTY IN THE ESTIMATES OF SOCIOECONOMIC IMPACT

Figure 24 Shows that what often really exists is an uncertain (non-deterministic or non-point) estimate of impacts for particular alternatives. For instance, the socioeconomic impact at Inyokern has a higher likelihood of being near 20% than 5%, which is depicted by the likelihood function $f(x_{4a})$. But there is some chance that it will be as low as 5% or as high as 35%. The probability distribution enables an expert to be candid about the uncertainty of his estimate. This uncertainty is formally assessed and used in the analysis.

SUMMARY OF ASSESSMENT

I. STRUCTURING THE PROBLEM

Alternatives: INYOKERN VS. MARION

Measures: ENVIRONMENTAL ATTRIBUTES $X_1, X_2, \ldots$

Advisors: TEAM OF ECOLOGISTS

II. DETERMINING CONSEQUENCES

$$\left.\begin{array}{llll} \text{INYOKERN:} & X_1 = \ ; & X_2 = \ ; \text{etc.} \\ \text{MARION:} & X_1 = \ ; & X_2 = \ ; \text{etc.} \end{array}\right\} \text{INCLUDES UNCERTAINTY}$$

Figure 25 Summarizes the first two steps of the environmental impact assessment methodology. The problem has been structured in terms of specific quantitative measures, and the alternatives have been described using these measures and probability distributions that capture the real uncertainty which exists in estimating impacts.

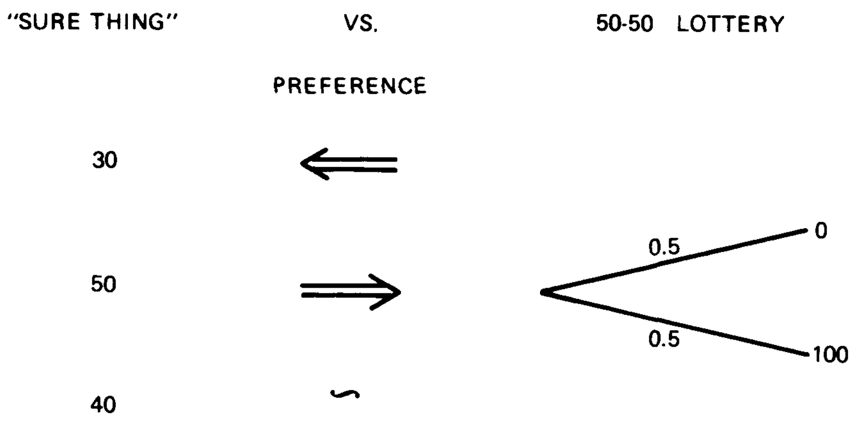
- **PREFERENCES FOR INDIVIDUAL IMPACTS**
- **TRADEOFFS BETWEEN INDIVIDUAL IMPACTS**
- **PREFERENCE OVER MANY IMPACTS**

Figure 26 Introduces the third step of decision analysis — determining the preferences for different consequences. Because of the complexity of the issues, what is needed is a methodology which breaks the problem into simpler parts that can be handled and put together again in a logical fashion to address the overall problem. Decision analysis employs formal preference models to accomplish this. As the figure illustrates, the methodology examines preferences for individual impacts and tradeoffs between impacts. This preference information is then logically synthesized to provide a preference ordering for consequences involving many measures and uncertainty.

DEVELOPMENT OF MULTIATTRIBUTE UTILITY FUNCTIONS

- **Development of single-attribute utility functions**
- **Assessment of tradeoff constants**
- **Specifying the multiattribute utility function**

Figure 27 Outlines the way decision analysis breaks the preference question down into simpler parts. Preferences for individual measures are first assessed by calibrating single-attribute utility functions. Tradeoffs between only two attributes at a time are then considered. These reveal how much one is willing to give up of one to gain on another. This information is quantified via tradeoff constants. In this way, the issue of competing objectives is addressed. Decision analysis supplies a preference model called a multiattribute utility function. This function puts together the tradeoffs and preferences assessed previously in a rational manner when certain reasonable assumptions are satisfied. The result is a function which evaluates any consequence by assigning to it a number called the utility of that consequence. The consequences can be ranked in order of utility. Those with higher utilities are preferred to those with lower utilities. The function is designed to evaluate consequences under uncertainty and provide a rational preference scale for comparison on the basis of expected utility.



$$u(40) = 0.5\,u(0) + 0.5\,u(100)$$
$$u(40) = 0.5\,u(1.0) + 0.5\,(0.0)$$
$$u(40) = 0.5$$

Utility Assesment for Continuous Scale

Figure 28 Illustrates the assessment techniques for obtaining preferences for individual attributes. A hypothetical lottery or uncertain situation on the right is compared to a certain impact on the left. The idea is to specify a certain impact such that the right and left sides are equally preferred. The measure in this case is average number of tortoises eliminated. The result indicates that a particular biologist would be indifferent between eliminating 40 tortoises for certain and taking a 50-50 gamble of destroying 100 or 0 tortoises. If his choice had been between the certain loss of 50 tortoises and the lottery, he would have taken the gamble. If it were between 30 and the lottery, he would have preferred the "safer" sure thing. The methodology of decision analysis takes this result and calibrates a scale over the range of 100 to 0 in terms of expected utility. The end points of the range are assigned numbers of 0 and 1 respectively as a scaling convention.

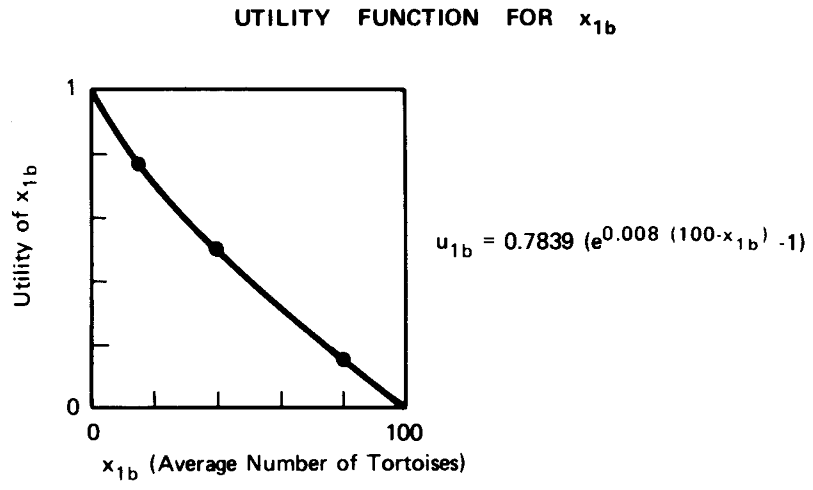


Figure 29 Shows a single-attribute utility function scale for average number of tortoises eliminated. The points on the curve are those assessed by asking questions similar to those shown in Figure 28. That is, 40 has a utility of 0.5, 65 has a utility of 0.25, and so on. A smooth curve is faired through these points, and a mathematical function is fit to the curve. This curve reflects the biologist's preferences for impacts on the desert tortoise under conditions of uncertainty. It, of course, does so for situations where no uncertainty is present, as well. Similar curves and functions are obtained for each of the measures in the problem.

ASSESSMENT OF TRADEOFFS

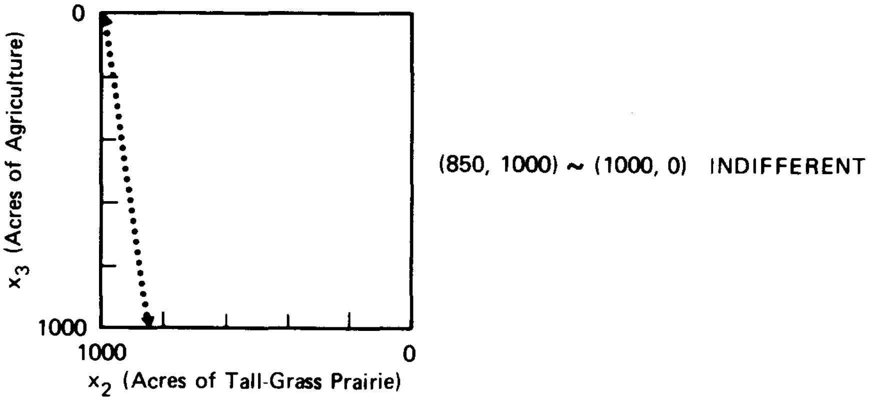


Figure 30 Shows the tradeoff assessment process. Considering only two measures at a time, it is determined that building on a site that requires the clearing of 1000 acres of tall-grass prairie and no acres of agriculture is equally preferred to building where 850 acres of tall-grass prairie and 1000 acres of agriculture will be cleared. The tradeoff was done on an ecological basis by a biologist who indicated that tall-grass prairie habitat was ecologically much more valuable than agricultural habitat in his view. He was willing to see 1000 acres of agriculture cleared to move from 1000 to only 850 acres of tall-grass prairie cleared. (No land costs or crop costs were considered in this tradeoff. Such considerations would be embodied in a cost attribute). In this way, the relative preferences for impacts on agriculture and tall-grass prairie are determined. Similar tradeoff questions for other attributes complete the assessment of the overall multiattribute utility function.

OVERALL PREFERENCE FUNCTION MODEL

$u = k_1 u_1 + k_2 u_2 + k_3 u_3 + k_4 u_4$

SUBMODELS

$u_1 = k_{1a} u_{1a} + k_{1b} u_{1b} + k^1 u_{1a} u_{1b}$ (DESERT HABITAT)

$u_4 = k_{4a} u_{4a} + k_{4b} u_{4b} + k^4 u_{4a} u_{4b}$ (SOCIOECONOMICS)

k_i = SCALING CONSTANTS REFLECTING TRADEOFFS

u_i = FUNCTIONS REFLECTING PREFERENCES OVER SINGLE VARIABLES AND ATTITUDES TOWARDS RISK

Figure 31 Indicates the mathematical representation of the preferences concerning the attributes. The functions represent a quantification of the previous preference information. They are consistent and will validate the tradeoffs already assessed. They will also evaluate more complicated alternatives in a manner consistent with the assessed tradeoffs. The submodels feature the methodology's ability to handle certain "dependencies" which arise in problems. They recognize that tradeoffs between habitat lost and socioeconomic impact per capita, for example, depend on how many people are affected. The submodels provide extra modeling parameters which are used to adequately quantify such tradeoff dependencies.

SUMMARY OF ASSESSMENT (CONTINUED)

III. DETERMINING PREFERENCES

ATTITUDES TOWARD RISK: u_i
TRADEOFFS BETWEEN COMPETING OBJECTIVES: k_i
OVERALL PREFERENCE MODEL: u

THEORETICALLY
SOUND
PROCEDURES

Figure 32 Summarizes the third step of the approach, which is to quantify preferences for consequences. The key features of this step are the theoretically sound considerations of attitudes toward risk and tradeoffs between competing objectives, which produce a valid way of comparing complicated alternatives.

CONSEQUENCES	UTILITIES (Preferences)	EXPECTED UTILITY
$\underline{X} = (x_1, x_2, \ldots, x_n)$	$u(x_1, x_2, \ldots, x_n)$	$P_{1,2,3}(x_1, x_2, \ldots, x_n)\ u(x_1, x_2, \ldots, x_n)$

Figure 33 Summarizes the concepts used in evaluating alternatives. This is the final step in the procedure. The consequences as expressed by different levels of the attributes are evaluated using the preferences as expressed by the utility function. When uncertainty is present, the probabilities are used to calculate the expected utility, which is the basis for comparing the desirability of alternative sites. The calculation of the expected utility is a mechanical computation now that all the relevant information has been appropriately quantified.

RESULTS OF EVALUATION AND COMPARISON

u(INYOKERN) = .786
u(MARION) = .854

MARION IS PREFERRED TO INYOKERN

Figure 34 Shows the preliminary evaluation of the sites. The result represents the systematic formalizing of preferences and consequences to compare complex alternatives. The results can be traced back step by step to the answers given in response to tradeoff and preference questions and to the estimates of the site-specific attribute levels.

SENSITIVITY ANALYSIS IMPLEMENTATION

- CHANGES IN ALTERNATIVES AND DIFFERENCES IN PREFERENCES ARE QUANTITATIVELY EXPLICIT
- SENSITIVITY TO CHANGES ARE QUANTITATIVELY EXPLICIT
- CHANGES CAN BE INPUT AND RESULTS CAN BE OUTPUT RAPIDLY

Figure 35 Shows an important step in the decision analysis, namely checking the sensitivity of final results to changes in the input parameters. We can ask how our comparison of sites would change if our estimates of attribute levels, tradeoffs, or preferences change. This gives a quantitative idea of what changes in expected impacts must occur before our ranking of the sites is altered.

SENSITIVITY ANALYSIS

CHANGES IN ESTIMATES OF CONSEQUENCES

INYOKERN

- TORTOISES : 50 → 10
- u(INYOKERN) = u(MARION) = .854
- INYOKERN IS PREFERRED TO MARION WHEN THERE ARE LESS THAN 10 TORTOISES AT INYOKERN

Figure 36 Shows that if we do not impact quite so many protected animals (tortoises) at the Inyokern site as we originally estimated, then the Inyokern site would be preferred to the Marion site. For a range of values for average number of tortoises eliminated, $(10<x_{1b}<100)$, our ranking will not change. The decision maker is thus given a range of circumstances for which the current decision will remain the optimal one. In this way, the decision analysis approach provides the decision maker with an explicit evaluation of the decision's sensitivity to changes in estimates.

SENSITIVITY ANALYSIS

CHANGES IN PREFERENCES

AGRICULTURE IS MORE IMPORTANT
FOR INTEREST GROUP A
u_A (INYOKERN) = .800
u_A (MARION) = .827
MARION STILL PREFERRED TO INYOKERN

Figure 37 Shows another type of sensitivity analysis that can be performed. If preferences for impacts for one group are not the same as another, will the choice between sites change? In this example, the ranking of sites does not change when the preferences for this interest group are used in place of the previous preferences. Thus, although there was a difference in opinion, it did not affect the preferred choice. If the ranking did reverse, the change could be traced back directly to the difference in opinion on tradeoffs. The nature and extent of the disagreement would be specifically identified. Because of this, a resolution or compromise might be more easily achieved.

SUMMARY OF ASSESSMENT (CONTINUED)

III. DETERMINING PREFERENCES

ATTITUDES TOWARD RISK: u_i
TRADEOFFS BETWEEN COMPETING OBJECTIVES: k_i
OVERALL PREFERENCE MODEL: u

THEORETICALLY
SOUND
PROCEDURES

IV. EVALUATING AND COMPARING ALTERNATIVES

- MARION PERFERRED TO INYOKERN
- SENSITIVITY ANALYSIS
  - CHANGES IN ESTIMATES
  - CHANGES IN PREFERENCES

Figure 38 Summarizes the last two steps of the approach to environmental impact assessment. Once we have quantified the preferences for attributes in a sound and consistent manner, the capability for evaluating alternatives and performing valuable sensitivity analysis is present. Because of these features, the decision analysis approach provides the means to adequately explain the basis upon which a decision was made, and to interact effectively with people who have different estimates or preferences from those used in the analysis.

COST EQUIVALENT COMPARISON

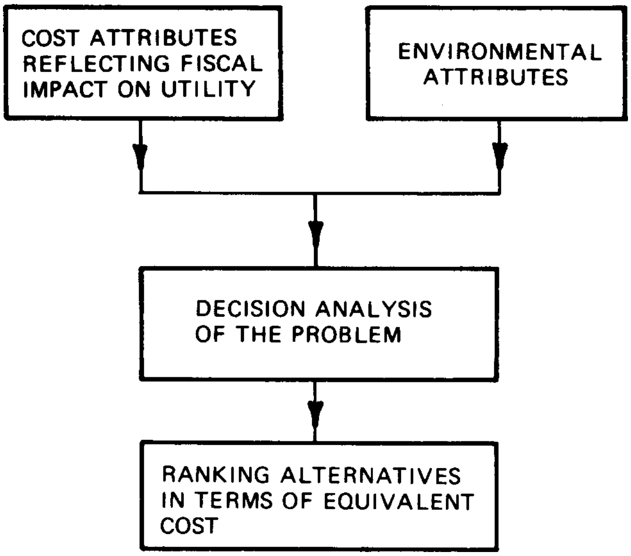


Figure 39 Illustrates how cost considerations can be brought into the environmental assessment problem. The chief task is to properly measure, in terms of the appropriate scales, the fiscal impact on a utility company in locating at a particular site. This task is discussed in the next figure. Once this is done, we can combine cost attributes with environmental attributes in an overall comparison of options. Decision analysis can be used to express the resulting ranking of alternatives in terms of an equivalent cost number for each option. Such a ranking gives some indication of how much better one alternative is than another in terms of a dollar yardstick familiar to decision makers.

COST EQUIVALENCE COMPARISON METHODOLOGY IN EIA

ISSUES

- COST ONE IS WILLING TO PAY TO AVOID IMPACT (TRADEOFF)
- COST REQUIRED TO MITIGATE IMPACT
- NATURE OF COSTS
  - CAPITAL VS. OPERATING
  - EFFECTS ON UTILITY CREDIT
  - EASE OF RECOVERING COSTS

Figure 40 Discusses some of the issues which may necessitate more than a simple dollar measure for a cost attribute. A capital dollar may be different from an operating dollar, even when we levelize with an interest rate, because of the differing effects on utility credit, the differing ways of recovering costs, and the difficulty of raising capital. Some of these considerations may require specific measures to adequately quantify fiscal impacts on the utility company. Also, we must be careful when comparing costs with environmental impacts to consider whether it is more appropriate to think of the cost one is willing to pay to avoid the impact or the cost of mitigating the impact. These are often very different.

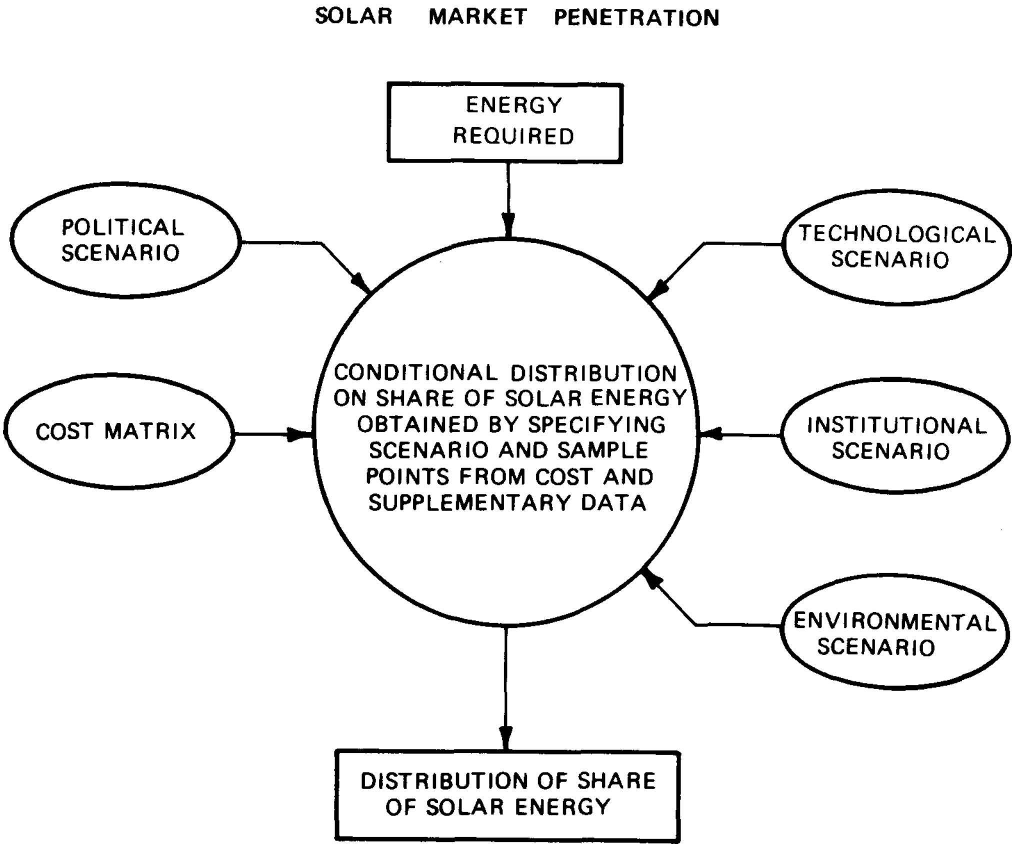


Figure 41 Portrays another task element of the overall project, which is to estimate the market penetration of central solar thermal and wind systems in the future decades. The market penetration may be dependent on a multitude of factors, including relative cost of competitive energy systems, government incentives, future environmental regulations, and world politics. Because solar technology is not well known and because it is difficult to model the effects of many factors, we have taken the Bayesian approach to estimating the market penetration. This approach utilizes the judgment of knowledgeable people (which is often all one has in situations with new technologies and future predictions) in a systematic manner to quantify the likelihood or probability distribution of future market penetration as a function of various factors.

BAYESIAN APPROACH

- IDENTIFICATION OF VARIABLES (FACTORS) AFFECTING SOLAR MARKET SHARE
  - a. COST
  - b. ENVIRONMENTAL
  - c. INSTITUTIONAL
  - d. POLITICAL
  - e. TECHNOLOGICAL
  - f. GAP

Figure 42 Shows the first step in the approach, which is to identify the important variables affecting the future solar market share.

BASIS FOR ALTERNATIVES

- DEVELOPMENT OF QUESTIONNAIRE
- IMPLEMENTATION OF QUESTIONNAIRE
- ANALYSIS OF QUESTIONNAIRE RESPONSES
- BAYESIAN TECHNIQUES USED TO ORGANIZE AND UPDATE INFORMATION

Figure 43 Outlines the implementation of the approach. Knowledgeable people are interviewed to obtain the estimates and uncertainties of market penetration. The important elements of the implementation are the design of the interview questionnaire and the selection of the individuals to be interviewed. A useful feature of the approach is the formal mechanism for updating the market share distribution as new data becomes available, especially with regard to the cost of solar systems.

COMPUTER PROGRAMS

- IMPLEMENTING DECISION ANALYSIS APPROACH
- ENVIRONMENTAL IMPACT MODELS
- INDUSTRIAL IMPLICATIONS MODEL
- COST-EFFECTIVENESS COMPARISON CALCULATIONS

Figure 44 Lists the types of computer programs which will be developed to implement the methodology in assessing environmental impacts. These programs will be used in completing Tasks 1, 3, and 4. The computer programs and their manuals will be part of the deliverables at the end of the project.

PROJECT REPORT ELEMENTS

- EXECUTIVE SUMMARY
- METHODOLOGY DOCUMENTATION
- EIA OF TWO SITES
- ASSESSMENT GENERALIZATION
- MARKET PENETRATION ASSESSMENT

Figure 45 Lists some of the elements which will make up the project's final report. There will be separate sections explaining the methodology, applying it to two of the data base sites, and generalizing the assessment of different plant-site characteristics. Another section will discuss the market penetration assessment. An executive summary will give a concise overview of the entire project.

SECTION 7

EPRI CONTRACT RP 648

REQUIREMENTS DEFINITION AND IMPACT ANALYSIS OF SOLAR THERMAL POWER PLANTS

WESTINGHOUSE ELECTRIC CORPORATION

Advanced Systems Technology Division
700 Braddock Avenue
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PROGRAM MANAGER

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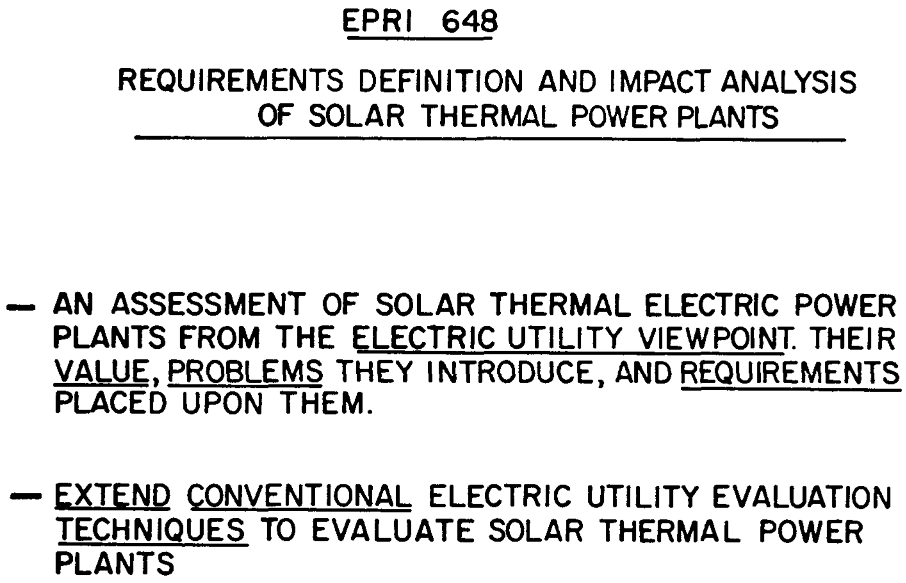
OCTOBER 1976

EPRI SOLAR REVIEW MEETING #2



EPRI 648

REQUIREMENTS DEFINITION AND IMPACT ANALYSIS OF SOLAR THERMAL POWER PLANTS

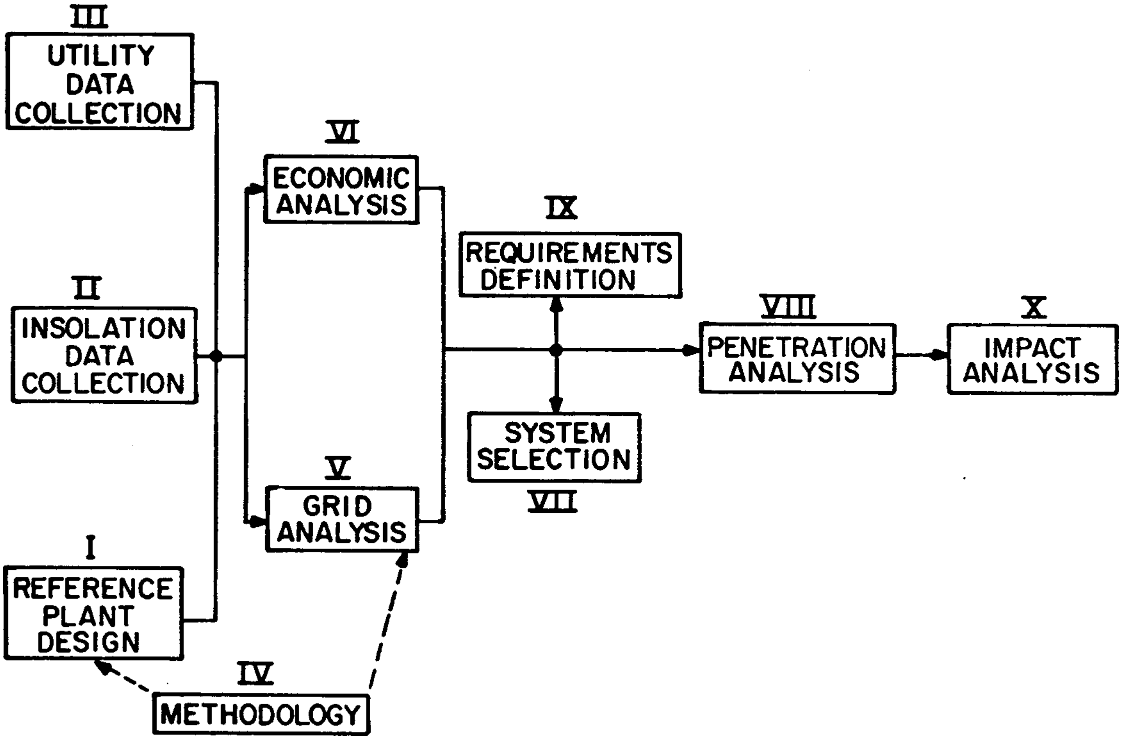
- AN ASSESSMENT OF SOLAR THERMAL ELECTRIC POWER PLANTS FROM THE ELECTRIC UTILITY VIEWPOINT. THEIR VALUE, PROBLEMS THEY INTRODUCE, AND REQUIREMENTS PLACED UPON THEM.
- EXTEND CONVENTIONAL ELECTRIC UTILITY EVALUATION TECHNIQUES TO EVALUATE SOLAR THERMAL POWER PLANTS

Figure 1. EPRI RP-648 is a study of "Requirements Definition and Impact Analysis of Solar Thermal Power Plants." It is a study to evaluate Solar Thermal Power Plants for their potential to generate electricity for Electric Utilities. Emphasis in this study is upon analyzing these plants from the Electric Utility perspective. This includes their value in terms of production costing, fuel displacement, and capacity credit; and problems they might introduce in terms of system reliability, operating characteristics, grid support, and resource requirements. The requirements placed upon solar thermal plants to enhance their compatibility and values to utilities will be developed. Such items as the amount of storage, operating mode, and plant size are among the characteristics being analyzed. In performing this analysis, conventional utility planning and analysis techniques are being used as much as possible, with extension of these techniques as required to properly represent the peculiarities of solar thermal plants. This study is building as much as possible upon the Aerospace Corporation Mission Analysis Study and will serve as an extension to that effort.

STUDY CONTRACTORS

WESTINGHOUSE ELECTRIC CORP.
McDONNELL-DOUGLAS ASTRO.
WATT ENGINEERING

Figure 2. Westinghouse Electric Corporation is the contractor responsible for this study. Specifically, the Advanced Systems Technology Division of Westinghouse Power Systems Company, located at East Pittsburgh, Pa., is the lead contractor. This activity traditionally provides analytical and planning services to Electric Utilities, and is performing the utility analysis in this study. The Westinghouse Advanced Energy Systems Division is coordinating Solar Plant design and parameter development, and insolation analysis. As subcontractors, McDonnell-Douglas Astronautics and Watt Engineering are assisting in the Reference Solar Plant parameter development and insolation analysis, respectively.



STC STUDY TASK FLOW

Figure 3. This study is organized into ten tasks as shown in the task flow chart. The first three tasks are primarily ones of data collection and development to create a data base for use in the balance of the study. Task four is a methodology development for use in subsequent tasks and, as such, influences both data requirements and the procedures to be used. Tasks five and six are where the majority of the numerical analysis is performed with parametrics on plant size, plant type and storage as well as economics. Detailed simulation of the operation of solar plants on utility systems will be used extensively in these tasks. Extensions, interpretation, and inferences from these numerical results are made in tasks seven through ten. Additional analyses as required are implemented to determine the preferred solar thermal reference designs for specific conditions, the requirements definition, penetration effects, and primary and secondary effects of solar thermal plant implementation.

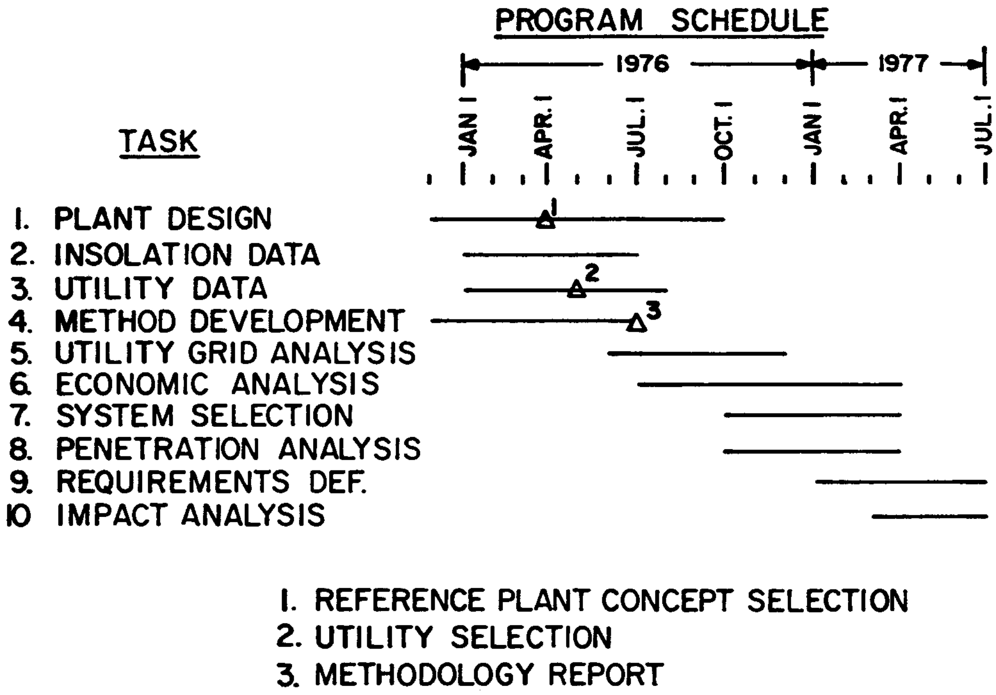


Figure 4. This study is being performed over a period of 18 months covering 1976 and the first half of 1977. The Kickoff meeting for this project was held the second week in January 1976. The first four tasks are almost complete, with data having been collected and characterized for the reference solar plants, utility systems, and insolation. Reference plants and utilities for detailed analysis have been selected. The methodology to be used in this study has been developed and is currently being documented.

PRINCIPAL STUDY GOALS

- THE VALUE OF SOLAR THERMAL POWER PLANTS
- PROBLEMS THEY MIGHT INTRODUCE
- PREFERRED CHARACTERISTICS
    - PLANT CONCEPT
    - PLANT SIZE
    - STORAGE
    - OPERATING MODE
- PENETRATION IMPACT
- RESOURCES REQUIRED

ISSUES NOT INCLUDED

- ENVIRONMENTAL IMPACT
- DEVELOPING NEW PLANT DESIGNS

Figure 5. The principal study goals of this study are to establish the value of solar thermal electric power plants to utilities, their associated problems, their preferred characteristics, penetration impact and required resources. Environmental issues will not be addressed in this study, nor will any attempt be made to develop new plant concepts and designs.

UTILITY RELATED ISSUES

COST OF SOLAR THERMAL PLANTS
- CAPITAL COSTS
- OPERATING COSTS

ECONOMIC VALUE OF SOLAR THERMAL PLANTS
- UTILITY SYSTEM OPERATING COSTS (FOSSIL FUEL DISPLACEMENT)
- CAPACITY CREDIT
- CAPACITY MIX CHANGE

RELIABILITY IMPACT OF ST PLANTS
- PLANT SIZE (MWe)
- AMOUNT OF STORAGE/HYBRID
- LOCATION (WEATHER/INSOLATION)
- MULTIPLE PLANT DISPERSION
- EQUIPMENT RELIABILITY

ST PLANT PENETRATION LEVEL
- ECONOMIC VALUE
- RELIABILITY IMPACT
- ELECTRIC GRID CAPACITY

OPERATING PROBLEMS
- CORRELATION OF ST OUTPUT DEGRADATION
- SYSTEM SPINNING RESERVE REQUIREMENTS
- ST PLANT OUTPUT RAMP RATE

Figure 6. Some of the utility related issues that are being addressed for each selected reference plant design, on each utility undergoing detailed analysis, are shown in this figure. The issues as shown are divided into economic, reliability, penetration, and operating categories. However, one can see that there is a great deal of overlap, with penetration having reliability and economic implications, as do the operating issues.

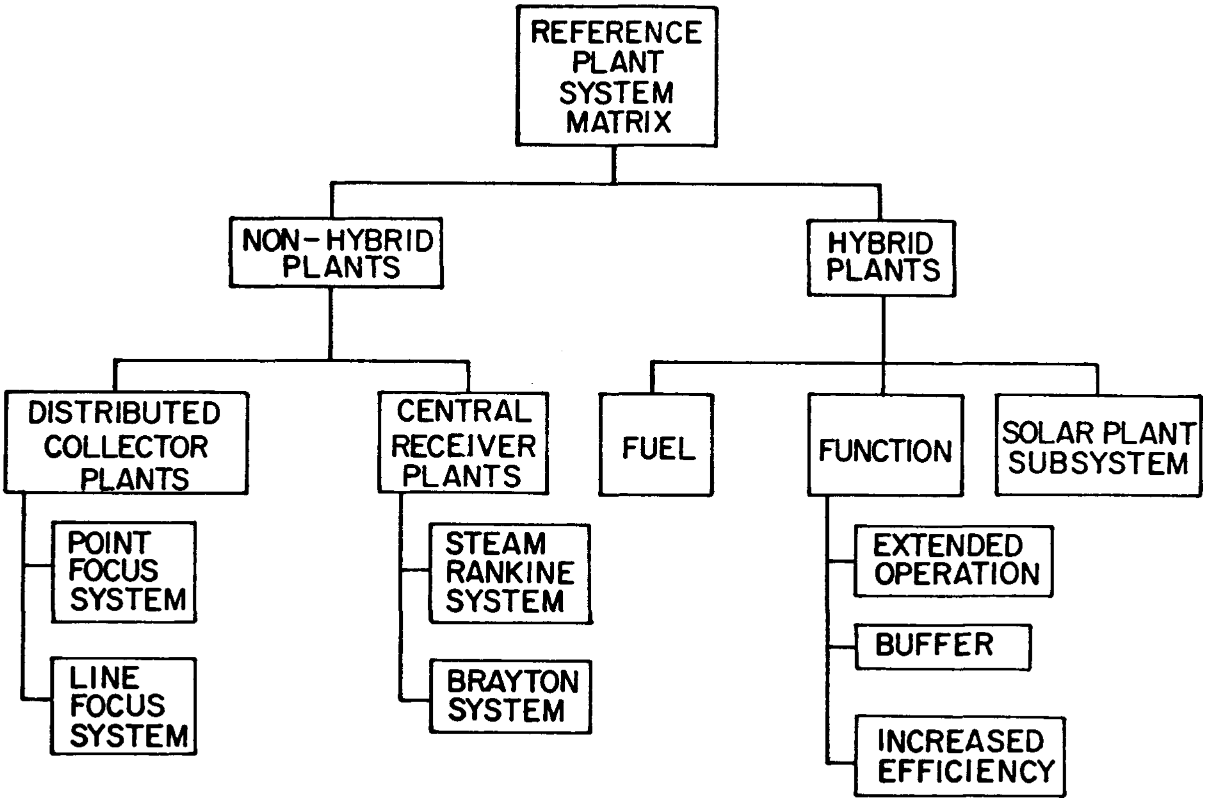


Figure 7. This matrix shows the principal alternatives for solar thermal power plant design. Three basically different solar plant types will be analyzed in this study. There will be one representative distributed collector concept, one central receiver concept, and a solar/fossil hybrid concept analyzed for utility impact. Parameters, such as size and storage capacity, will be varied in the analysis. In addition to the three principal reference plants, data will be assembled on two additional (alternate) plant configurations (concepts). The principal and alternate solar reference plants for central receiver and hybrid are shown in the next two figures. The parameters for the representative distributor concept have not been finalized. The selection of the specific concepts for reference plants does not mean that they are considered most promising, only that they appear to be good representatives of their generic classes of plants.

CENTRAL RECEIVER (NON-HYBRID) POWER PLANTS

	Steam Rankine	Helium Brayton
Plant Rated Capacity (MWe)	100	50
Collector Area (M^2)	9×10^5	5×10^5
Field Area (M^2)	2.7×10^6	1.3×10^6
Receiver Type	External (One Pass to Superheat)	Cavity
Tower Height (M)	305	260
Fluid Conditions (°F/PSI)	950/1950	1500/500
Thermal Storage Type	Sensible Heat, Caloria/Rock, 6 Hours	Fusible Salt (Fluoride Eutectic) 6 Hours
Heat Rejection Type	Wet Cooling Tower	Dry Cooling Tower

Figure 8. The principal central receiver concept to be evaluated is the steam rankine central receiver. Representative data for this concept is shown. Data will also be assembled on the central receiver helium brayton concept to allow future analysis when it appears desirable.

SOLAR HYBRID POWER PLANTS
CENTRAL RECEIVER SYSTEMS

	Open Cycle Gas Turbine	Steam Rankine
Plant Rated Capacity (MWe)	60	290
Collector Area (M^2)	2.7×10^5	9×10^5
Field Area (M^2)	8.0×10^5	2.7×10^6
Receiver Type	Cavity	External
Tower Height (M)	215	305
Turbine Inlet Temperature (^{0}F)	1800-1950	950
Fossil	Fuel Oil	Fuel Oil
Buffer Operation	Parallel Fossil/Solar	Steam Drum
Heat Rejection	Exhaust to Ambient	Wet Cooling Tower

Figure 9. The principal hybrid concept to be investigated will be a representative open cycle hybrid configuration. Some of the major parameters for this concept are shown. Data will also be assembled on the hybrid steam rankine concept, but current plans do not include a utility impact analysis of this alternate plant.

SOLAR RADIATION
DIRECT NORMAL TERM

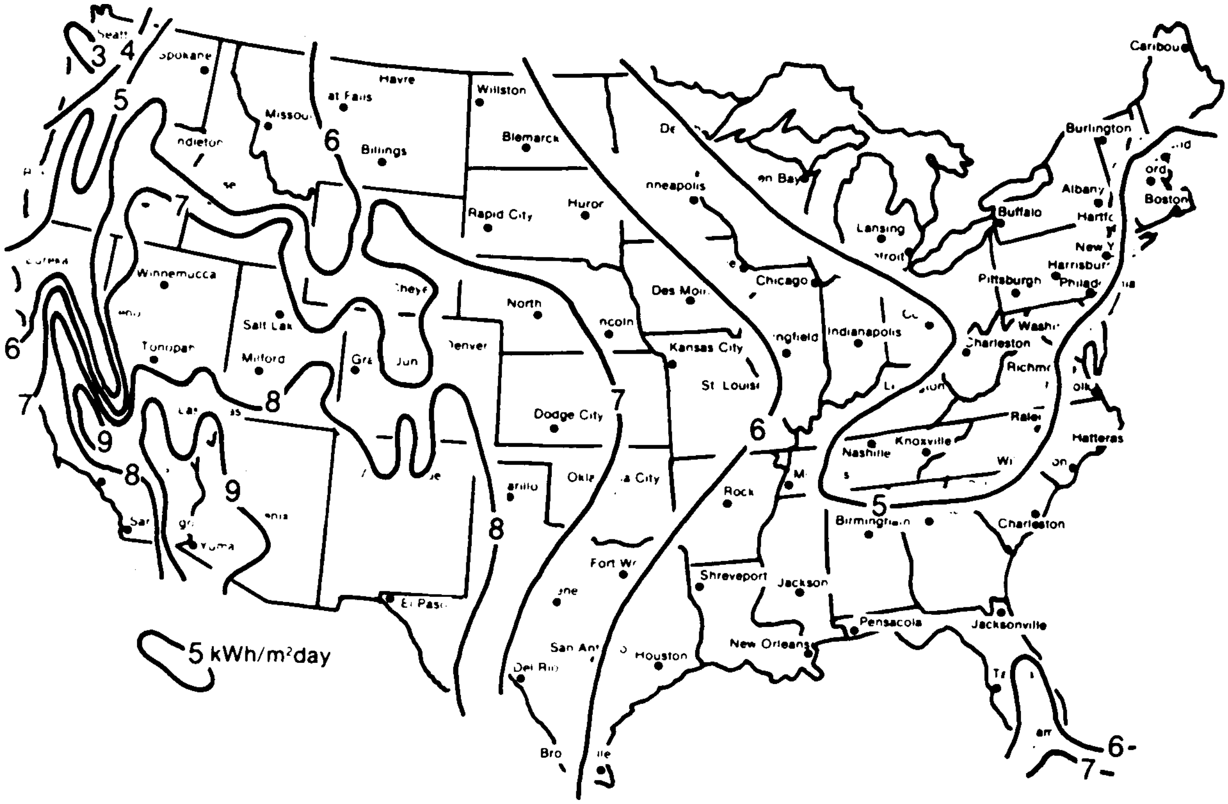


Figure 10. Task two of this study has been one of insolation characterization. The above map shows contours of equal normal insolation across the United States. The values and lines are for average daily normal insolation in kilowatt hours per square meter (for the average day), the average considering variations throughout the year.

INSOLATION EXCURSIONS

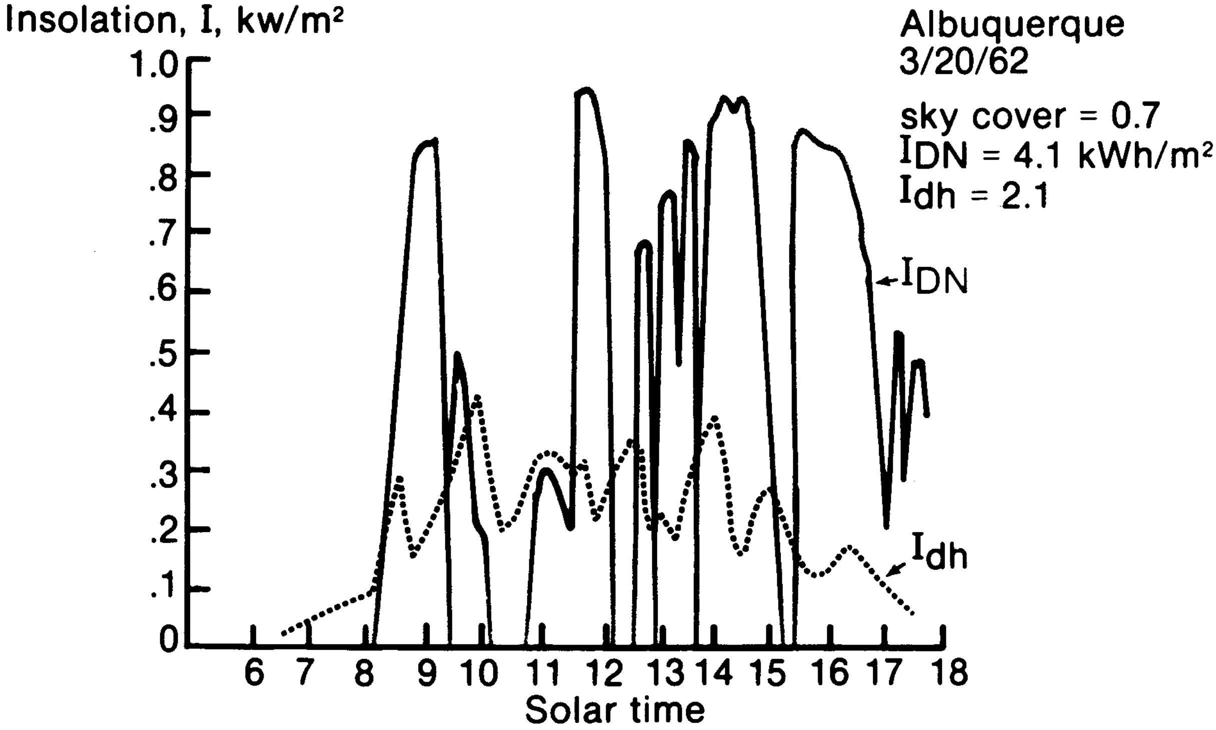


Figure 11. This figure shows insolation transients for a seven-tenths sky cover day in Albuquerque. The direct normal insolation is labeled IDN and the diffuse horizontal insolation Idh. Such excursions will likely require operation through storage all day to isolate the turbine from the resulting thermal transients. This provision is being included in the solar plant being used in this study. Lack of short time interval measurements of direct normal insolation for different locations precludes constructing these characteristics for different locations. Correlation of sky cover with available short interval data has been performed to allow estimation of the insolation transient characteristics of sites where sky cover data exists without detailed insolation data. Some sky cover characteristics are shown in the following figure.

SKY COVER

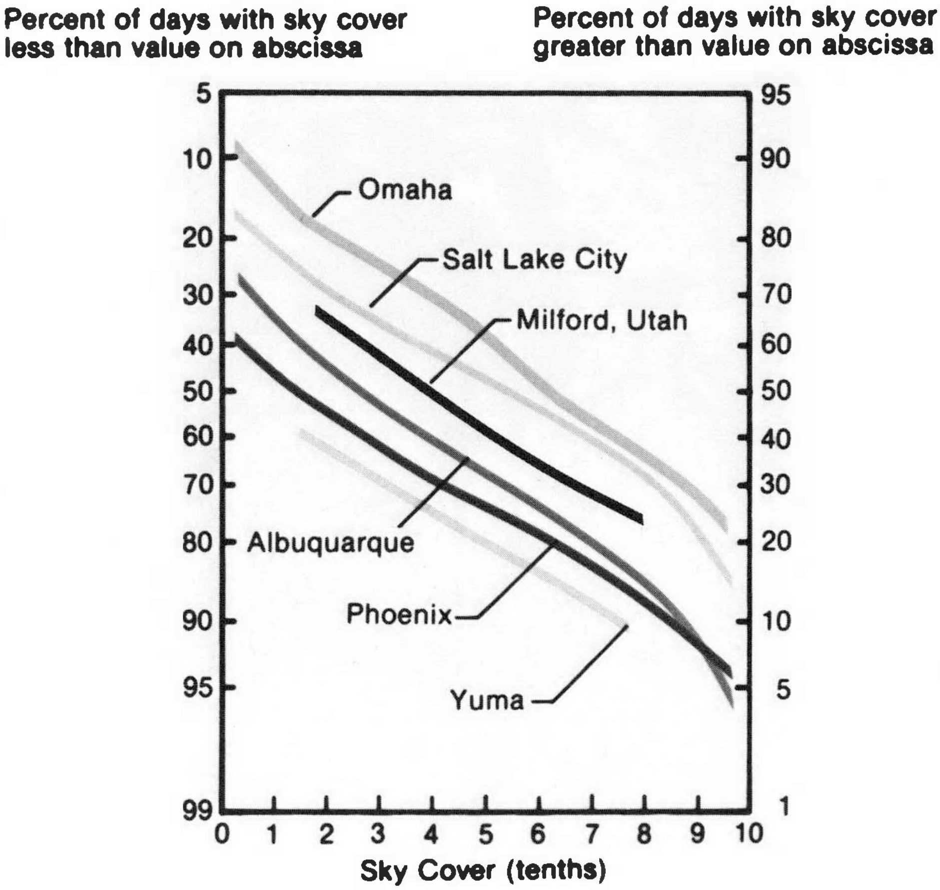


Figure 12. As mentioned with the previous figure, the quality of insolation, particularly regarding transients, is strongly a function of sky cover. This figure shows the frequency of average daily sky cover for several locations. Such information can be used to estimate the number of days in a year a solar thermal plant would be operating in specific modes (through or from storage).

UTILITY CHARACTERIZATION

- INSOLATION
- LOAD
- GENERATION MIX

Figure 13. The principal utility factors that have been identified for characterization are insolation, load, and generating plant mix. Of particular concern to the application of solar thermal conversion plants is the quality of the direct normal insolation. This includes both annual energy available and seasonal variations. Average daily insolation for several sites is shown in Figure 14. The time of daily electrical demand peaks, load factors, and seasonal load variations of the utility are also of importance. The generating unit types and fuels making up the balance of the utility system will effect the solar plant value because of the fuels and capacity potentially displaced. Three utility service areas with differing characteristics have been selected for detailed analysis in this study. They are not listed here since agreement from the utilities has not been finalized.

QUALITY OF NORMAL INSOLATION

A INSOLATION (> 8.0 KWh/m^2 /DAY)

SOUTHERN CALIFORNIA EDISON (9.01)
EL PASO ELECTRIC (8.41)
ARIZONA PUBLIC SERVICE (8.32)
SALT RIVER PROJECT (8.32)
PUBLIC SERVICE OF NEW MEXICO (8.24)

B INSOLATION (7.0 – 8.0 KWh/m^2/DAY)

TUCSON GAS AND ELECTRIC (7.97)
NEVADA POWER (7.69)
UTAH POWER AND LIGHT (7.38)
PACIFIC GAS AND ELECTRIC (7.36)

C INSOLATION (6.0–7.0 KWh /m^2/DAY)

LOS ANGELES DEPARTMENT OF WATER AND POWER (6.92)
SAN DIEGO GAS AND ELECTRIC (6.62)
IDAHO POWER (6.51)
OMAHA PUBLIC POWER DISTRICT (6.24)

Figure 14. This figure shows the average daily direct normal insolation for selected western utilities. The numerical data shown has been extracted from an AEC/Arizona State University report by Charles E. Backus, dated August 1975, "Terrestrial Photovoltaic Power Systems with Sunlight Concentration."

STUDY METHODOLOGY

OBJECTIVE: ESTABLISH METHODS FOR PERFORMING UTILITY GRID AND RELIABILITY ANALYSIS, ECONOMIC ANALYSIS, AND PENETRATION ANALYSIS.

GUIDELINES: USE CONVENTIONAL UTILITY PLANNING METHODS AND TOOLS AS MUCH AS POSSIBLE

BUILD ON AEROSPACE CORP. MISSION ANALYSIS WHERE APPLICABLE

PRINCIPAL PROBLEMS: RELIABILITY—CAPACITY CREDIT

OPERATIONAL ECONOMICS - SIMULATION

PROBLEM DIMENSION - EXPERIMENT DESIGN

Figure 15. One of the principal objectives of this study is the development of a methodology to evaluate solar thermal conversion plants. The methods involved include procedures for calculating solar plant reliability and capacity credit, simulating the integrated operation of a solar plant with a utility system, and effects of increasing solar penetration with time.

SOLAR PLANT ECONOMIC MEASURES

Solar Plant Value
- Operating Cost Savings
- Capital Investment Displacement

Solar Plant Busbar Energy Cost
- Plant Capital Cost
- Plant Operating Cost
- Energy Produced

Utility System Cost Impact
- Solar Plant Costs
- Utility Differential Costs

Figure 16. Three measures of solar plant economics will be used in this study. As shown in Figure 16 they are: (1) Solar Plant Value, (2) Busbar Energy Cost, and (3) Utility System Cost Impact. Heavy emphasis will be placed on plant value calculations since this can be done independent of solar plant cost estimates. Both operating credits and capital credit, as seen by the balance of the utility system, will be used to establish solar plant value. The procedures outlined in the joint ERDA/EPRI document, "The Cost of Energy from Utility-Owned Solar Electric Systems," will be used to calculate solar plant busbar energy costs.

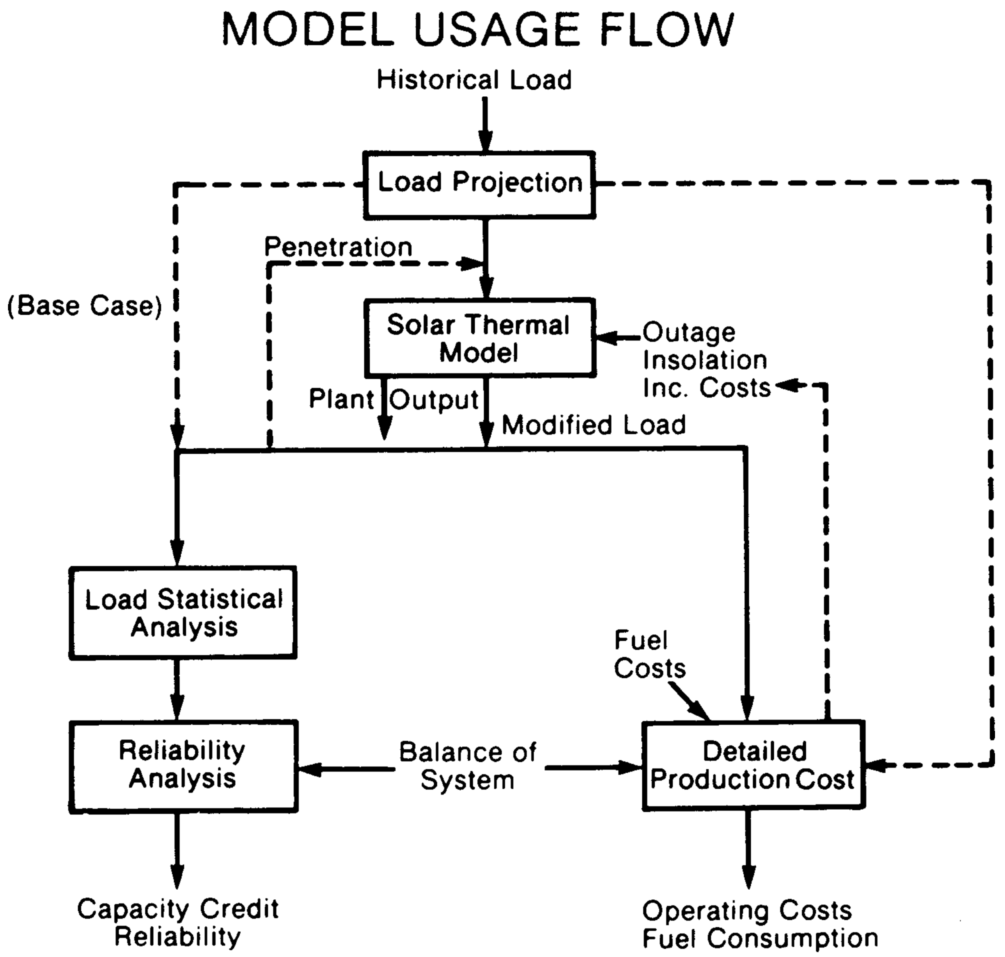
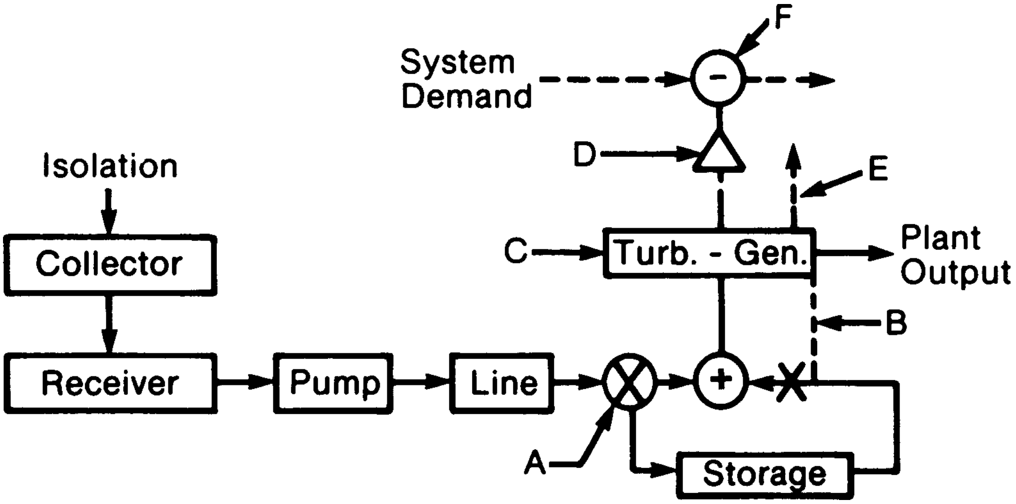


Figure 17. The methodology for economic and reliability system impact assessment will rely heavily on system simulation. The Load Projection, Load Statistical Analysis, Reliability Analysis and Detailed Production Cost blocks shown above are separate existing Westinghouse models (computer programs) which are routinely used to analyze and plan utility systems. These models have had minor modifications to allow them to interface with the Solar Thermal Plant Model. This latter model is a modified version of the one developed by the Aerospace Corporation and used in their Mission Analysis effort. The projected hourly system load is input to the solar plant model which simulates the operation of the solar plant and outputs the remaining load to be served, for further analysis. The solar plant model uses incremental operating cost data for the balance of the utility system to guide its dispatch.

SOLAR PLANT MODEL MODIFICATIONS
Mods to Aerospace Corp. Model



A. Economic Dispatch of Heat to Storage.

B. Different Heat Quality From Storage, T-G Efficiency and MW Limit.

C. Variable T-G Efficiency With Heat Input Rate, Dry Cooling Temp.

D. Output Multiplier for Scheduled, Forced Outages, and Multiple Units.

E. Hybrid Unit Control for Fossil Side Output Limit.

F. Residual System Load Format.

Figure 18. Several modifications have been made by Westinghouse to the original Aerospace Corporation Solar Plant model. Included have been a dispatch routine which recognizes balance of utility system incremental costs, turbine efficiency modifications, a plant availability table, and residual system load format changes. These changes have been made to enhance the applicability of this model to this EPRI study. The new dispatch rule that has been implemented is shown in Figure 19.

SOLAR PLANT DISPATCH RULE

1. Dispatch Insolation Directly to Turbine Generator
2. Minimize Waste Heat Using Storage
3. Dispatch Storage on Incremental Cost
4. Economic Exchange of Direct Use Vs. Through Storage

RECOGNIZING

1. Foreknowledge of Day's Insolation Profile
2. Foreknowledge of Day's Load Profile
3. Utility System Incremental Cost Curve
4. Storage Limits and Efficiency
5. Turbine-Generator Limits and Efficiencies

Figure 19. This figure summarizes the solar plant dispatch rule recently implemented into the Aerospace Corporation Solar Thermal Model by Westinghouse. This rule assumes knowledge of the full day's insolation and load profile at the beginning of each day. It also uses information as to the incremental operating cost of the utility system at various load levels. The solar plant dispatch is a daily iterative procedure which relies upon a simple preliminary dispatch which is iteratively adjusted.

SOLAR PLANT DISPATCH

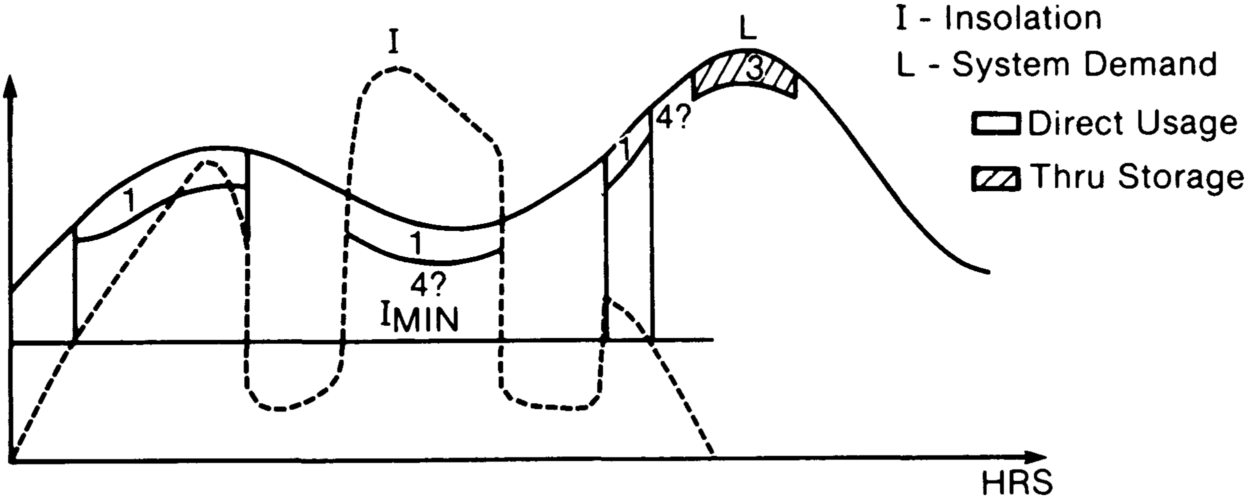
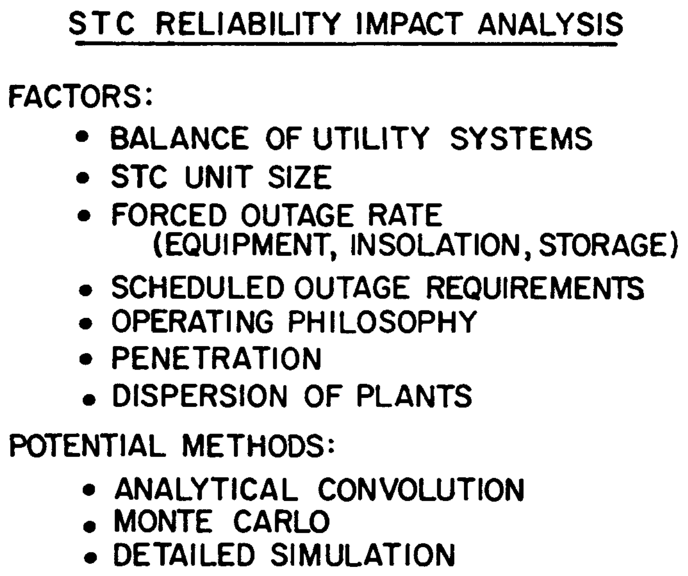


Figure 20. This figure shows a day's insolation and a load profile which are not to the same vertical MW scale. An insolation threshold level, Imin, is shown, below which the plant is incapable of operating directly from the receiver. The numbered areas represent solar plant operation derived from one of the four steps listed in the previous figure. The lower limb of these areas represent the net residual load after solar plant operation. The "4?" is used to show a possible exchange consideration in step 4. That is, is it preferable to shut the plant down during the low load interval (first 4?) and store the energy for use at a higher load level (later 4?)?



STC RELIABILITY IMPACT ANALYSIS

FACTORS:

- BALANCE OF UTILITY SYSTEMS
- STC UNIT SIZE
- FORCED OUTAGE RATE
  (EQUIPMENT, INSOLATION, STORAGE)
- SCHEDULED OUTAGE REQUIREMENTS
- OPERATING PHILOSOPHY
- PENETRATION
- DISPERSION OF PLANTS

POTENTIAL METHODS:

- ANALYTICAL CONVOLUTION
- MONTE CARLO
- DETAILED SIMULATION

Figure 21. The major factors identified as affecting solar plant reliability impact and capacity credit are shown. Methods including analytical convolution, Monte Carlo, and simulation were considered. For this study a combination of analytical convolution and simulation was selected. The convolution is a manipulation of system capacity and load probability distributions to obtain a loss of load probability. This is shown in Figure 22.

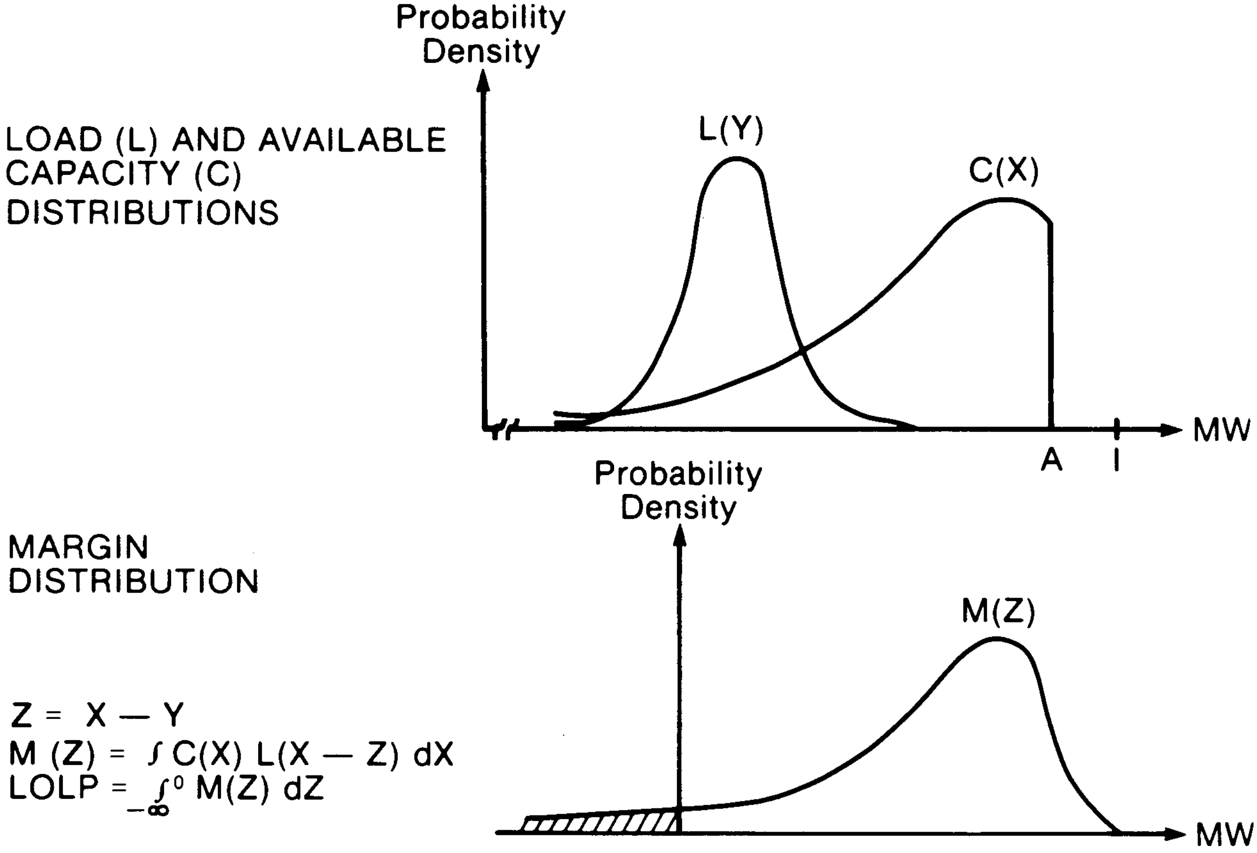


Figure 22. This figure depicts the calculation of the loss of load probability which is commonly used as a utility reliability index. Margin is the amount of the available capacity which exceeds the load. The area under the negative portion of the margin density function represents the loss of load probability (LOLP).

PENETRATION ANALYSIS

1. Iterative Static Analysis by Simulating Various Levels of Solar Penetration
2. Dynamic Expansion Analysis
   - Selected Penetration Rate
   - Expand Balance of Utility Using Generation Expansion Optimization Model

Figure 23. The effects of solar penetration into a utility system's generating mix will be analyzed using two approaches. One will be through simulating various levels of penetration in a single year, and another by letting the penetration increase with time. This latter time dynamic analysis will begin by presuming a solar penetration rate and letting an automatic expansion computer program develop the most economic expansion for the balance of the utility system.

PENETRATION— DYNAMIC EXPANSION ANALYSIS FLOW

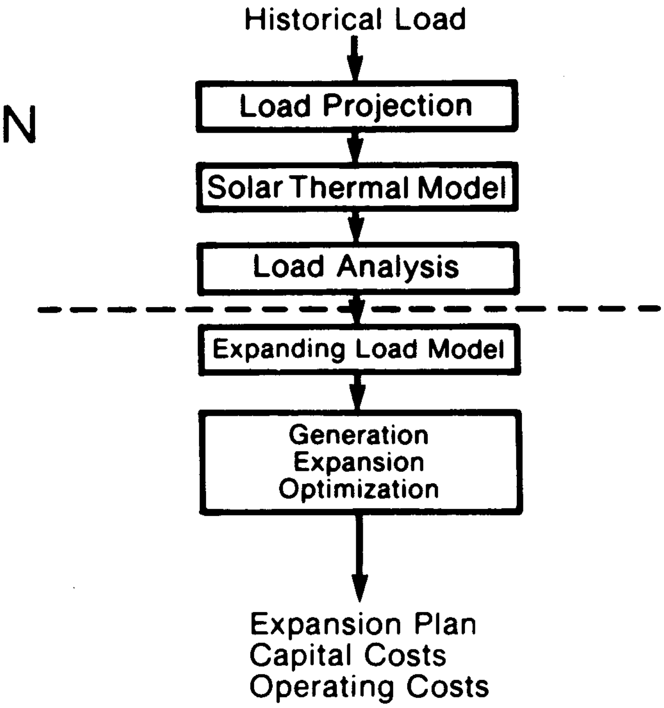


Figure 24. This figure shows the sequential use of computer models to achieve the dynamic penetration analysis. Various penetrations are simulated on the solar plant model for different years, and the net residual load is used to construct a residual expanding (growing) load to be served by the balance of the utility system. Then the automatic expansion program develops the most economic utility expansion to serve this load with acceptable reliability.

SECTION 8

EPRI CONTRACT RP 377

CLOSED CYCLE, HIGH TEMPERATURE CENTRAL RECEIVER CONCEPT FOR SOLAR ELECTRIC POWER

BOEING ENGINEERING AND CONSTRUCTION
A Division of the Boeing Company
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OCTOBER 1976

EPRI SOLAR REVIEW MEETING #2

Program Summary
RP-377

RP-377-1

	1975												1976					
D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Phase 1																		

Objectives:

- **Receiver configuration**
- **Technical feasibility—materials**
- **Storage requirements**
- **Operations analysis**

RP 377-2

1976						1977												1978						
J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J
Phase 2																Phase 3								

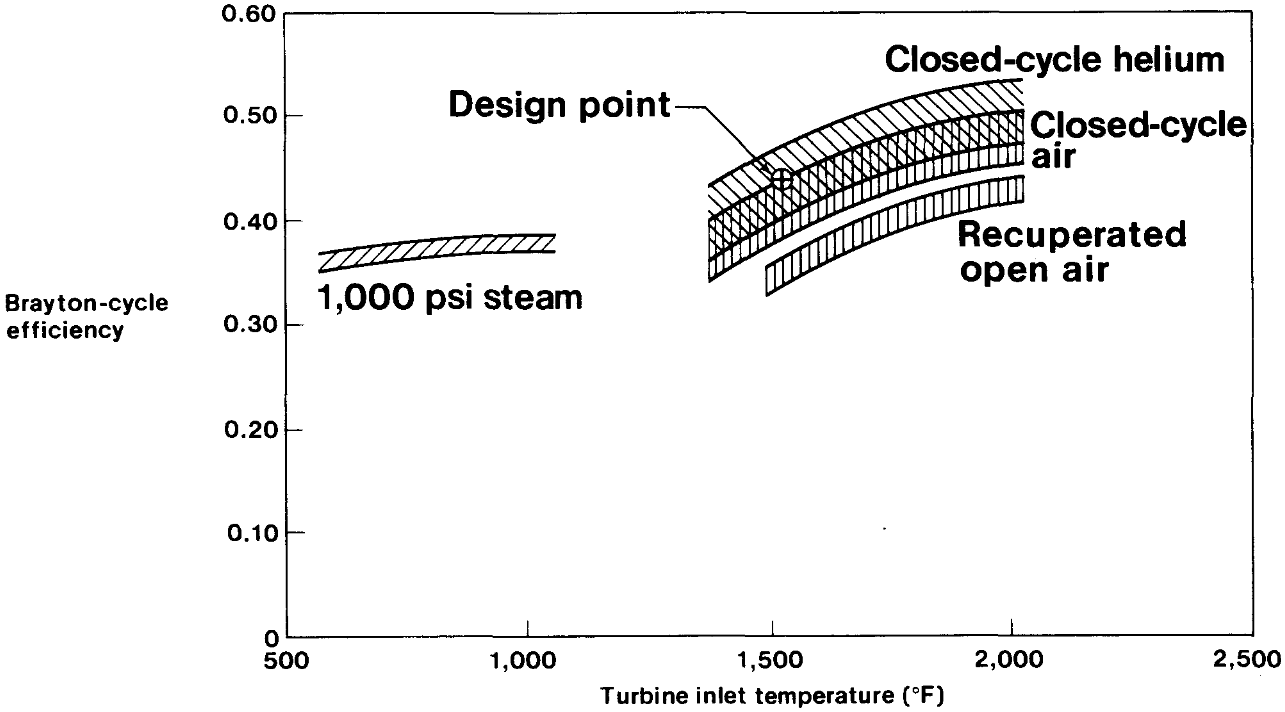
Objectives:

- **Design and fabrication 1 MW_{th} receiver**
- **Test in 5 MW STF**
- **Concurrently conduct planning studies for 10 MWe equivalent**

Boeing Engineering and Construction has been under contract by EPRI since December, 1944, in various phases of receiver design and plant implementation. The first phase, under RP377-1, involved the concept definition of a closed cycle, high temperature central receiver plant capable of producing 100 MW_e of electrical power. The left side of the figure shows the contract span and the primary objectives - all of which were successfully accomplished. Much of the subsequent material describes the results of the Phase I study.

Phase 2, under EPRI Contract RP377-2, was initiated in July of 1976. The basic objective is the design and fabrication of a 1 MW_{th} receiver which simulates the 100 MW_e receiver and plans for testing the materials and concepts selected in an operational environment. Phase 3 includes the test period and data evaluation of the 1 MW_{th} receiver design. The test is currently planned in the 5 MW_{th} Solar Test Facility at Albuquerque, New Mexico, but has features incorporated which could adapt it to the CNRS facility at Odeillo, France, or to IR facilities. Along with the Phase 2 and 3 efforts, planning studies are being conducted for a 10 MW_e equivalent pilot plant.

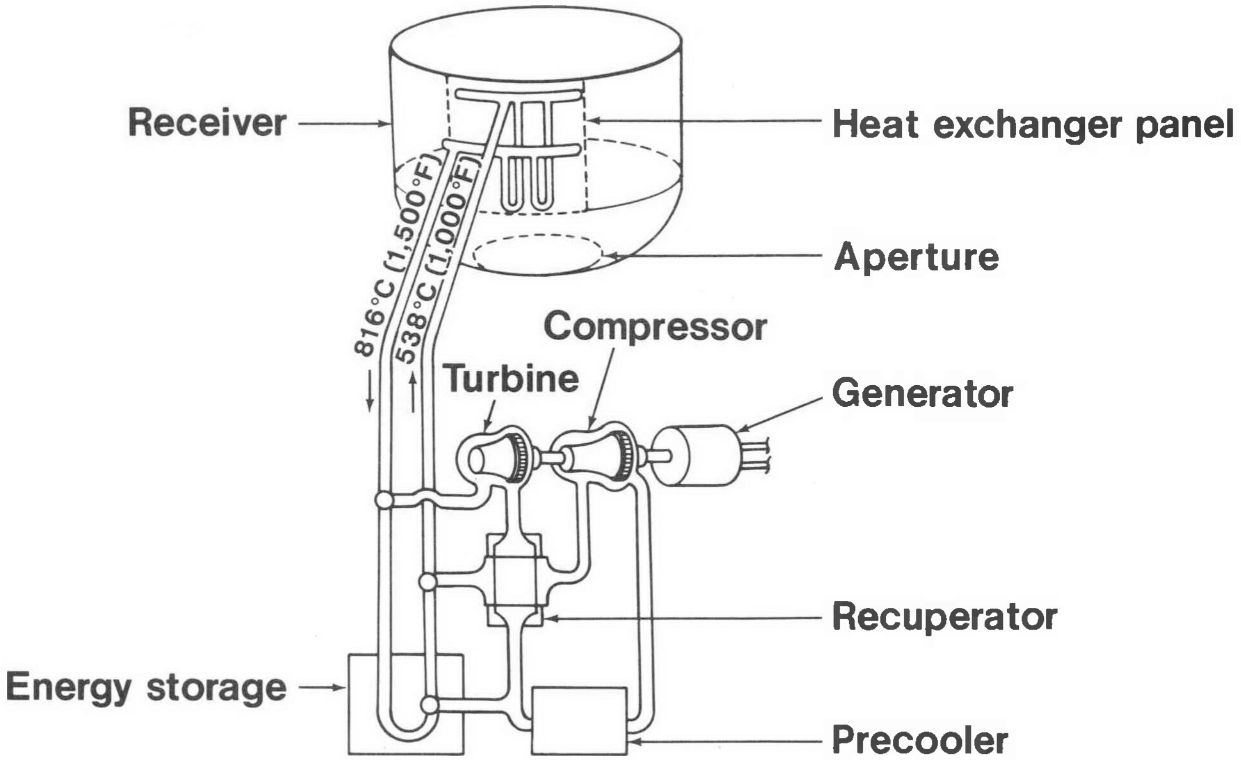
Cycle Efficiency



The design philosophy followed in the initial system selection was to emphasize thermal cycle efficiency to reduce collector system costs. A comparison of the engine efficiency available from various systems is shown on the above figure. A closed cycle system was selected as a baseline because of the high efficiencies obtainable. A comparison of various working fluids such as helium and air has been a continuing activity. The design point shown at 816°C (1500°F) was chosen as a practical upper limit for both metallic tube heat exchangers and turbine blades considering the long life requirements of the system. Data provided to us by turbine manufacturers have tended to support this conclusion.

The range of efficiency shown as a band for each system represents the practical upper and lower limits as determined by selection of cycle type, recuperators, and precoolers. The selection of the optimum point within the range is a function of the effect on overall system cost.

Receiver Concept/Schematic

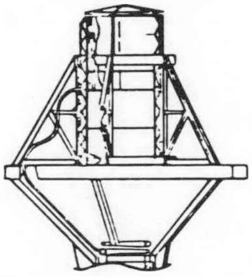


The most promising receiver concept is displayed above. An aperture at the receiver bottom admits the reflected energy from the collector field into the receiver interior. The receiver configuration has a hemispherical lower section and a cylindrical upper section. Heat exchanger panels are mounted on the interior of the upper cylindrical section and facilitate heat transfer from the receiver to the circulating helium.

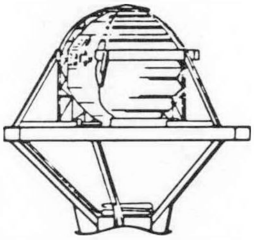
Helium inlet and outlet temperatures are 538°C (1000°F) and 816°C (1500°F) respectively. The upper limit of 816°C (1500°F) was chosen as high as possible to elevate cycle efficiency, yet remain within the state-of-the-art of high temperature metals. The associated energy conversion and helium processing equipment shown below the receiver would be located at the base of the tower, along with the thermal energy storage equipment. The turbine could be located at the top of the tower for the hybrid concept.

Cavity Receiver Evaluation

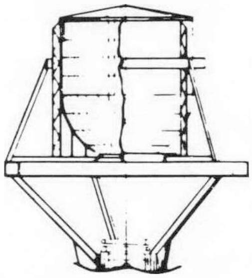
Cylinder



Sphere



Composite



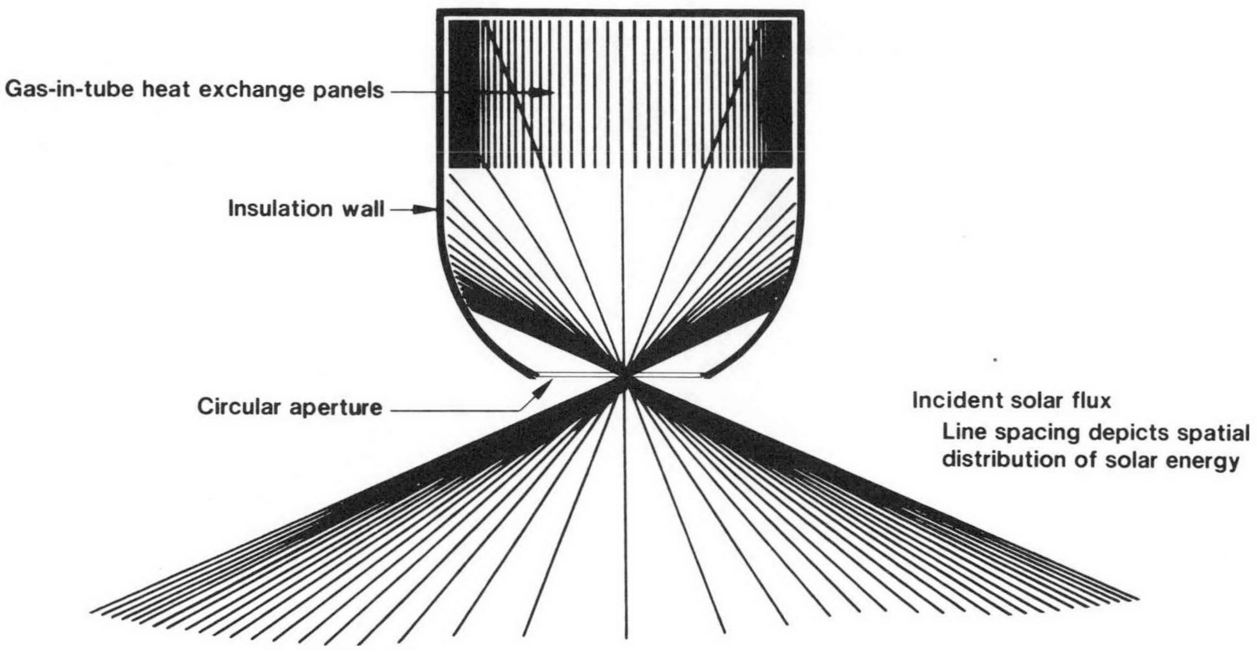
Considerations for selection	Rating		
Heat distribution	Poor	Best	Good
Reflection Losses (%)	13.1	3.7	3.8
Overall thermal efficiency (%)	74	87	83
Estimated cost ratio	1.0	2.0	1.5

The most desirable receiver for the high temperature concept is supported above a tower, with the receiver having a bottom circular aperture to admit reflected energy from the collector field. The figure presents the three bottom-aperture receiver shapes analyzed. The composite shape finally selected (extreme right) combines portions of the cylindrical and spherical shapes used as the initial baseline and alternative.

The table below the illustration summarizes the selection rationale. Detailed thermal analyses were performed first on the initial cylindrical receiver and an alternative spherical receiver shape. The absorbed heat flux and temperature on the lower interior walls of the cylinder reached much higher (and intolerable) levels than on the walls of a sphere. Careful ray-tracing analyses indicated reflection losses from the cylinder to be 13% compared to under 4% for the sphere. The selected shape has reflection losses comparable to the spherical shape due to the similar lower geometry.

The heat exchanger panels are mounted in the upper half of the receiver to escape direct solar impingement and consequent overheating. A cylindrical upper section was chosen to facilitate mounting heat exchanger panel modules.

Solar Flux Distribution

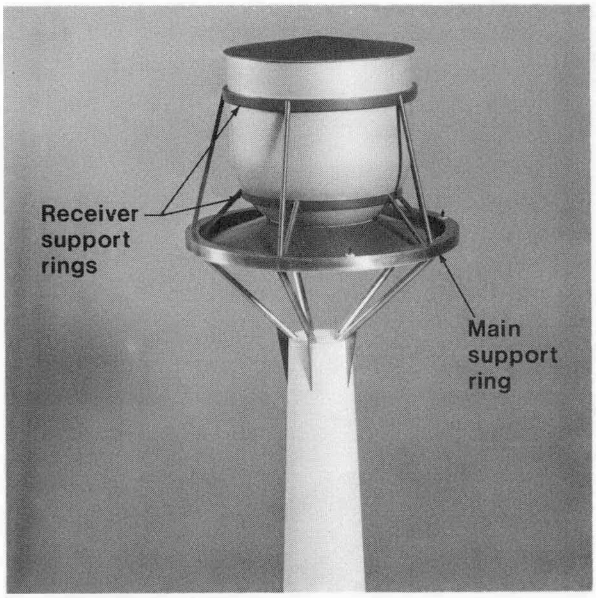


The receiver cavity is designed to accommodate solar flux from a circular symmetric collector field. In this sketch the solar energy is depicted by 81 characteristic rays entering at the center of the circular aperture. Each of these represents an equal portion of the solar input. The elevation angle of each ray is representative of the direction of incidence of each portion of energy.

The proximity of ray lines is proportional to the vertical distribution of solar flux entering and initially striking the receiver walls. Less than ten percent of the incident flux strikes the heat exchanger panels.

The design, providing for multiple solar reflections from cavity walls before striking the heat exchanger tubing, provides a nearly uniform solar flux environment at the location of the heat exchanger panels. In addition, due to the receiver geometry, it is physically impossible for more than a small fraction of the solar collectors to be errantly focused on any portion of the active heat exchanger surface.

Selected Receiver Configuration



Receiver and upper tower

Receiver with roof removed exposing heat exchanger panels

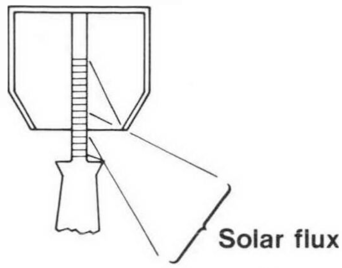
Two views of the design are contained in the photos of a scale model shown above. The receiver, its main supports, and the upper tower are shown in the picture at the left. The receiver is mounted approximately 30 meters (98 feet) above the tower top to allow reflected solar energy to enter the aperture at the bottom of the receiver. The aperture is 19 meters (62 feet) in diameter and is located 260 meters (850 feet) above ground level. Receiver interior dimensions are approximately 39 meters (128 feet) in diameter and 39 meters high.

The receiver is supported by five support struts which extend out from the tower top to the main support ring. These supports are located away from the aperture to minimize heating by direct radiation and to reduce field blockage. Vertical members extend from the main support ring to the receiver support rings. The size of these vertical support members is such that a helium riser or downcomer can be contained with an individual support. There are two risers and two downgraders.

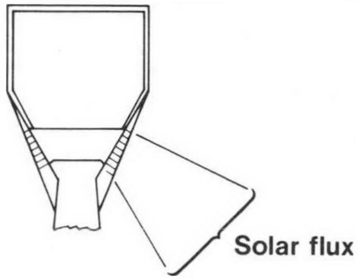
The photo on the right shows the mounting arrangement of heat exchanger panels in the upper half of the receiver. There are three rows of these panels with 70 panels in each row. The lower hemispherical section has insulation panels which direct field energy to the heat exchanger panels and also reduce conductive heat loss.

Receiver Support Structure Evaluation

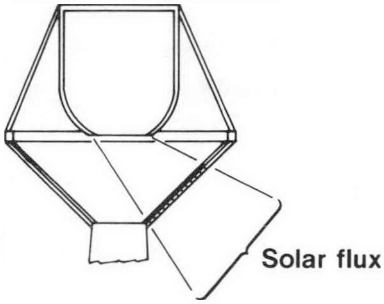
Central column

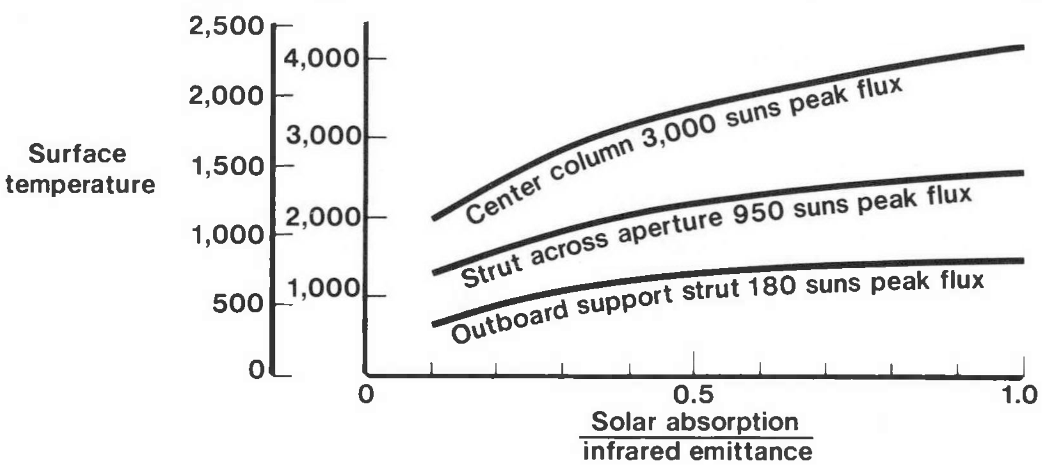


Strut across aperture



Outboard support strut



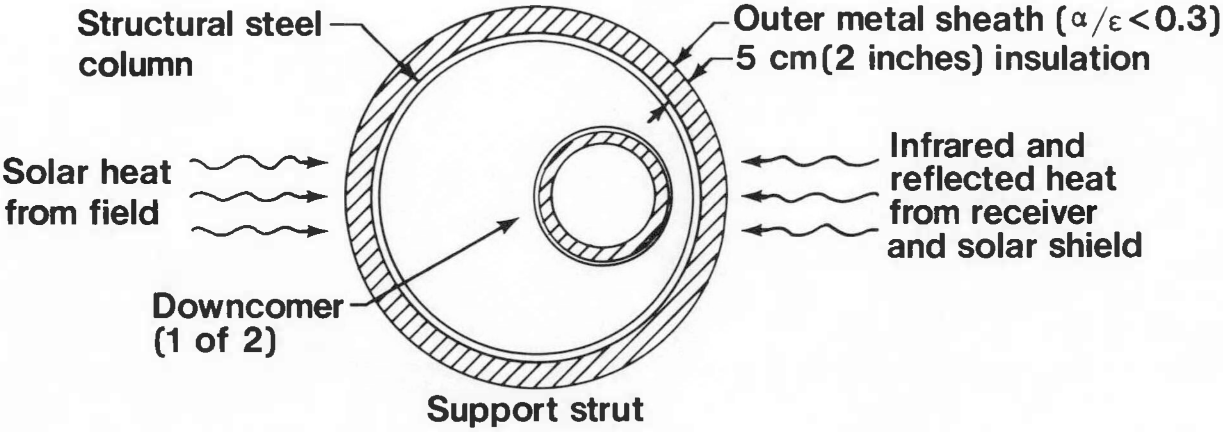


Selection of a receiver concept with a circular aperture at the bottom required a configuration where the receiver supports, helium risers and downcomers must necessarily traverse the concentrated solar flux from the collector field. Various support structure candidates were examined ranging from a central column to outboard support struts. The figure shows three configurations, with the outboard support configuration at the extreme right being selected.

The rationale for the selection is shown on the flux and temperature graph. Quite clearly, the flux exposure of the outboard supports is significantly less. Surface temperatures are in a range where only passive protection is required. This support system is also advantageous because it presents a single large aperture to the entire field. This allows larger collector units in the field while maintaining a favorable flux capture ratio.

The heating on the outboard strut is very localized. The 180 suns peak flux shown is confined to a few meters with a rapid dropoff on either side.

Receiver Support Structure Design/ Temperatures



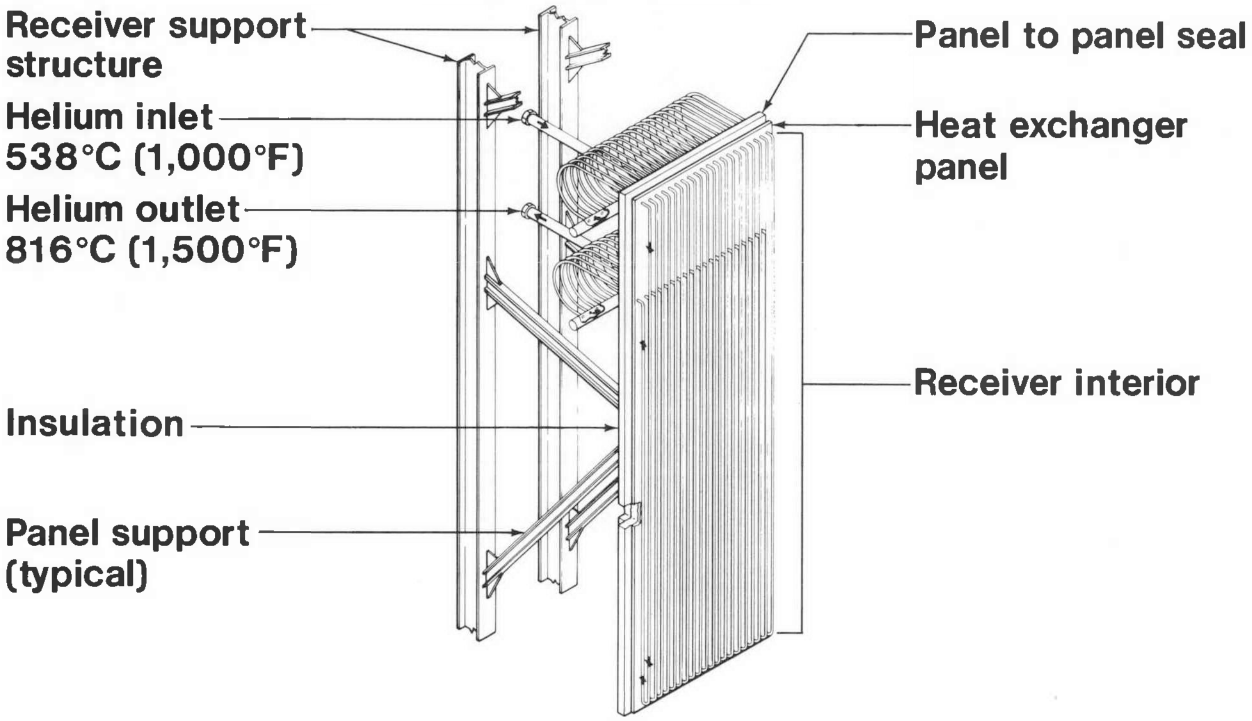
Local maximum temperatures	Solar heated side	Cavity heated side
Outer sheath	816°C (1,500°F)	610°C (1,130°F)
Steel column wall	370°C (700°F)	195°C (384°F)

Note: Strut interior cooled by natural air draft

The receiver support struts located below the receiver aperture plane are heated by the external field and also by the radiated and reflected heat flux from the receiver back through the aperture. The figure illustrates the heating situation and the selected strut design. The structural steel column is protected by 5 centimeters (2 inches) of insulation covered by an outer metal sheath with a low absorptance-to-emittance ratio. The local maximum temperatures on either side of the support strut are presented in the table.

The risers supplying 518°C (1000°F) helium to the receiver and the downcomers returning 816°C (1500°F) helium to the tower must also traverse the stand-off distance between the receiver and the tower top. Heating problems and associated costs for thermal protection of risers and downcomers are alleviated by placing each pipe within a separate support leg. There are two risers and two downcomers. A typical downcomer is shown within the support strut on the figure. The pipe containing 816°C (1500°F) helium is insulated on the inside so that a carbon steel pipe may be used. The risers with 518°C (1000°F) helium will be externally insulated. The vertical height of the support structure columns has been utilized to produce a natural draft cooling of the interior structure.

Interior Arrangement



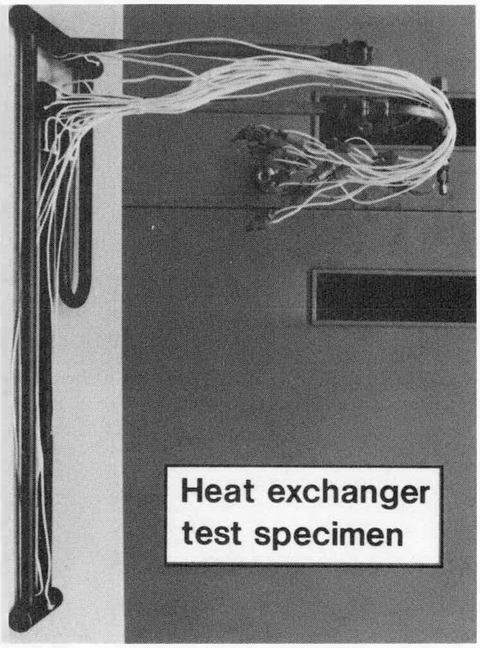
The figure illustrates a heat exchanger panel module and its structural supports. Progressing outward from the cavity, each panel consists of two offset columns of heat exchanger tubing, insulation, tubing loops to the helium manifolds, and the support structure to the outside wall. Each panel is designed to be removable as a unit, should replacement be necessary.

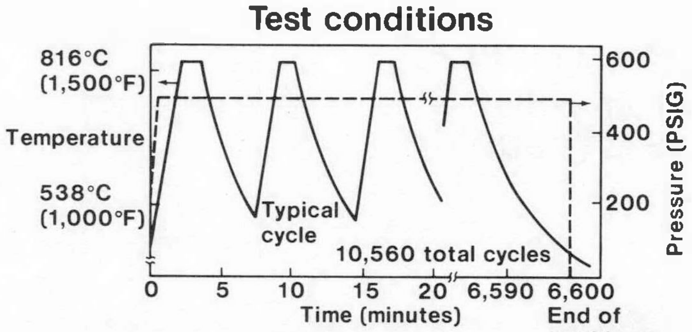
There are 20 tubes on a panel module. Each tube is U-shaped with one leg from the inlet down to the bend, and the other leg back close to the insulation up to the outlet. The difference in path length and the loops behind the insulation provide for tube expansion during thermal cycling to keep the interior tubes and tube pass-throughs in a stable position.

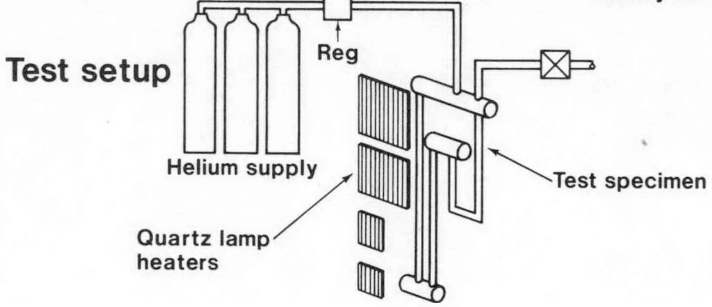
Tube materials can be either Haynes 188 or Inconel 617 alloy. Both materials were successfully thermal-cycled over a simulated 30-year lifetime. Tube dimensions are 2.54 centimeters (1 inch) outside diameter with a 0.17 centimeter (0.062 inch) wall and 9.5 meters (31 feet) length. Exposed tube surface area per panel is 17 square meters (182 square feet). Total panel weight is 1200 kilograms (2650 pounds).

Panel insulation behind the tube consists of three successive layers of alumina-silica blanket, alumina-silica block and mineral wool block for a total thickness of 0.15 meters (6 inches). The insulation panels for the lower hemispherical section (without heat exchangers) are the same.

Thermal Cycling Tests







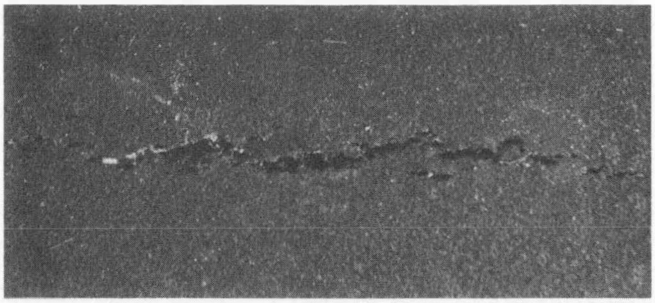
A number of metal alloys were chosen as candidates for high temperature tubing applications based upon present manufacturing capability, performance capability, and economic considerations. The high temperature limit was established at about 816°C (1500°F) to meet the 30-year lifetime requirement at repeated thermal cycles and stresses. Detailed screening of major property data (stress-rupture strength, creep, oxidation resistance, and metallurgical stability) resulted in selection of Haynes 188 and Inconel 617 alloys for further evaluation.

Test specimens of 188 and Inconel 617 were fabricated and subjected to 10,560 thermal cycles, while under pressure, to simulate a 30-year lifetime. A typical test specimen is shown on the left-hand side of the figure. Each specimen was pressurized to 3.45 MN/m^2 (500 psi) helium pressure, and tube temperatures were cycled between 482°C (900°F) and 830°C (1525°F). The graph on the right-hand side shows test conditions for each weekly run. The bottom sketch shows a schematic of the test setup featuring quartz lamp heaters and a regulated helium bottle supply.

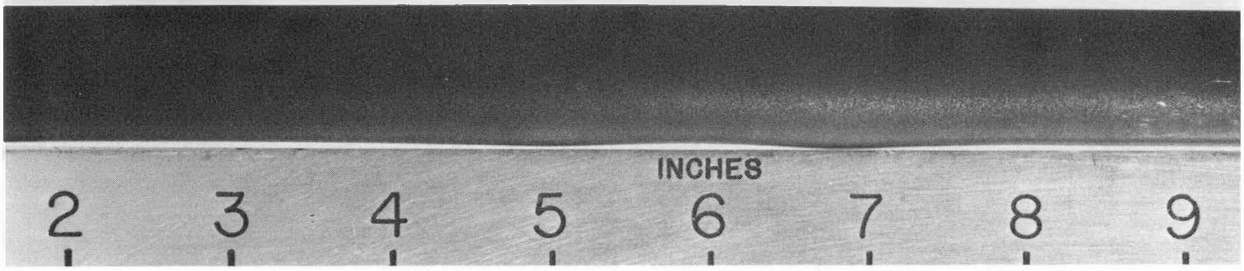
Haynes 188 and Inconel 617 have been verified as excellent materials for high temperature applications with performance such that a final material selection can be based on economics and quantity availability.

Elevated Temperature Rupture Tests

Test specimens



Haynes 188 rupture site 1,037°C (1,900°F)



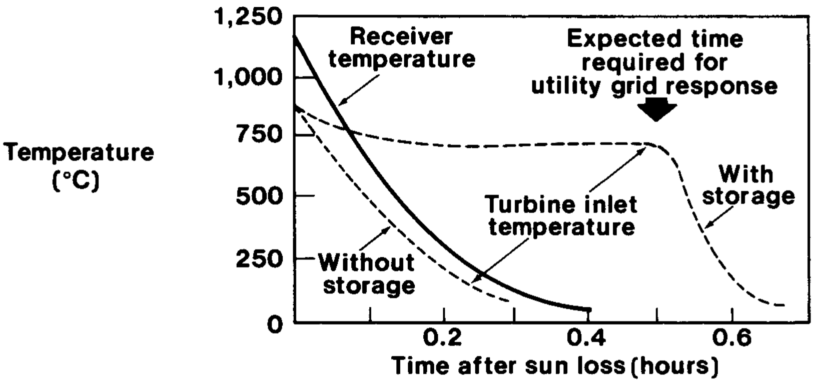
Haynes 188 tube ballooning 1037°C (1,900°F)

EPRI requested that elevated temperature tests-to-rupture be performed to determine the capability of Haynes 188 and Inconel 617 tubes to sustain temperatures in excess of the proposed service maximum of 830°C (1525°F). Additional information was desired on the safety hazard of accidental or intentional overheating and on high temperature material behavior.

Tubular specimens of Haynes 188 and Inconel 617 alloys, both in the new and after-thermal cycling condition, were pressurized with helium at 3.45 MN/m^2 (500 psi) and thermally cycled at successively higher temperatures until stress-rupture failure occurred. The upper left photo shows the four subject test specimens. Test temperature levels were 871°C (1600°F), 926°C (1700°F), 982°C (1800°F), 1027°C (1900°F), and 1092°C (2000°F). Fifty cycles of fifty minutes each were performed at each test temperature level.

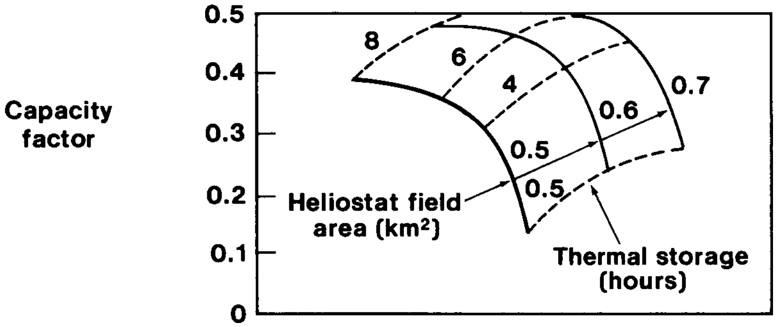
All ruptures of test specimens occurred in the 1037°C (1900°F) to 1092°C (2000°F) range, with the Haynes 188 and Inconel 617 tubes previously exposed to thermal cycling surviving the longest. Failures were non-catastrophic with small fissures occurring in the tubes permitting helium leakage without explosions or fast crack propagation. The lower photo shows the ballooning of a new material Haynes 188 tube prior to rupture. The photo to the right shows the rupture site on the same tube and is typical of all ruptures. No ruptures occurred on the weld lines of the tubes.

Thermal Energy Storage Requirements



Thermal buffering

- **Very little thermal inertia in bare system**
- **Moderate storage system will provide 1/2 hour at 730°C**



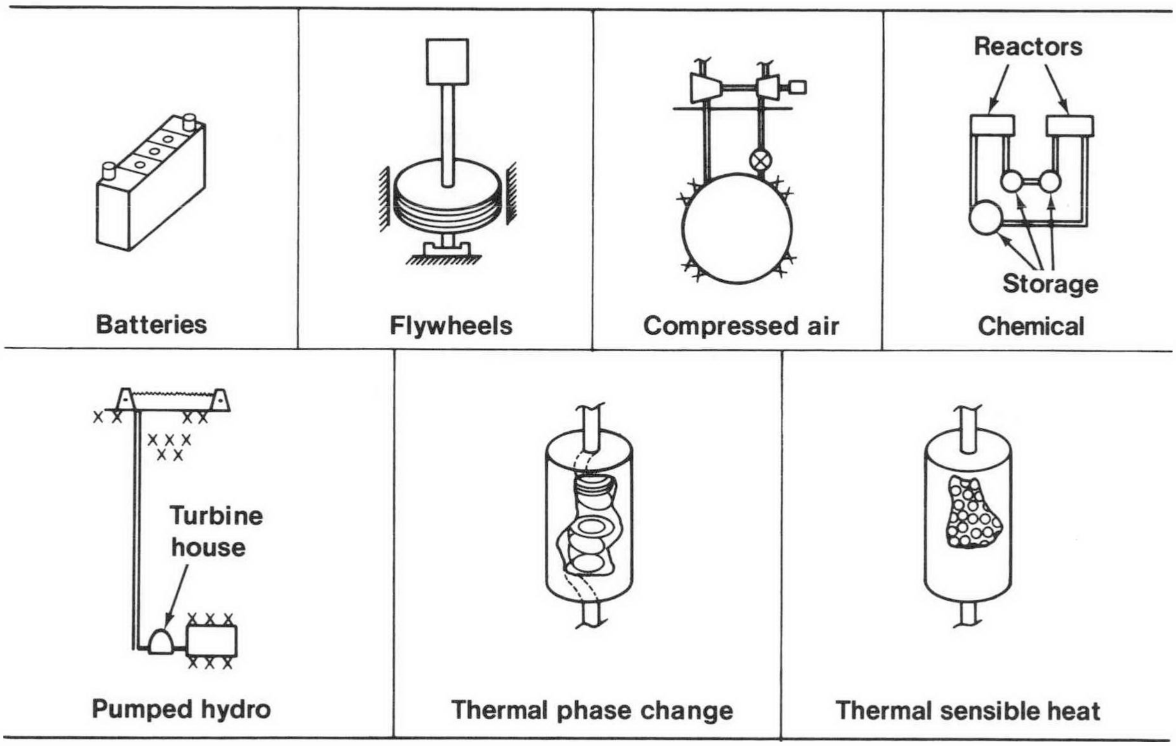
Peaking and intermediate energy and capacity displacement

- **Requirements strongly coupled to heliostat field sizing**
- **Very large storage system to provide 6 hours at 730°C**

Thermal energy storage requirements for a Solar Thermal Conversion (STC) power plant fall into two basic categories: thermal buffering and capacity development. The receiver and the associated heat transport system, less the required thermal storage device, have very little thermal inertia, as illustrated here. Consequently, the plant generating capacity would be very sensitive to solar insolation variation without the addition of some form of thermal buffering. The turbomachinery would be stressed by such rapid cycling, and the utility grid would have little chance to respond to generation losses.

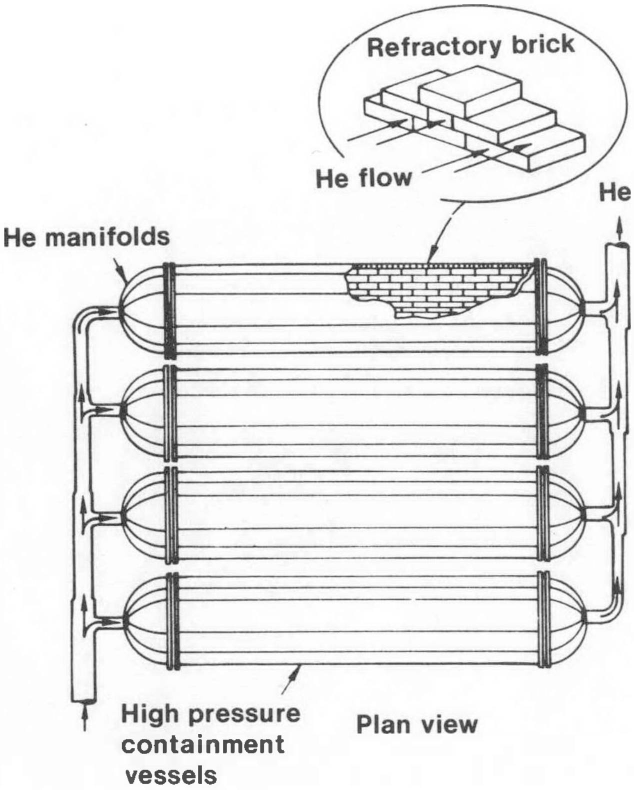
The half-hour thermal buffering storage requirement is commonly accepted as a reasonable buffering requirement. Based on the projections of the Thermal Energy Storage (TES) technology, the cost associated with this requirement is 60-235$/KW. The yearly average capacity factor of the STC power plant without long term storage is about 30%. By the addition of up to 6 hours of TES with the proper heliostat field size the yearly average capacity factor can be nearly doubled. The costs of a six-hour TES device is projected at 100-400 $/KW. Long term storage of four to eight hours will be an economic plus to the STC power plant.

Energy Storage Concepts



The requirements for providing 6 hours of storage for a stand-alone plant and one-half (½) hour of storage for "thermal buffering" for a hybrid plant led to a review of energy storage devices used in other applications. The figure shows the candidate devices included in the review. The load side energy storage devices are represented by batteries, flywheels, pumped hydro, and compressed air. The need for thermal control as well as storage in the solar plant dictated examining energy storage devices on the source side of the generator. Three such thermal energy storage devices were examined in detail for performance and costs. Chemical, phase change, and sensible heat storage devices were conceptually designed and integrated into solar plant operations. Resultant cost estimates showed a cost advantage for phase change storage for the 6-hour requirement.

Sensible Heat Storage Concept

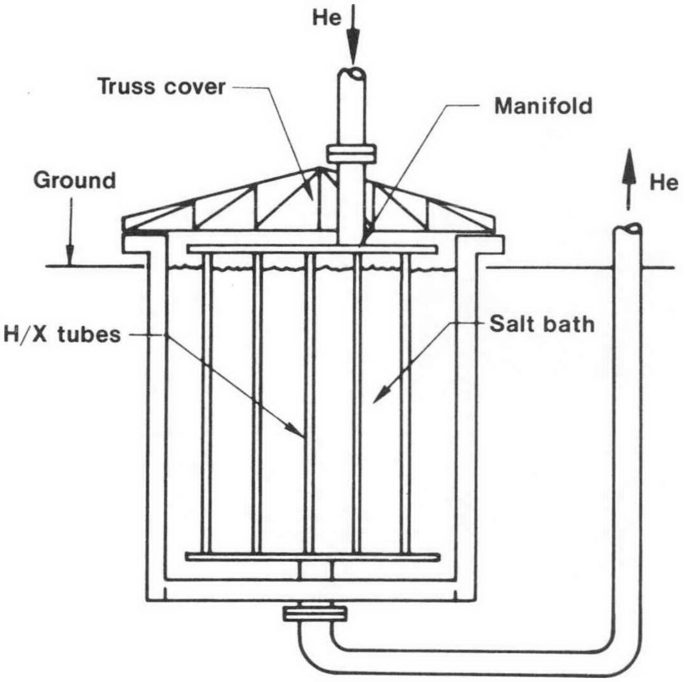


- Magnesia (Mg O) brick checkerwork
- Temperature swing = 246°C
- Key thermophysical properties
    - ρ Cp = 0.902 cal/cm² - °C
    - k = 0.0248 cal/cm-sec-°C
    - Cost = 0.26 \$/kgm
- Critical technical problems
    - Brick erosion
    - He stream contamination
    - Large insulated pressure vessels

Energy stored as sensible heat in materials is attractive because it is a state-of-the-art technology. Material cost per pound is small but the low specific heats of materials result in a low energy storage density. The 6-hour sensible heat storage device selected has a system weight of approximately 10 million kilograms (22 million pounds) with a cost of $\$336/KW_e$.

Two design concepts were investigated in detail: a liquid NaOH bath/tube arrangement; and a solid porous media/pressure vessel arrangement. Potential corrosion problems with molten NaOH and the impact of the relatively low thermal conductivity of NaOH on the number of helium tubes required resulted in choosing MgO refractory bricks as the storage media. MgO has superior thermal conductivity and moderate values of density and cost when compared to other refractories. High strength is retained at elevated temperatures, spalling resistance is excellent, and large quantities of MgO brick are radily available. The refractory brick is contained in horizontally placed, insulated, cylindrical pressure vessels as is illustrated by the schematic on the right side of the figure. The helium flow is distributed and collected by a piping system to each vessel.

Phase Change Storage Concept



- Fusible fluoride salt bath
- Temperature swing 246°C
- Key thermophysical data
  - $T_{melt} = 635°C$
  - $\rho C_p = 0.672$ cal/cm^3-°C
  - $h_f = 143$ cal/gm
  - $k = 0.0103$ cal/sec-cm-°C
  - Cost = 0.97 \$/kgm
- Critical technical problems

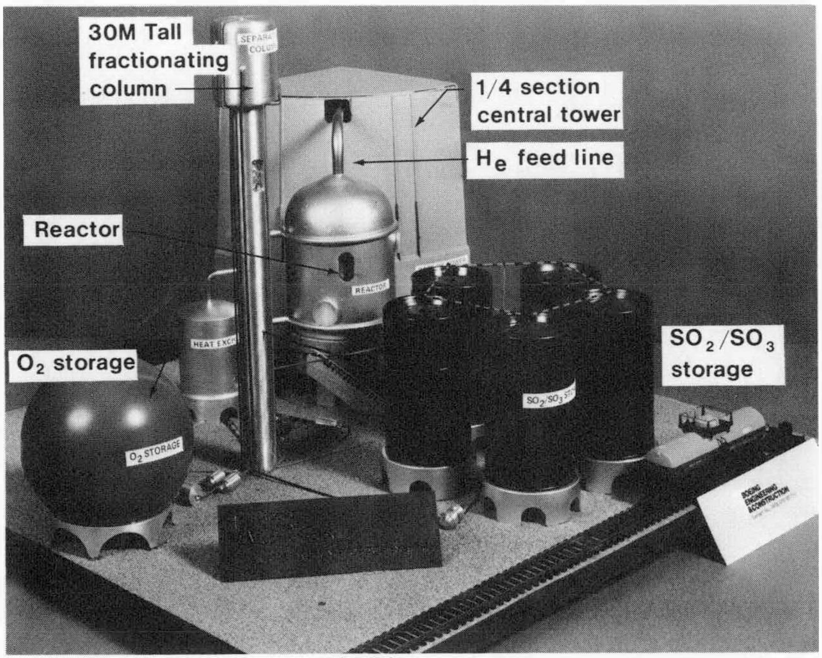
  material compatibility

Energy storage in the latent heat of fusion of molten salts is an attractive concept because of the very high energy storage density and the relatively low cost. A system designed to provide 6 hours storage has a system weight of approximately 4 million kilograms (8.8 million pounds) and a system cost of \$164/KW_e.

Fusible salts and eutectic mixtures of those salts with substantial heat of fusion were chosen for the melt temperature range of interest of 600°C (1110°F) to 900°C (1650°F). Fluoride salts operate in this range, have high heats of fusion, are abundant, inexpensive, and are chemically and thermally stable. The salt selected melts at 635°C (1175°F) with a heat of fusion of 143 calories/gram (257 BTUs/pound). The melt temperature was chosen to give the highest storage round-trip efficiency.

A schematic diagram of the design concept in the charging mode is shown on the left side of the figure. The vertical arrangement maintains the liquified salt above the solid salt. The helium flow path is reversed during discharge.

Thermochemical Storage Concept



Model

- **Reaction**

  $SO_3 + H_r \rightleftharpoons SO_2 + {}^1/_2\, O_2$
- **Helium temperature swing 221°C**
- **Key process data**
  - **Endothermic reaction**

    $P = 1$ ATM

    $\eta_{con} = 64\%$

    $H_r = 295$ cal/gm
  - **Exothermic reaction**

    $P = 10$ ATM

    $\eta_{con} = 90\%$

    $H_r = 295$ cal/gm
- **Critical technical problems**

  Dissociation reactor design

  Material compatibility

Thermal energy storage in reversible thermochemical reactions was also examined in detail because such systems offer the highest energy storage density of any of the concepts studied. The concept/reaction chosen resulted in a weight of 3.6 million kilograms (8 million pounds). Costs were higher than other concepts at $\$472/KW_e$. The technology, while considered long-term for the high temperature solar plant application, is based on well understood commercial chemical processes.

The Rocket Research Corporation of Redmond, Washington, carried out the investigation of thermochemical storage. The reaction is based on the reversibility of the dissociation of sulfur trioxide into sulfur dioxide and oxygen. The reaction involves absorption of 295 calories/gram (532 BTUs/pound) in dissociating sulfur trioxide in the charging process, and release of the same amount of heat when SO_2 and O_2 are recombined on storage discharge. A photograph of a thermochemical storage model is shown above with key elements identified by arrows. The fractionating column separates the dissociation or reaction products so that the undissociated or unreacted species can be returned to the reactor.

Storage/Plant Performance Summary (Yearly Average Data)

	Overall plant conversion efficiency %	Solar availability %	Excess insolation %	Storage round trip efficiency %	Storage utilization factor %
Sensible heat concept	16.9	63.4	8.5	72.1	89.8
Phase change concept	15.9	61.8	4.6	62.1	84.9
Thermochemical concept	15.5	60.5	3.4	52.7	81.4

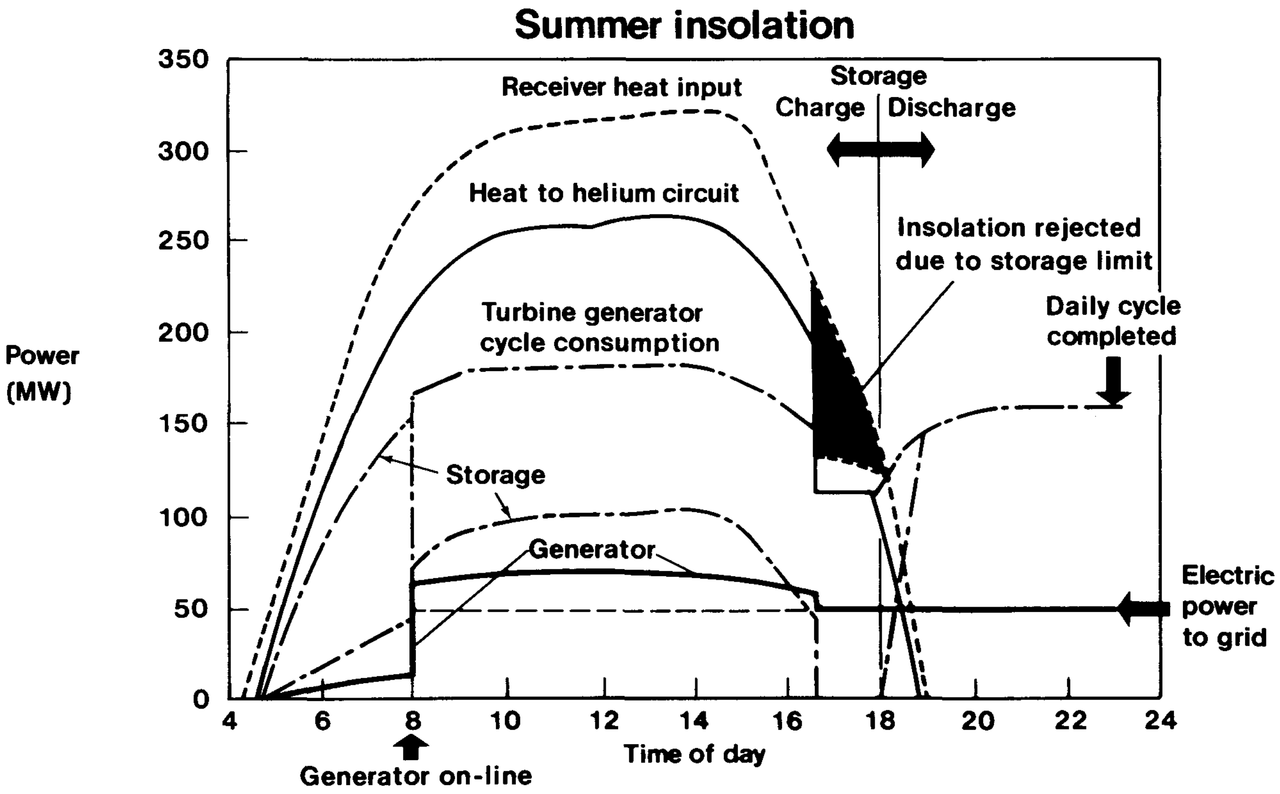
- **Inyokern, California**
- **Strawman field = 1.0 km^2**
- **Storage = 6 hours**
- **Plant capacity = 100 MWe (2 modules)**

An available plant operation program provides an evaluation of the performance on a daily basis. An accrual of such data over a year provide the yearly average performance data shown above for the three thermal energy storage (TES) concepts.

There is little variation between the three devices in plant operation hours or daily storage hours although this is a result of repressing the summer and spring performance due to excess insolation availability. The sensible heat storage subsystem has slightly higher plant efficiencies than the other two storage subsystems due to lower parasitic load requirements and a better round trip storage efficiency. The sensible heat storage device outperforms the phase change and thermochemical devices in all the categories listed in the table. However, the large delta cost of the sensible heat subsystem over that of the phase change subsystem makes the latter a preferred economic choice.

The balance between collector area and storage time is one of the most critical design decisions to be made for the solar power plant. Reducing the six hour storage limit to three hours for the same size collector field could give a storage utilization of 100%. Increasing storage to eight hours with the 1.0 km^2 field would reduce the excess insolation to zero. This trade is basically an economic system performance issue and an initial investigation of system sensitivities has been carried out.

Plant Operation and Integration-Daily Cycle (Power Distribution)



The study defined major plant subsystems; namely, the receiver, thermal engine cycle, and thermal energy storage. These subsystems were integrated into a solar plant to determine operational modes and performance. A math model was developed to support plant design and performance analysis work. The figure above shows typical results obtained for a solar plant operating over a representative summer daily cycle with a phase change storage device.

The upper curve shows the receiver heat input from the collector field. The solid curve below it is the amount of heat absorbed in the helium circuit. The first few hours insolation are used to charge storage. Heat used in the turbine-generator produces the power to run the storage mode. The generator furnishes 50 MW_e to the grid starting at 8 AM. Two plant modules thus furnish the required 100 MW_e. The plant runs uninterrupted until 1700 hours (5 PM) when the 6-hour storage limit is achieved. From this time until 1800 hours, the heat from the collector field is excessive and some heat must be rejected (Shaded region). At 1800 hours, the storage system discharges as the receiver output drops off until finally the plant is running only on storage heat. The daily cycle is completed at 2300 hours (11 PM), after the plant has operated for 15 hours on the grid.

Relative Cost of System Elements
100 MW_e Intermediate Plant

Plant type	Stand alone		Hybrid	
	Strawman	Helium	Strawman	Helium
Collector area (km^2)	1.0	0.84	0.5	0.42
Storage time (hour)	6	6	0.5	0.5
Account				
Land	2	2	1	1
Structures and facilities	44	44	51	51
Heliostats*	600	505	300	258
Central receiver/tower**/heat exchanger	95	197	68	98
Storage/tanks***	180	164	15	15
Boiler plant	–	–	73	73
Turbine plant equipment	80	119	80	105
Electric plant equipment	21	20	21	20
Misc plant equipment	4	4	4	4
Allowance for cooling towers	20	15	20	15
Total direct cost	1,046	1,070	633	640
Contingency allowance & Spare parts allowance (5%)	52	53	32	32
Indirect costs (10%)	105	107	63	64
Total capital investment (1975)	1,203	1,230	728	736
Interest during construction (15%)	180	185	109	110
Total cost at year of comm'l operation (1975 $)	1,383	1,415	837	846

* Collector cost–\$60/m^2

** Tower height–260M (2, and 1 tower(s), respectively)

*** Thermal storage cost–\$30/kWHe

EPRI design guidelines included cost accounts for intermediate stand-alone and hybrid plants based on a central receiver concept using a steam/Rankine cycle. These strawman plant accounts were furnished so side-by-side cost comparisons could be made with central receiver solar plant designs using alternative cycles. Relevant account items for closed cycle helium plants have been determined, and results are displayed above. Total costs for the two concepts are comparable for the stand-alone solar plants. The hybrid plant utilizing the helium cycle is about 11% more costly than the steam/Rankine cycle (strawman) hybrid plant.

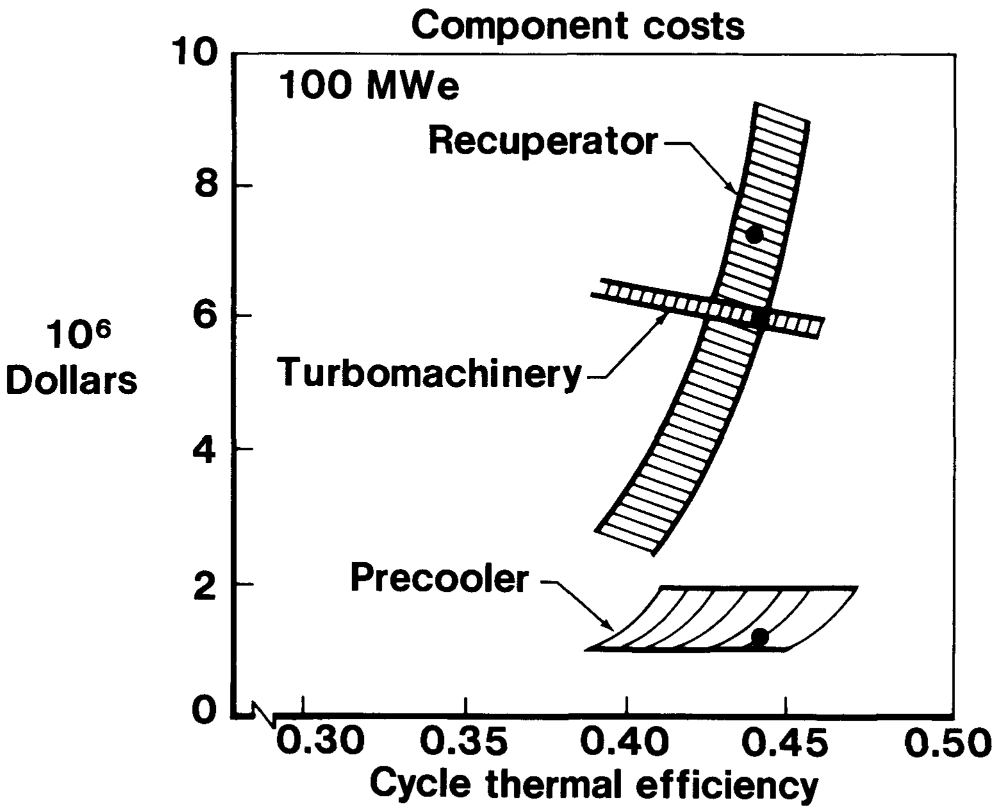
The strawman plants were used as a baseline for the cost comparison, i.e., the costs of the higher performance helium system were adjusted so the plants would have the same direct electrical power production. Major adjustments thus occurred in field size and cost. Other major differences are in the receiver, turbine equipment, and miscellaneous plant equipment accounts (cost of helium risers and downcomers between tower top and bottom). Total costs for these comparisons of intermediate plants turned out to be reasonably close and provide an encouraging basis for continued consideration of closed cycle gas plants.

Receiver Cost Estimate

Account	Cost (10^6 dollars)
Heat exchanger panel assemblies (210)	1.80
Insulation panel assemblies and insulation buy for heat exchanger panels	.40
Downcomers to tower top (2) and exit manifolds in receiver	1.24
Risers from tower top (2) to receiver and inlet manifolds in receiver	.51
Shields, insulation protection on supports and aperture lip	.35
Support structure and receiver top	2.00
Flow control valves	.04
Erection, fitting, and welding	1.50
Total	7.84

The baseline receiver cost is estimated at slightly over \$7.8 million for the 100 MW_e hybrid plant configuration. The figure above shows the cost breakdown. For the 100 MW_e stand-alone plant with 6 hours thermal storage, which requires two receivers, the total cost is \$15.7 million or \$157/kilowatt. These costs have been based on use of Inconel 617 for heat exchanger panel tubing and the adjacent helium distribution lines. The design practice employed avoids the use of the more expensive superalloys for the large diameter, longer flow runs.

Closed Cycle Cost Elements



The four major components of a closed cycle are the receiver, turbomachinery, recuperator, and precooler. The receiver costs have been discussed on the previous chart. The estimated costs of the turbomachinery, recuperator, and precooler for the 100 MW_e solar plant are shown on the figure above.

Precooler costs are relatively constant with overall cycle thermal efficiency. Dry cooling was prescribed for the study. Turbomachinery costs tend to decrease with increased efficiency, as less mass flow is required and the machines are smaller. The recuperator costs increase rapidly with increase of cycle thermal efficiency. This effect is not restricted to closed cycles, because recuperator cost curves for open cycle and steam Rankine cycles would parallel the trend shown. High cycle efficiencies are obtained with high turbine inlet temperature and high recuperator effectiveness. With turbine inlet temperature fixed, the burden is on recuperator effectiveness. Increase in recuperator effectiveness requires a disproportionate increase in recuperator size and cost. A 94% effectiveness was chosen for the recuperator to attain the 44% overall thermal cycle efficiency. The higher cost of the recuperator was more than compensated for in the reduced size of the turbomachinery, the receiver, and in the costs of the heliostat field.

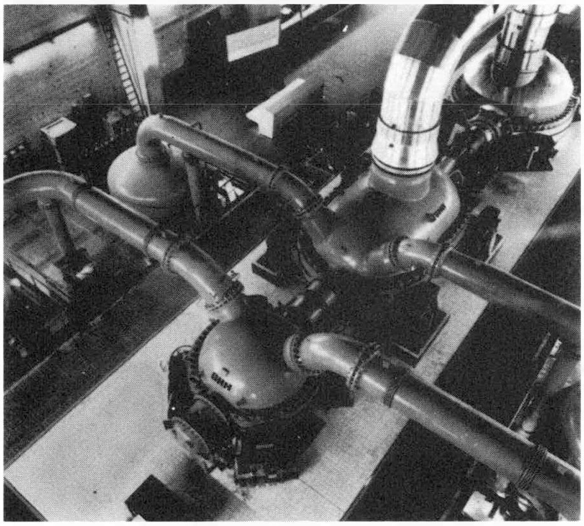
Qualitative Assessment of Alternate Systems

System	Advantages	Disadvantages
Closed cycle	High efficiency Operational flexibility Good bottoming-cycle potential	No operating experience in U.S. Large precooler High Brayton-cycle costs
Open cycle	No precooler required Similar to combustion turbine design System simplicity	Low efficiency Poor operational flexibility Large recuperator
Steam	Proven systems available Utility familiarity High heat flux receiver	Large precooler Moderate efficiency Complex system

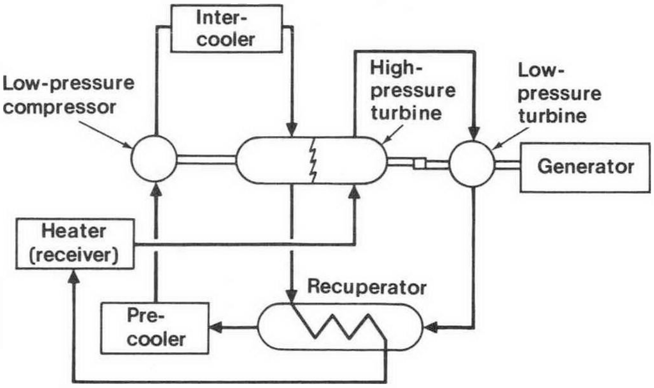
Cycle analysis was extended to making comparisons between closed helium, closed air and open air cycles. These cycles were examined for performance, cost, and qualitative considerations. A performance comparison based on efficiency gave the following results. The strawman steam cycle has maximum cycle efficiency of 0.36. The efficiency design range determined for helium is 0.428-0.447 followed closely by closed cycle air at 0.401-0.415. Open cycle air would be 0.352-0.362.

The table above lists some of the qualitative considerations for cycle selection. Closed cycle helium and air have been grouped together due to their inherent similarities. Closed cycles offer high efficiencies, and have the potential for operational flexibility and bottoming cycle usage. However, there is no operational experience in the United States (outside of very small units), as there is with open cycle and steam cycles in other commercial operations. The open cycle is a simple system requiring no precooler but its operational flexibility and efficiency are poor. Steam cycles are familiar to utilities and reliability is known for many applications. The solar plant usage of steam adds additional complexities in the high heat flux receiver design and in the control complexity to handle variable solar input.

Oberhausen II Powerplant-50 MWe Helium Turbine Installation



Helium turbine installation at Oberhausen, Germany



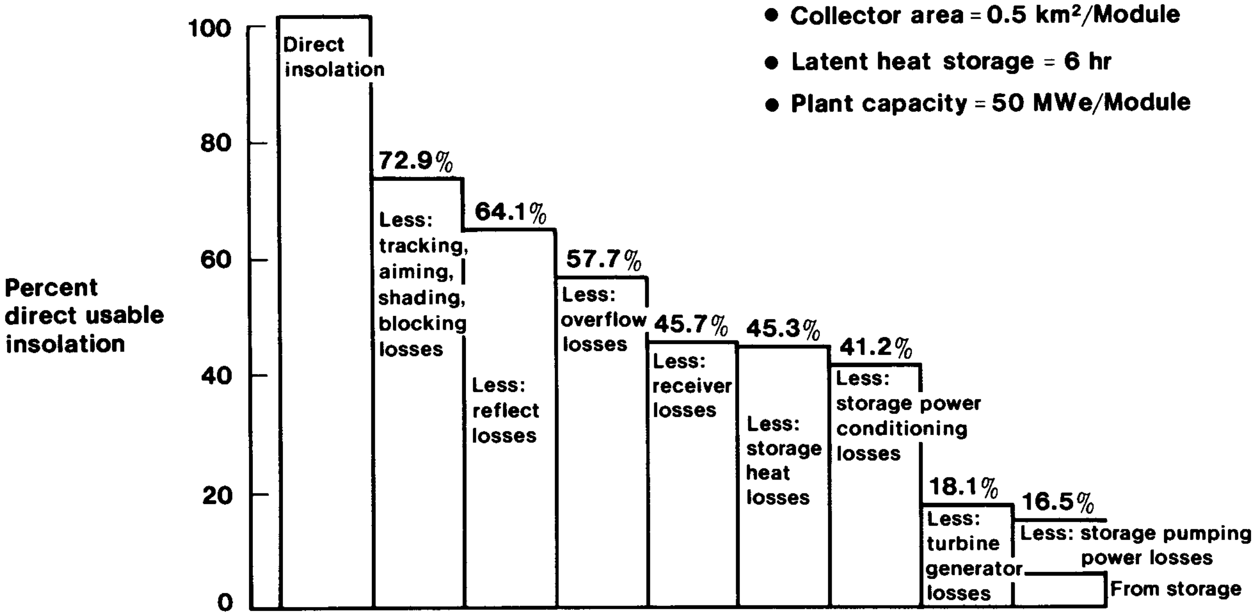
Helium-cycle schematic

The helium turbine installation shown photographically and schematically above is in a commercial power plant at Oberhausen, Germany. It is owned and operated by Energieversorgieng, Oberhausen A G (EVO). This electric utility has had a 14.3 MW_e closed cycle air system (Oberhausen I) in operation for over 100,000 hours and was encouraged by their experience with this unit to proceed with the helium turbine development. The closed cycle systems are attractive because the utility has a large district heating load as well as electric power requirements. The operational flexibility of the closed cycle system allows the electrical plant to load - follow at a high efficiency and still maintain a steady heat output. The West German government is also participating in the program since they consider the plant a prototype for larger power units for high temperature reactors with helium turbines.

The turbomachinery and associated heat exchangers were built by Gutehoffnungshutte Sterkrade (GHH) with design support from the Institute for Turbomachinery and Gas Dynamics of the University of Hanover. Gebruder Sulzer built the heater which is fired with coke gas. The system is currently in the checkout phase.

Daily Plant Performance Closed-Cycle Helium

- Summer insolation
- Inyokern, California
- Collector area = 0.5 km²/Module
- Latent heat storage = 6 hr
- Plant capacity = 50 MWe/Module



The selected receiver, the selected thermal cycle, and three thermal energy storage concepts were combined with the specified field to determine plant performance and operational characteristics. The results are typified by the bar chart above. The chart shows energy production over a summer day. A phase change thermal energy storage concept is represented here but results have been determined for sensible heat and thermochemical energy storage, for winter, fall, and spring days; and for yearly averages.

The chart shows the efficiency losses in going from the direct insolation through the plant subsystems to the generator output. The performance of a stand-alone solar plant over a summer day cycle shown by the chart is representative of the results obtained using each thermal energy storage concept. The integrated insolation from the "strawman" field for a summer day actually exceeds the requirements for direct energy production and 6 hours' storage by 17.8%. Overall plant efficiencies of 16.5% are typical for summer day performance. Efficiencies drop to 14-15% for winter operation with storage availability reduced to 3-4 hours.

1 MW_{th} Bench Model Receiver Program

- Simulate 300 MW_{th} commercial receiver
- Extend RP377-1 gas cooled receiver technology to working model
- Gain operational experience
    - Materials
    - Design concept
    - Heat transfer
    - Flow control
- Evaluate solar energy conversion efficiency

Phase 2–16 months

- Design/analyses
- Model fabrication
- Test planning
- Functional tests
- 10 MWe (equivalent) pilot plant development planning

Phase 3–8 months

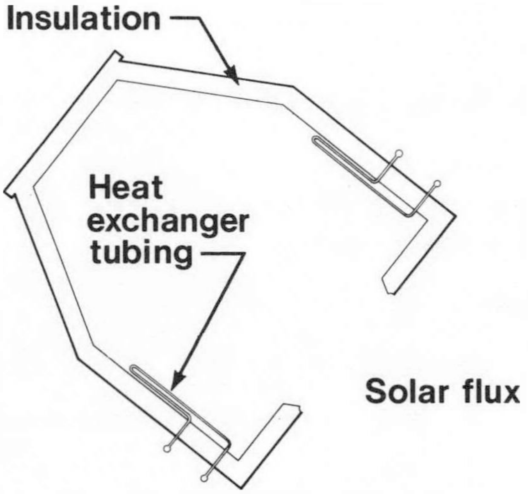
- Test assembly and checkout
- Test
- Data evaluation

Definition of the 100 MW_e receiver concept provides the performance, configuration guidelines, and materials to enter a model receiver program. A 1 MW_{th} model receiver would be designed and tested.

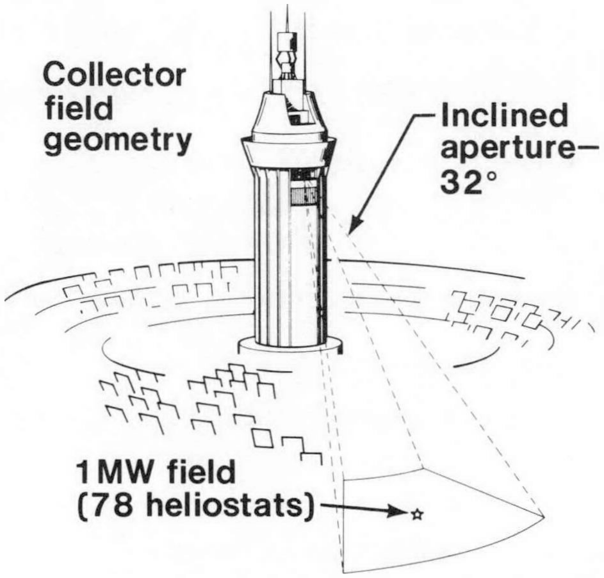
The purposes of scale model testing are to validate the technology for central receiver power plants using gas, to verify the design concepts proposed for commercial size plants, and to gain test experience with the selected high temperature materials. The 1 MW_{th} model receiver design will duplicate the operational characteristics of the 100 MW_e receiver. In particular, the model will exhibit all the energy transport functions of the commercial receiver; and utilize as many of the materials, manufacturing processes, and design details as possible. Technology derived from the program will be applicable to either open or closed cycle, and various working fluids, specifically including helium.

Two program phases are planned. The first phase of approximately 16 months would include design definition and development, test planning, fabrication, and functional testing. The second phase of about 8 months would be comprised of test setup, checkout, test conduct and data evaluation.

Bench Model Installation—
140 Ft Test Level



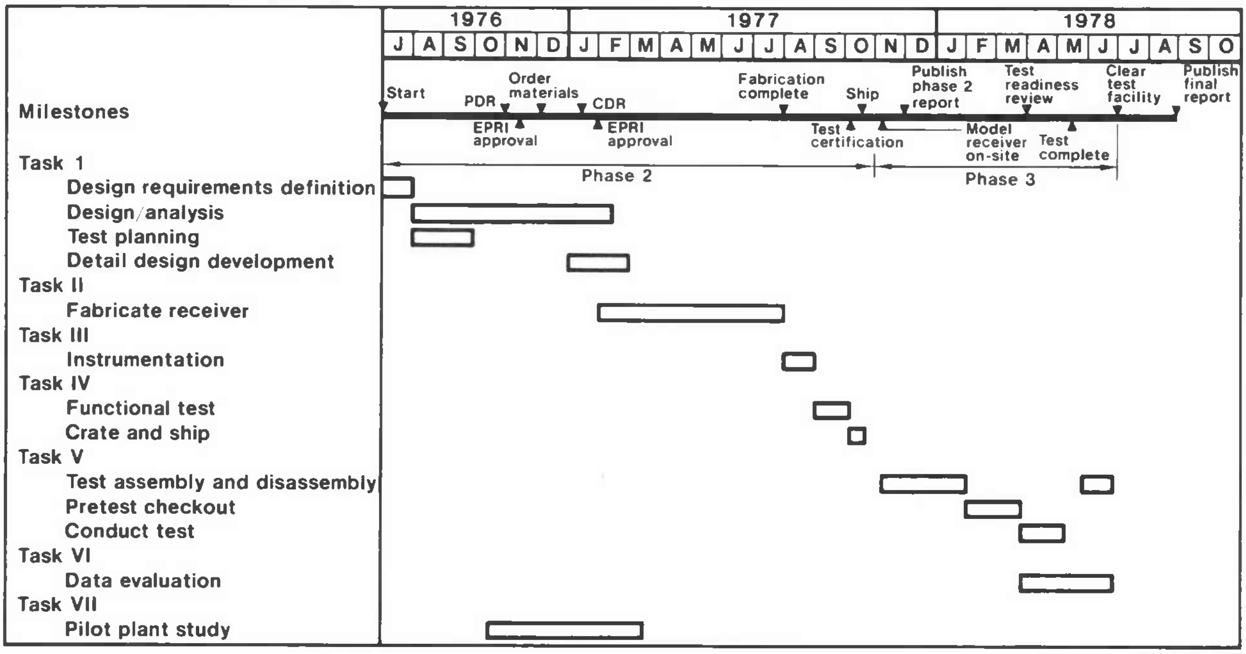
Bench model section view



Two views of the bench model receiver are shown as the receiver would be oriented to the solar flux from the 1 MW_{th} field at the ERDA Solar Test Facility at Albuquerque, New Mexico. The figure on the left shows the extremal rays from the field entering the model receiver to begin their reflections from the wall on to the heat exchanger panels. The receiver is designed on the interior and oriented to the field to prevent direct impingement of the flux on the heat exchanger panels.

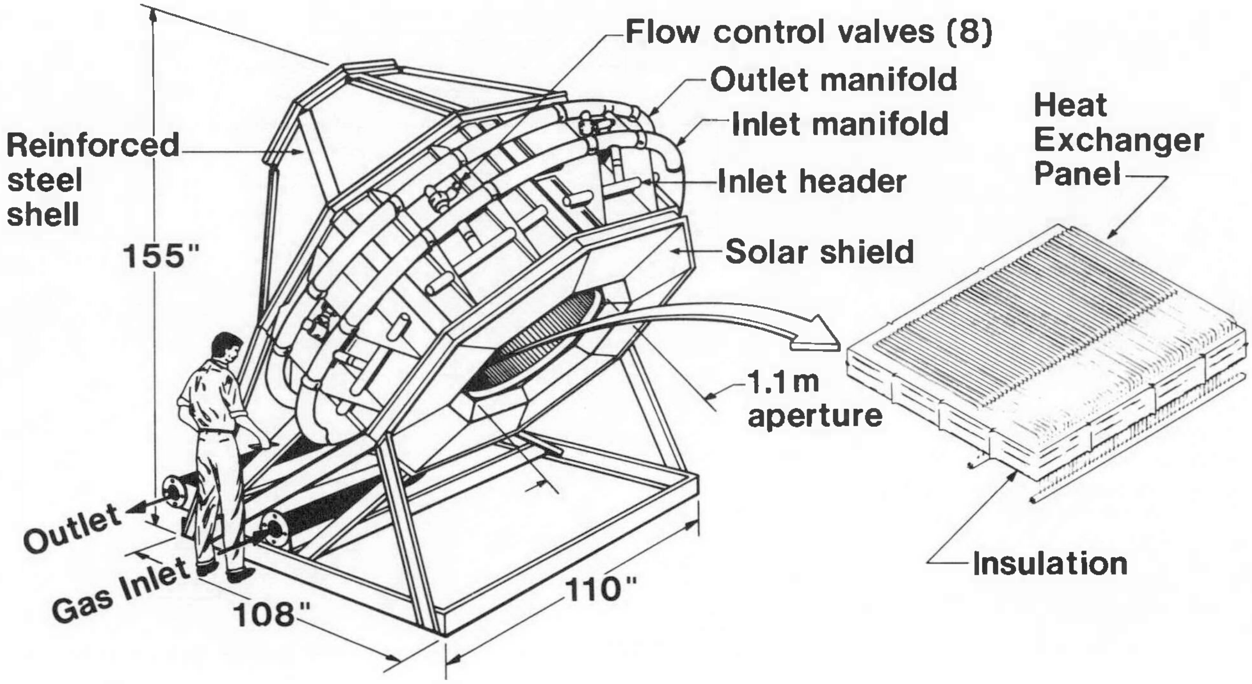
The figure on the right shows the installation at the 140 foot test level in the planned tower at the facility.

Program Schedule



The schedule shown above lists all the significant milestones on the 1 MW_{th} bench model receiver design and test program, and the tasks to accomplish the schedule. The program encompasses Phase 2 and Phase 3 of EPRI Contract RP377-2. Phase 2 includes the design, fabrication, and functional test of the bench model receiver and is to be completed by November 1, 1977. The schedule includes planning work for the 10 MW_e-rated closed cycle pilot plant. Phase 3 is an 8-month period to check out and test the model at the ERDA 5 MW_{th} Solar Test Facility at Albuquerque, New Mexico, and to evaluate the data.

1 MW_{th} Bench Model Configuration



The figure above shows the model receiver as configured for testing in the 5 MW_{th} ERDA Solar Thermal Test Facility. With minor modifications the receiver concept shown can be tested in the CNRS Solar Energy Laboratory at Odeillo, France. A third test option using electric heat is also retained in the event that solar test facilities cannot be available in the appropriate time frame. Test of the model receiver at the 5 MW_{th} ERDA facility would be scheduled for the second quarter, CY 1978.

The model receiver has an octagonal shape with eight independently controlled heat exchanger panels around the inner periphery. Each heat exchanger panel has 54 Inconel 617 tubes in a U-shaped configuration. Receiver walls are steel and lined with 0.15 meters (6 inches) of high temperature insulation as in the commercial receiver concept. Eight flow control valves, one in each heat exchanger panel. will regulate mass flow and gas temperature allowing evaluation of normal operating conditions as well as rapid start-up and shutdown, non-symmetrical input, scattered cloud cover, and emergency conditions.

SECTION 9

EPRI CONTRACT RP 475-1

OPEN CYCLE GAS TURBINE SOLAR ELECTRIC SYSTEM

CONCEPTUAL DESIGN OF HIGH TEMPERATURE RECEIVER AND TURBINE INTERFACES

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OCTOBER 1976

EPRI SOLAR REVIEW MEETING #2

ABSTRACT

The completed conceptual design of a solar/electric power plant intended for intermediate load range utility applications is reported in this paper. The conceptual design effort encompassed all principal aspects of the plant system, with particular attention directed toward the crucial heliostat field, high temperature solar receiver, and turbine/receiver interface elements.

The plant employs a conventional and commercially available open cycle, regenerative gas turbine as the prime mover. A high temperature ceramic heat exchanger is used to capture concentrated solar radiation and to heat air to the high temperatures (~982 C, ~1800 F) required for efficient turbine operation. The gas turbine generator unit and the solar receiver/heat exchanger are both located atop a tall, steel-reinforced concrete tower that is surrounded by an array of sun tracking reflecting surfaces (heliostats). The capital costs, in 1976 dollars, of the conceptually designed plant are estimated to be in the $1346 to $1659 per kilowatt range, depending upon the cost of heliostat subsystems. The estimated costs are lower than, and the efficiency of this system is superior to, that of a water-steam solar/electric system.

Because this solar/electric system uses an open cycle gas turbine, it is capable of hybrid operation. That is to say that the turbine can be powered by solar generated heat from the receiver/heat exchanger and/or by combustion heat from fossil fuels. This hybrid capability, unique to the open cycle gas turbine concept, enables the solar power plant to be a reliable source of electricity despite weather or time-of-day circumstances. Hybrid operation represents the only practical and economic approach to storage currently available and further, it makes utility demand capacity credit feasible for a solar/electric power plant.

This conceptual design demonstrates promise for a commercial size solar/electric plant. To pursue the maturation of this concept into a commercial demonstration plant, the next developmental step should be the design, fabrication, and test of a 1 MWt high temperature cavity heat exchanger. Following those successful tests, a 10 MWe (equivalent) open cycle, solar/electric pilot plant should be designed, constructed, and operated as a forerunner to the commercial demonstration plant.

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1. INTRODUCTION

STATEMENT OF PROJECT OBJECTIVES AND APPROACH

The central receiver, solar thermal conversion system has been chosen by the Electric Power Research Institute (EPRI) and by the Energy Research and Development Administration (ERDA) as that system possessing the greatest technical and economic potential for further development. ERDA is concentrating their initial efforts on the water-steam Rankine cycle. EPRI has chosen to develop the Brayton cycle for solar/electric applications because it precludes the problems of two-phase flow inherent in water-steam systems, because higher cycle efficiencies are possible, and because water requirements are much lower, particularly for the open Brayton cycle.

In July 1975, EPRI awarded a one year contract to Black & Veatch to develop a conceptual design of a central receiver, solar/electric system which utilizes an open cycle gas turbine as the prime mover. The two primary objectives of the project were to

- Prepare a conceptual design for a high temperature cavity receiver/heat exchanger suitable for commercial applications (50 to 100 MWe) and capable of delivering compressed air at approximately 0.931 MPa (135 psia) and 982 to 1093 C (1800 to 2000 F).
- Utilize existing turbomachinery to the maximum extent possible and identify practical means and necessary interfaces for hybrid operation from either the solar receiver or a fossil fuel combustor.

Other important objectives were to verify the performance of promising heat exchanger materials and design concepts by means of small scale laboratory tests; to design the heliostat field and receiver cavity geometry for the most efficient operation of the open Brayton cycle; and to develop costs for the overall system design.

2. OVERVIEW

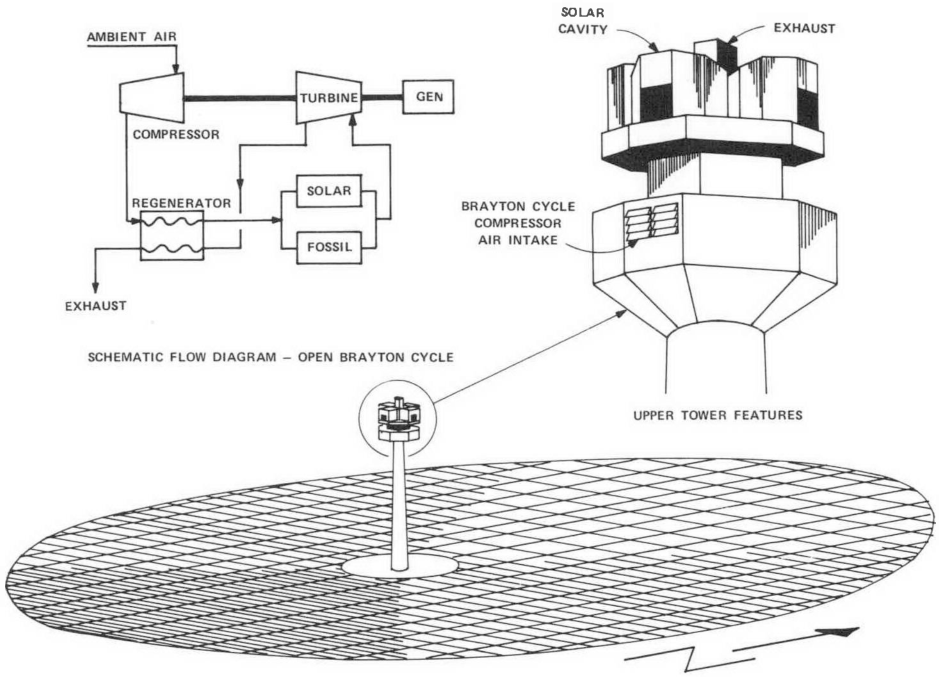

FIGURE 1 PERSPECTIVE VIEW OF THE OPEN CYCLE SOLAR THERMAL CENTRAL RECEIVER SYSTEM

DESCRIPTION OF THE OPEN CYCLE, SOLAR THERMAL CENTRAL RECEIVER SYSTEM

The central receiver system consists of a large field of individual mirrors (heliostats) which continuously track the sun in order to redirect and concentrate the sun's rays into a central receiver mounted atop a tower. Within the receiver, the concentrated solar thermal energy heats the working fluid (compressed air) which is then used to drive a turbine-generator. An artist's perspective view, shown in Figure 1, illustrates the general arrangement.

The inset at upper left is a schematic flow diagram of the regenerative, open Brayton cycle. Ambient air is compressed by about a factor of nine and directed to a regenerator where it is further heated to about 482 C (900 F) by the turbine exhaust gases. From this point the air may enter either a standard fossil fuel combustor or the solar receiver heat source where it is heated to a turbine inlet temperature of 982 to 1066 C (1800 to 1950 F). Finally, the heated air is permitted to expand through the turbine and is exhausted through the regenerator.

To minimize the air flow path lengths among compressor, heat source, and turbine, the turbine-generator set is mounted just below the central receiver cavities (one for each field quadrant) as shown in the right hand inset.

The heliostat field design is based on a non-uniform density of heliostats (ground cover) in each of four field quadrants. The most closely packed heliostats are near the base of the tower in each quadrant; the south quadrant has the highest average ground cover. The north quadrant is larger because of the larger effective mirror aperture (cosine factor) for this part of the field for a northern hemisphere plant location.

APPROACHES TO THE DESIGN OF MAJOR SUBSYSTEMS

The major subsystems that comprise the Open Cycle Gas Turbine Solar/Electric System are highly interdependent. Therefore, each subsystem was designed by considering the constraints and requirements imposed by the other subsystems before selecting the best design from among the available options.

The major requirements and problems which were addressed are summarized here. The trade-offs, analyses, and final conceptual designs are described later in the report.

Heliostat Field/Receiver Configuration

The heliostat field/receiver configuration can be thought of as a degenerate parabolic dish spread flat upon the ground, and made up of individual facets (heliostats). The focal point of this dish is the receiver at the tower top. The field/receiver configuration is therefore a coupled design problem. Both 360° fields and sector fields were analyzed, as well as uniform and non-uniform heliostat ground covers (spacings). Both single and multiple aperture receivers were considered as well as multiple receivers. The criteria for choosing the final design included high performance, flexibility, reliability, and low cost.

Electric Power Generation

The selection of the gas turbine for the electric power generation subsystem establishes several system design requirements. The heat rate (or cycle efficiency) of the turbine establishes the amount of solar thermal energy required from the receiver and, hence, the size of the heliostat field/receiver subsystem. The inlet temperature of the turbine specifies the required heat exchanger outlet air temperature, and the turbine compression ratio influences the stresses in the heat exchanger tubing and in the interface ducting network. A requirement for turbine selection was that existing hardware be utilized to the fullest extent possible in order to avoid lengthy and costly turbine development programs. Finally, the turbine selected must be capable of hybrid operation in either the solar or fossil fuel modes.

Storage

Storage in the Open Cycle Gas Turbine Solar/Electric System is provided by operating the turbine from conventional fossil fuels (fuel oil or gas) during periods of solar outage. Hybrid operation of the turbine represents one of the principal advantages of the open cycle system. Both short and long term storage can be provided in this way. The design requirement is to interface the selected turbine with both solar and fossil heat sources so that rapid transition between heat sources, or simultaneous operation with solar and fossil energy, can occur.

Receiver Cavity Heat Exchanger

Design of the receiver cavity/heat exchanger was the single most important problem addressed in this project. An acceptable design must meet the following requirements.

- Production of outlet air temperature in the range of 982 to 1066 C (1800 to 2000 F).
- Minimum pressure drop between compressor and turbine.
- Materials selection to withstand internal gas pressure of ~931 kPa (~135 psia) and thermal stresses of 34.5 to 68.9 MPa (5,000 to 10,000 psi) at the working temperatures (1204 C, 2200 F).
- Configuration to minimize losses by reradiation, reflection, and convection.

Because of the importance of this subsystem to the success of the overall open cycle conversion system, laboratory tests of candidate materials and model heat exchanger designs were carried out to support the final conceptual design choice.

Receiver Tower

Although the structures for supporting the receiver and electric power generation subsystems were not identified as a major subsystem (nor included in the receiver/heat exchanger subsystem), that design is crucial to the successful operation of the system. The tower must be capable of supporting the combined weights of the equipment located atop it when subjected to both wind and seismic loading. Sway must be minimized to prevent excessive loss of redirected sunlight at the receiver.

The system conceptual design was directed toward a commercial size utility system (50 to 100 MWe) under the assumption that if the feasibility of a system this size could be demonstrated, then further development of small scale pilot or bench model systems and subsystems would be justified.

Nominal Plant Capacity	60MWe
Nominal Turbine Heat Rate	9300 Btu/kWh
Heliostat Field/Receiver Configuration	
Total land area	643,000 m^2 (6.9 x 10^6 ft^2)
Field shape	Oval
Number of heliostats	6990
Average ground cover	0.42
Total heliostat area	260,000 m^2 (2.8 x 10^6 ft^2)
Heliostat area (each)	37.17 m^2 (400 ft^2) – circular
Receiver configuration	4, octagonal, cylindrical cavities
Receiver tower height	213.4 m (700 ft)
Receiver Cavity Heat Exchanger	
Type	Multiple U-tube
U-tube length/diameter	12.1 m/10.2 cm (40 ft / 4 in)
Number of U-tubes (4 cavities)	280
U-tube material	Silicon carbide
Air inlet conditions, nominal	931 kPa, 482 C (135 psia, 900 F)
Air outlet conditions, nominal	896 kPa, 1038 C (130 psia, 1900 F)
Energy Storage	
System type	Hybrid – solar and combustion
Storage medium	Fossil fuel
Receiver Tower	
Tower structure	Steel reinforced concrete
Turbine/Receiver platform	Structural steel space frame

FIGURE 2 BASELINE CONCEPTUAL DESIGN SUMMARY

DESCRIPTION OF BASELINE CONCEPTUAL DESIGN

The principal result of this project was the specification of a commercial size, baseline conceptual design of the open cycle central receiver system. As in the case of conventional power plants, the design was built around a commercially available gas turbine, and sized by EPRI direction to meet utility, intermediate load requirements.

At the outset, it was decided to utilize the regenerative Brayton cycle to obtain the highest thermal cycle efficiency, thereby minimizing the number of heliostats required for a given plant capacity rating. Gas turbines which will be commercially available in the mid 1980's were considered in the selection process. The largest available regenerative, open cycle turbine is the General Electric MS 7001R nominally rated at 60 MWe. This turbine was selected for the baseline design. Establishing the turbine rated capacity and guaranteed heat rate permits the sizes of the heliostat field, tower height, and receiver cavities to be determined.

A summary of the baseline conceptual design is given in Figure 2.

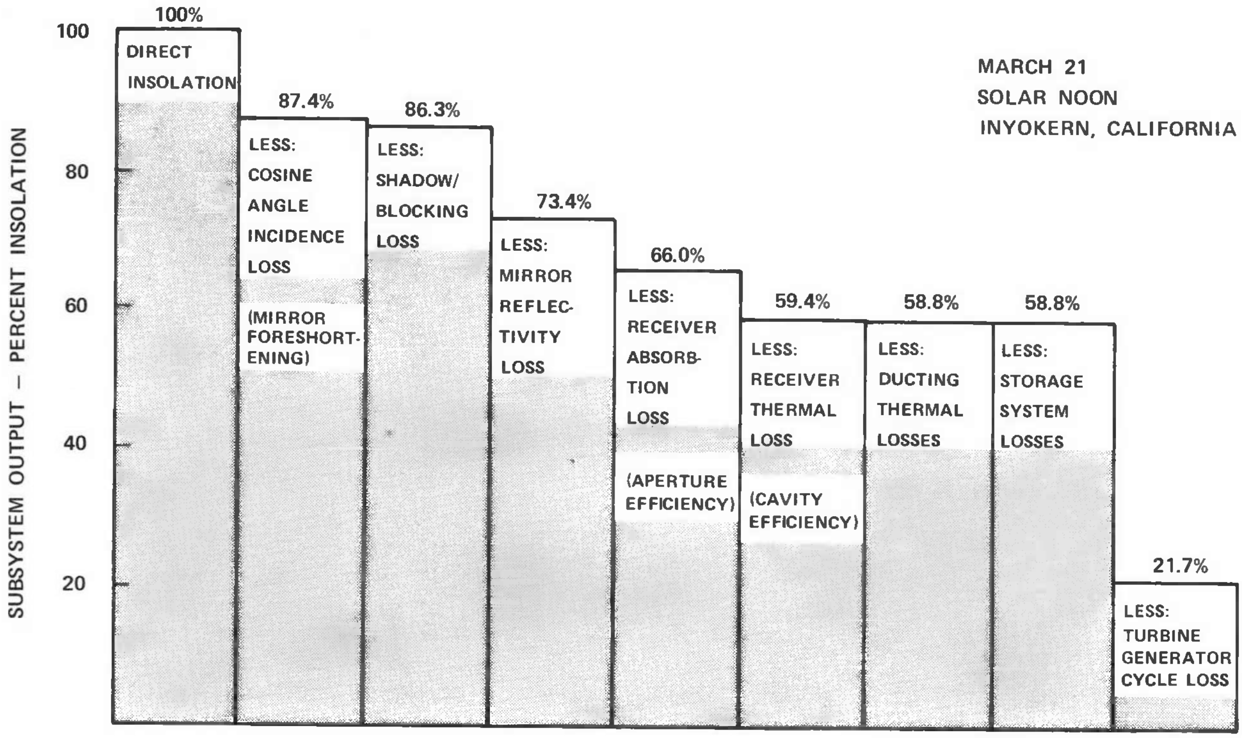

FIGURE 3 SOLAR THERMAL, HYBRID OPEN CYCLE GAS TURBINE SYSTEM PERFORMANCE

PERFORMANCE OF BASELINE SYSTEM

Diligent system design utilizing commercially available turbomachinery permits the achievement of a 21.7 per cent overall efficiency for the complete energy conversion process. This value is approximately 20 per cent higher than comparable water-steam central receiver system efficiencies.

Categorization of Loss Mechanisms

The efficiency performance of this hybrid system, subdivided into pertinent loss mechanisms for the major subsystems, is shown in Figure 3. Heliostat field performance is impaired by three factors: (1) mirror surface foreshortening, (2) heliostat shadowing and blocking, (3) mirror reflectivity losses. Aperture efficiency and cavity efficiency collectively describe the central receiver's capability to capture redirected solar energy and to subsequently affect a heat exchange process with the working fluid of the gas turbine. There are minor system performance losses due to thermal and pressure losses in the interfacing network that links the central receiver to the turbine. No losses are encountered in the energy storage subsystem because the hybrid nature of the solar thermal open cycle concept permits the turbine to operate at the same level of effectiveness regardless of whether the heat source is solar energy or fossil fuel.

The solar related subsystems convert 58.8 per cent of the incoming solar energy into usable thermal energy. The General Electric MS 7001R regenerative gas turbine, with a quoted thermal efficiency of 37 per cent, is coupled with the solar subsystems to give an overall system efficiency of 21.7 per cent.

Collector/Concentrator Subsystem		
Land and fencing	210,000	
Heliostats at $100/M^2	25,989,000	
		26,199,000
Heat Transfer Subsystem		
Heat exchangers	5,626,000	
Receiver cavities	2,865,000	
Balance	1,380,000	
		9,871,000
Electric Power Generation Subsystem		
Turbine-Generator	10,200,000	
Electrical equipment	1,600,000	
Fuel storage equipment	240,000	
Balance	2,500,000	
		14,540,000
Receiver Support Tower		
Tower and mat	5,900,000	
Cavity and turbine pedestals	2,100,000	
Balance	1,275,000	
		9,275,000
Balance of Plant		2,600,000
Total Direct Cost		62,485,000
Contingency and Spare Parts (5%)		3,125,000
Indirect Cost (10%)		6,250,000
Total Capital Investment (1976)		71,860,000
Interest During Construction (15%)		10,779,000
Total Cost at Commercial Operation		$ 82,639,000
Cost per Peak Kilowatt		$ 1,502

FIGURE 4 **60 MWe OPEN CYCLE GAS TURBINE SOLAR/ELECTRIC SYSTEM – ESTIMATED COST SUMMARY (1976 Dollars)**

SUMMARY OF CAPITAL COSTS

The projected cost, in 1976 dollars, of the open cycle solar/electric system ranges from \$1346/kW to \$1659/kW, depending upon the cost of the heliostat field system. The total estimated cost at commercial operation of a nominally 60 MWe plant is \$82,639,000, assuming a median heliostat subsystem cost of \$100/M^2. The cost per kilowatt figures were developed using the 55 MWe capacity expected from a General Electric MS 7001R at the Inyokern, California plant site.

Origin of Cost Estimates

The costs displayed in Figure 4 were generated by breaking the various subsystems into their principal components. Costs were subsequently gathered from the appropriate manufacturers and integrated with the power plant cost estimating experience of Black & Veatch. The total projected cost includes allowances for estimated interest during construction and for construction contingencies. Allowances for the development efforts where required are not included. Additional information supporting this cost summary may be found in the detailed technical report.

While the costs of many system elements can be identified rather clearly, the immature nature of some technologies precludes the projection of related costs with certainty. A notable area of concern is the heliostat field. To allow for heliostat cost uncertainty and due to the significant impact of this cost element on the total system cost, a \$75/M^2 to \$125/M^2 range of heliostat subsystem costs was utilized to calculate the costs per kilowatt quoted above. This range of heliostat costs is anticipated to bracket the commercial application price of heliostat systems, based upon the present expectations of various ERDA development programs.

3. HELIOSTAT FIELD/RECEIVER CONFIGURATION DESIGN

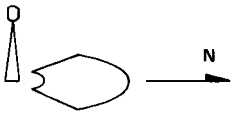

FIGURE 5a NORTH FIELD CONCEPT

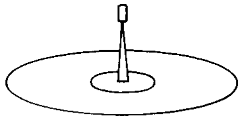

FIGURE 5b 360° FIELD CONCEPT

FIELD	TOWER HEIGHT	MIRROR AREA
NORTH CONCEPT	396 M (1300 FT)	219,000 M^2 (2,356,000 FT^2)
360° CONCEPT	213 M (700 FT)	268,000 M^2 (2,883,000 FT^2)

FIGURE 5c SYSTEM CHARACTERISTICS

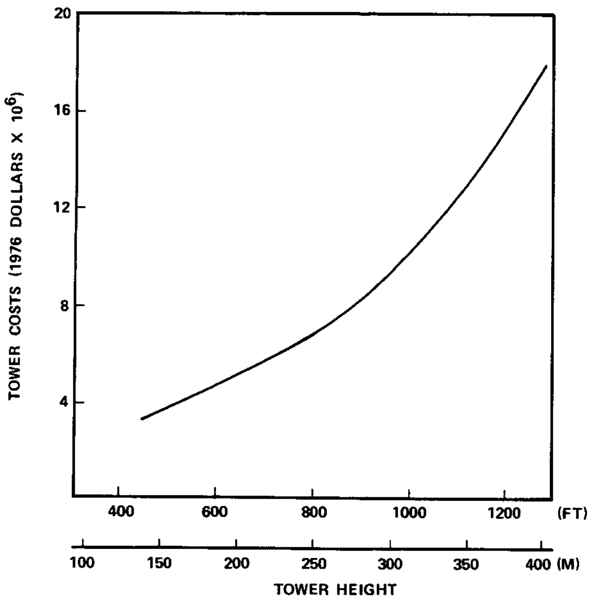

FIGURE 5d SUPPORT TOWER COSTS

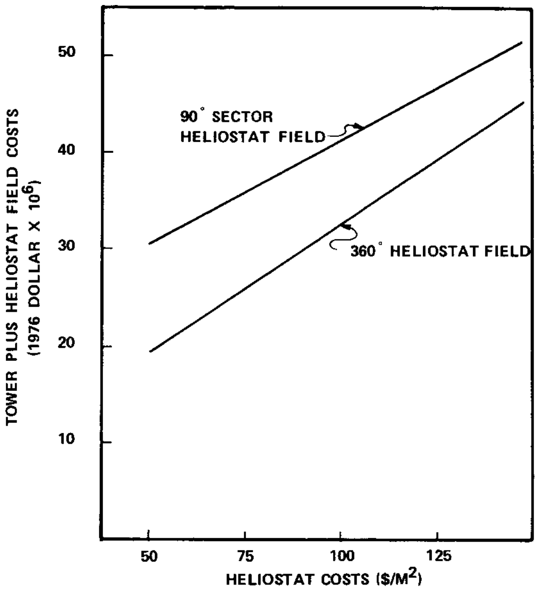

FIGURE 5e COST CHARACTERISTICS OF HELIOSTAT FIELD-TOWER ALTERNATIVES

CHOICE OF HELIOSTAT FIELD CONFIGURATION

A 360° heliostat field was chosen because it resulted in lower total heliostat-tower costs, lower tower height, and higher receiver efficiency.

Characteristics of Alternative Field Geometries

Figure 5a illustrates the north field heliostat geometry concept. A pie-segment field of mirrors to the north of the tower redirects sunlight into a receiver atop the tower. In the northern hemisphere, heliostats in this field are more efficient than those located in other sectors. The sun's rays strike the mirror surfaces at more nearly normal incidence, thus leading to a larger effective mirror aperture area per heliostat (the so-called cosine effect). Accordingly, fewer heliostats are required to meet the power specification. On the other hand, placing all the heliostats north of the receiver tower results in a large field radius. Consequently, slant ranges from the northernmost heliostats are large and a tall tower is required to reduce blocking of sunlight from these heliostats.

The 360° field concept is shown on Figure 5b. Completely encircling the tower with heliostats reduces the heliostat field radius, heliostat slant ranges, and the required tower height. However, additional mirror area is necessary because of a less favorable cosine effect associated with the southern heliostats.

Implications for Receiver Design

Efficient collection and conversion of redirected sunlight to high temperature thermal energy within the receiver requires that the receiver aperture be large enough to collect a high percentage of the redirected solar flux (aperture efficiency) yet small enough to prevent excessive reradiation and reflection losses (cavity efficiency). Because reflected sun image sizes increase with the slant range, short slant ranges are preferred in order to maximize the product of aperture and cavity efficiencies. Shorter towers are preferred because erection and maintenance of the receiver and turbomachinery at the top is facilitated.

Evaluation of Alternatives

The heliostat area and tower heights required for the two field geometry alternatives are shown on Figure 5c. Figure 5d demonstrates the relationship of support tower cost to tower height. The cost effective design identified by Figure 5e, reinforced by receiver considerations, is the 360° field concept.

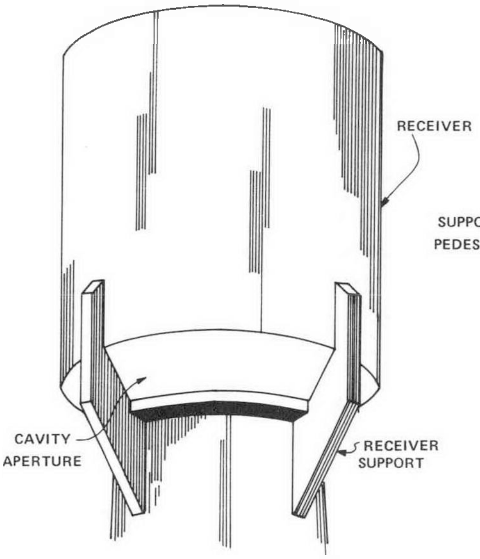

FIGURE 6a ANNULUS APERTURE RECEIVER CONFIGURATION

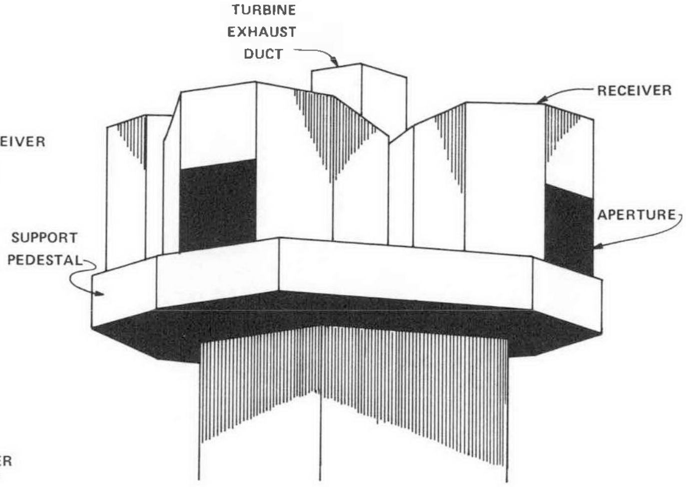

FIGURE 6b MULTIPLE APERTURE RECEIVER CONFIGURATION

CHOICE OF RECEIVER CONFIGURATION

Four independent cavities, each facing a 90° sector of the 360° heliostat field, were chosen to constitute the central receiver because turbine/receiver interface ducting was simplified while overall efficiency and system operational flexibility were enhanced.

Description of Receiver Options

The annulus receiver configuration, illustrated on Figure 6a, consists of an open-bottom, cylindrical enclosure that circumferentially admits redirected sunlight via the tower-receiver annular separation space between the three receiver supports. The multiple cavity alternative, shown on Figure 6b, consists of four independent cavities. Each cavity accepts solar energy from a 90° sector of the heliostat field via a vertical aperture.

Advantages of Multiple Cavities

Large volumes of hot, compressed air must flow between the receiver and turbine, and turbine exhaust gases need to be vented to the atmosphere. Large ducts are required to transport these gases in order to maintain turbine cycle efficiency. It is not possible to route these large ducts through the annular separation zone without unacceptably compromising receiver performance because of aperture size and cavity loss considerations. Alternatively, the four-cavity concept permits routing the ducts between and behind the cavities without obstructing the apertures.

The multiple cavity concept offers the additional advantage of simplifying receiver structural support design since the cavity floor and walls are directly accessible. Further, system reliability and flexibility are enhanced because individual cavities can be isolated in the event of component failure, and they can be selectively operated in response to time-varying insolation conditions.

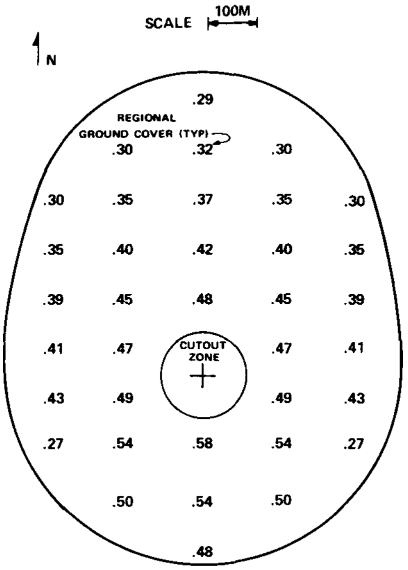

FIGURE 7a PLAN VIEW OF BASELINE DESIGN HELIOSTAT FIELD

FIELD	
NUMBER OF HELIOSTATS	6990
HELIOSTAT AREA	260,000 M^2
LAND AREA (INCLUDING CUTOUT)	643,000 M^2
GROUND COVER	
MAXIMUM	0.58
MINIMUM	0.27
AVERAGE	0.42
REDIRECTED POWER– NOON, MARCH 21	187 MW_t
HELIOSTAT	
HELIOSTAT SIZE	37.17 M^2
SHAPE	CIRCULAR
MIRROR REFLECTIVITY	0.85
FOCUSING: FOCAL LENGTH EQUAL TO SLANT RANGE	

FIGURE 7b FIELD CHARACTERISTICS

DESCRIPTION OF HELIOSTAT FIELD LAYOUT

An oval field, with the tower south of center and a non-uniform heliostat ground cover, was chosen as the baseline heliostat field geometry. The field boundary and ground cover at all points within the field were selected to reduce the number of heliostats and the land area required to meet the plant thermal power requirements.

Sensitivities in Heliostat Field Design

The density of heliostat ground coverage and the position of the receiver tower relative to the field boundaries is influenced by slant range-receiver aperture considerations, cosine effects, and the shadowing/blocking of heliostats by near neighbors.

Parametric evaluation of these various effects by means of an optical, ray-trace computer code established a proper heliostat ground cover ratio as a function of distance and direction from the tower. The proper ground cover was that which provided the best trade-off among the previously listed effects. The boundary of the field was established by minimizing the number of heliostats required to meet the desired power level into the four cavity receivers (187 MWt). The baseline field design layout, shown on Figure 7a, is comprised of circular, focusing heliostats with each one's focal length equaling its slant range.

The pertinent characteristics of the heliostat field are tabulated on Figure 7b. An overview of the field is provided on Figure 1.

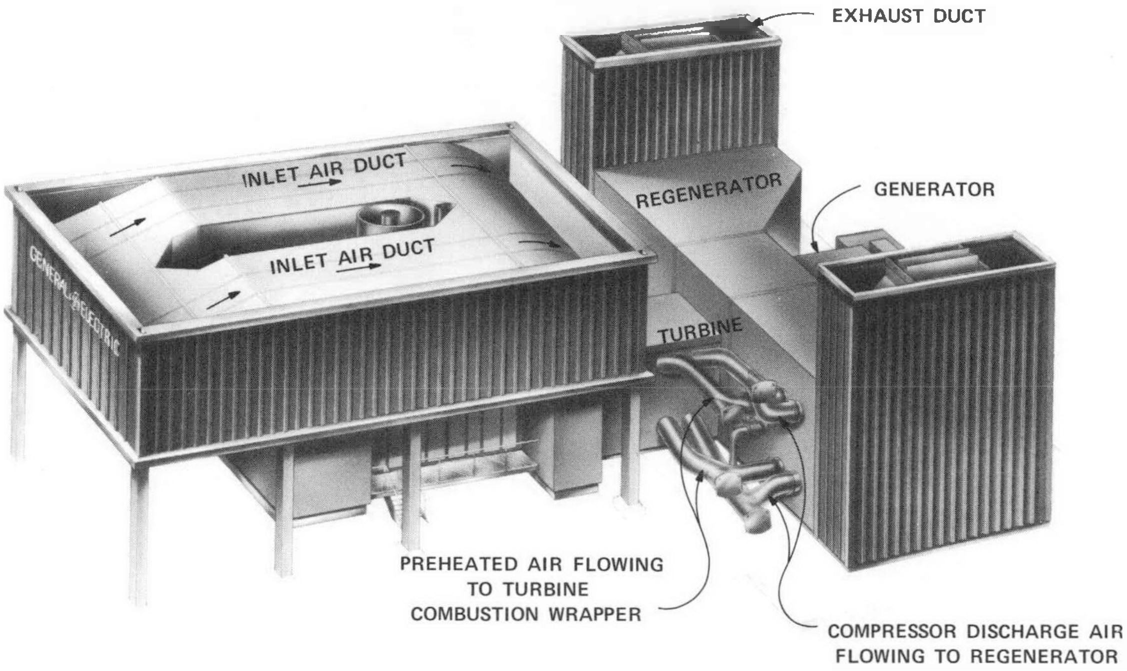

FIGURE 8 **THE BASELINE CONCEPTUAL DESIGN TURBINE — GENERAL ELECTRIC MS 7001R**

SELECTION OF GAS TURBINE

The General Electric MS 7001R gas turbine, nominally rated at 60 MWe, was selected for the conceptual baseline design because it is the largest regenerative gas turbine expected to be commercially available in the mid 1980's.

Assessment of Turbine Characteristics

Solar thermal power plant designs are built around the requirements of the system prime mover, just as in conventional plant design. Specifying a gas turbine permits central receiver mass flow rate, inlet pressure, outlet temperature, and other design objectives to be established with confidence of turbine compatibility.

The uncertain nature of the future solar market discourages manufacturers from undertaking costly turbine development programs and argues forcefully for using existing, proven machines. Moreover, the practicality, complexity, and cost of required modifications to these existing turbines must be considered in the selection process. High turbine thermal cycle efficiency is clearly desirable because it reduces the heat input requirements, and thus the number of heliostats, of the system. A regenerative Brayton cycle machine utilizing waste exhaust gas heat improves simple cycle efficiency without undue complexity and without increasing plant water requirements.

Dialogues with major turbine manufacturers were established to ascertain their plans with respect to commercial offerings in the 1980's. Turbine configurations were evaluated to determine the adaptive modifications required to permit turbine/receiver interfaces. The General Electric MS 7001R was the superior machine, based upon these considerations and a criterion of near-term, utility-type commercial operation. The standard configuration of this gas turbine package power plant is shown on Figure 8.

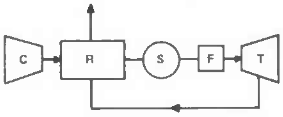

FIGURE 9a SERIES PATH HEAT SOURCE CONCEPT

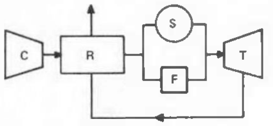

FIGURE 9b PARALLEL PATH HEAT SOURCE CONCEPT

LEGEND:
C - COMPRESSOR
R - REGENERATOR
S - SOLAR HEAT EXCHANGER
F - FOSSIL FUEL COMBUSTER
T - TURBINE

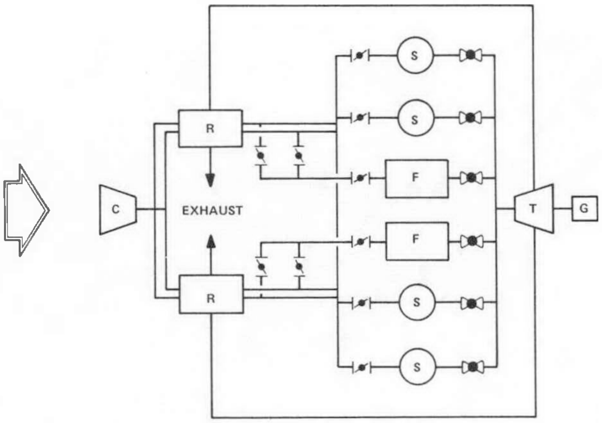

FIGURE 9c RECOMMENDED SYSTEM FLOW DIAGRAM

DESIGN FOR HYBRID OPERATION

A concept was developed that allows hybrid turbine operation from either solar energy or fossil fuel, or a combination of both, so that power generation is not subject to fluctuation due to the intermittent and variable nature of available sunlight.

Advantages of Hybrid Design

Two types of energy storage are pertinent for solar conversion systems. Buffer storage provides power to the turbine subsystem during transient or short-term solar outages such as passing clouds. Long-term storage is needed during extended solar outages. Conventional gas turbine operation with fuel combustion provides a feasible means by which both storage requirements are satisfied. Therefore, hybrid operation represents a principal advantage of this plant because it provides the power system with a high level of availability and a dependable generating capability. Hybrid operation permits the turbine to operate continuously, despite transient or long-term solar outages, thereby guaranteeing plant capacity credit and enabling the plant to respond to evening peak power demand.

Possible fossil fuel combustor arrangement, shown on Figures 9a and 9b, include either a series or a parallel path with the solar cavities. The parallel path arrangement has distinct advantages.

- Lower working fluid pressure drop enhances cycle thermal efficiency.
- No combustion products pass through the solar cavity.
- Controllable combustor air flow facilitates pilot flame ignition and stabilization just prior to fuel use.
- Cool air is readily available for fossil fuel combustor cooling.
- Heat source air flow can be modulated to maximize solar energy utilization while maintaining a constant turbine inlet temperature.

An external combustor location is required to implement the parallel path heat source arrangement. The external combustors would replace the existing internal combustors in the combustion wrapper of the GE MS 7001R. Preliminary discussions with General Electric technical personnel indicate that such a modification is feasible. The superior, parallel path-external combustor arrangement shown on Figure 9c, was incorporated in the four solar receiver system design.

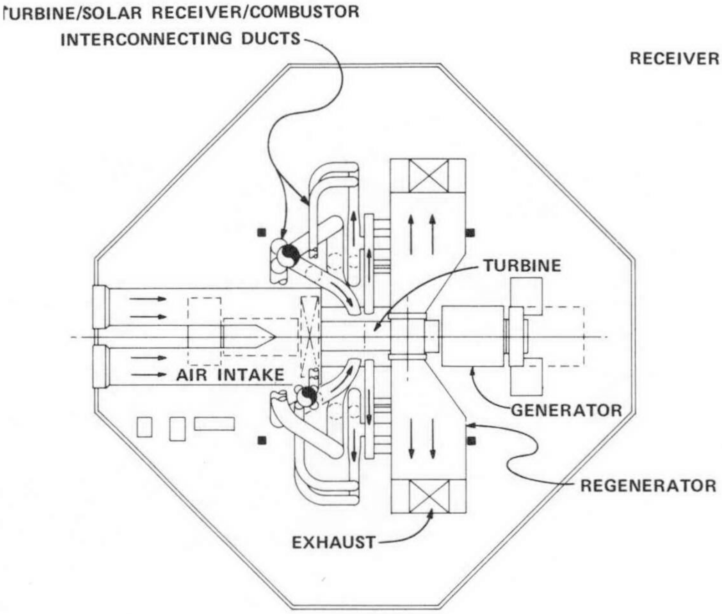

FIGURE 10a PLAN VIEW OF TURBINE PLATFORM HYBRID, SOLAR/ELECTRIC GAS TURBINE SYSTEM WITH INTERFACES

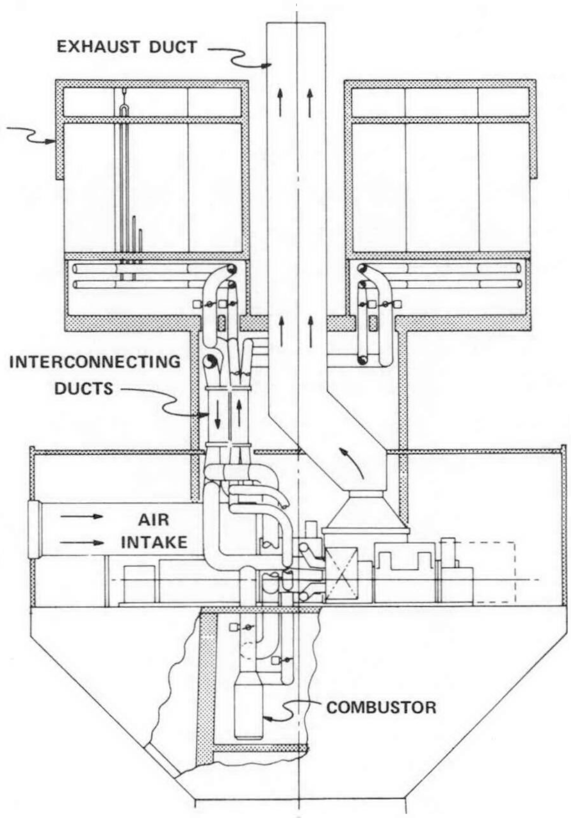

FIGURE 10b ELEVATION VIEW OF HYBRID, SOLAR/ELECTRIC GAS TURBINE SYSTEM WITH INTERFACES

DESIGN OF TURBINE/RECEIVER INTERFACES

The turbine/receiver conceptual interface design was selected because it enhances system operational flexibility and reliability while minimizing the need for adaptive turbine modifications.

Requirements of Component Interfaces

The solar and fossil heat sources must be linked with the gas turbine. Preheated, compressed air from the regenerator must be directed to the heat sources and, subsequent to attaining design temperature, be ducted into the turbine for expansion. The network linking these system components, shown on the Figure 9c flow diagram, should minimize heat loss and pressure drops in the working fluid, include a means to modulate heat source air flow, interconnect the heat sources to provide operating flexibility, and utilize existing technology where possible. Alterations in the turbine frame cannot be permitted due to the production line techniques used in turbine manufacture.

Detailing the Interface Network

The normal MS 7001R regenerative ducting and combustion wrapper constitute key elements of the interface scheme. Conventional piping attached to each of the four, large regenerator discharge ports carries preheated air to the cavities, with branches leading to the combustors. These four lines are interconnected upstream of the butterfly valves that are used to control the air flow. At the heat source outlet, a shutoff valve is provided for component isolation. Although such high temperature (1038 C, 1900 F) valves are not available at present, valve manufacturers indicate that they can be fabricated using existing technology. Special high temperature ducts are necessary to carry the hot gases to the turbine combustion wrapper connection flange. These ducts would be fabricated of alloy steel with an internal thermal barrier to insulate the metal from the high gas temperature. Since the combustors have been removed from the turbine frame, a similar lining would be placed within the combustion wrapper to provide protection from the 1038 C (1900 F) air. Piping interconnections on this return circuit of the network ensure turbine heat source operational flexibility. The piping network and system components layouts are depicted on Figures 10a and 10b.

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GRAPHICAL DATA ARE REPRESENTATIVE OF PERFORMANCE TRENDS ONLY. THE SIMPLE NATURE OF THE MODELING ALGORITHMS PRECLUDES THE CONSIDERATION OF ALL LOSS MECHANISMS THAT REDUCE MACHINE EFFICIENCY.

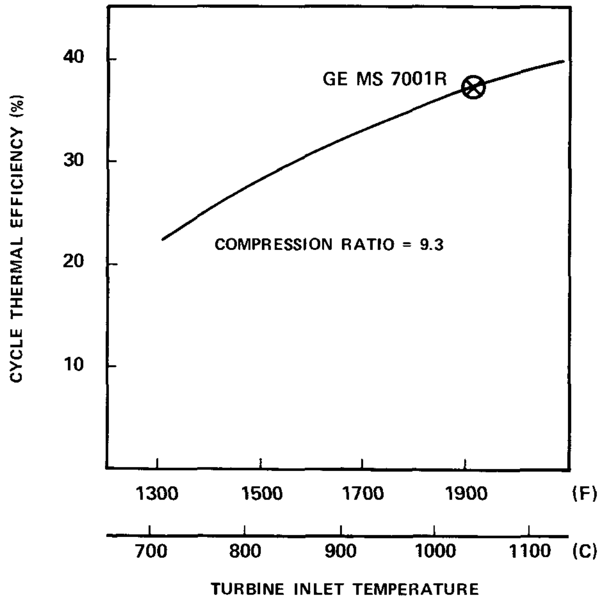

FIGURE 11a EFFECTS OF TURBINE INLET TEMPERATURE ON TURBINE CYCLE EFFICIENCY

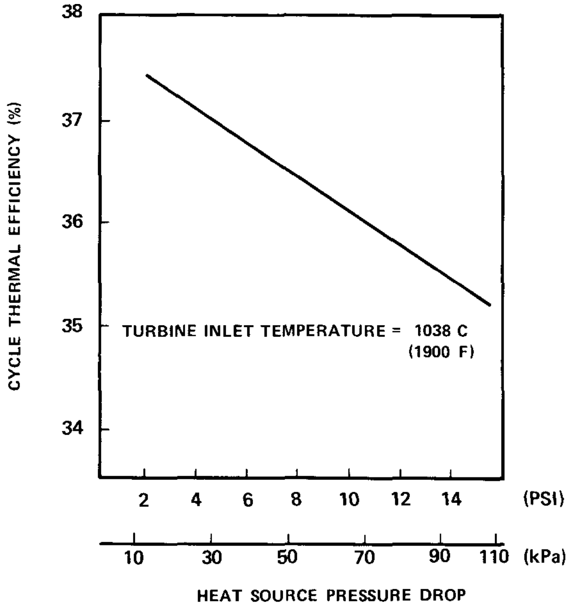

FIGURE 11b EFFECTS OF PRESSURE DROP WITHIN HEAT SOURCE ON TURBINE CYCLE EFFICIENCY

DEFINITION OF IMPORTANT RECEIVER DESIGN REQUIREMENTS

Receiver design requirements were determined with regard to outlet gas temperature, gas pressure drop, overall receiver efficiency, receiver size, and receiver weight.

Advantages of High Outlet Gas Temperature

For an open regenerative Brayton cycle, the cycle efficiency increases as the turbine inlet gas temperature increases, as Figure 11a illustrates. The turbine selected for the baseline design, the GE MS 7001R, has turbine inlet temperatures of about 1010 and 1066 C (1850 and 1950 F) for baseload and peak operation, respectively. Receiver outlet temperatures below these values would lower both the cycle efficiency and the turbine rating, while a receiver outlet temperature above these values would not be compatible with the turbo-machinery. Therefore, the receiver outlet gas temperature should be about 1038 C (1900 F).

Determination of Proper Pressure Drop

The pressure drop between the compressor outlet and the turbine inlet has a strong impact on cycle efficiency as shown on Figure 11b. In conventional operation, the compressor-to-turbine pressure drop, exclusive of the regenerator, is 34 to 48 kPa (5 to 7 psi). Because there will be duct losses, the receiver pressure drop should be in the range of 21 to 34 kPa (3 to 5 psi). While reducing this value would increase cycle efficiency, it would also lead to flow distribution problems within the heat exchanger, with associated "hot spots" and potential material problems.

Determination of Proper Aperture Size

The aperture size has two effects on system efficiency. The first, denoted aperture efficiency, is that fraction of the power, cleanly redirected from the heliostat field, which enters the aperture. The second, denoted cavity efficiency, is that fraction of the power, cleanly entering the aperture, which is retained within the cavity and absorbed by the working fluid. Clearly, as aperture size increases, aperture efficiency increases and cavity efficiency decreases. The aperture should be sized so as to maximize the product of aperture and cavity efficiencies.

Penalties for Receiver Size and Weight

As the receiver size and weight increase, the costs of the receiver and associated equipment increase. Further, in order to adequately support the receiver subsystem, the tower structure size and cost increase. Therefore, the size and weight of the receiver should be as small as is consistent with the receiver operating requirements.

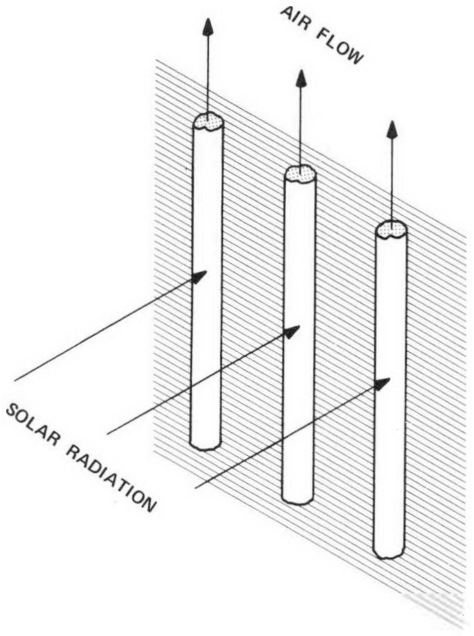

FIGURE 12a TUBE-TYPE RECEIVER HEAT TRANSFER SURFACE

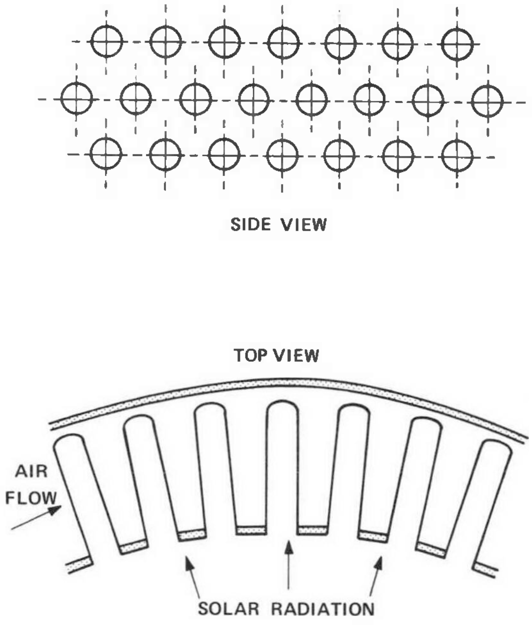

FIGURE 12b EXTENDED SURFACE RECEIVER HEAT TRANSFER SURFACE

SELECTION OF HEAT TRANSFER SURFACE GEOMETRY

A tube-type geometry was selected as superior to an extended-surface geometry with regard to reliability, fabricability, commercial availability of components, cavity efficiency, and the cost. The performance characteristics of the two geometries were determined by detailed, three-dimensional, multi-modal heat transfer and stress analyses. These analyses were later experimentally verified.

Advantages of Tube-Type Geometry

The tube-type geometry is shown in Figure 12a. The compressed, preheated air flows through tubes, the outsides of which are heated by redirected solar radiation. The tubes are separated from each other and are located in front of a diffusely reflecting surface. This arrangement minimizes the circumferential variation of tube temperature, and therefore the thermal stresses in the tubes. Analysis showed that this geometry, when properly configured, has lower stresses, lower material temperatures, lower gas pressure drop, and higher heat transfer surface efficiency than the extended-surface geometry. The high heat transfer surface efficiency results in higher cavity efficiency, as well as smaller receiver size and reduced weight. Further, this geometry can be fabricated from commercially available components with a minimum of field erection.

Disadvantages of Extended Surface Geometry

The extended-surface geometry is shown in Figure 12b. The air flows between a web and a back surface. The web contains many hollow fingers which protrude into the gas flow path. The redirected solar radiation strikes the concave side of the web, where a portion is trapped within the fingers and heat is transferred to the gas. In addition to performing poorly in comparison with the tube-type geometry, this geometry requires extensive field erection from components not currently commercially available. Further, repair or replacement of a portion of the heat transfer surface would be more difficult, time consuming, and expensive than for the tube-type geometry.

- COMMERCIAL AVAILABILITY
- AVAILABLE JOINING TECHNIQUES
- CAPITAL COST
- STRENGTH
- MECHANICAL & THERMO-OPTICAL PROPERTIES
- RESISTANCE TO THERMAL SHOCK
- RESISTANCE TO OXIDATION

FIGURE 13a CERAMIC MATERIALS EVALUATION CRITERIA

MATERIAL SELECTION

SILICON CARBIDE (Design Choice)

HIGH ALLOWABLE STRESS
LOW THERMAL STRESS
AVAILABLE HIGH TEMPERATURE JOINING TECHNIQUES

CORDIERITE (Design Alternative)

HIGH ALLOWABLE STRESS
LOW THERMAL STRESS
HIGH TEMPERATURE JOINING TECHNIQUES NOT AVAILABLE
EASY TO FABRICATE

ALUMINUM OXIDE

LOW ALLOWABLE STRESS
HIGH THERMAL STRESS
VERY GOOD JOINING TECHNIQUES AVAILABLE

FIGURE 13b COMPARATIVE CHARACTERISTICS OF CANDIDATE MATERIALS

SELECTION OF HEAT EXCHANGER TUBE MATERIAL

Silicon carbide and cordierite were selected as the design and back-up materials, respectively, because they are superior to all other materials considered with regard to mechanical properties, resistance to thermal shock, resistance to oxidation, fabricability, commercial availability, and cost.

Rejection of Metals

Metals currently available in tube form (e.g. Inconel 600, Inconel 617, Haynes 188) are not suitable for extended operation above 871 C (1600 F) at the stress levels expected in the high-temperature heat exchanger. With this material temperature limit, a maximum receiver outlet gas temperature of about 732 C (1350 F) could be attained. Because this gas temperature is significantly below the required turbine inlet temperature, metals were rejected.

Identification of Suitable Ceramics

A large number of ceramic materials were considered. Three of these materials, silicon carbide, cordierite, and alumina, were initially selected as the most suitable for this application. The criteria used in this selection are listed in Figure 13a.

Final Material Selection

Each of the three candidate materials was analyzed in detail. Each had advantages and disadvantages with respect to the other two. These are summarized in Figure 13b. Silicon carbide and cordierite were selected because reliability and resistance to thermal shock are considered to be the most important criteria. Reliability was defined as the ratio of allowable stress to operating stress.

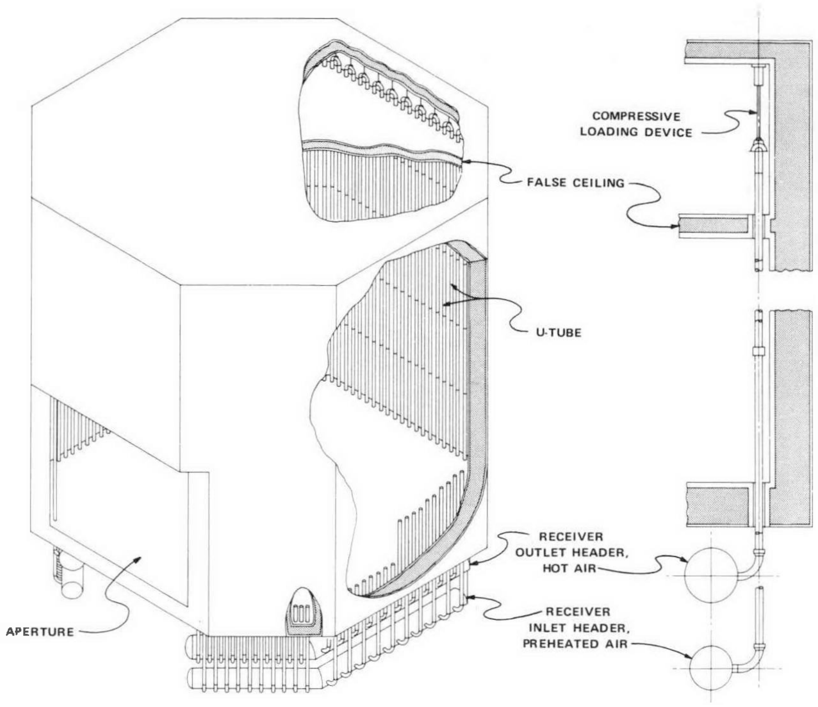

FIGURE 14 CUTAWAY OF U-TUBE-TYPE CAVITY RECEIVER HEAT EXCHANGER

ADVANTAGES OF U-TUBE CAVITY RECEIVER DESIGN

The cavity heat transfer surface was designed as a series of vertical U-tubes, because of ease of erection, simple component replacement, and low operating stresses.

Description of U-Tube Configuration

The U-tube cavity receiver is shown in Figure 14. Both the inlet and outlet headers are located beneath the cavity floor. The U-bend is located above the cavity ceiling. Pneumatic cylinders, located above the U-bends, keep each U-tube in compression.

The U-tubes, constructed of 10.2 centimeter (4 inch) diameter tubes, are all 12.2 meters (40 feet) long, but the four cavities vary in width according to which sector of the non-uniform heliostat field they face and hence, the amount of solar thermal power input to the cavities. A nominal cavity dimension is 14.6 meters (48 feet) between opposite octagonal faces. Each cavity houses approximately 70 U-tubes, although the exact number is dependent upon cavity size and power level.

Advantages of the U-Tube Configuration

- Because the headers and U-bends are outside the flux zone, the stresses in these components are reduced.
- Because the tube-header and the tube-U-bend joints are out of the flux zone, these joints can be designed to withstand only the temperature and pressure of the heated air.
- Because the tubes are in compression, the joints can be pressure seals. Joints of this type are not rigid, but will permit some displacement of the tube ends. This will reduce thermal stresses in the tubes.
- Because the headers are both below the cavity, the hot and cold legs of the U-tubes can be of unequal length, thereby

equalizing the total thermal expansion of both legs. These header locations also minimize duct lengths, and therefore the working fluid pressure drops and material costs.

- The compressive load can be designed to just overcome internal gas pressure or to prestress the tubes so as to minimize tensile stresses. The degree of compression will depend on the tube manufacturing characteristics, particularly tolerances and straightness.
- Any single tube can be readily replaced.

6. HEAT EXCHANGER TUBE TESTS AND EVALUATION

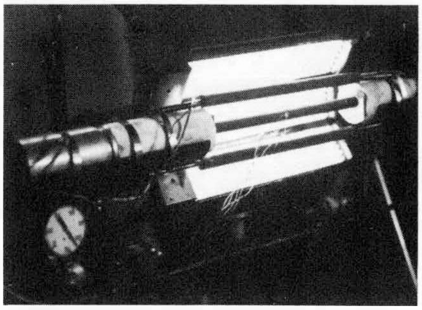

FIGURE 15a **SINGLE TUBE TEST**

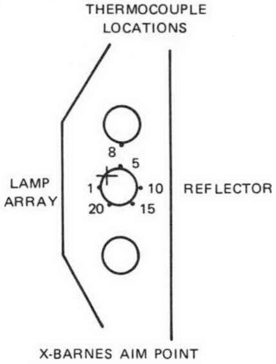

FIGURE 15b **END VIEW OF THE SINGLE TUBE TEST SETUP**

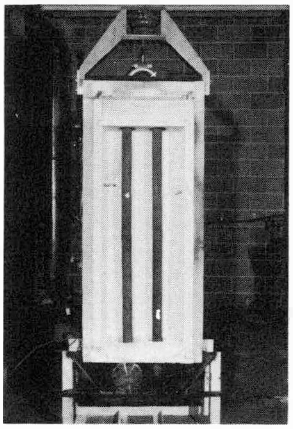

FIGURE 15c **U-TUBE TEST SETUP**

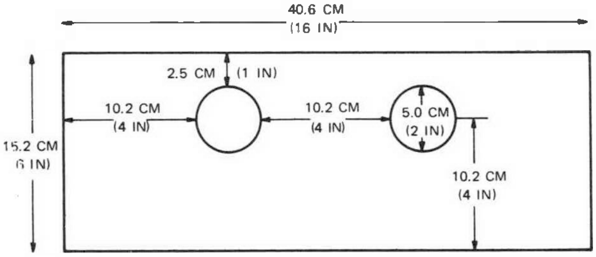

FIGURE 15d **U-TUBE THERMAL CYCLING EXPERIMENT CONFIGURATION**

RATIONALE FOR MATERIAL AND CONFIGURATION TESTS

The design materials and tube configuration were experimentally tested because the material thermo-optical properties were not known, the heat transfer analytic methodology had not been verified, and the structural stability of a ceramic U-tube subjected to thermal cycling had not been determined.

Measurement of Material Thermo-Optical Properties

The material thermo-optical property tests were performed by the TRW Systems Group Thermophysics Laboratory. Both the directional and hemispherical reflectivity and emissivity, as functions of wavelength and material temperature, were measured for silicon carbide and cordierite. These measurements were made using both the Gier Dunkle Heated Cavity Reflectometer and the TRW Paraboloid Reflectometer.

Verification of Analytic Methodology

In order to verify the heat transfer analytic methodology, a series of single tube test experiments, which duplicated as closely as possible the heat transfer surface of the baseline design, were performed at Georgia Institute of Technology. The experimental set-up is shown on Figures 15a and 15b. The center tube contains the preheated compressed air; the side tubes are cooled with ambient air. With the flow conditions in the center tube held constant for each test run, the ambient flow in the side tubes was varied until thermocouples at positions 8 and 5 (Figure 15b) indicated the same temperatures. This single tube test arrangement duplicated the effect of a large number of identical, parallel tubes.

Determination of U-Tube Structural Stability

A silicon carbide U-tube was assembled and thermally cycled at Georgia Institute of Technology. The test set-up is shown on Figure 15c. The U-bend was made from Inconel 600 pipe, and was compressively loaded with a pneumatic cylinder. The vertical legs of the tube assembly were enclosed in a rectangular cavity, three sides of which were lined with a diffusely reflecting material and one side of which was composed of quartz lamps. The dimensions of the cavity, shown on Figure 15d, were calculated so as to yield the same material temperatures and stresses as in the baseline design.

CONVECTIVE COOLING COEFFICIENT

$\frac{W}{M^2\text{-}C} \left(\frac{BTU}{HR\text{-}FT^2\text{-}F}\right)$

CASE	EXPERIMENTAL RESULTS		ANALYTIC RESULTS	
1	210	(37)	199	(35)
2	295	(52)	278	(49)
3	420	(74)	386	(68)
4	698	(123)	534	(94)

FIGURE 16a CALCULATED AND EXPERIMENTAL TUBE CONVECTIVE COOLING COEFFICIENTS – SILICON CARBIDE

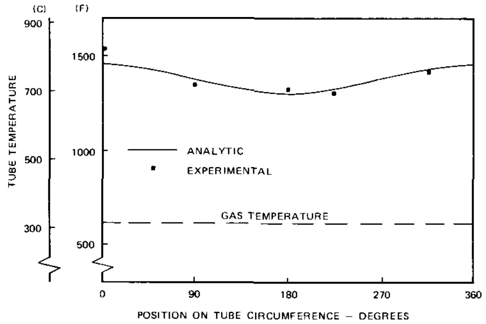

FIGURE 16b CALCULATED AND EXPERIMENTAL TUBE WALL TEMPERATURES – SILICON CARBIDE

RESULTS OF MATERIAL PROPERTY AND SINGLE TUBE TESTS

The results of the material property and single tube tests provided the material properties used in the analyses and demonstrated that the analytic methodology correctly predicted the heat transfer characteristics of the tube-type geometry.

Results of Material Property Tests

The thermo-optical properties of silicon carbide were measured, for various angles of incidence and wavelength, from room temperature to about 1093 C (2000 F). These measurements indicated that, independent of material temperature and angle of incidence, the thermo-optical properties of silicon carbide are almost constant for wavelengths between 2 and 10 microns. The average reflectivity is about 0.15 and the average emissivity is about 0.85. The cordierite properties were found to be dependent on angle of incidence and wavelength.

Results of Single-Tube Tests

The single-tube tests with silicon carbide demonstrated that the analytic methodology had correctly predicted the level of the material temperatures, the circumferential variation of those temperatures, and the gas convective cooling coefficient. Of the many experimental runs, four were selected for analysis because they most nearly duplicated the baseline design with respect to flux level, gas pressure, and gas velocity. Figure 16a compares the calculated and measured values of the convective cooling coefficient. Figure 16b shows the calculcated and measured tube wall temperatures for one of the four cases. As a whole, the experimental results were in very good agreement with the analytic predictions. No material or joint failures occurred during these tests.

100 KW THERMAL CYCLING TESTS
PRESSURIZED SILICON CARBIDE U-TUBE
SUMMARY OF RESULTS

Number of Cycles	Cumulative Cycles	Cycle Period (minutes)	Inlet Air Temperature C	(F)	Minimum Material Temperature C	(F)	Maximum Material Temperature C	(F)	Maximum Circumferential ΔT C	(F)
245	245	15	71	(160)	207	(405)	752	(1385)	224	(435)
25	270	15	149	(300)	274	(525)	763	(1405)	157	(315)
71	341	15	399	(750)	521	(970)	993	(1820)	77	(170)
159	500	15	510	(950)	* 549	(1020)	1018	(1865)	43	(110)
100	600	15	Static		532	(990)	1210	(2210)	27	(80)
3	603	15	Static		535	(995)	1332	(2430)	21	(70)

* Baseline Conditions

- The basic U-tube heat exchanger design utilizing SiC tubes does not present any serious materials problems.
- Joined, 5 cm (2 in) diameter SiC tubes can withstand repeated thermal cycling at high temperatures without damage.
- At baseline conditions, the observed 43 C (110 F) circumferential temperature variation about SiC tubes directly irradiated from one side confirms the heat exchanger design geometry for minimizing thermal stresses.

FIGURE 17

RESULTS OF U-TUBE THERMAL CYCLING TESTS

The results of the thermal cycling tests demonstrate that a silicon carbide U-tube, with ceramic-to-ceramic joints and an Inconel 600 U-bend, is stable under thermal cycling between temperature extremes of 207 and 1332 C (405 and 2430 F).

Performance of Silicon Carbide U-Tube

A silicon carbide U-tube, 5 cm (2 in) in diameter, 1.2 m (4 ft) in length, and containing flowing air at approximately 862 kPa (125 psia), has been thermally cycled 500 times using a 100 kW radiant lamp test facility. Following these tests, the U-tube was subjected to an additional 103 thermal cycles with static, pressurized air; the lack of air flow made it possible to attain higher tube material temperatures. This U-tube assembly is pictured in its test enclosure on Figure 15c.

The flowing air temperature at the U-tube inlet during the first 245 thermal cycles was 71 C (160 F) at a pressure of 862 kPa (125 psia). The tube temperature was cycled between 207 and 752 C (405 and 1385 F) with the increasing and decreasing temperature ramps each requiring 7 minutes. During this series of comparatively low temperature test cycles, the temperature gradients through the tube walls and around the tube circumference, and hence the thermal stresses, were much greater than those predicted and experienced under the baseline conditions (see Figure 17). Despite these excessive stress levels, no material failure or degradation was observed.

The inlet air temperature was increased to the baseline conditions of 510 C (950 F) in three increments during the 255 remaining thermal cycles with flowing air. The progressively higher inlet air temperatures made it possible to attain greater tube material temperatures than in the first 245 cycles. Typical test results are summarized on Figure 17.

In order to subject the silicon carbide tubes to even higher temperatures, test facility power limitations made it necessary to eliminate the flowing air heat sink. With static, pressurized air, the U-tube was cycled between 532 and 1210 C (990 and 2210 F) 100 times with temperature ramps of approximately 6 minutes. The final three cycles reached an operating temperature of 1332 C (2430 F). The number of cycles and the upper temperature of this most extreme test were restricted because the quartz lamp and reflector assembly were self-destructing, not because of a silicon carbide U-tube capability limit.

Performance of Cordierite U-Tube

A cordierite U-tube was also fabricated and tested. This assembly had a cordierite U-bend and sleeve-type joints. This assembly did not perform successfully. Two joint failures and one tube failure occurred within a few tens of cycles.

Conclusions from SiC U-Tube Thermal Cycling Tests

Silicon carbide U-tubes are suitable for use in a high temperature cavity heat exchanger. The U-tube configuration, with ceramic-to-ceramic joints, survived over 600 thermal cycles with material temperatures up to 1332 C (2430 F). No tube failures were experienced and low power (7X) microscrope inspection did not reveal any change in tube or brazed joint appearance.

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7. CONCLUSIONS

PROJECT CONCLUSIONS AND DEFINITION OF FUTURE DEVELOPMENT NEEDS

Conclusions

The major conclusions to be drawn from the work reported here are:

- The conceptual design of a commercial size, Open Cycle Gas Turbine Solar/Electric Plant, with overall conversion efficiency of 21.7 per cent, has been completed utilizing state-of-the-art methods and hardware. The capital cost is expected to be in the range of $1346 to $1659 per kilowatt, depending on the cost of heliostat subsystems.
- The estimated costs are less than, and the efficiency of this system is superior to, that of a water-steam system.
- Hybrid operation of this system using fossil fuel during periods of solar outage is feasible. This capability enables the solar/electric power plant to be a source of reliable power to serve peak loads and qualifies the utility to receive a demand capacity credit for the plant. Further, hybrid operation represents the only practical and economic approach to storage now available.
- Mounting the gas turbine-generator set near the top of the receiver tower is feasible from the standpoint of safe design, erectibility, and cost.

Future Development Requirements and Recommendations

There are three hardware developments which are required for the successful operation of this system concept. The required developments are:

1. A high temperature solar heat exchanger that utilizes high temperature ceramic tubes (silicon carbide). Sufficient testing has been performed to demonstrate that existing SiC tubing can be utilized. A reliable ceramic-ceramic joint compatible with field erection practices is a major item requiring serious research effort.
2. High temperature isolation valves and internally insulated metal ducting that are capable of carrying 1038 C (1900 F) air at velocities of 38 m/sec (125 ft/sec).
3. External combustors for regenerative gas turbines configured so that hybrid operation is both flexible and easily controlled. This development appears to be limited to design modifications rather than serious redesign of the existing turbomachinery.

It is recommended that a timely and logical program plan be pursued toward the final objective of demonstrating a commercial size, open cycle solar/electric system. The conceptual design herein constitutes the first step of such a program plan. The recommended next step in the open cycle solar/electric system development is the design, fabrication, and test of a 1 MWt high temperature cavity heat exchanger, the least conventional component of the solar/electric system. Following that development phase, it is recommended that a 10 MWe (equivalent) Solar/Electric Pilot Plant be designed, constructed, and operated as the forerunner to the first commercial demonstration plant.

SECTION 10

EPRI CONTRACT RP 651-1

REQUIREMENTS ASSESSMENT OF PHOTOVOLTAIC ELECTRIC POWER SYSTEMS

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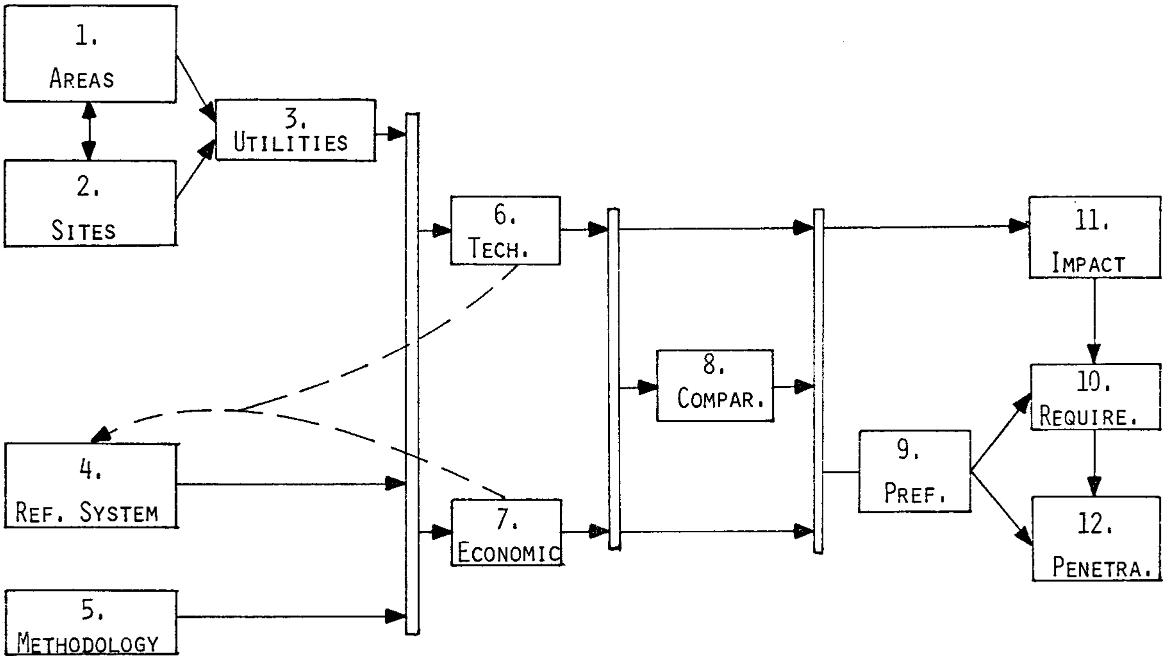
OCTOBER 1976
EPRI SOLAR REVIEW MEETING #2



PROJECT FLOW CHART

Figure 1 Is a flow chart showing the 12 tasks which make up this requirements assessment. The first three tasks develop the environment within which photovoltaic systems will be studied. In Task 1 suitable areas are selected for study. In Task 2 preliminary site analyses are made within these areas, and in Task 3 specific utilities on whose electric power systems photovoltaic electric power systems (PEPS) will be studied and assessed are selected. An important part of these three tasks is the collection of climatic, insolation, and utility data.

In Task 4 several reference photovoltaic systems will be synthesized and described in terms of their performance, reliability, and costs. In Task 5 the methodology of the study will be developed.

In Tasks 6 and 7 the technical and economic analyses of the reference systems, operating in the selected utilities, will be made. The dashed lines and arrow connecting Tasks 6 and 7 to Task 4 indicate that preliminary technical and economic analyses will be necessary in the selection of a manageable number of reference PEPS.

In Task 8 a comparative analysis of reference systems will be made for each utility, and in Task 9 preferred systems will be identified for each utility. From this work and the results of Tasks 6, 7, and 8 preliminary impact and penetration analyses will be made. In Task 10 the requirements of viable PEPS in utility systems will be determined.

MAJOR ISSUES

- CAPACITY DISPLACEMENT

  (EFFECTIVE CAPACITY)

- ENERGY DISPLACEMENT

  (KWH & $)

- ECONOMIC VIABILITY

Figure 2 The first major issue of this study is the determination of the capacity displacement of PEPS operating in utility systems. By capacity displacement is meant the capacity of conventional generation which may be safely omitted because of the existence of a PEPS plant. A major factor in capacity displacement is the effective capacity as determined by probability methods to be discussed later.

Energy displacement is simply the amount of energy generated by a PEPS which will displace energy otherwise generated by conventional power plants. The amount of energy displaced is a relatively straightforward determination, but the value of the energy displaced is highly dependent upon the detailed characteristics of the utility system involved.

There is no question about the economic viability of current PEPS technology. It is not viable. A major question to be addressed, however, is what levels of performance and cost of PEPS will be required for future viability. It will be important to identify the trade-offs among potential future improvements in PEPS technology.

AREA & SITE SELECTION

- TOTAL INSOLATION
- DIRECT INSOLATION RATIO
- CLIMATE
- TOPOGRAPHY
- POWER COSTS
- LAND COSTS

Figure 3 Is a list of the major factors involved in area and site selection. The purpose is not to select areas all of which are highly favorable in all factors, but to cover a range of values of each so that their relative impacts may be assessed and a reasonable extrapolation made to a national penetration estimate.

REFERENCE SYSTEMS

- CONFIGURATION
- TRACKING
- PHOTOVOLTAIC CELLS
- APPLICATION

Figure 4 Lists the four basic characteristics which distinguish the reference systems to be selected. The major aspects of configuration are the concentration ratio of the collectors and the cooling methods. Tracking has to do with the following of the sun either hourly or seasonally and ranges from no tracking at all to a two-axis system whose aperture plane is always normal to the sunbeam.

There are a number of photovoltaic cell materials which vary in their efficiency, temperature-efficiency coefficient, packing factor capability, durability, and cost. The application of PEPS from residential roof-top systems to utility central power plants will influence not only the size and configuration but also the desirability of energy storage.

There are a huge number of combinations of these factors making up potential reference systems, and it is necessary to select those which as the study proceeds appear to have the most potential for further study.

METHODOLOGY

- PEPS PERFORMANCE MODEL
- PROBABILITY MODEL
- PRODUCTION COST MODEL
- ECONOMIC ANALYSIS MODEL

Figure 5 Shows the four major components of the methodology which has been developed. The PEPS performance model uses technical performance characteristics of each PEPS reference system together with hourly weather data for a specific site to produce hourly PEPS output. The probability model combines this PEPS output data with hourly load data and outage data of conventional generation of a specific system to calculate the effective capacity of the PEPS. This ultimately provides a measure of the PEPS capacity displacement. The production cost model takes the hourly PEPS output, the hourly loads, and details of the utility generating system to simulate hour by hour operation in order to obtain fuel, operation, and maintenance costs for the system with PEPS in place. The economic analysis model uses the results of the preceding models' operations to provide an economic comparison of alternate PEPS on the utility system involved. Details of these models are covered in ensuing figures.

PEPS PERFORMANCE MODEL

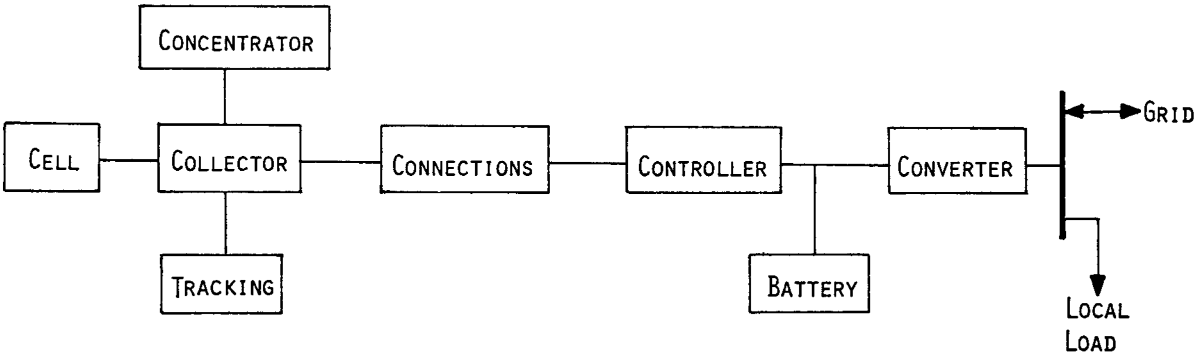


Figure 6 Is a block diagram of the PEPS performance model. The characteristics of the cell material as integrated into a collector with or without concentration and tracking produce the photovoltaic array output for a specific location weather tape. This output flows through the dc cable connections where losses are incurred to the controller-converter which produces ac power at the output bus. For central station applications this power will be delivered directly to the utility transmission grid. For on-site applications the characteristics of the local load will be modeled under both passive and active connection assumptions. In the passive connection the PEPS output is devoted entirely to the local load; no power is delivered to the grid. In the active connection there is the possibility of output to the grid when the PEPS output exceeds the local load. In both connections the grid may supply power to the local load and in the reverse direction through the converter to the battery. The operation of the storage battery may be specified to hold a fixed output over a daily time schedule or it may be scheduled to "shave" the local load peaks so as to minimize the cost of energy purchased from the grid. The storage may also be considered as non-PEPS-dedicated, system-wide storage in which case it is dispatched according to the economics of production of the total generating system.

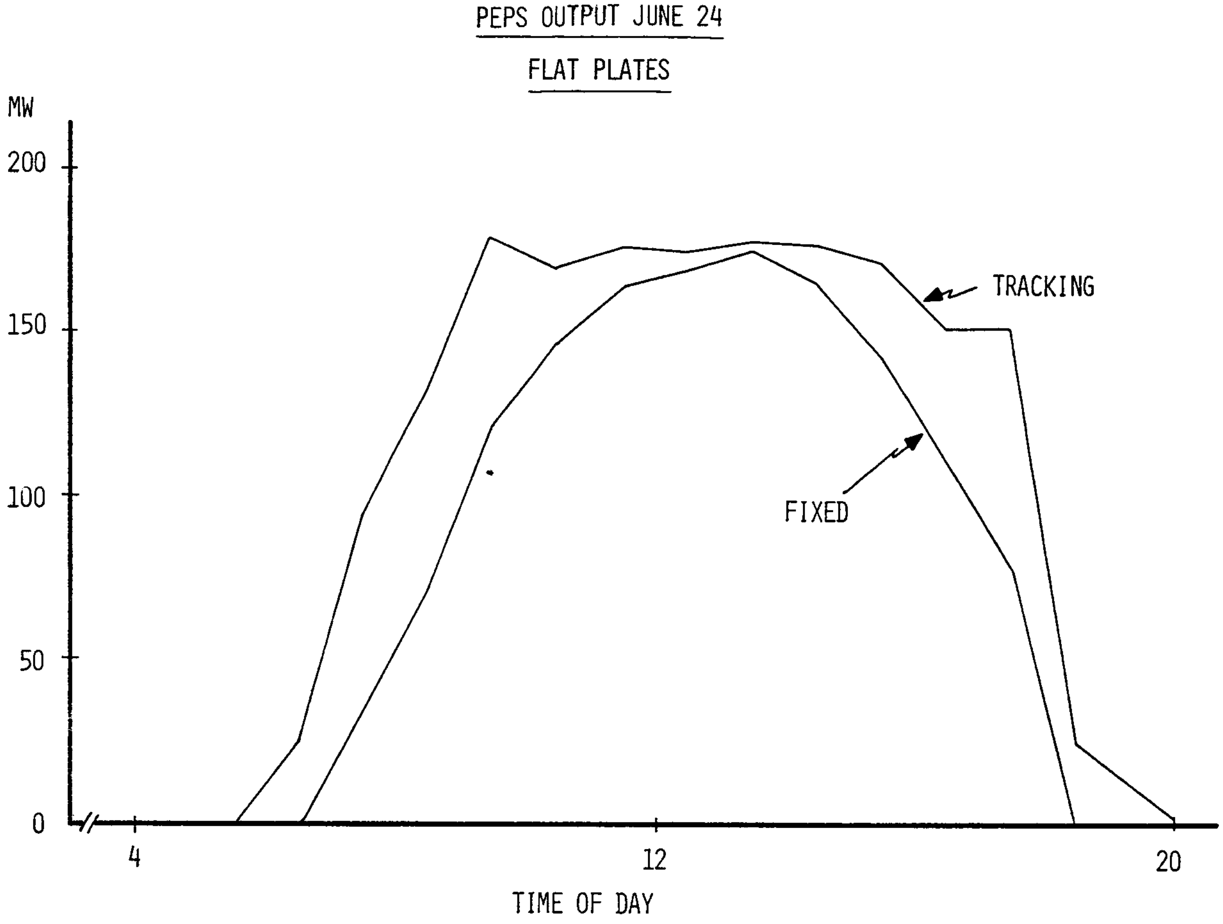


Figure 7 Is an example of the output of the PEPS performance model for flat-plate arrays having a maximum yearly peak output of about 200 MW. The curves show the hourly output on one day of the year for a fixed flat-plate array and for an array arranged for two-axis tracking.

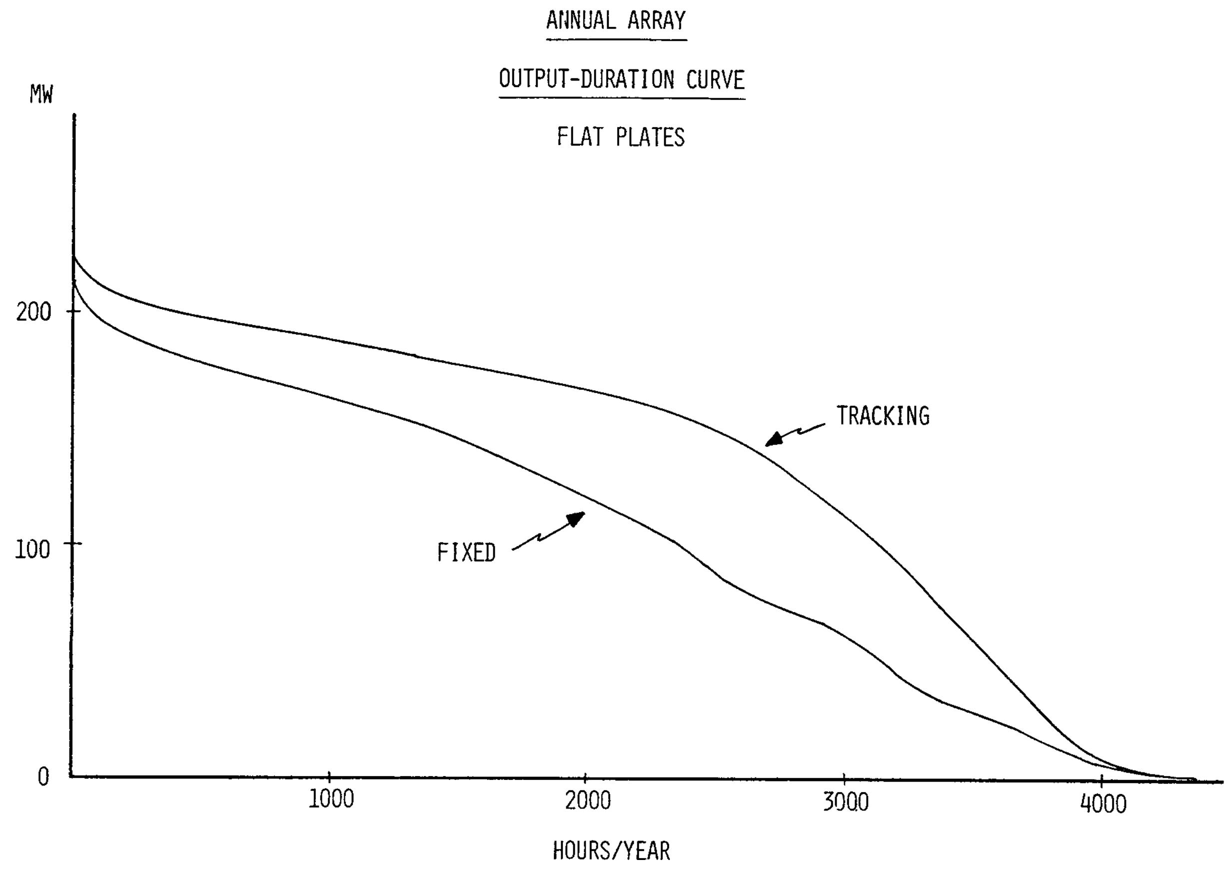


Figure 8 The PEPS performance model is arranged for computer plotting of several output quantities. This figure is one of these plots of annual output arranged in decreasing order of hourly outputs.

PROBABILITY MODEL

- CONVENTIONAL LOLP

- HOURLY LOAD INPUT

- DAILY & HOURLY OUTPUT

Figure 9 Lists the characteristics of the probability model. It is a conventional loss-of-load probability (LOLP) which calculates an outage probability table for conventional generating units using the binomial expansion coefficients. In the usual model used for electric utility reserve planning only the peak hour of each day is used with this outage table to determine the probability of insufficient generation each day. The sum of these probabilities is the LOLP which is mathematically an expected value for the year (expected days per year of insufficient capacity). In order to adequately analyze PEPS it is necessary to consider all hourly loads in the day. The output then becomes expected hours of insufficient capacity per year. The program is arranged to produce both the traditional daily as well as the new hourly output.

EFFECTIVE CAPACITY

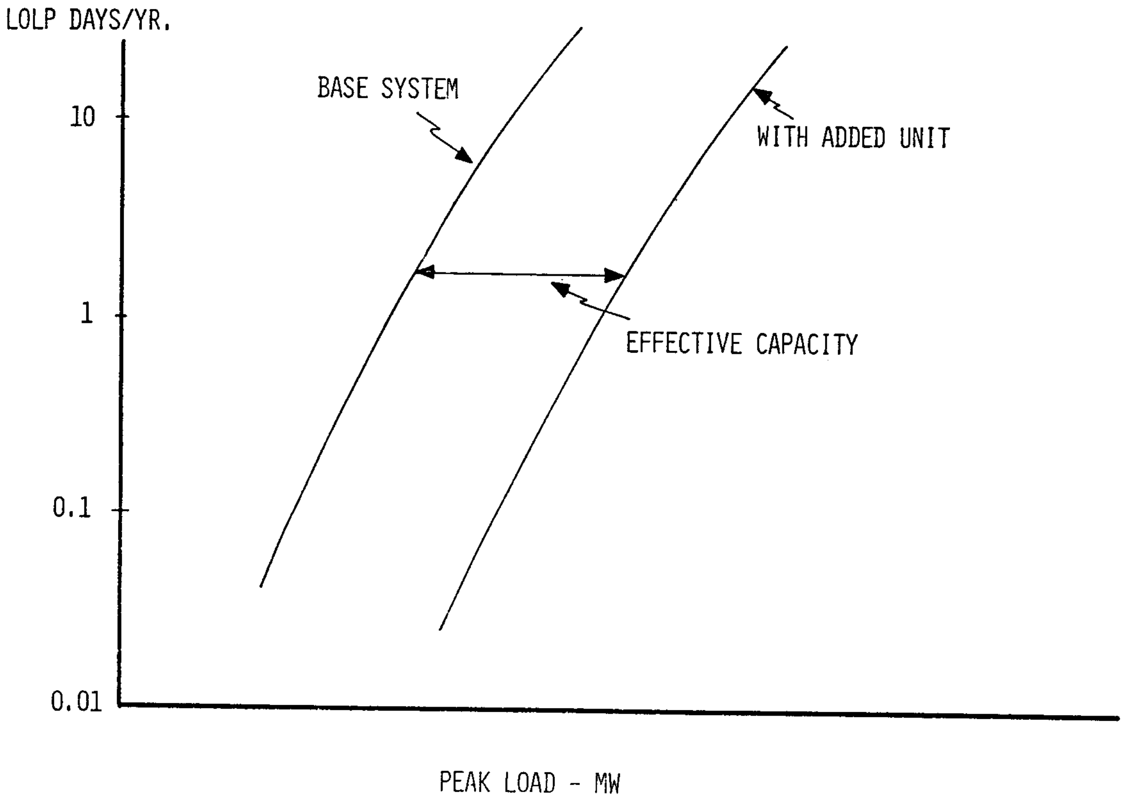


Figure 10 Shows graphically how the conventional LOLP calculation is used to obtain effective capacity of a generating unit. The probability calculation is first made using the base generating system and with a range of assumed load levels as shown on the horizontal axis. This produces a curve of LOLP vs. peak load. The calculation is then repeated with a generating unit added and a second curve produced. The horizontal distance between these two curves is defined as the effective capacity, which is actually the increment of new load which could be carried by the system at a fixed level of LOLP as the result of a new unit addition.

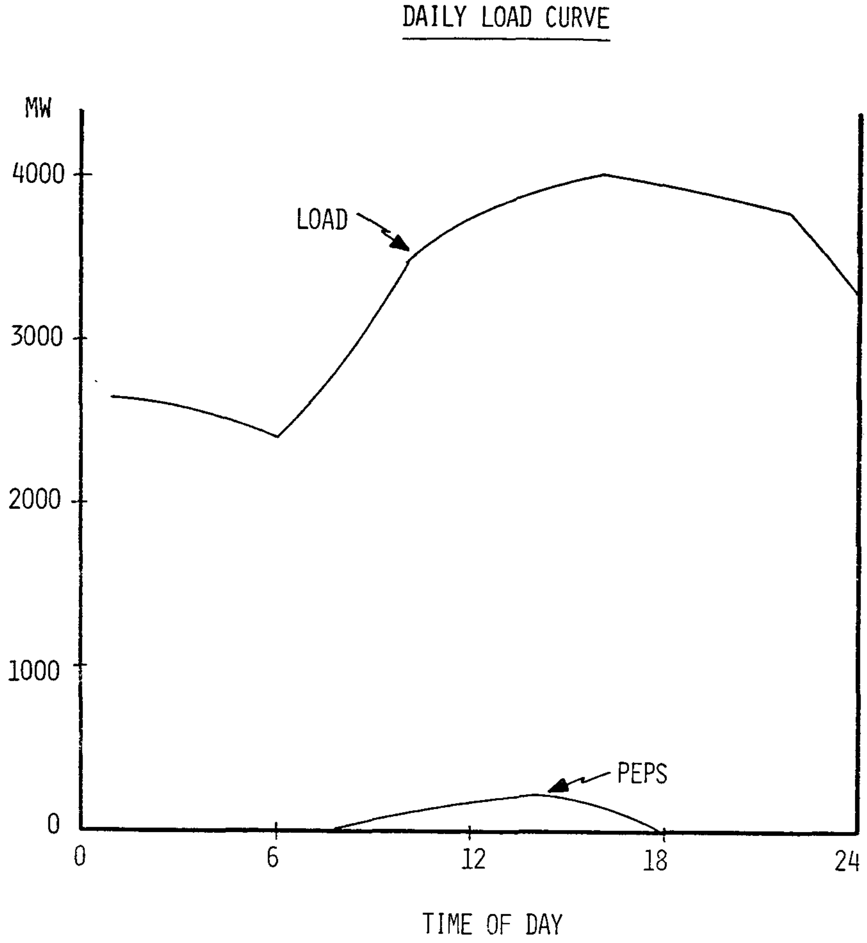


Figure 11 Shows a typical daily load curve and a typical PEPS output. When the hourly probability calculation is considered it is apparent that the shape of the daily load curve relative to the shape of the PEPS output curve will have a significant impact upon the effective capacity of the PEPS unit. There is a further issue involved here. Even with no PEPS under consideration the use of hourly rather than daily probability calculations raises the question of how the hours per year of expected capacity deficiency are to be related to the traditional days per year of expected insufficient capacity. In order to emphasize this uncertain relationship a new name has been given to the hourly calculation: Expected Hours of Capacity Deficiency (EHCD).

LOSS-OF-LOAD PROBABILITY (LOLP)
VS. EXPECTED HOURS OF CAPACITY DEFICIENCY (EHCD)

- FLAT LOAD SHAPE:

  EHCD = LOLP x 24

- PEAKED LOAD SHAPE:

  EHCD = LOLP

- TYPICAL LOAD SHAPE:

  EHCD = LOLP x 14

Figure 12 Indicates the relationship between LOLP in days per year and EHCD expressed in hours per year. If the daily load curve were completely flat, i.e., identical loads for 24 hours, then the probability calculation shows that the EHCD is exactly equal to the LOLP times 24. At the other extreme, with a completely peaked load shape having 23 hours of zero load and one hour of peak load, EHCD is equal to LOLP. For typical load shapes the multiplier will be somewhere between one and 24. Current experimental runs of the program have shown values of about 14.

EFFECTIVE CAPACITY METHODOLOGY

- LOLP (EHCD) CALCULATION BY HOURS
- TYPICAL UTILITY HOURLY LOAD MODEL
- LET PEPS MODIFY HOURLY LOADS
- CALCULATE EHCD

Figure 13 Shows the steps in the effective capacity methodology. First the LOLP or, rather, the EHCD calculation is made hourly for a typical utility load model for a year. The hourly PEPS output is then used to modify the hourly loads and the EHCD is recalculated. Curves like those of Figure 10 are prepared to determine the PEPS effective capacity.

TYPICAL EFFECTIVE CAPACITY

(% OF PEAK OUTPUT)

LARGE THERMAL UNIT	75%
PHOENIX PEPS	40 - 60%

Figure 14 Shows typical effective capacities for large thermal units and PEPS using a Phoenix weather tape and a typical medium size utility.

EFFECTIVE CAPACITY

FLAT PLATE SYSTEMS
(204 MW PEAK)

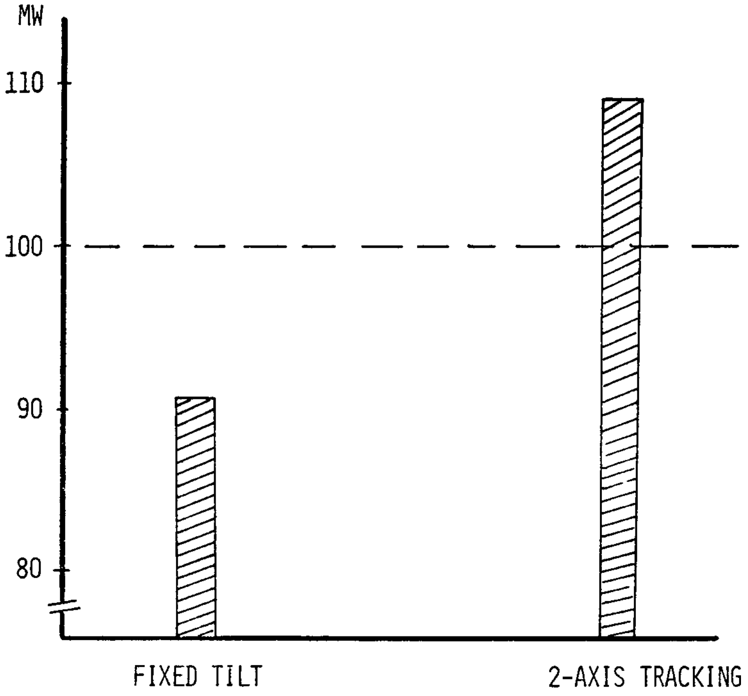


Figure 15 Shows how the effective capacity of a flat-plate system of 204 MW peak varies depending upon the configuration of the PEPS. There is about a 20% difference depending upon whether the panels are fixed or arranged for two-axis tracking.

PRODUCTION COST MODEL

- CONVENTIONAL HOURLY SIMULATION
- MAINTENANCE SCHEDULING
- COMMITMENT AND DISPATCH
- OUTPUT
    - UNIT LOADINGS
    - FUEL CONSUMPTION
    - FUEL COSTS
    - O&M COSTS

Figure 16 Lists the essential elements of the production cost model. It is a conventional hourly simulation such as is currently used for generation planning in many utilities. In addition to hourly loads the model requires, as input, detailed performance and cost characteristic of each individual generating unit. The units are first scheduled for routine maintenance and then the model commits and dispatches units to meet each hourly load, calculating, as it proceeds, the fuel, operation, and maintenance cost. The output consists of the unit loadings, their fuel consumption, fuel costs, and operation and maintenance costs.

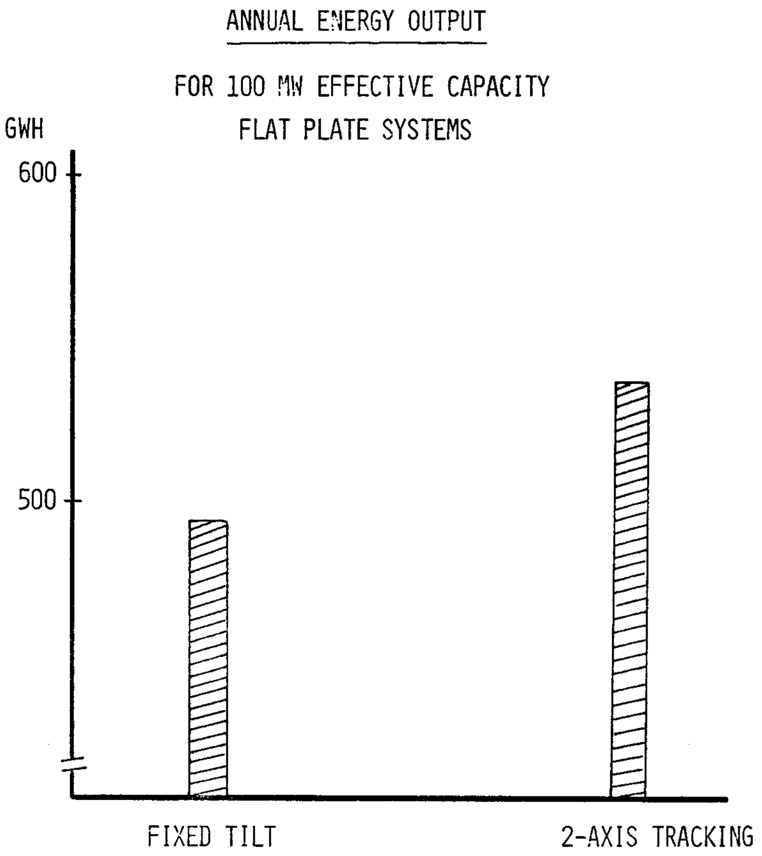
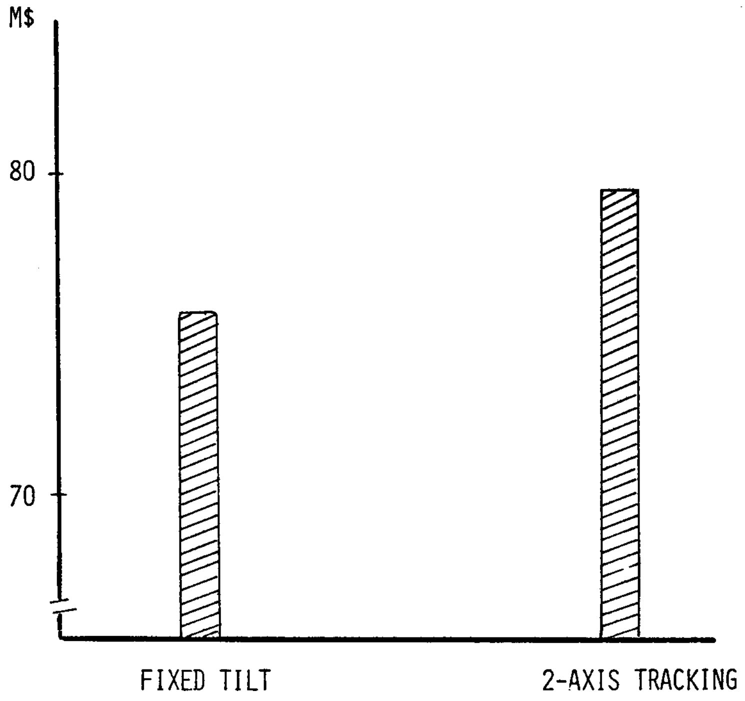


Figure 17 Gives the annual energy output for the fixed and two-axis tracking flat-plate arrays. In order to reflect equal capacity impact the sizes of these plants have been adjusted on the basis of the probability calculations so as to each provide 100 MW of effective capacity. Referring to Figure 15 this has meant an increase in the array size of the fixed panel array and a reduction in the size of the two-axis tracking array. Even so the two-axis tracking system still provides more energy output annually than the fixed array.



ENERGY DISPLACEMENT (CAPITALIZED)

FLAT PLATE SYSTEMS

Figure 18 By running the production cost model first without PEPS and then with each of the two example systems we can obtain the value of the energy displaced by each by subtraction. This figure shows the values for the two systems adjusted for future fuel and O&M cost inflation and capitalized at the annual fixed charge rate of the utility. We now have a comparison of the economic effect of PEPS installations on the utility operating costs with PEPS of equal effective capacity and hence equal impact on the utility generating system reliability.

ECONOMIC ANALYSIS MODEL

- INPUTS

  PEPS EFFECTIVE CAPACITIES

  PEPS ENERGY DISPLACEMENT VALUE

  PEPS CAPITAL COSTS

  PEPS O&M COSTS

  PARAMETRIC VARIATIONS

- OUTPUTS

  RELATIVE ECONOMIC VIABILITY INDEXES

Figure 19 Gives the inputs and outputs of the economic analysis model which will be used to compare alternate reference PEPS. The inputs include effective capacities and energy displacement values obtained from the preceding models plus estimated PEPS capital and O&M costs. The program also takes as input desired variations in PEPS plant component costs as well as performance parameters such as cell efficiency and packing factor. The major output of the program is an index of relative economic viability which is measured by the plant capital cost, O&M costs, and system energy credits all normalized to equal effective capacity.

CURRENT STATUS

- REFERENCE SYSTEM SCREENING
- DATA COLLECTION

Figure 20 Indicates the current status of the project. The reference PEPS are being screened according to the methodologies previously described in order to select a few systems for further detailed costing and evaluation in actual utility systems. Siting and insolation data is being collected for areas to be studied and utilities are being contacted for their system data needed to make the detailed utility studies. The program which was initiated in March of this year is scheduled to be complete in April of 1977.