Assessment of Solar Options for Small Power Systems Applications

Volume V

SOLSTEP - A Computer Model for Solar Plant System Simulations

S. P. Bird

September 1980

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FOREWORD

Under the sponsorship of the U.S. Department of Energy's Division of Central Solar Technology, the Pacific Northwest Laboratory performed a comparative analysis of solar thermal conversion concepts that are potentially suitable for development as small electric power systems (1 to 10 MWe). Cogeneration and total energy systems were beyond the scope of this study.

Seven generic types of collectors, together with associated subsystems for electric power generation, were considered. The collectors can be classified into three categories: 1) two-axis tracking (with compound-curvature reflecting surfaces), 2) one-axis tracking (with single-curvature reflecting surfaces), and 3) nontracking (with low-concentration reflecting surfaces). All seven collectors were analyzed in conceptual system configurations with Rankine-cycle engines. In addition, two of the collectors (the Point Focus Central Receiver and the Point Focus Distributed Receiver) were analyzed with Brayton-cycle engines, and the latter of the two also was analyzed with Stirling-cycle engines. With these engine options, 10 systems were formulated for analysis.

This is the fifth volume of a five-volume report on the work performed to analyze the alternative concepts, and the results obtained. This volume includes a description of the computer code, SOLSTEP, used to calculate the thermodynamic and economic performance of the solar thermal concepts analyzed in this study. The five volumes are:

- Volume I Executive Summary
- Volume II Identification and Characterization of Concepts for Analysis
- Volume III Analysis of Concepts
- Volume IV Comparative Ranking of Concepts
- Volume V SOLSTEP - A Computer Model for Solar Plant System Simulations.

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ABSTRACT

The simulation code, SOLSTEP, was developed at the Pacific Northwest Laboratory to facilitate the evaluation of proposed designs for solar thermal power plants. It allows the user to analyze the thermodynamic and economic performance of a conceptual design for several field size-storage capacity configurations. This feature makes it possible to study the levelized energy cost of a proposed concept over a range of plant capacity factors.

The thermodynamic performance is analyzed on a time step basis using actual recorded meteorological and insolation data for specific geographic locations. The flexibility of the model enables the user to analyze both central and distributed generation concepts using either thermal or electric storage systems. The thermodynamic and economic analyses view the plant in a macroscopic manner as a combination of component subsystems. In the thermodynamic simulation, concentrator optical performance is modeled as a function of solar position; other aspects of collector performance can optionally be treated as functions of ambient air temperature, wind speed, and component power level. The power conversion model accounts for the effects of ambient air temperature, partial load operation, auxiliary power demands, and plant standby and startup energy requirements. The code was designed in a modular fashion to provide efficient evaluations of the collector system, total plant, and system economics.

SOLSTEP has been used to analyze a variety of solar thermal generic concepts involving several collector types and energy conversion and storage subsystems. The code's straightforward models and modular nature facilitated simple and inexpensive parametric studies of solar thermal power plant performance.

ASSESSMENT OF SOLAR OPTIONS FOR SMALL POWER SYSTEMS APPLICATIONS

VOLUME V

SOLSTEP - A COMPUTER MODEL FOR SOLAR PLANT SYSTEM SIMULATIONS

1.0 INTRODUCTION

The solar thermal power plant is one promising alternative for generating electricity using solar energy. In such a plant, solar insolation is collected by fields of concentrating mirrors and converted to electricity in a heat engine/generator set. Numerous alternative designs have been proposed for solar thermal plants. The various designs offer a wide range of collector configurations, heat engine types, and energy storage methods. Because of the large number and great diversity of contending solar thermal power plant designs, analytical performance simulation can serve as an extremely useful tool in their evaluation.

Such an evaluation was conducted by researchers at the Pacific Northwest Laboratory (PNL) as part of the Small Power Systems Program in the U.S. Department of Energy's Division of Central Solar Technology. The study (Laity et al. 1979) aimed to investigate the thermodynamic and economic performance of several proposed designs for solar thermal power plants. This goal required the development of a computer code that could be used to perform a thermodynamic simulation and economic analysis of a plant design under a wide variety of operating conditions. The code was to meet three major criteria:

- general applicability to model a diversity of solar thermal plant designs
- flexibility to allow an analysis of a design over a range of collector field and storage configurations
- low cost to provide analysis of numerous plant designs at a reasonable expense.

The code developed at PNL to fulfill these needs is SOLSTEP (Simulation of Localized Solar Thermal Electric Production). It is based on the framework of computer programs used in earlier solar thermal studies. Specifically, these were a set of programs developed by the Aerospace Corporation's Energy Programs Group (1975) that were subsequently consolidated and modified at the California Institute of Technology's Jet Propulsion Laboratory (JPL) (Caputo 1977; Fujita et al. 1977; El Gabalawi et al. 1978).

This report describes the features and methodology of the PNL simulation code. Section 2.0 briefly discusses the overall operation of the code. In Section 3.0 each of the models is briefly described. Section 4.0 provides some comments on using the code for plant simulations. The Appendix contains a sample set of input variables and presents the various types of output available.

2.0 OVERVIEW

The SOLSTEP code provides an integrated analysis of the thermodynamic and economic performance of a solar thermal power plant design. Input parameters describe the operating performance and costing relationships for major plant components and the economic conditions under which the postulated plants will be constructed. Results of the analysis include the electrical energy production, plant capacity factor, construction and operating costs, and the resulting levelized busbar energy cost.

The simulation model in SOLSTEP is quasi-steady-state. Simulations are performed over a long time period by analyzing plant performance during a series of short time intervals. Steady-state analysis at each time step, then, yields an approximate estimate of the transient performance of the plant over the longer time period. An analysis may be conducted for any number of days. The low cost of running the code makes year-long simulations highly feasible and, in fact, the standard practice.

Actual site-specific meteorological and insolation data are used in the performance simulation. Consequently, plant designs can be evaluated under a variety of realistic operating conditions. The performance of a number of plant concepts may be compared at a particular geographic location. Likewise, the performance of a single design may also be compared at various locations.

The primary results obtained with the SOLSTEP code are the estimated quantity and cost of energy produced using a postulated solar thermal power plant design. Energy production levels are quantified in terms of a dimensionless plant capacity factor:

$$\text{Capacity factor} = \frac{\text{Energy generated in a time interval (kWh)}}{\text{Nominal plant rating (kW)} \times \text{length of time interval (hr)}}$$

Describing energy generation rates in this manner normalizes results for the length of the simulation period and the nominal size of the plant design. The

cost of a solar thermal plant design is expressed as a levelized busbar energy cost:

$$\text{Levelized energy cost (mills/kWh)} = \frac{\text{Annualized cost of plant (\$)}}{\text{Energy generated in a year (kWh)}} \times 1000.$$

This term provides a single quantity that includes the long-term energy production levels, plant construction costs, and life cycle operating and maintenance, component replacement, and financial charges.

In the design of a solar thermal power plant, it is important to achieve an optimal balance between the collector field size and storage capacity for a given electrical generating capacity. SOLSTEP, using a multipoint analysis technique from the JPL simulation program (El Gabalawi et al. 1978), is especially suited for optimization studies of this type. After selecting a nominal plant output, the user may specify an array of alternative field sizes and storage capacities. A simulation is performed for each combination of field and storage to determine the plant energy production. When the thermodynamic analysis has been completed for every combination, an economic analysis is performed. This second step uses the energy production results for each configuration, generates plant cost figures based on the configurations, and then calculates a levelized energy cost at each point.

Typical results for an analysis of this type are presented in Figure 2.1. The series of adjacent curves represents the results for each specified field size. Points on each curve correspond to the array of storage capacities (in terms of hours of storage) considered. Each point on the graph depicts an energy production figure, specified in terms of a plant capacity factor, and a levelized energy cost for a particular plant configuration. Note that at smaller field sizes only the smaller storage capacities are represented. This is because the code considers one field size at a time and calculates performance at increasing storage capacities. When it is clear that the addition of further storage capacity yields no increase in plant output and, therefore, would not be cost effective, the calculation for that field size is completed and the next field size is considered, again starting at the lowest storage capacity.

FIGURE 2.1. Sample Plot of Energy Cost Versus Capacity Factor

The significant portion of the plot in Figure 2.1 is the broad curve across the bottom of the matrix. This envelope represents the locus of field and storage combinations that yields the minimum levelized energy costs over the range of capacity factor. These are the plant designs in which field size and storage capacity are matched to achieve optimal performance. This curve has a number of uses. It shows how levelized energy cost varies with capacity factor for a concept; or it may be used to select the least-cost field and storage combination at a specific capacity factor, or to select the overall least-cost plant design and the corresponding capacity factor and levelized energy cost.

The preceding discussion points out that SOLSTEP does not simulate a single plant design but rather conducts a multipoint analysis of a variety of

design configurations for a solar thermal concept. To conduct this analysis efficiently, SOLSTEP employs a modular structure based on the framework used in the JPL simulation program (El Gabalawi et al. 1978). The code is actually three distinct computer programs that may be run independently. Normally, they are run consecutively, passing information from one program to the next. The first program unit, FIELD, reads the meteorological and insolation data and models the concentrator and receiver subsystems. It simulates these components in the quasi-steady-state manner previously discussed, conducting performance calculations at a series of successive time steps. The time history of energy collected as calculated by FIELD is used as input by the second program, POWER. This section of the code evaluates the thermodynamic performance of the energy transport, storage, and conversion subsystems, again with the time step analysis. The array of collector field sizes and storage capacities is introduced into this section of the code. The capacity factor for each field-storage combination is calculated in an iterative fashion. This information is then used in the economic analysis conducted by ECON, the third program unit. The ECON section calculates capital costs and operating and maintenance costs for each plant configuration and the corresponding levelized energy cost. The organization of the SOLSTEP code is represented schematically in Figure 2.2.

This modular scheme has numerous advantages. Reading the meteorological and insolation data and calculating the concentrator optical performance at each time step is an expensive operation. These tasks are performed only once, in the FIELD program, on a unit collector field area basis. The POWER program can then use these results to calculate plant performance for numerous field sizes without repeating the calculations. In addition, it is possible to run the FIELD program once for a collector system, store the results, and run the POWER program many times to study the performance of alternative energy conversion subsystems operated with the same collector design. Separation of the economic analysis provides a similar advantage. The FIELD and POWER programs can be run once to determine the thermodynamic performance of a concept design. Storing this information, several sets of economic assumptions may be tested by repeated runs of the ECON program.

FIGURE 2.2. SOLSTEP Code Organization

The code performs all thermodynamic calculations using a macroscopic approach. Major component subsystems are treated as units in the computational procedure. The component breakdown for a typical plant using thermal storage and central power conversion is shown in Figure 2.3. Following this macroscopic concept, thermodynamic relationships for component performance are reduced to equations involving the rate or amount of energy transport. That is, the component operations are described in terms of kilowatts or kilowatt-hours of energy received, converted, stored, etc., rather than by the more

FIGURE 2.3. Component Subsystems
for a Central Generation, Thermal
Storage Concept

exact specification of temperature, pressure, enthalpy, and mass flow rate. This leads to a greatly simplified performance model with correspondingly reduced computer run times. For the economic evaluation, system costs are also based on the major component subsystems.

Variable inputs to the code are supplied in a series of FORTRAN NAMELIST files. The NAMELIST structure provides numerous advantages: it minimizes formatting problems, lends itself readily to setting up default values for variables, and provides an input stream that is easily read and understood without additional descriptive information.

3.0 METHODOLOGY

This section presents the methodology used in the performance simulation models and the general method of the economic evaluation. The intent here is to familiarize the reader with the major equations used but not with the details of the computational procedures. The discussion should enable users to understand the role of each of the input variables in the calculations and to assemble their own set of input data. The discussion is organized to follow the modular framework of the program units in the code.

3.1 FIELD PROGRAM

The FIELD program contains the models for the concentrator and receiver subsystems. Calculations are performed on a unit collector area basis for each of the time steps in the analysis period. This section presents the methodology used in the FIELD program and each of the supporting subroutines, briefly discusses the various types of output available, and summarizes the input variables.

FIELD considers both direct and diffuse solar insolation to determine the total energy available to the solar thermal system:

$$SOL = XDRC \times DRCSOL + XDFS \times DFSSOL$$

where

SOL - total available energy (kWh/m^2)
XDRC - fraction of direct insolation collected
DRCSOL - direct insolation (kWh/m^2)
XDFS - fraction of diffuse insolation collected
DFSSOL - diffuse insolation (kWh/m^2).

The fraction of direct insolation collected would normally be one. The fraction of diffuse insolation would be zero for focusing systems but could be set to a nonzero value for systems that use a portion of the diffuse insolation, such as the compound parabolic concentrator.

The overall efficiency of the collector subsystem is expressed by a series of component efficiencies. The total energy collected by the field is then expressed as

$$ECF = SOL \times AC \times ETACOL \times ETACR \times ETAREC - THRLSS \times DTIME \times AC$$

where

ECF - total energy collected (kWh/m^2)

SOL - total available energy (kWh/m^2)

AC - unit area used in analysis (normally 1 m^2)

ETACOL - concentrator efficiency

ETACR - concentrator-receiver transfer efficiency

ETAREC - receiver efficiency

THRLSS - receiver thermal loss (kW/m^2)

DTIME - analysis time step.

Each of the component efficiencies is, itself, also made up of a number of parameters. The concentrator efficiency is expressed as

$$ETACOL = OPTEFC \times DEGFAC \times ETAGO(\text{solar position})$$

where OPTEFC is the optical efficiency of the concentrator surface (reflectivity for a mirror, transmissivity for a lens). DEGFAC is a quantity equal to one minus the average fractional reduction in optical performance that can be expected due to surface degradation during the analysis period. The geometric optics efficiency, ETAGO, is a function of solar position. SOLSTEP can handle the functional relationship in two ways: ETAGO can be entered as a function of time of day and time of year or as a function of solar altitude and azimuth. Separate subroutines are used depending on which option is selected. These subroutines are discussed in Section 3.1.2.

The concentrator-receiver transfer efficiency is expressed as

$$ETACR = ATMOS \times COLREC(WIND)$$

ATMOS is one minus the fractional reduction of transfer efficiency due to atmospheric attenuation between the concentrator and receiver. COLREC is the concentrator-receiver interception factor that accounts for tracking and spillage errors. COLREC may be optionally input as a function of wind speed.

The receiver efficiency is described by two quantities:

$$ETAREC = ABSORB \times ETATHR$$

and

$$THRLSS = THRLSS (PTRAN, TAMB, WIND)$$

ABSORB is absorptivity of the receiver surface. ETATHR is the receiver thermal loss efficiency factor. The receiver performance is also characterized by a constant thermal loss per unit area, THRLSS. This quantity is a threshold energy loss term that can optionally be treated as a function of three parameters. PTRAN is the power reaching the receiver, TAMB is the ambient air temperature, and WIND is the wind speed.

3.1.1 Insolation Data Input Subroutines

Currently, SOLSTEP is capable of reading meteorological and insolation data in five formats. The first four are standard insolation data sources that include two types of data prepared by the Aerospace Corporation (1978), data in the standard SOLMET format prepared by the National Climatic Center (NCC) (1977) and Typical Meteorological Year (TMY) data prepared by Sandia Laboratories, Albuquerque, also available from NCC. A summary of these data and the geographical sites they represent appears in Table 3.1. The SOLSTEP code contains a separate subroutine to read and decode insolation data in each of these formats (subroutines AERO, BARSTW, SOLMET, and TMY, respectively). Each data source provides direct insolation, ambient dry bulb air temperature, and wind direction and speed. Depending on the source, various other types of information may be provided. A summary of the available data appears in Table 3.2. Although not currently incorporated into the analysis, these

TABLE 3.1. Meteorological and Insolation Data Compatible
with the SOLSTEP Code

<u>Organization</u>	<u>Recording Interval</u>	<u>Locations Available</u>
Aerospace	1 hour	Albuquerque, New Mexico Inyokern-China Lake, California Yuma, Arizona Edwards AFB, California Riverside, California
Aerospace	15 minutes	Barstow, California
National Climatic Center (SOLMET)	1 hour	Fort Worth, Texas Lake Charles, Louisiana Columbia, Missouri Apalachicola, Florida Miami, Florida Brownsville, Texas Charleston, South Carolina Nashville, Tennessee Stephenville, Texas Dodge City, Kansas Caribou, Maine Madison, Wisconsin El Paso, Texas Albuquerque, New Mexico Ely, Nevada Phoenix, Arizona Santa Maria, California Bismarck, North Dakota Great Falls, Montana Medford, Oregon Seattle Tacoma, Washington Fresno, California Cape Hatteras, North Carolina Sterling, Virginia Boston, Massachusetts New York, New York Omaha, Nebraska
National Climatic Center (Sandia TMY)	1 hour	Same as SOLMET

TABLE 3.2. Available Insolation and Meteorological Data

	Data Source			
	<u>Aerospace</u>	<u>Barstow</u>	<u>SOLMET</u>	<u>TMY</u>
Direct insolation	X	X	X	X
Diffuse insolation		X	X	X
Global radiation	X	X	X	X
Solar altitude	X	X		
Solar azimuth	X	X		
Solar declination	X	X		
Dry bulb temperature	X	X	X	X
Dewpoint temperature	X	X	X	X
Wind direction	X	X	X	X
Wind speed	X	X	X	X

additional data items are read and decoded by the appropriate input subroutines in the event that the user may wish to modify the program to account for additional factors.

The fifth format provides an efficiency step that can be used when the FIELD program is to be run many times using the same data. The process of reading the insolation data tape and decoding the useful information represents a significant portion of the cost of running the FIELD program. When the process must be repeated many times, it is advantageous to read and decode the tape once and write out the useful information in noncoded binary format. Using the fifth format, these binary data can then be read much faster than normal input. This procedure reduces the required computer time for a typical FIELD run by a factor of three.

The type of insolation data used has a direct effect on the simulation time step that may be used in the FIELD and POWER programs. Except for the Aerospace Barstow tape, all of the data in Table 3.1 are recorded at hourly intervals and, therefore, simulations using these data must use a 1-hour time step. The Aerospace Barstow data are recorded at 15-minute intervals. SOLSTEP is capable of using these data to perform simulations with any time step that is an integral multiple of 15 minutes and divides evenly into 24 hours.

An auxiliary subroutine, ERTRAN, is called by the four input data subroutines to manipulate the insolation data tape used in the analysis. The Aerospace, Barstow, and SOLMET data tapes are formatted with very large data blocks that must be read using buffer input routines. In addition, some of the tapes contain multiple data sets that are partitioned into separate files (Aerospace and SOLMET) or a series of blocks (TMY) on one tape. ERTRAN performs the buffer input and tape positioning required to handle these two characteristics.

3.1.2 Geometric Optics Subroutines

One very important aspect of the concentrator performance is the geometric optical efficiency of the mirror field. This quantity includes optical losses associated with cosine effects, blocking, and shading. It is determined for each time step by interpolating a table of geometric optics data supplied by the user.

The table of optical efficiencies is entered into the program as a function of the sun's position. SOLSTEP employs two separate subroutines that enable the user to express solar position in terms of the time of day and day of year (Subroutine FIT) or the solar altitude and azimuth angle (Subroutine FITAA) as desired. Either method has advantages. For the first approach the time-of-day specification for the table is matched to the time step of the analysis. This makes it possible to enter the table of optics data at one point along the time-of-day axis and perform a one-dimensional interpolation to determine the correct value for the day of year. The second approach requires a two-dimensional interpolation for altitude and azimuth. However, it requires fewer points in the table to obtain comparable accuracy.

As noted in Table 3.2, the SOLMET and TMY insolation tapes do not contain solar altitude and azimuth information. If the altitude/azimuth optics option is selected when using either of these data bases, an auxiliary subroutine, ANGLE, is called. ANGLE calculates solar altitude and azimuth angle based on the day of year and solar time read from the data tape and the latitude at the plant's location input by the user.

A table of geometric optics data, then, is input to the code for each collector concept. This method presents numerous advantages over performing the optics calculations in the simulation code. Data may be obtained from a variety of sources such as experiments, manufacturers' publications, or other computer programs.^(a) They can then be converted to the appropriate format and used with no changes to the simulation code. They may also be modified at any time, again with no program changes. The geometric optics efficiency values need be calculated only once, and can then be used for any number of simulation studies without the computation charges of recalculating the values during each computer run. Finally, it is possible to prepare various sets of optical data and use them interchangeably for a single concept. This feature allows the user to account for geometric optics variations with factors such as plant size or ground cover ratio.

3.1.3 FIELD Output

The user may select various levels of printed output from the FIELD program. At each time step, a listing is available of the incident insolation, field collection efficiency, energy collected, ambient air temperature, and geometric optics efficiency. This optional information may be printed for each day in the analysis period or for one day from each month. A summary table providing the total insolation and total energy collected during the analysis period, the number of intervals with insolation, and the average insolation and energy collected for sunny periods is printed for all cases.

3.1.4 Summary of FIELD Input Variables

The first record of input to the FIELD program is an alphanumeric string that is used to input the title to be printed on all computer output. Following this record are three NAMELIST files. They include parameters for conducting the simulation (SIMPAR), geometric optics data (GOEDAT), and performance variables for the concentrator and receiver subsystems (SYSTIN).

(a) One computer program, SHADE (Apley 1979), calculates geometric optics data for point-focused, distributed receiver systems and outputs the results in a format designed for use with SOLSTEP.

SIMPAR

- AC - unit collector area to be used in analysis. Default 1.0 m^2 .
- STARTD - day of year on which analysis is to begin. Integer variable.
Default 1.
- NDAYS - number of days to be used in analysis period (1-366).
- DTIME - time step for analysis (hours):
Hourly data - DTIME = 1.0
15-minute data - DTIME = 0.25.
- ITYPE - type of insolation data to be used. The data tape must be assigned to Unit 11:
- 1 - Aerospace
 - 2 - Barstow
 - 3 - SOLMET
 - 4 - Typical Meteorological Year
 - 5 - Pre-decoded binary file.
- NFILE - tape file containing insolation data, used with multi-file data tapes (Aerospace, SOLMET and TMY).
- IBF - set equal to 1 to create a decoded binary file that can be used in future analysis with ITYPE = 5. The file is written to Unit 10. Default 0.
- IPRNT - output print option:
- <0 - print data for each day analyzed
 - 0 - do not print daily data
 - N - print data for Nth day of each month.
- Default 1.

GOEDAT

- GOEOPT - option for type of geometric optics data.
- 1 - data as function of time of day and day of year.
User must input GOE, BEGINT, and NINT.
 - 2 - data as function of altitude and azimuth angles. User must input GOE, NALT, ALTDAT, NAZM, and AZMDAT. To use this option with SOLMET (ITYPE = 3) or TMY (ITYPE = 4) data, user must also input XLAT.

GOE - array of geometric optics data.

GOEOPT = 1 The array is treated as GOE (12, NINT).
 Supply 12 values (one for the 21st day of each month) for each time interval.

GOEOPT = 2 The array is treated as GOE (NAZM, NALT).
 Supply NAZM x NALT values corresponding to the angles specified in ALTDAT and AZMDAT.

BEGINT - time of day at end of first interval for which GOE data are supplied (hours, minutes). (4:15 a.m. would be expressed as 4.15.)

NINT - number of time intervals during each day for which GOE data are supplied. Maximum 64.

NALT - number of altitude angles. Maximum 10.

ALTDAT - array of altitude angles.

NAZM - number of azimuth angles. Maximum 15.

AZMDAT - array of azimuth angles.

XLAT - latitude of site being analyzed.

SYSTIN

OPTEFC - concentrator optical efficiency.

DEGFAC - concentrator surface degradation factor.

COLREC - concentrator-receiver interception factor.

NCRW - number of points in optional array of wind speed correction factors for COLREC. Maximum 10. Default 0.

CRWFC - array of correction factors.

CRW - array of corresponding wind speeds (m/s).

ATMOS - efficiency factor for atmospheric attenuation between collector and receiver.

ABSORB - receiver absorption coefficient.

ETATHR - receiver thermal loss efficiency.

THRLSS - constant receiver thermal loss (kW/m^2 of field area).

NTHRP - number of points in optional array of energy transfer rate correction factors for THRLSS. Maximum 20. Default 0.

THRPFC - array of correction factors.

THRP - array of corresponding energy transfer rates (kW/m^2 of field area).

NTHRT - number of points in optional array of ambient air temperature correction factors for THRLSS. Maximum 10. Default 0.

THRTFC - array of correction factors.

THRT - array of corresponding air temperatures ($^{\circ}\text{C}$).

NTHRW - number of points in optional array of wind speed correction factors for THRLSS. Maximum 10. Default 0.

THRWFC - array of correction factors.

THRW - array of corresponding wind speeds (m/s).

XDRC - fraction of direct insolation to be used. Default 1.

XDFS - fraction of diffuse insolation to be used. Default 0.

3.2 POWER PROGRAM

The POWER program models the energy transport, storage, and conversion subsystems. It reads and uses the results from the FIELD program for energy collected during each analysis time interval. To this point the collected energy values are expressed on a per unit area of collector field basis. In the POWER program a series of field sizes is introduced and iteratively analyzed.

The user also inputs an array of storage sizes. For each field size the POWER program selects the smallest storage size and conducts a thermodynamic simulation of the field-storage combination. POWER then repeats the analysis with the next larger storage capacity. The program continues to analyze the current field size with increasingly larger storage capacities until the addition of storage does not yield an increase in capacity factor. At this point, the collector field is not large enough to produce enough energy to utilize any additional storage capacity, and adding storage would be uneconomical. POWER selects the next field size and repeats the procedure, again starting with the smallest storage size.

Two distinctly different operational configurations are handled by the POWER program, each in a separate subroutine. The first, THRMAL, considers a

plant design with a thermal storage subsystem and a centralized power conversion unit. This type of plant would typically operate on a Rankine cycle. Electric battery storage is employed in the second configuration using the ELCTRC subroutine. For electric options the power conversion subsystem may be either a large central unit or many smaller distributed engines. They would typically employ Brayton or Stirling conversion cycles.

Either subroutine calculates the plant output at each time step by considering the performance of the plant in a number of different operational modes. The operational modes involve various combinations of using energy from the field to run the heat engines, cycling energy into and out of storage, and starting the heat engines after inoperative periods. At the beginning of each time step, the model checks the available energy from the field and in storage. Based on this available energy, it then calculates the total electrical energy output (TEO) that could be produced by operating in each of the modes. In calculating TEO the program considers both the direct electric energy (DE) that could be produced during this time step and the potential electric energy (PE) that could be produced at a future time by operating in this mode:

$$TEO = DE + PE$$

That is, the model gives credit for putting energy into storage, but also accounts for a decrease in available potential energy when energy is drawn out of storage. The TEO value is calculated for each operating mode; that mode resulting in the maximum TEO is selected as the operational mode during that time step.

The remainder of this section discusses each of the POWER subroutines, briefly describes the various types of output available, and summarizes the required input variables.

3.2.1. Subroutine THRMAL

Subroutine THRMAL contains the energy transport, storage, and conversion models for systems operating with thermal storage. The thermal storage option

models six plant operational modes as shown in Figure 3.1. In determining the plant output from each mode, THRMAL considers the effect of auxiliary loads, standby and startup energy requirements, partial load operation, and ambient conditions on the performance of the energy conversion subsystem. These effects will be discussed first so that the subsequent discussion of the operational modes might be more clear.

Four major plant auxiliary loads are treated in the model: the feedwater pump, the field recirculating pump, the storage input pump, and the storage output pump. These four were found to be the primary loads on an energy conversion unit operating with a thermal storage subsystem. The value for each load for a specific set of conditions is calculated in a separate function subprogram. These functions are discussed in more detail later in this section.

For many solar thermal power plant designs, significant energy will be required to start the turbine and keep the turbine, condenser, and heat exchangers at standby readiness. It is possible to incorporate these energy requirements into a simulation using THRMAL. The turbine startup energy demand is calculated in Mode 2. This process is characterized by two quantities: a bulk amount of energy required to heat the turbine and bring it to synchronization at zero load (SUENG), and a minimum time limit required to ramp the turbine to full load (TMSUE). In addition to energy for startup, certain standby requirements may be considered for various components. These include a turbine standby demand (SBENG) that can be used to keep the turbine at warm standby or maintain condenser vacuum, and standby heating for input (SBSTI) and output (SBSTO) storage heat exchangers. The standby requirements are included in each of the six operational modes, where appropriate. They are satisfied from thermal storage, when it is available; otherwise, they require electric energy.

The engine model includes a nominal operating efficiency and corrections for partial load operation and ambient air temperature effects. Each of the correction relationships is input as a series of correction factors and a corresponding series of partial load or ambient air temperature values. Heat engines operating from thermal storage at a lower temperature than energy from

FOR EACH COMBINATION
OF COLLECTOR FIELD SIZE
AND STORAGE CAPACITY:

CALCULATE PLANT
OUTPUT AND ENERGY
STORED FOR EACH MODE:

FIGURE 3.1. Operational Modes for POWER Model - Thermal Storage Option

the field have a lower nominal operating efficiency and often have different partial load and ambient air temperature performance. For this reason the user may input a second set of the above-mentioned variables for operation from storage. Normally, the model attempts to provide a net electrical generation equal to the nominal plant rating (PLSIZE) whenever possible. If desired, the user may specify a derated power generation level ($SRAT \times PLSIZE$) as the maximum plant output when operating from storage.

The thermal storage model is very simple. It is characterized by an input efficiency (ETASI), an output efficiency (ETASO), and a thermal loss per

hour as a percentage of the energy in storage (ASLOSS). A fourth variable (QSMIN) makes it possible to specify a minimum storage level below which stored energy may not be extracted. The user specifies storage sizes by specifying a number of hours for which the plant should operate at rated output while running from storage (ST). The model then converts this hour value to a thermal capacity:

$$STSIZE = \frac{QENG \times ST}{DTIME \times ETASO \times (1-QSMIN) \times (1-ASLOSS \times 24)}$$

where

STSIZE - thermal storage capacity (kWh)
 QENG - thermal energy input to heat engine (kWh)
 ST - storage size (hr)
 DTIME - length of time step (hr)
 ETASO - storage output efficiency
 QSMIN - minimum storage level
 ASLOSS - storage hourly loss (hr^{-1})

and

$$QENG = \frac{PLSIZE \times 1000 \times DTIME \times SRAT + AUXFW + AUXSTO}{ETAS}$$

where

PLSIZE - nominal plant rating (MW)
 SRAT - storage rating factor
 AUXFW - feedwater pump energy requirement calculated by Function
 AUXFW (kWh)
 AUXSTO - storage outlet pump energy requirement calculated by
 Function AUXSTO (kWh)
 ETAS - nominal engine efficiency when operating from storage.

The thermal energy in storage (QST) at the end of each time step is some fraction of STSIZE. It is calculated as

$$QST_t = QST_{t-1} - QSOUT + QSIN - QSLOSS$$

where

- QST_t - stored thermal energy (kWh)
- QST_{t-1} - stored thermal energy after previous time step (kWh)
- $QSOUT$ - storage discharge during time step (kWh)
- $QSIN$ - storage charge during time step (kWh)
- $QSLOSS$ - storage losses during time step (kWh).

The losses are determined by

$$QSLOSS = QST_{t-1} \times ASLOSS \times DTIME$$

where

$DTIME$ - length of time step (hours).

At the beginning of each time step the program calculates the available energy that can be drawn out of storage ($QSAVL$) and the unused storage capacity that can be charged ($QSACC$):

$$QSAVL = QST - (STSIZE \times QSMIN)$$

and

$$QSACC = STSIZE - QST.$$

The energy available from the field is also calculated at the beginning of each time step. The energy per unit area value determined by the FIELD program is multiplied by each of the field sizes input by the user. A corresponding series of field correction ratios makes it possible to account for the cases where total available energy may not necessarily be directly proportional to field size (for example, added optical losses in extremely large central receiver field layouts). A second series of correction factors can be used to account for thermal losses from the energy transport system as a function of field size. The total energy available from the collector field for each time step is then

$$QF = ECF \times AC(I) \times ECR(I) \times TRNEFF(I)$$

where

QF - energy made available to energy conversion subsystem (kWh)

ECF - energy collected (kWh/m²)

AC(I) - array of field sizes to be analyzed (m²)

ECR(I) - array of field correction ratios

TRNEFF(I) - array of energy transport thermal efficiencies.

Each of the six operational modes considered in Subroutine THRMAL is shown in Figure 3.1. After checking the energy available from the field and in storage, the model proceeds to calculate the energy that could be produced and stored by operating in each of the six modes. Following is a brief description of the computational procedure used for each mode.

MODE 1 Plant Shut Down

This mode would be selected if there were insufficient energy available from the field or in storage to run the heat engine efficiently. The standby requirements are

$$QSB = (SBENG + SBSTI + SBSTO) \times DTIME$$

where

QSB - standby energy requirement (kWh).

If there is enough energy in storage to supply the standby requirements, the energy produced during the time step (DE) and the energy in storage at the end of the time step (PE) are expressed as

$$DE = 0$$

and

$$PE = (QSAVL - QSB - QSLOSS) \times ETASO \times ETAS.$$

Otherwise, the plant must "purchase" electrical energy to provide the standby requirement and the amount is subtracted from the total energy production:

$$DE = -QSB$$

and

$$PE = (QSAVL - QSLOSS) \times ETASO \times ETAS.$$

There is a further refinement to the model described. If the heat engine is shut down it will have to be restarted at a future time and the plant will incur an energy penalty (SUENG) at that time. Therefore, if the plant were not already shut down in the previous time step, SUENG would be subtracted from the potential energy value to more accurately reflect the ultimate disposition of stored energy.

MODE 2 Start Up Heat Engine

This operational mode is investigated any time the plant was shut down in the previous time step, and must be selected before the plant can cycle to any of the subsequent modes. The start-up operation modeled in Mode 2 has two phases. During the first phase the model attempts to warm and synchronize the heat engine by supplying an initial amount of bulk energy, SUENG, from the FIELD. During this period, auxiliary demands are met from the grid; standby requirements are satisfied from storage.

$$AXLD = AUXFW + AUXFLD$$

where

AXLD - auxiliary load requirement (kWh)

AUXFW - feedwater pump energy requirement calculated by Function
AUXFW (kWh)

AUXFLD - field recirculating pump energy requirement calculated by
Function AUXFLD (kWh).

In addition,

$$QSB = (SBSTI + SBSTO) \times DTIME,$$

$$DE = - AXLD,$$

and

$$PE = (QSAVL - QSB - QSLOSS) \times ETASO \times ETAS.$$

Or, if no energy is available in storage,

$$DE = -(AXLD + QSB)$$

and

$$PE = (QSAVL - QSLOSS) \times ETAS \times ETAS.$$

The program will continue selecting Mode 2 until the SUENG requirement has been satisfied. The second phase brings the heat engine from synchronization to full load at a rate set by the user-specified ramp rate, TMSUE. In this phase the energy conversion system will produce some electrical output.

$$AXLD = AUXFW + AUXFLD,$$

$$QSB = (SBSTO + SBSTI) \times DTIME,$$

and

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL - AXLD$$

where

QENG - thermal energy input to heat engine (kWh)

ETAF - nominal heat engine efficiency operating from the field

TEMPCF - ambient air temperature correction calculated for operation from the field

ETAPL - partial load correction calculated for QENG from the field
and

$$PE = (QSAVL - QSB - QSLOSS) \times ETASO \times ETAS.$$

Or, if no energy is available in storage,

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL - AXLD - QSB$$

and

$$PE = (QSAVL - QSLOSS) \times ETASO \times ETAS.$$

If the energy available from the field is greater than that which the ramp rate permits to go to the heat engine, the excess thermal energy will be provided to storage (QSIN). In this case,

$$AXLD = AUXFW + AUXFLD + AUXSTI$$

where

AUXSTI - storage input pump energy requirement calculated by Function AUXSTI (kWh).

In addition,

$$QSB = SBSTO \times DTIME,$$

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL - AXLD,$$

and

$$PE = (QSAVL + QSIN - QSB - QSLOSS) \times ETASO \times ETAS.$$

After entering the second phase, the program will continue to select Mode 2 during subsequent time periods until TMSUE has elapsed.

MODE 3 Run from Storage, Field Shut Down

The third mode is an option for running the heat engine from thermal storage. It would normally be selected at the end of a day when storage is charged but insufficient energy is available from the field to efficiently run the heat engine.

$$AXLD = AUXSTO$$

where

AUXSTO - storage output pump energy requirement calculated by Function AUXSTO (kWh).

In addition,

$$QSB = SBSTI \times DTIME$$

and

$$DE = QENG \times ETAS \times TEMPCS \times ETAPL - AXLD$$

where

QENG - thermal energy input to heat engine (kWh)

ETAS - nominal heat engine efficiency operating from storage

TEMPCS - ambient air temperature correction calculated for operation from storage

ETAPL - partial load correction calculated for QENG from storage

and

$$PE = (QSAVL - QENG/ETASO - QSB - QSLOSS) \times ETASO \times ETAS.$$

MODE 4 Run from Storage, Charge Storage

This mode represents a somewhat complicated operational scheme. It would be selected when there was a large quantity of thermal energy available in storage and a relatively small amount from the field. Under these conditions partial load penalties would not allow efficient operation of the heat engine from the field. The heat engine is then run at full load (or near full load) from storage, while energy from the field is channeled into storage. The utilization of all major subsystems leads to high auxiliary loads and no standby requirements:

$$AXLD = AUXFW + AUXFLD + AUXSTI + AUXSTO,$$

$$QSB = 0,$$

and

$$DE = QENG \times ETAS \times TEMPCS \times ETAPL - AXLD$$

where

QENG - thermal energy input to heat engine (kWh)

ETAS - nominal heat engine efficiency operating from storage

TEMPCS - ambient air temperature correction calculated for operation from storage

ETAPL - partial load correction calculated for QENG from storage.

In addition,

$$PE = (QSAVL + QSIN - QENG/ETASO - QSLOSS) \times ETASO \times ETAS$$

where

QSIN - thermal energy input to storage (kWh).

MODE 5 Run from Field, Storage Shut Down

In this mode the heat engine is run directly from energy coming from the field. Mode 5 would be the normal daily operating mode for plant designs

without thermal storage subsystems. It can also be selected by plants with storage when storage is fully charged or when the amount of energy available to put in storage is not large enough to balance the added auxiliary requirement of running the storage input pumps.

$$AXLD = AUXFW + AUXFLD,$$

$$QSB = (SBSTO + SBSTI) \times DTIME,$$

and

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL - AXLD$$

where

QENG - thermal energy input to heat engine (kWh)

ETAF - nominal heat engine efficiency operating from the field

TEMPCF - ambient air temperature correction calculated for operation from the field

ETAPL - partial load correction calculated for QENG from the field.

In addition,

$$PE = (QSAVL - QSB - QSLOSS) \times ETASO \times ETAS.$$

If the energy available from the field is more than the energy required to run the heat engine at full load and meet all auxiliary requirements, or if there is no thermal storage subsystem, the extra energy is not used. Further, in systems with no storage, the standby requirements (QSB) are set equal to zero.

MODE 6 Run from Field, Charge Storage

Mode 6 is the normal daily operational mode for plant designs with thermal storage subsystems. The heat engine is run at full load with energy from the field and any extra available energy is sent to storage.

$$AXLD = AUXFW + AUXFLD + AUXSTI,$$

$$QSB = SBSTO \times DTIME,$$

and

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL - AXLD$$

where

QENG - thermal energy input to heat engine (kWh)

ETAF - nominal heat engine efficiency operating from the field

TEMPCF - ambient air temperature correction calculated for operation from the field

ETAPL - partial load correction calculated for QENG from the field.

In addition,

$$PE = (QSAVL + QSIN - QSB - QSLOSS) \times ETASO \times ETAS$$

where

QSIN - thermal energy input to storage (kWh).

When storage becomes fully charged the extra energy available from the field is not used.

At each time step the program generally calculates a direct energy (DE) and potential energy (PE) for each of the operational modes. These two values are added together to arrive at the total eventual energy production (TEO). The mode yielding the highest TEO is selected as the operational mode for this time step. This procedure is followed for each time step with three exceptions. If the heat engine was not running during the previous time step, it must be started by selecting Mode 2. In this case only Mode 1 (leaving the plant shut down) and Mode 2 are checked. The second exception occurs when there is no energy available from the field and a small amount of energy is available in storage (as would occur at the end of a day). In this case the

stored energy above a specified value is extracted to run the heat engine even though ambient conditions or partial load considerations might cause the direct energy that can be produced (Mode 3) to be slightly less than the potential energy that might be produced if the energy was left in storage (Mode 1) and used at a later time. The third exception is actually a set of exceptions, each with slightly different results. Before performing the calculations for some modes, some minor checking is done for the amount of energy available from the field, the amount of available energy in storage, and the available, uncharged capacity remaining in storage. Based on these checks, the program bypasses modes that are obviously not practical. For example, with no energy from the field, the program would skip Modes 4, 5, and 6; if storage were completely full, Mode 6 would be bypassed.

The engine model for plants using thermal energy storage requires the computation of four types of auxiliary loads: the feedwater pump, field recirculating pump, storage input pump, and storage output pump. The appropriate value for each load for a specific set of operating conditions is calculated via FORTRAN statement functions internal to Subroutine THRMAL. The computational procedure in each subprogram includes the effects of field size, ground cover ratio, storage size, and energy flow rate as indicated in Table 3.3.

Generally, specifying pumping power requirements as a function of energy flow rates is an acceptable alternative to the more exact mass flow rate relationship. It can be assumed that the plant will be operated in a fashion that will maintain subsystem temperatures near design points. It is, therefore, simple to convert a mass flow rate relationship to one based on energy flow rates. This is not true, however, for the feedwater pump, which may operate with energy from storage at a significantly lower temperature than energy from the field. In this case the pumping requirement would be correspondingly higher for a given energy flow rate from storage than for an equal energy flow rate from the field. To correct for this effect, the feedwater pump model includes a correction factor to account for increased pumping loads

TABLE 3.3. Auxiliary Loads for Engines Operating with Thermal Storage Systems

<u>Auxiliary Load</u>	<u>Function of</u>	<u>Function Name</u>
Feedwater pump	Field size	AUXFW
	Ground cover ratio	
	Energy flow rate	
Field recirculating pump	Field size	AUXFLD
	Ground cover ratio	
	Energy flow rate	
Storage input pump	Storage size	AUXSTI
	Energy flow rate	
Storage output pump	Energy flow rate	AUXSTO

while operating the heat engine from storage. The form of each auxiliary load calculation appears in the following paragraphs. Factors common to all four auxiliary loads are

IPP - installed pumping power (kW)

DTIME - length of time step (hr).

Feedwater pump load, AUXFW

$$IPP = (FW1 + FW2 \times AC + FW3 \times AC^2) \times (FW4 + FW5 \times \ln GCR)$$

and

$$AUXFW = FW7 \times (IPP \times DTIME) + FW8 \times (FW6 \times Q \times SF)$$

where

AC - concentrator area (m²)

GCR - ground cover ratio

Q - energy flow rate through feedwater pump

SF - correction factor for operation from storage
 FW1-FW8 - pumping power coefficients. FW1 through FW5 define the installed pumping power as a function of concentrator area and ground cover ratio. FW6 describes the variable pumping power in kWh of pumping energy required per kWh of energy pumped. FW7 and FW8 define the total pumping requirement as a function of the fixed term (installed pumping power) and the variable term.

Field recirculating pump load, AUXFLD

$$IPP = (FLD1 + FLD2 \times AC + FLD3 \times AC^2) \times (FLD4 + FLD5 \times \ln GCR)$$

and

$$AUXFLD = FLD7 \times (IPP \times DTIME) + FLD8 \times (FLD6 \times Q)$$

where

AC - concentrator area (m^2)
 GCR - ground cover ratio
 Q - energy flow rate through field recirculating pump
 FLD1-FLD8 - pumping power coefficients.

Storage input pump load, AUXSTI

$$IPP = STI1 + STI2 \times STSIZE + STI3 \times STSIZE^2$$

and

$$AUXSTI = STI5 \times (IPP \times DTIME) + STI6 \times (STI4 \times Q)$$

where

STSIZE - storage capacity (kWh)
 Q - energy flow rate through storage input pump
 STI1-STI6 - pumping power coefficients.

Storage output pump load, AUXSTO

$$IPP = ST01$$

and

$$AUXSTO = ST03 \times (IPP \times DTIME) + ST04 \times (ST02 \times Q)$$

where

Q - energy flow rate through storage output pump

ST01-ST02 - pumping power coefficients.

Obviously, other auxiliary loads, such as the concentrator tracking/drive unit, would appear in a solar thermal power plant. However, in the systems investigated, these were found to be at least an order of magnitude smaller than the loads considered and so were neglected. It should be noted that, if necessary, other types of loads could be included by adding their effects to one of the loads considered. For example, a concentrator drive unit would be operating only when the field recirculating pump was operating. The drive unit's power demand could be added to that of the recirculating pump and properly accounted for in the model.

3.2.2 Subroutine ELCTRC

Subroutine ELCTRC contains the power conversion and energy storage models for systems operating with electric storage. The operational mode methodology is similar to that used for thermal storage plants except that only three modes are considered:

1. plant shut down
2. heat engine shut down, discharge storage
3. heat engine operating, charge or discharge storage.

The total energy calculation on which the mode of operation decision is based is the same as that described for the thermal storage option. Energy conversion systems that would operate in this configuration do not have the auxiliary loads discussed for thermal systems. In addition, it was found that

engine startup requirements, especially for the small distributed Brayton and Stirling engines that would most often use this model, are insignificant compared to the time step intervals used in the simulation.

The engine model includes a nominal operating efficiency and corrections for partial load operation and ambient air temperature effects. Each of the correction relationships is input as a series of correction factors and a corresponding series of partial load or ambient air temperature values.

The manner in which generating capacity is handled differs considerably from that in subroutine THRMAL. In the thermal case the energy conversion subsystem was a large central unit with a generating capacity equal to the nominal plant rating plus that required to satisfy auxiliary demands. Electric storage is used most often with point-focused dish systems in which the heat engines are small units installed at the focal point of each dish. In this case the generating capacity is no longer a constant for a nominal plant rating, but varies with field size; as the field size increases, the number of dishes increases, and the generating capacity increases. The plant output to the grid is restricted to the nominal plant rating, but the extra generating capacity of a large field size may be used to charge storage.

The electric storage model is analogous to the thermal storage model. It is characterized by an input efficiency (ETASI), an output efficiency (ETASO), an electrical loss per hour as a percentage of the energy in storage (ASLOSS), and a minimum storage level (ESMIN) below which stored energy may not be extracted. The electric model has the added feature of being able to specify a maximum storage charge rate (SCRMAX) that might be used for battery storage systems. Like the thermal model, electric storage sizes are input as hours and converted to electrical capacity by the program:

$$STSIZE = \frac{PLSIZE \times 1000 \times SRAT \times ST}{ETASO \times (1-ESMIN) \times (1-ASLOSS \times 24)}$$

where

STSIZE - electric storage capacity (kWh)

PLSIZE - nominal plant rating (MW)

SRAT - storage rating factor (normally 1 for electric storage systems)

ST - storage size (hr)

ETASO - storage output efficiency

ESMIN - minimum storage level

ASLOSS - storage hourly energy loss (hr^{-1}).

The calculations for energy in storage (EST), storage energy losses (ESLOSS), available storage energy (ESAVL), and acceptable storage energy (ESACC) are performed in the same manner as for thermal systems in Subroutine THRMAL.

The energy available from the field is calculated as was done for thermal storage systems except that there are no thermal losses from the transport system:

$$QF = ECF \times AC(I) \times ECR(I)$$

where

QF - energy made available to energy conversion subsystem (kWh)

ECF - energy collected (kWh/m^2)

AC(I) - array of field sizes to be analyzed (m^2)

ECR(I) - array of field correction ratios.

The ELCTRC subroutine considers three operational modes as described at the beginning of this section. At the beginning of each time step the program checks the energy available from the field and in storage. It then calculates the direct and potential energy output for each mode and selects the optimal operating scheme. The computational procedure used for each mode will now be described.

MODE 1 Plant Shut Down

When insufficient energy is available from the field or from storage, the program will shut the plant down by selecting Mode 1. In this mode there is no direct energy output and the potential energy decreases due to losses:

$$DE = 0$$

and

$$PE = (ESAVL - ESLOSS) \times ETASO$$

where

ESAVL - available electrical energy in storage (kWh)

ESLOSS - storage losses during time step (kWh)

ETASO - storage output efficiency.

MODE 2 Engine Shut Down, Discharge Storage

This mode is selected when energy from the field is insufficient to run the heat engine but some energy is available in storage. The plant will attempt to extract any stored energy, up to the nominal plant rating, and send it to the grid. In this mode the plant output represents a direct energy production equal to the decrease in potential energy:

$$DE = ESOUT \times ETASO$$

and

$$PE = (ESAVL - ESLOSS) \times ETASO + DE$$

where

ESOUT - storage output (kWh) ($ESOUT \leq PLSIZE/ETASO$)

ESAVL - available electrical energy in storage (kWh)

ESLOSS - storage losses during time step (kWh)

ETASO - storage output efficiency.

MODE 3 Heat Engine Operating, Charge or Discharge Storage

Mode 3 is the normal operating mode for plants with electrical storage systems. The heat engine is operating on thermal energy from the field and producing electrical energy for the grid. Within the operational methodology for Mode 3 are three options concerning the use of electric storage.

The first option arises when the energy produced from the field is less than the nominal plant rating and there is no available energy in storage. (It could also occur if the energy produced from the field was exactly equal to the plant rating.) For this option the heat engine is operating but storage is not used:

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL \times TRNEFF(I)$$

where

QENG - thermal energy input to heat engine (kWh)

ETAF - nominal heat engine efficiency operating from the field

TEMP CF - ambient air temperature correction calculated for operation from the field

ETAPL - partial load correction calculated for QENG from the field

TRNEFF(I) - transport subsystem efficiency for this field size

and

$$PE = (ESAVL - ESLOSS) \times ETASO.$$

In the second option the energy available from the field is the same, but there is also electrical energy available in storage. In this case the program attempts to supplement the energy output from the field by discharging storage:

$$DE = (QENG \times ETAF \times TEMPCF \times ETAPL \times TRNEFF(I)) + (ESOUT \times ETASO)$$

where

ESOUT - electric energy output from storage (kWh)

ETASO - storage output efficiency

and

$$PE = (ESAVL - ESOUT - ESLOSS) \times ETASO.$$

With this option ESOUT is adjusted to ensure that the total plant output does not exceed the nominal plant rating.

The third option in Mode 3 models the situation in which the heat engine output operating on energy from the field is greater than the nominal plant rating. The program then channels the additional produced energy into electric storage:

$$DE = QENG \times ETAF \times TEMPCF \times ETAPL \times TRNEFF(I)$$

$$PE = (ESAVL + ESIN - ESLOSS) \times ETASQ.$$

where

ESIN - electric energy input to storage (kWh).

If this option is used, ESIN is adjusted so it does not exceed available storage capacity, ESACC. When storage becomes fully charged energy available before the nominal plant rating is not used.

At each time step the program calculates a direct energy (DE) and potential energy (PE) for each of the operational modes. These two values are added together to arrive at the total eventual energy production (TEO). The mode yielding the highest TEO is selected as the operational mode for this time step.

3.2.3 POWER Output

As with the FIELD program, it is possible to specify several levels of printout detail from the POWER program. The lowest level provides a summary of the annual average field, transport, storage, and system efficiencies and plant capacity factor for each field size-storage capacity plant configuration. A more detailed printout yields a summary of each plant's year-end accounting data for energy flows between component subsystems. Another option allows the user to check the percentage of time during the analysis period that the plant operated at various power levels and in each operational mode. It is possible to print out the mode of operation for each time step during a day for a user-specified number of days in an analysis period. Finally, a very detailed

printout can be selected that lists the mode of operation and component energy flow rates at each time step during certain days specified by the user.

3.2.4 Summary of POWER Input Variables

Inputs to the POWER program are supplied in three NAMELIST files. They contain the parameters necessary to model the energy conversion and storage subsystems (POWRIN), the standby and startup energy requirements (TRANS), and the auxiliary loads (FACTRS).

POWRIN

- NAC - number of collector size inputs. Maximum 20.
- AC - array of collector sizes (m^2).
- TRNEFF - array of corresponding energy transport efficiencies.
- ECR - array of corresponding collector efficiency correction ratios.
- NS - number of storage size inputs. Maximum 20.
- ST - array of storage sizes (hr).
- PLSIZE - nominal plant size (MW).
- ENGSE - individual heat engine size (MW).
- ETAF - efficiency of heat engine operating from field.
- ETAS - efficiency of heat engine operating from storage.
- NPLF - number of points in array of partial load correction factors for engine operating from field. Maximum 25.
- XPLF - array of partial load points.
- ETAPLF - array of corresponding efficiencies.
- NPLS - number of points in array of partial load correction factors for engine operating from storage. Maximum 25.
- XPLS - array of partial load points.
- ETAPLS - array of corresponding efficiencies.
- NTF - number of points in array of ambient air temperature correction factors for engine operating from field. Maximum 25.
- TXF - array of ambient air temperatures ($^{\circ}C$).
- ETATF - array of corresponding efficiencies.

NTS - number of points in array of ambient air temperature correction factors for engine operating from storage. Maximum 25.

TXS - array of ambient air temperatures ($^{\circ}\text{C}$).

ETATS - array of corresponding efficiencies.

SRAT - storage rating (fraction of nominal plant output).

ETASI - storage input efficiency.

ETASO - storage output efficiency.

SCRMAX - maximum storage charge rate (kW).

ASLOSS - storage energy loss (fraction per hr).

QSMIN - minimum storage capacity (fraction of storage size). Also used as ESMIN when ISTR = 2.

STSTF - fraction of storage size charged at beginning of analysis period.

STFCTR - feedwater pump energy requirement correction factor for operation from storage.

ISTR - storage type flag:

- 1 - thermal storage (before heat engine), use Subroutine THRMAL
- 2 - electrical storage (after heat engine), use Subroutine ELCTRC.

GCR - ground cover ratio.

APC - area for each collector unit (m^2).

DTIME - time interval of insolation data (hr). Must be equal to DTIME specified in FIELD program.

ICHK - option to check plant mode on hourly basis:

- 0 - no printout
- N - hourly printout every Nth day.

ITOT - option to print year-end summary of the length of time the plant operated at various power levels and in each operational mode:

- 0 - no printout
- 1 - print summary.

IDBUG - option to print year end energy accounting information for each plant configuration (field size - storage size combination):

0 - no printout

1 - print results.

ND - number of days for which detailed interval energy flow printout is desired. Maximum 25.

NDTAIL - array of selected days for detailed printout.

NDAYS - number of days to be analyzed. Read in only if less than NDAYS value specified in FIELD.

TRANS

SBENG - engine standby load requirement (kW).

SBSTI - storage input heat exchanger standby load requirement (kW).

SBSTO - storage output heat exchanger standby load requirement (kW).

SUENG - preliminary, unrecoverable engine startup requirement (kWh).

TMSUE - time required for engine ramp to full power (hr).

FACTORS

FW1-FW8 - constant coefficients for feedwater pumping system energy requirement relationships.

FLD1-FLD8 - constant coefficients for field recirculating pumping system energy requirement relationships.

STI1-STI6 - constant coefficients for storage input pumping system energy requirement relationships.

STO1-STO4 - constant coefficients for storage output pumping system energy requirement relationships.

3.3 ECON PROGRAM

After a thermodynamic performance simulation has been completed for each field-storage plant configuration, the ECON program performs an economic analysis of the conceptual design. From the POWER results ECON obtains a field size, storage capacity, and capacity factor for each plant analyzed. Using

this information and component cost and economic data supplied by the user, the program calculates levelized energy costs for each plant.

The main program serves as an executive program for the economic evaluation. Energy costs for each plant configuration are actually calculated in a subroutine, BUSBAR. The main program calls BUSBAR to determine the levelized energy cost for each plant configuration analyzed by POWER. These configurations represent each field size specified by the user, and each storage size up to the storage size at which the capacity factor ceased to increase.

ECON then selects the minimum levelized energy cost configuration for each field size. It also determines the locus of points that represents the minimum energy costs over the capacity factor range. This second set of points is referred to as the design envelope. As indicated in Figure 3.2, the curve of global minima represented by the design envelope may not be the same as the curve of local minimum energy costs for each field size. The design envelope data can also be used for a more specific economic analysis. Interpolation using the design envelope can determine the approximate field size and storage capacity required to provide any user specified capacity factor. With these data it is possible to repeat the economic calculations to determine a minimum levelized energy cost at a specific capacity factor (here referred to as design capacity factors) that might not have been provided by the field size-storage capacity matrix originally input by the user.

After calling BUSBAR to evaluate the plant configurations analyzed by POWER and the design capacity factors input by the user, ECON calls Subroutine PLOTIT to prepare the energy cost versus capacity factor plot shown in Figures 2.1 and 3.2. The remainder of this section briefly discusses Subroutines BUSBAR and PLOTIT, the available output from the ECON program, and the input variables.

3.3.1 Subroutine BUSBAR

Subroutine BUSBAR performs the actual economic evaluation of each plant configuration. The subroutine, developed by T. A. Williams of PNL, performs two major functions. The first section determines the capital costs of major system components, capital equipment replacement costs, and annual operation

FIGURE 3.2. Comparison of Design Envelope (Global Minima) and Minimum Energy Cost Points for Each Field Size (Local Minima)

and maintenance charges. The second portion analyzes the economic performance of the plant using a discounted cash flow analysis (Doane et al. 1976).

The first statement in BUSBAR allows the user to decrease the plant energy production by including factors for scheduled and unscheduled maintenance. These factors are used to calculate an adjusted capacity factor as follows:

$$SMF = SMF1 + SMF2 \times CF^{SMF3}$$

where

SMF - scheduled maintenance factor

SMF1-SMF3 - scheduled maintenance factor coefficients

CF - capacity factor

and

$$SCF = CF \times SMF \times UMF$$

where

SCF - adjusted capacity factor

UMF - unscheduled maintenance factor.

The component costing relationships consider 12 major cost accounts. Each account has a functional relationship that models the component cost in terms of the appropriate plant parameters. Another part of the relationship is an escalation factor that allows the user to escalate component costs determined in different years to a common base year for analysis. Each of the functional relationships was derived for the Small Power Systems Study and was designed to meet the needs of that study. They do, however, attempt to be general enough that they might be used in other applications. In addition, the structure of the subroutine allows the user to easily change the cost equations without making major changes to the rest of the procedure. A summary of each of the component relationships follows.

Factors common to all relationships are

ESC - escalation factor

YB - base year for analysis.

Concentrator cost, CC

$$CC = (CC1 + CC2 \times AC^{CC3}) \times ESC^{(YB-YPCC)}$$

where

CC1-CC3 - cost coefficients

AC - concentrator area (m^2)

YPCC - price year for concentrator cost estimate.

Receiver cost, RC

$$RC = (RC1 + RC2 \times AC^{RC3} + RC4 \times AC^{RC5}) \times ESC^{(YB-YPRC)}$$

where

RC1-RC5 - cost coefficients

AC - concentrator area (m²)

YPRC - price year for receiver cost estimate.

NOTE: The two concentrator area terms allow the user to express component receiver costs that vary differently with concentrator area. For example, in a central receiver plant the receiver and supporting tower are both functions of the concentrator area, but not necessarily the same function.

Thermal energy transport cost, TETC

$$TETC = \left(TETC1 + TETC2 \times NCOL^{TETC3} + \frac{TETC4 \times NCOL^{TETC5}}{\sqrt{GCR}} \right) \times ESC^{(YB-YPTT)}$$

where

TETC1-TETC5 - cost coefficients

NCOL - number of collectors

GCR - ground cover ratio

YPTT - price year for thermal energy transport cost estimate.

NOTE: The two NCOL terms allow the user to express both thermal energy transport costs that are a function only of the number of collectors (for example, steam drums, accumulators, and valves) and costs that are a function of both the number of collectors and the ground cover ratio (for example, pipe).

Electric energy transport cost, EETC

$$EETC = \left(EETC1 \times NCOL + \frac{EETC2 + EETC3 \times NCOL}{\sqrt{GCR}} \right) \times ESC^{(YB-YPET)}$$

where

EETC1-EETC3 - cost coefficients

NCOL - number of collectors

GCR - ground cover ratio

YPET - price year for electric energy transport cost estimate.

Energy conversion subsystem cost, ECSC

$$ECSC = \left(ECSC1 + ECSC2 \times GENCAP^{ECSC3} \right) \times ESC^{(YB-YPEC)}$$

where

ECSC1-ECSC3 - cost coefficients

GENCAP - installed generating capacity (MWe)

YPEC - price year for energy conversion subsystem cost estimate.

Power conditioning subsystem cost, PCSC

$$PCSC = \left(PCSC1 + PCSC2 \times P^{PCSC3} \right) \times ESC^{(YB-YPPC)}$$

where

PCSC1-PCSC3 - cost coefficients

P - nominal plant rating (MWe)

YPPC - price year for power conditioning subsystem cost estimate.

Thermal or electric storage cost, TESC

$$TESC = \left(TESC1 + TESC2 \times P^{TESC3} + TESC4 \times STS^{TESC5} \right) \times ESC^{(YB-YPTS)}$$

where

TESC1-TESC5 - cost coefficients

P - nominal plant rating (MWe)

STS - storage capacity (kWh)

YPTS - price year for thermal or electric storage cost estimate.

Structure cost, SC

$$SC = SC1 + SC2 \times P^{SC3} \times ESC^{(YB-YPSC)}$$

where

SC1-SC3 - cost coefficients

P - nominal plant rating (MWe)

YPSC - price year for structures cost estimate

Land cost, LC

$$LC = LC1 \times (LC2 + LC3 \times P + AC/GCR) \times ESC^{(YB-YPLC)}$$

where

LC1-LC3 - cost coefficients

P - nominal plant rating (MWe)

AC - concentrator area (m²)

GCR - ground cover ratio

YPLC - price year for land cost estimate.

Instrumentation and control subsystem cost, ICSC

$$ICSC = ICSC1 + ICSC2 \times CC + ICSC3 \\ \times (RC + TETC + EETC + ECSC + PCSC + TESC + SC) \times ESC^{(YB-YPIC)}$$

where

ICSC1-ICSC3 - cost coefficients

YPIC - price year for instrumentation and control subsystem cost estimate.

Spare parts cost, SPC

$$SPC = SPC1 \times (CC + RC) + SPC2 \\ \times (TETC + EETC + ECSC + PCSC + TESC + SC + ICSC)$$

where

SPC1-SPC2 - cost coefficients.

Service facilities cost, SFC

$$\begin{aligned} \text{SFC} &= \text{SFC1} \times (\text{CC} + \text{RC}) + \text{SFC2} \\ &\quad \times (\text{TETC} + \text{EETC} + \text{ECSC} + \text{PCSC} + \text{TESC} + \text{SC} + \text{ICSC}) \end{aligned}$$

where

SFC1-SFC2 - cost coefficients.

The preceding twelve component costs are then added to determine the total direct capital cost, DC:

$$\begin{aligned} \text{DC} &= \text{CC} + \text{RC} + \text{TETC} + \text{EETC} + \text{ECSC} \\ &\quad + \text{PCSC} + \text{TESC} + \text{SC} + \text{LC} + \text{ICSC} + \text{SPC} + \text{SFC}. \end{aligned}$$

At this point the cost estimates for the major plant components have been completed. BUSBAR now determines the indirect construction costs and contingency costs.

Indirect construction costs, ICC

$$\text{ICC} = \text{ICC1} \times \text{DC}^{\text{ICC2}}$$

where

ICC1-ICC2 - cost coefficients.

Contingency, C

$$\text{C} = \text{C1} \times \text{DC}^{\text{C2}}$$

where

C1-C2 - cost coefficients.

These two indirect costs are added to the direct cost to determine the total capital investment.

In the next few steps the subroutine estimates the operating and maintenance (O&M) and plant overhead charges. The operating charges are based on the nominal plant rating and storage size for the plant configuration being analyzed:

$$DPC = (DPC1 \times P + DPC2 \times ST + DPC3) \times DPC4$$

where

DPC - direct production cost

DPC1-DPC4 - direct production cost coefficients

P - nominal plant rating (MWe)

ST - storage size (hr).

Total maintenance charges are equal to the sum of five maintenance accounts. The charges for each account are based on the size and cost of various component subsystems:

$$CMNT = MC1 \times MC2 \times AC$$

$$SMNT = MC3 \times TESC$$

$$TMNT = (MC4 \times CF + MC5) \times AC \times MC6$$

$$AMNT = (MC7 \times P + MC8 \times AC + MC9) \times MC10$$

$$MMNT = MC11 \times (CC + RC) + MC12 (ECSC + EETC + ICSC + TETC)$$

where

CMNT - collector maintenance cost

SMNT - storage maintenance cost

TMNT - transport maintenance cost

AMNT - auxiliary maintenance cost

MMNT - maintenance materials cost

MC1-MC12 - maintenance cost coefficients.

Plant overhead charges are calculated by

$$POC = POC1 \times (DPC + MC)$$

where

POC - plant overhead cost

POC1 - overhead rate

DPC - direct production cost

MC - maintenance charge.

The production, maintenance, and overhead charges are added to determine the total annual operating and maintenance cost.

BUSBAR has now completed the calculations for the initial capital costs and the yearly operating and maintenance charges. In addition to the components that are installed during construction, certain capital items may have to be replaced during the lifetime of the plant. In the next few steps BUSBAR calculates the cost of replacing three major types of plant components (storage, concentrators, and heat engines) and one miscellaneous account that can be used to specify various replacement items not covered by normal maintenance. For the storage cost calculation, different relationships are used for thermal or electric systems. If a thermal storage system is used, it is assumed that some makeup is required each year. The annual replacement cost, in base-year dollars, is a function of the storage size (hr) and the storage capacity (kWh):

$$SMRAC = SMR1 \times ST^{SMR2} \times SMR3 \times STS \times SMR4$$

where

SMRAC - thermal storage medium annual replacement cost

SMR1-SMR4 - cost coefficients

ST - storage size (hr)

STS - storage capacity (kWh).

NOTE: SMR1, SMR3, and SMR4 could, obviously, be combined into one term. They are separated merely for the convenience of the user. In this form SMR1 defines the storage medium decomposition rate, SMR3 provides the volume of storage medium per kWh, and SMR4 is the cost per unit volume.

For electric storage systems it is assumed that the batteries are replaced at regular intervals equal to the battery lifetime. Each time they are replaced the cost prior to escalation is

$$\text{SMRCO} = \text{SMR2} + \text{SMR3} \times \text{STS}$$

where

SMRCO - electric battery replacement cost

SMR2-SMR3 - cost coefficients

STS - storage capacity (kWh).

NOTE: For electric storage systems SMR1 represents the battery lifetime and SMR4 is not used.

Concentrator and engine replacement costs are treated like those for electric storage systems, replaced at regular intervals (CLIFE and ELIFE). The cost at each replacement, prior to escalation, is

$$\text{CCRCO} = \text{CPER} \times \text{CC}$$

where

CCRCO - concentrator replacement cost

CPER - cost coefficient

CC - concentrator cost

CLIFE - concentrator lifetime

and

$$\text{ERCCO} = \text{EPER} \times \text{ECSC}$$

where

ERCCO - engine replacement cost

EPER - cost coefficient

ECSC - energy conversion subsystem cost
ELIFE - engine lifetime.

The final capital replacement item is for miscellaneous recurring capital costs. These may be arbitrarily specified for any year during the plant's lifetime (YEARX) by entering values into an array (COST).

At this point the capital costs for plant construction, annual operating and maintenance charges, and the cost of replacing plant capital equipment have been determined. BUSBAR now enters the phase in which the financial analysis is performed. As mentioned previously, this analysis is performed according to a discounted cash flow methodology (Doane et al. 1976). The calculated life cycle costs are summed, deflated to a base year, and divided by the yearly plant electrical output to determine the levelized busbar energy cost.

The financial analysis begins by calculating the present value of the major cost components in the first year of plant operation. BUSBAR first determines the present value of the capital investment during construction. Each of the capital replacement costs is converted to a present value and added to the construction cost to determine the present value of the total capital investment. After calculating the present value of the operating and maintenance costs, all of the expenditures have now been expressed in present value terms. The present values for capital items and labor charges are multiplied by the fixed charge rate and capital recovery factor, respectively; added together; and converted to an annualized total cost for building and operating the plant. This figure is divided by the total energy production to determine the levelized energy cost, and converted to base-year dollars.

3.3.2 Subroutine PLOTIT

Subroutine PLOTIT prepares the plot of levelized energy cost versus capacity factor for each of the field size-storage capacity configurations analyzed. This routine was developed by A. S. Koontz of PNL. It was designed for the Calcomp plotting software in use at PNL and would have to be modified for other systems.

3.3.3 ECON Output

The ECON program provides substantial printed output. A detailed page for each plant configuration is supplied by the costing subroutine. This sheet includes a brief description of the plant, a component cost breakdown, component replacement and O&M costs, and the calculated levelized energy cost. The program also provides an economic summary for all the plants. The first table lists the field size, storage size, capacity factor, and levelized energy cost for each configuration. The second and third tables present the least-cost configurations for each field size and the configurations on the design envelope. Following the tables are brief descriptions of the plants configured by the program to satisfy the user-specified design capacity factors, the user-specified design storage size, and the least-cost field size-storage capacity combination. An optional table can be printed that summarizes the plant configuration at each design capacity factor. This table is printed to an output unit specified by the user so that it may be stored, printed, or stored and printed at a later time. Finally, Subroutine PLOTIT can be called to prepare a plot of energy cost versus capacity factor for each field size-storage capacity configuration.

3.3.4 Summary of ECON Input Variables

Input variables for the ECON program are specified by the user in three NAMELIST files. These files contain the variables required to perform the selection of optimal plant configurations (OPTDAT) and the data for the component costing (CSTDAT) and financial analysis (ECNDAT) in the economic evaluation.

OPTDAT

- NPLOT - Set equal to 1 to have PLOTIT prepare a plot of energy cost versus capacity factor. Default 0.
- NDCF - number of design capacity factors for which to repeat economic analysis. Maximum 9.
- DCF - array of design capacity factors.
- DST - design storage size for which the program should select the least-cost plant configuration.

NTABLE - set greater than 0 to obtain a summary table of the plant configuration at each design capacity factor. The table is written to unit NTABLE.

ECNDAT

For a more detailed explanation of the ECNDAT variables see Doane et al. (1976).

BETA1 - ratio of all non-income annual taxes to the present value of the total capital investment.

BETA2 - ratio of all insurance premiums to the present value of the total capital investment.

CFRAC - ratio of common stock to total capitalization.

CRF - capital recovery factor.

DFRAC - ratio of debt to total capitalization.

FCR - annualized fixed charge rate.

G1 - escalation rate for capital cost.

G2 - escalation rate for operating and maintenance costs.

GI - general inflation rate

IKNOW - set equal to 1 to use the user-input value of FCR, CRF, and K rather than the value calculated by the program. Default 0.

K - utility's internal rate of return.

KC - common stockholder's rate of return.

KD - interest rate on corporate debt.

KP - preferred stockholder's rate of return.

N - system lifetime (years).

PCT - plant construction time (years).

PFRAC - ratio of preferred stock to total capitalization.

SMF1-SMF3 - scheduled maintenance factor coefficients.

TAXR - effective corporate income tax rate.

UMF - unscheduled maintenance factor.

YB - base year for constant dollars.

YCO - first year of commercial operation.

YPCC - price year for concentrator cost estimate.

YPEC - price year for energy conversion subsystem cost estimate.

YPET - price year for electric energy transport cost estimate.
 YPIC - price year for instrumentation and control cost estimate.
 YPLC - price year for land cost estimate.
 YPPC - price year for power conditioning estimate.
 YPRC - price year for receiver cost estimate.
 YPSC - price year for structures cost estimate.
 YPTS - price year for storage subsystem cost estimate.
 YPTT - price year for thermal energy transport cost estimate.

CSTDAT

APC - concentrator area of each collector unit (m^2).
 C1-C2 - contingency cost coefficients.
 CC1-CC3 - concentrator cost coefficients.
 CLIFE - concentrator lifetime (years).
 COST - array of miscellaneous capital replacement costs. COST(n) is the cost for the YEARX(n) year of operation. Maximum 30.
 CPER - fraction of original concentrator cost required for concentrator replacement every CLIFE years.
 DPC1-DPC4 - direct production cost coefficients.
 ECSC1-ECSC4 - energy conversion subsystem cost coefficients.
 EETC1-EETC3 - electric energy transport cost coefficients.
 ELIFE - engine lifetime (years).
 EPER - fraction of original engine cost required for engine replacement every ELIFE years.
 GCR - collector field ground cover ratio.
 ICC1-ICC2 - indirect construction cost coefficients.
 ICSC1-ICSC3 - instrumentation and control cost coefficients.
 LC1-LC3 - land cost coefficients.
 MC1-MC12 - maintenance cost coefficients.
 P - nominal plant rating (MWe).
 PCSC1-PCSC3 - power conditioning cost coefficients.
 POC1 - plant overhead cost coefficient.
 RC1-RC5 - receiver cost coefficients.
 SC1-SC3 - structures cost coefficients.

SFC1-SFC2 - service facilities cost coefficients.
SMR1-SMR4 - storage medium replacement cost coefficients.
SPC1-SPC2 - spare parts cost coefficients.
TESC1-TESC5 - thermal or electric storage cost coefficients.
TETC1-TETC6 - thermal energy transport cost coefficients.
YEARX - array of years in which miscellaneous capital replacement costs occur. YEARX(n) is the year in which the COST(n) capital replacement cost occurs. Maximum 30.

4.0 USE OF SOLSTEP

The SOLSTEP code was written in the ASCII FORTRAN language used on the UNIVAC 1100/44 computer. SOLSTEP should be readily adaptable to any computer system although two points should be noted. Reading the insolation data tapes requires a buffer input routine. On the UNIVAC system this need is fulfilled using the FIOW executive requests, which are called by Subroutine ERTRAN. This subroutine would have to be modified to run on other computers. Second, many portions of the SOLSTEP code use curve fitting and interpolating routines. Currently, these routines are taken from the International Mathematics and Statistics Library (IMSL 1979). These routines are accurate, economical, and readily available on many computer systems.

The SOLSTEP code requires approximately 65,000 words of core storage on the UNIVAC computer. The computer time required for an analysis is dependent on the number of time steps simulated, the number of plant configurations considered, and the type of storage used by the plant design. Table 4.1 compares the computational requirements for several cases. Each case was a year-long

TABLE 4.1. SOLSTEP Computational Requirements

	<u>Case</u>	<u>Computer Time</u>	<u>Cost</u>
1	1-hr time step 9 field sizes 7 storage sizes thermal storage	10 min	\$25
2	1-hr time step 9 field sizes 7 storage sizes electric storage	4 min	\$10
3	1-hr time step 14 field sizes 7 storage sizes thermal storage	18 min	\$45
4	15-min time step 9 field sizes 7 storage sizes thermal storage	36 min	\$89

(366-day) simulation using the Aerospace 1976 Barstow insolation data. The figures for computer time include system time, execution time, and input/output time. All results are for use on the UNIVAC 1100/44 computer.

Because no solar thermal power plant has yet been built, it is difficult to verify the accuracy of SOLSTEP. As an approximate check, a comparison was made with the STEAEC computer program developed by researchers at Sandia Laboratories, Livermore (Woodard and Miller 1978). The STEAEC code is a more detailed, more expensive algorithm developed to analyze central receiver plant designs. For a year-long simulation of a 100-MWe central receiver plant, SOLSTEP predicted a capacity factor of 0.39 compared to a value of 0.37 calculated by STEAEC.

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APPENDIX

INPUT VARIABLES AND SELECTED OUTPUT FOR A SAMPLE SOLSTEP ANALYSIS

APPENDIX

INPUT VARIABLES AND SELECTED OUTPUT FOR A SAMPLE SOLSTEP ANALYSIS

This appendix presents a list of input variables and selected pages of output for a SOLSTEP analysis of a 100-MWe point focus, central receiver, Rankine-cycle solar thermal power plant.

FIELD PROGRAM INPUT DATA

Input data for the FIELD program are shown in Figure A.1. Note that the calculation is a 366-day simulation (NDAYS) using a 1-hour time step (DTIME) and a predecoded binary data file (ITYPE), and altitude/azimuth optics (GOEOPT). FIELD output will be printed for the first day of each month (IPRNT).

```

PFCR RANKINE 100 MW. OPEN RECEIVER. OIL/ROCK STORAGE
$SIMPAR
AC=1..
STARTD=1.
NDAYS=366.
DIME=1..
ITYPE=5.
NFILE=1.
IBF=0.
IPRNT=1.
$END
$GEOEDAT
GEOOPT=2.
GNE= .000. .000. .000. .000. .000. .000. .000.
      .240. .239. .229. .227. .221. .214. .213.
      .496. .498. .472. .470. .450. .436. .428.
      .622. .620. .597. .580. .573. .553. .546.
      .799. .711. .696. .687. .672. .660. .666.
      .760. .744. .746. .742. .733. .728. .712.
      .759. .759. .762. .747. .758. .763. .757.
NALT=7.
ALTDAT=0.0,5.0,15.0,25.0,45.0,65.0,89.5.
NAZM=7.
AZMDAT=0.0,30.0,60.0,75.0,90.0,110.0,130.0.
$END
$SYSTEM
OPTFC=.92.
DEGFAC=.95.
COLREC=1.02.
NCRW=0.
ATMOS=1.0.
ABSORB=.852.
ETATHR=1.0.
THPLSS=.03509.
NTHRP=0.
NTHRT=7.
THRTFC=1.1,1.066,1.033,1.0,.967,.934,.902.
THRT=-10.0.,10.,20.,30.,40.,50..
NTHRW=9.
THRWFC=1.,1.414,1.828,2.242,2.656,3.01,3.484,4.312,5.14.
THRW=0.,2.5,5.0,7.5,10.,12.5,15.0,20.0,25.0.
$END

```

FIGURE A.1. FIELD Program Input Data

FIELD PROGRAM OUTPUT

Output from the FIELD program is shown in Figure A.2. The variables listed are defined as:

- N - number of the time step during this day
- DAY - day of the year
- HOURL - local standard time at end of time step
- SOL - available insolation during time step (kWh/m^2)
- ETAFLD - field efficiency during time step
- ECF - energy collected in the field during time step (kWh/m^2)
- TAMB - average ambient air temperature during time step ($^{\circ}\text{C}$)
- ETAGO - geometric optics efficiency of concentrators during time step
- ALT - altitude angle
- AZM - azimuth angle
- WIND - wind speed (m/s).

Note that this type of output is available for the nth day of each month ($\text{IPRNT} = n$), for every day of each month ($\text{IPRNT} < 0$), or may be suppressed ($\text{IPRNT} = 0$). The summary table at the end of the listing is printed in any case.

23	336	23.00	.0000	.0000	.0000	14.1	.0000	-1.00	.00	2.22
24	336	24.00	.0000	.0000	.0000	13.5	.0000	-1.00	.00	2.47

DATE = 12- 1-76

N	DAY	HOUR	SOL	ETAFLD	ECF	TAMR	ETAGO	ALT	ATM	WIND
1	336	1.00	.0000	.0000	.0000	6.5	.0000	-1.00	.00	3.97
2	336	2.00	.0000	.0000	.0000	6.1	.0000	-1.00	.00	4.72
3	336	3.00	.0000	.0000	.0000	5.7	.0000	-1.00	.00	5.10
4	336	4.00	.0000	.0000	.0000	5.2	.0000	-1.00	.00	5.10
5	336	5.00	.0000	.0000	.0000	5.7	.0000	-1.00	.00	5.10
6	336	6.00	.0000	.0000	.0000	5.4	.0000	-1.00	.00	4.35
7	336	7.00	.0694	.0000	.0000	4.3	.0000	-1.00	.00	4.10
8	336	8.00	.5219	.1219	.0636	5.5	.3403	8.37	54.00	5.67
9	336	9.00	.7514	.3093	.2316	8.1	.5246	17.87	45.50	5.37
10	336	10.00	.8611	.4098	.3529	10.6	.6244	25.64	33.00	3.22
11	336	11.00	.9128	.4572	.4173	12.7	.6714	30.96	18.00	2.05
12	336	12.00	.9414	.4986	.4694	14.7	.7095	33.14	2.00	.38
13	336	13.00	.9389	.4730	.4441	17.3	.6816	31.81	14.00	1.12
14	336	14.00	.8947	.4228	.3783	19.4	.6379	27.19	29.50	3.46
15	336	15.00	.7750	.3562	.2760	20.0	.5574	19.95	42.50	2.97
16	336	16.00	.5050	.2001	.1011	20.0	.4001	10.81	53.50	2.97
17	336	17.00	.0733	.0000	.0000	17.1	.0192	.38	31.00	3.47
18	336	18.00	.0000	.0000	.0000	14.6	.0000	-1.00	.00	2.22
19	336	19.00	.0000	.0000	.0000	12.7	.0000	-1.00	.00	2.72
20	336	20.00	.0000	.0000	.0000	10.4	.0000	-1.00	.00	2.22
21	336	21.00	.0000	.0000	.0000	9.1	.0000	-1.00	.00	2.10
22	336	22.00	.0000	.0000	.0000	8.5	.0000	-1.00	.00	1.65
23	336	23.00	.0000	.0000	.0000	6.5	.0000	-1.00	.00	1.95
24	336	24.00	.0000	.0000	.0000	5.9	.0000	-1.00	.00	2.10

THIS ANALYSIS WAS PERFORMED USING INSOLATION AND METEOROLOGICAL DATA FROM WRAN NO. 23161

NUMBER OF INTERVALS DURING ANALYSIS PERIOD WITH SOLAR INSOLATION = 4496
TOTAL SOLAR INSOLATION DURING ANALYSIS PERIOD = 2848. KW-HR/M**2
AVERAGE SOLAR INSOLATION DURING ANALYSIS PERIOD = .634 KW/M**2
TOTAL COLLECTED ENERGY DURING ANALYSIS PERIOD = 1125. KW-HR/M**2
AVERAGE COLLECTED ENERGY DURING ANALYSIS PERIOD = .250 KW/M**2

FIGURE A.2. FIELD Program Output

POWER PROGRAM INPUT DATA

Input data for the POWER program are presented in Figure A.3. POWER will consider ten field sizes (NAC) and seven storage capacities (NS). The plant will use thermal storage (ISTR) and plant output will be limited to 70% of the nominal rating when operating from storage (SRAT).

```

$POWRIN
NAC=10.
AC = 300000., 400000., 500000., 750000., 1000000., 1250000., 1500000.,
    2000000., 2500000., 3000000.
ECR=1.00,1.00,0.99,0.97,0.96,0.95,0.94,0.92,0.91,0.90,
TRNEFF=.999,.999,.999,.999,.999,.999,.999,.999,.999,.999,
NS=7,
ST=0.,3.,6.,9.,12.,15.,18.,
PLSIZE=100.,
ETAF=.350,
ETAS=.250,
NPLF=11,
XPLF=0.0,.104,.209,.312,.417,.521,.625,.729,.833,.937,1.00,
ETAPLF=0.0,.42,.87,.90,.93,.96,.98,.99,.99,1.00,1.00,
NPLS=10,
XPLS=0.0,.110,.220,.330,.440,.550,.660,.770,.880,1.00,
ETAPLS=0.0,.373,.806,.847,.845,.929,.962,.985,1.00,1.00,
NTF=12,
TXF=-10.,-5.,0.,5.,10.,15.,20.,25.,30.,35.,40.,45.,
ETATF=1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,.999,.994,.982,.978,.963,
NTS=12,
TXS=-10.,-5.,0.,5.,10.,15.,20.,25.,30.,35.,40.,45.,
ETATS=1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,.999,.994,.982,.978,.963,
SRAT=.7,
ETASI=.999,
ETASO=.999,
ASLOSS=.000833,
QSMIN=.15,
STSTF=.15,
STFCTR=1.00,
ISTR=1,
GCR=.25,
OTIME=1.0,
ICLK=25,
ITOT=1,
IDRUG=1,
ND=0,
NDTAIL=0,
$END
$TRANS
SBENG=400.,
SBSTI=76.,
SBSTO=127.,
SUENG=1000000.,
TMSUE=.5,
$END
$FACTRS
FW2=.0018,
FW4=1.0,
FW6=.00409,
FW7=.25,
FW8=.75,
STI2=.000624,
STI4=.00456,
STI5=.25,
STI6=.75,
STO1=118.,
STO2=.00392,
STO3=.25,
STO4=.75,
$END

```

FIGURE A.3. POWER Program Input Data

POWER PROGRAM OUTPUT - INDIVIDUAL PLANT CONFIGURATION ANALYSIS

One form of output from the POWER program is listed in Figure A.4. This output provides a summary of each plant configuration (field size/storage capacity combination) analyzed. The Plant Description and Year-End Operating Information are obtained by setting IDBUG equal to 1. Setting ICHK equal to 25 provided the hourly printout of the plant operational mode for every 25th day. Setting ITOT equal to 1 provided a summary of the time the plant operated at each power level and in each operational mode. The Generating Capacity is the approximate gross output rating required to supply the nominal plant rating as well as to meet auxiliary loads under normal operating conditions. The Operating Information variables describe operating parameters for the entire year as follows:

- SOLY - available insolation (kWht)
- ECF - energy collected by the field (kWht)
- PET - energy produced by the plant (kWhe)
- CF - capacity factor
- ETAFLD - average field efficiency
- ETAETS - average energy transport efficiency including thermal losses and field-associated auxiliary loads
- ETAESS - average energy storage efficiency including thermal losses and storage-associated auxiliary loads
- ETASYS - average overall plant efficiency
- PAVG - average plant net output during the time the plant was running
- ETAFAV - average efficiency of the energy conversion system operating from the field
- ETASAV - average efficiency of the energy conversion system operating from storage
- ENGF - approximate energy required from the field to run the heat engine at full load (kWht). (Does not include ambient air temperature corrections or auxiliary loads.)
- ENGs - approximate energy required from storage to run the heat engine at full load (kWht). (Does not include ambient air temperature corrections or auxiliary loads.)

QENGFY - energy supplied to heat engine from field (kWht)
QENGSY - energy supplied to heat engine from storage (kWht)
AXREQY - auxiliary energy requirement (kWhe)
QSINY - energy input to storage (kWht)
QSOUTY - energy output from storage (kWht)
QSLOS Y - energy losses from storage (kWht)
QWT - energy from field that was not used (kWht)
QSBSUY - standby and startup energy requirement (kWht).

PLANT NUMBER 20 PFCR RANKINE 100 MW, OPEN RECEIVER, OIL/ROCK STORAGE
 I = 7
 J = 2

PLANT DESCRIPTION

PLANT SIZE (MW) = 100.
 GENERATING CAPACITY (MW) = 103.32
 COLLECTOR SIZE (M**2) = 1500000.
 STORAGE SIZE (HRS) = 3.
 STORAGE SIZE (KW-HRS) = 993375.

PRINTOUT OF PLANT OPERATIONAL MODE ON AN HOURLY BASIS FOR EVERY 25TH DAY

25 11111112266666653331111
 50 111111122666653311111111
 75 111111122666666653331111
 100 111111226666666655333111
 125 111111226666666665333111
 150 111112266666666654333111
 175 11111226666666665433111
 200 11111226666666665333111
 225 11111122666666665333111
 250 111111226666331111111111
 275 111111122666666533311111
 300 111111121266666533311111
 325 111111122666666533311111
 350 111111122666666533311111

SUMMARY OF PLANT POWER OUTPUT LEVELS AND OPERATIONAL MODES DURING ANALYSIS PERIOD

POWER OUTPUT (MWE)	NUMBER OF INTERVALS	% OF ANALYSIS PERIOD	OPERATIONAL MODE	NUMBER OF INTERVALS	% OF ANALYSIS PERIOD
< 0	203	2.	1	4210	48.
0- 20	4363	50.	2	847	10.
20- 40	215	2.	3	935	11.
40- 60	197	2.	4	48	1.
60- 80	1035	12.	5	460	5.
80-100	2771	32.	6	2284	26.

YEAR END PLANT OPERATING INFORMATION

SOLY =	4271997344.	ETAFV =	.3461	QENGFY =	89261888.
ECFY =	1585745552.	ETASV =	.2478	QENGSY =	25878858.
PET =	364839356.	ENG =	295200.	AXREQY =	8226639.
CF =	.4153	ENG =	293751.	QSINY =	265008868.
ETAFLD =	.3712			QSOUTY =	261917022.
ETAETS =	.9842			QSLOS =	261728.
ETAESS =	.9598			QWT =	38905244.
ETASYS =	.0854			QSBSUY =	39934901.
PAVG =	79.76				

FIGURE A.4. POWER Program Output - Individual Plant Configuration Analysis

POWER PROGRAM OUTPUT - DETAILED ENERGY BALANCE

The output from the POWER program shown in Figure A.5 is a detailed energy balance for each time step during a specified day (or days). This printout can be obtained by setting ND greater than zero and specifying the desired days in NDTAIL. The variables are defined as

- MODE - operational mode selected for this time step
- QF - energy available from field (kWht)
- QSACC - available storage capacity at beginning of time step (kWht)
- QSAVL - available energy in storage at beginning of time step (kWht)
- QENG - energy input to heat engine (kWht)
- QSIN - energy input to storage during time step (kWht)
- QSOUT - energy output from storage during time step (kWht)
- AXREQ - auxiliary energy requirement (kWhe)
- QSBSU - standby and startup energy requirement (kWht)
- QWST - energy available from field that was not used (kWht)
- TEOMAX - total energy output calculated for operational mode specified in MODE; this is the maximum TEO calculated for any mode (kWhe)
- P - plant energy output (kWhe).

PLANT NUMBER 11 PFCR RANKINE 100 MW. OPEN RECEIVER. OIL/ROCK STORAGE
I = 4
J = 2

PLANT DESCRIPTION

PLANT SIZE (MW) = 100.
GENERATING CAPACITY (MW) = 103.32
COLLECTOR SIZE (M**2) = 1500000.
STORAGE SIZE (MWS) = 3.
STORAGE SIZE (KW-HRS) = 993375.

PRINTOUT OF PLANT OPERATIONAL MODE ON AN HOURLY BASIS FOR EVERY 25TH DAY

1 DETAILED ENERGY FLOW PRINTOUT FOR THIS DAY:

MODE	QF	QSACC	QSAVL	QENG	QSH	QSOUT	AXREQ	QCRSU	QWST	TEOMAX	P
1	0.	844368.	0.	0.	0.	604.	0.	403.	0.	-182.	0.
1	0.	845096.	-728.	0.	0.	604.	0.	403.	0.	-363.	0.
1	0.	845823.	-1455.	0.	0.	604.	0.	403.	0.	-545.	0.
1	0.	846550.	-2181.	0.	0.	604.	0.	403.	0.	-726.	0.
1	0.	847276.	-2907.	0.	0.	604.	0.	403.	0.	-907.	0.
1	0.	848001.	-3633.	0.	0.	604.	0.	403.	0.	-1088.	0.
1	0.	848726.	-4357.	0.	0.	604.	0.	403.	0.	-1269.	0.
2	9694.	849450.	-5081.	0.	0.	203.	705.	9097.	0.	-2054.	-705.
2	314341.	849773.	-5404.	224034.	0.	203.	1639.	90009.	0.	74554.	75985.
2	490307.	850096.	-5727.	293121.	135800.	127.	2611.	127.	61251.	132424.	100000.
6	604824.	714543.	129826.	293120.	135800.	127.	2611.	127.	175768.	166250.	100000.
6	629068.	579102.	265266.	293120.	135800.	127.	2611.	127.	200013.	200048.	100000.
6	602158.	443775.	400593.	293120.	135800.	127.	2611.	127.	173103.	233818.	100000.
6	547995.	308561.	535808.	293121.	135800.	127.	2611.	127.	118939.	267560.	100000.
6	456691.	173459.	670910.	293121.	135800.	127.	2611.	127.	27635.	301273.	100000.
5	261188.	38469.	805899.	261188.	0.	203.	1476.	903.	0.	290506.	89482.
3	0.	39468.	804901.	283159.	0.	283518.	862.	76.	0.	200017.	70000.
3	0.	323781.	520588.	283159.	0.	283518.	862.	76.	0.	129069.	70000.
3	0.	607857.	236512.	236275.	0.	236588.	724.	76.	0.	57729.	57828.
1	0.	844766.	-397.	0.	0.	604.	0.	403.	0.	-25256.	0.
1	0.	845493.	-1125.	0.	0.	604.	0.	403.	0.	-462.	0.
1	0.	846220.	-1851.	0.	0.	604.	0.	403.	0.	-644.	0.
1	0.	846946.	-2578.	0.	0.	604.	0.	403.	0.	-825.	0.
1	0.	847671.	-3303.	0.	0.	604.	0.	403.	0.	-1006.	0.

25 11111112266666653331111
50 111111122666653311111111
75 111111122666666653331111
100 11101122666666655333111
125 11111122666666665333111
150

1 DETAILED ENERGY FLOW PRINTOUT FOR THIS DAY:

MODE	QF	QSACC	QSAVL	QENG	QSH	QSOUT	AXREQ	QCRSU	QWST	TEOMAX	P
1	0.	846974.	-2606.	0.	0.	604.	0.	403.	0.	-832.	0.
1	0.	847699.	-3331.	0.	0.	604.	0.	403.	0.	-1013.	0.
1	0.	848424.	-4056.	0.	0.	604.	0.	403.	0.	-1194.	0.
1	0.	849149.	-4780.	0.	0.	604.	0.	403.	0.	-1375.	0.
1	0.	849872.	-5504.	0.	0.	604.	0.	403.	0.	-1555.	0.

FIGURE A.5. POWER Program Output - Detailed Energy Balance

POWER PROGRAM OUTPUT - ALL PLANT CONFIGURATION ANALYSIS RESULTS

Figure A.6 illustrates output from the POWER program summarizing results for all plant configurations. This printout is provided any time the POWER program is run. The variables are defined as

- I - number of field size iteration
- J - number of storage size iteration
- AC - concentrator area (m^2)
- ST - storage size (hr)
- STSIZE - storage capacity (kWht)
- ETAFLD - average field efficiency
- ETAETS - average energy transport efficiency
- ETAESS - average energy storage efficiency
- ETAFAV - average energy conversion system efficiency while operating from the field
- ETASAV - average energy conversion system efficiency while operating from storage
- ETASYS - average plant efficiency
- CF - capacity factor.

SUMMARY OF RESULTS FOR ALL PLANT COMBINATIONS:

I	J	AC (M**2)	ST (HRS)	STSIZE (KWH)	GC (MWE)	FTAFLD	ETAETS	ETAESS	ETAFAV	FTASAV	ETASYS	CF
1	1	300000.	.00	0.	100.540	.395	.985	.000	.317	.000	.107	.104
1	2	300000.	3.00	993375.	101.160	.395	.985	.000	.314	.000	.105	.107
2	1	400000.	.00	0.	100.720	.395	.985	.000	.310	.000	.116	.150
2	2	400000.	3.00	993375.	101.340	.395	.985	.000	.318	.000	.114	.148
3	1	500000.	.00	0.	100.900	.391	.986	.000	.316	.000	.119	.193
3	2	500000.	3.00	993375.	101.520	.391	.986	.000	.315	.000	.118	.191
4	1	750000.	.00	0.	101.350	.383	.985	.000	.313	.000	.114	.278
4	2	750000.	3.00	993375.	101.970	.383	.986	.912	.313	.230	.120	.292
4	3	750000.	6.00	1991739.	102.593	.383	.986	.878	.313	.229	.120	.291
5	1	1000000.	.00	0.	101.800	.379	.985	.000	.315	.000	.096	.311
5	2	1000000.	3.00	993375.	102.420	.379	.986	.956	.315	.245	.113	.367
5	3	1000000.	6.00	1991739.	103.043	.379	.986	.949	.315	.245	.115	.373
5	4	1000000.	9.00	2995131.	103.669	.379	.986	.940	.315	.245	.115	.373
6	1	1250000.	.00	0.	102.250	.375	.984	.000	.316	.000	.081	.329
6	2	1250000.	3.00	993375.	102.870	.375	.985	.959	.316	.247	.098	.399
6	3	1250000.	6.00	1991739.	103.493	.375	.986	.959	.316	.247	.109	.443
6	4	1250000.	9.00	2995131.	104.119	.375	.986	.955	.316	.247	.111	.448
6	5	1250000.	12.00	4003588.	104.748	.375	.986	.949	.316	.247	.110	.447
7	1	1500000.	.00	0.	102.700	.371	.983	.000	.316	.000	.070	.340
7	2	1500000.	3.00	993375.	103.320	.371	.984	.960	.316	.248	.085	.415
7	3	1500000.	6.00	1991739.	103.943	.371	.985	.961	.316	.248	.098	.477
7	4	1500000.	9.00	2995131.	104.569	.371	.986	.959	.316	.248	.106	.513
7	5	1500000.	12.00	4003588.	105.198	.371	.986	.956	.316	.248	.107	.519
7	6	1500000.	15.00	5017150.	105.831	.371	.986	.952	.316	.248	.107	.519
8	1	2000000.	.00	0.	103.600	.363	.980	.000	.316	.000	.055	.355
8	2	2000000.	3.00	993375.	104.220	.363	.983	.960	.317	.248	.067	.434
8	3	2000000.	6.00	1991739.	104.843	.363	.984	.961	.317	.249	.078	.507
8	4	2000000.	9.00	2995131.	105.469	.363	.985	.961	.317	.249	.088	.571
8	5	2000000.	12.00	4003588.	106.098	.363	.985	.959	.317	.249	.096	.622
8	6	2000000.	15.00	5017150.	106.731	.363	.985	.955	.317	.249	.098	.633
8	7	2000000.	18.00	6035854.	107.366	.363	.985	.951	.317	.249	.098	.635
9	1	2500000.	.00	0.	104.500	.359	.978	.000	.317	.000	.045	.365
9	2	2500000.	3.00	993375.	105.120	.359	.981	.960	.317	.248	.055	.445
9	3	2500000.	6.00	1991739.	105.743	.359	.983	.961	.317	.249	.064	.521
9	4	2500000.	9.00	2995131.	106.369	.359	.984	.961	.317	.249	.073	.593
9	5	2500000.	12.00	4003588.	106.998	.359	.984	.960	.317	.249	.081	.660
9	6	2500000.	15.00	5017150.	107.631	.359	.985	.956	.317	.249	.085	.690
9	7	2500000.	18.00	6035854.	108.266	.359	.985	.951	.317	.249	.086	.699
10	1	3000000.	.00	0.	105.400	.355	.976	.000	.317	.000	.038	.371
10	2	3000000.	3.00	993375.	106.020	.355	.979	.960	.317	.248	.047	.452
10	3	3000000.	6.00	1991739.	106.643	.355	.981	.961	.317	.249	.054	.530
10	4	3000000.	9.00	2995131.	107.269	.355	.983	.961	.317	.249	.062	.605
10	5	3000000.	12.00	4003588.	107.898	.355	.984	.960	.317	.249	.070	.677
10	6	3000000.	15.00	5017150.	108.531	.355	.984	.956	.317	.250	.074	.717
10	7	3000000.	18.00	6035854.	109.166	.355	.984	.951	.317	.250	.075	.732

FIGURE A.6. POWER Program Output - Summary of Results for All Plant Configurations

ECON PROGRAM INPUT DATA

Input data for the ECON program are shown in Figure A.7. ECON will prepare a plot of levelized energy cost versus capacity factor (NPLLOT). The program will estimate the required field size, storage capacity, and minimum levelized energy cost for eight user-specified design capacity factors (NDCF, DCF). ECON will select the minimum levelized energy cost plant configuration with zero thermal storage (DST). Subroutine BUSBAR will use the discount rate, capital recovery factor, and fixed charge rate input by the user rather than calculating these rates internally (IKNOW).

```

$OPTDAT
NPLOT=1,
NDCF=8,
DCF=0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,
DST=0.,
NTABLE=6,
$END
$CSTDAT
APC=49.0,
C1=0.07,C2=1.0,
CC1=0.0,CC2=80.0,CC3=1.0,
CLIFE=30.0,
COST=0.0,
CPER=0.0,
DPC1=0.0,DPC2=0.19,DPC3=2.62,DPC4=20000.0,
ECSC1=0.0,ECSC2=211600.0,ECSC3=1.0,ECSC4=0.0,
EETC1=0.0,EETC2=0.0,EETC3=0.0,
ELIFE=30.0,
EPR=0.7,
GCR=0.25,
ICC1=0.18,ICC2=1.0,
ICSC1=1100000.0,ICSC2=0.01,ICSC3=0.03,
LC1=2.05,LC2=0.0,LC3=0.0,
MC1=1.48E-5,MC2=18600.0,MC3=0.005,MC4=3.21E-7,MC5=3.02E-8,
MC6=27000.0,MC7=0.0129,MC8=0.0,MC9=3.53,MC10=26000.0,
MC11=0.003,MC12=0.01,
P=100.0,
PCSC1=8480.0,PCSC2=134000.0,PCSC3=0.52,
POC1=0.15,
RC1=0.0,RC2=377.000,RC3=0.7124,RC4=7.5523,RC5=0.99303,
SC1=0.0,SC2=184823.76,SC3=0.3590863,
SFC1=0.00185,SFC2=0.01535,
SMR1=.092,SMR2=0.364,SMR3=1.3,SMR4=1.1,
SPC1=0.00065,SPC2=0.00135,
TESC1=208000.,TESC2=9290.,TESC3=1.0,TESC4=1.95,TESC5=1.0,
TETC1=0.0,TETC2=510.664,TETC3=0.83856,TETC4=0.0,
TETC5=0.0,TETC6=0.0,
YEARX=0.0,
$END
$ECNDAT
BETA1=0.0 , BETA2=0.0 ,
CFRAC=0.0 ,
CRF=0.0939 ,
DFRAC=0.0 ,
FCR=0.1568 ,
G1=0.06 , G2=0.07 , G3=0.06 ,
IKNOW=1 ,
K=0.086 ,
KC=0.0 , KD=0.0 , KP=0.0 ,
N=30.0 ,
PCT=4.0 ,
PFRAC=0.0 ,
SMF1=1.0 , SMF2=0.0 , SMF3=1.0 ,
TAXR=0.0 ,
UMF=1.0 ,
YB=1978.0 ,
YCO=1985.0 ,
YPCC=1978., YPEC=1978., YPET=1978., YPIC=1978., YPLC=1978., YPPC=1978.,
YPRC=1978., YPSC=1978., YPTS=1977., YPTT=1978.,
$END

```

FIGURE A.7. ECON Program Input Data

ECON PROGRAM OUTPUT - INDIVIDUAL PLANT CONFIGURATION ANALYSIS

One form of output from the ECON program is shown in Figure A.8. This output presents an economic summary for each plant configuration analyzed by the ECON program.

SMALL SOLAR THERMAL POWER PROGRAM

SYSTEM TYPE : PFCR RANKINE 100 MW. OPEN RECEIVER. OIL/ROCK STORAGE

A.SYSTEM VARIABLES

SYSTEM CAPACITY(MWE)	100.0
COLLECTOR AREA(M2)	1500000.00
STORAGE TIME(HOUR)	3.0
PLANT CAPACITY FACTOR	.415
STORAGE SIZE(KWH)	993375.00

B.SYSTEM COST SUMMARY

	COST \$	UNIT COST \$/KW	LEVELIZED COST MILLS/KWH	FRACTION OF LEC
LEVELIZED BUSBAR ENERGY COST			116.7	
CAPITAL INVESTMENT COSTS	234087932.	2341.	104.5	.895
O+M COSTS (ANNUAL)	1529875.	15.	10.1	.087
REPLACEMENT CAPITAL COSTS (PV)	4222528.	42.	2.2	.018
COLLECTOR COST	139725910.	1397.	62.3	.534
ENERGY TRANSPORT COST	2950037.	30.	1.3	.011
ENERGY CONVERSION COST	21862512.	219.	9.8	.084
ENERGY STORAGE COST	3258526.	33.	1.5	.012
OTHER PLANT COST	19473367.	195.	8.7	.074
INDIRECT AND CONTINGENCY	46817584.	468.	20.9	.179

C.COMPONENT COSTS

CONCENTRATOR COST	120000000.	1200.	53.5	.459
RECEIVER COST	19725912.	197.	8.8	.075
THERMAL ENERGY TRANSPORT COST	2950037.	30.	1.3	.011
ELECTRIC ENERGY TRANSPORT COST	0.	0.	0.	.000
ENERGY CONVERSION EQ. COST	21862512.	219.	9.8	.084
POWER CONDITIONING EQ. COST	1477761.	15.	.7	.006
ENERGY STORAGE COST	3258526.	33.	1.5	.012
STRUCTURES COST	965896.	10.	.4	.004
LAND COST	12300000.	123.	5.5	.047
INSTRUMENTATION AND CONTROL COST	3807219.	38.	1.7	.015
SPARE PARTS COST	137156.	1.	.1	.001
SERVICE FACILITIES COST	785335.	8.	.4	.003
INDIRECT CAPITAL COST	33708662.	337.	15.0	.129
CONTINGENCY COST	13108924.	131.	5.8	.050
DIRECT PRODUCTION COST (ANNUAL)	63800.	1.	.4	.004
MAINTENANCE COST (ANNUAL)	1266526.	13.	8.4	.072
PLANT OVERHEAD COST (ANNUAL)	199549.	2.	1.3	.011
STORAGE MEDIA REPLACEMENT COST (PV)	4222528.	42.	2.2	.018
COLLECTOR REPLACEMENT COST (PV)	0.	0.	0.	.000
ENGINE REPLACEMENT COST (PV)	0.	0.	0.	.000
MISC. REPLACEMENT COST (PV)	0.	0.	0.	.000

FIGURE A.8. ECON Program Output - Individual Plant Configuration Analysis

ECON PROGRAM OUTPUT - ALL PLANT CONFIGURATION ECONOMIC ANALYSES

Another form of output from the ECON program is shown in Figure A.9. The first page presents the summary of the economic analysis for all plant configurations. The adjusted capacity factor is equal to the capacity factor unless the user inputs scheduled (SMF1, SMF2, and SMF3) or unscheduled (UMF) maintenance factors that are less than 1. Figure A.10 lists the plant configurations selected as least cost for each field size and selected as the global least-cost points. ECON then outputs a description of the plant configuration selected to obtain each of the user-specified design capacity factors.

PFCR RANKINE 100 MW, OPEN RECEIVER, OIL/ROCK STORAGE

SUMMARY OF ECONOMIC ANALYSIS:

I	J	AC (M\$2)	ST (HRS)	CF	ADJ. CF	EC (MILLS/KW-HR)
1	1	300000.	.00	.104	.104	149.
1	2	300000.	3.00	.102	.102	169.
2	1	400000.	.00	.150	.150	121.
2	2	400000.	3.00	.148	.148	135.
3	1	500000.	.00	.193	.193	107.
3	2	500000.	3.00	.191	.191	118.
4	1	750000.	.00	.278	.278	98.
4	2	750000.	3.00	.292	.292	100.
4	3	750000.	6.00	.291	.291	107.
5	1	1000000.	.00	.311	.311	108.
5	2	1000000.	3.00	.367	.367	97.
5	3	1000000.	6.00	.373	.373	101.
5	4	1000000.	9.00	.373	.373	107.
6	1	1250000.	.00	.329	.329	122.
6	2	1250000.	3.00	.399	.399	105.
6	3	1250000.	6.00	.443	.443	99.
6	4	1250000.	9.00	.448	.448	103.
6	5	1250000.	12.00	.447	.447	109.
7	1	1500000.	.00	.340	.340	137.
7	2	1500000.	3.00	.415	.415	117.
7	3	1500000.	6.00	.477	.477	106.
7	4	1500000.	9.00	.513	.513	103.
7	5	1500000.	12.00	.519	.519	107.
7	6	1500000.	15.00	.519	.519	112.
8	1	2000000.	.00	.355	.355	167.
8	2	2000000.	3.00	.434	.434	141.
8	3	2000000.	6.00	.507	.507	125.
8	4	2000000.	9.00	.571	.571	115.
8	5	2000000.	12.00	.622	.622	110.
8	6	2000000.	15.00	.633	.633	112.
8	7	2000000.	18.00	.635	.635	116.
9	1	2500000.	.00	.365	.365	198.
9	2	2500000.	3.00	.445	.445	166.
9	3	2500000.	6.00	.521	.521	146.
9	4	2500000.	9.00	.593	.593	132.
9	5	2500000.	12.00	.660	.660	123.
9	6	2500000.	15.00	.690	.690	121.
9	7	2500000.	18.00	.699	.699	124.
10	1	3000000.	.00	.371	.371	229.
10	2	3000000.	3.00	.452	.452	192.
10	3	3000000.	6.00	.530	.530	168.
10	4	3000000.	9.00	.605	.605	151.
10	5	3000000.	12.00	.677	.677	138.
10	6	3000000.	15.00	.717	.717	134.
10	7	3000000.	18.00	.732	.732	136.

FIGURE A.9. ECON Program Output - Summary of All Plant Configuration Economic Analyses

MOST ECONOMICAL OPERATING POINTS FOR EACH FIELD SIZE:

FIELD SIZE (M**2)	STORAGE SIZE (HOURS)	CAPACITY FACTOR	ENERGY COST (MILLS/KW-HR)
300000.	.00	.1040	149.
400000.	.00	.1500	121.
500000.	.00	.1930	107.
750000.	.00	.2780	98.
1000000.	3.00	.3670	97.
1250000.	6.00	.4430	99.
1500000.	9.00	.5130	103.
2000000.	12.00	.6220	110.
2500000.	15.00	.6900	121.
3000000.	15.00	.7170	134.

DESIGN ENVELOPE OF GLOBAL MINIMUM ENERGY COST POINTS:

FIELD SIZE (M**2)	STORAGE SIZE (HOURS)	CAPACITY FACTOR	ENERGY COST (MILLS/KW-HR)
300000.	.00	.1040	149.
400000.	.00	.1500	121.
500000.	.00	.1930	107.
750000.	.00	.2780	98.
1000000.	3.00	.3670	97.
1250000.	6.00	.4430	99.
1500000.	9.00	.5130	103.
2000000.	12.00	.6220	110.
2500000.	15.00	.6900	121.
2500000.	18.00	.6990	124.
3000000.	18.00	.7320	136.

FIGURE A.10. ECON Program Output - Least-Cost Plant Configurations

OPTIMUM PLANT CONFIGURATIONS AT DESIGN POINTS:

DESIGN POINT: .200 CAPACITY FACTOR

COLLECTOR FIELD SIZE = 520588.
STORAGE SIZE = .00
CAPACITY FACTOR = .200
ENERGY COST = 106.

DESIGN POINT: .700 CAPACITY FACTOR

COLLECTOR FIELD SIZE = 2515151.
STORAGE SIZE = 18.00
CAPACITY FACTOR = .700
ENERGY COST = 124.

DESIGN POINT: .300 CAPACITY FACTOR

COLLECTOR FIELD SIZE = 811798.
STORAGE SIZE = .74
CAPACITY FACTOR = .300
ENERGY COST = 94.

DESIGN POINT: .800 CAPACITY FACTOR

COLLECTOR FIELD SIZE = *****
STORAGE SIZE = *****
CAPACITY FACTOR = .800
ENERGY COST = ****

DESIGN POINT: .400 CAPACITY FACTOR

COLLECTOR FIELD SIZE = 1108553.
STORAGE SIZE = 4.30
CAPACITY FACTOR = .400
ENERGY COST = 98.

DESIGN POINT: .900 CAPACITY FACTOR

COLLECTOR FIELD SIZE = *****
STORAGE SIZE = *****
CAPACITY FACTOR = .900
ENERGY COST = ****

DESIGN POINT: .500 CAPACITY FACTOR

COLLECTOR FIELD SIZE = 1453571.
STORAGE SIZE = 8.44
CAPACITY FACTOR = .500
ENERGY COST = 102.

DESIGN POINT: OPTIMAL CAPACITY FACTOR

COLLECTOR FIELD SIZE = 1000000.
STORAGE SIZE = 3.00
CAPACITY FACTOR = .367
ENERGY COST = 97.

DESIGN POINT: .600 CAPACITY FACTOR

COLLECTOR FIELD SIZE = 1899083.
STORAGE SIZE = 11.39
CAPACITY FACTOR = .600
ENERGY COST = 108.

DESIGN POINT: .00 HOURS STORAGE TIME

COLLECTOR FIELD SIZE = 750000.
STORAGE SIZE = .00
CAPACITY FACTOR = .278
ENERGY COST = 98.

FIGURE A.10. (contd)

ECON PROGRAM OUTPUT - PLANT CONFIGURATION AND ASSOCIATED COSTS

Figure A.11 is a one-page summary of the plant configuration and associated costs at the optimal capacity factor, design storage size, and each of the design capacity factors. Each of the cost items is expressed in present value terms, including capital replacement costs that may appear throughout the plant lifetime. This summary was printed with the normal output by setting NTABLE = 6. Alternatively, it could have been printed to another file for permanent storage or subsequent printing by setting NTABLE to another output unit number, or it could have been eliminated by setting NTABLE = 0.

PFCR RANKINE 100 MW, OPEN RECEIVER, OIL/ROCK STORAGE

100 MW

09-09-80 15:10:04

DESIGN POINT CAPACITY FACTORS

	0 STR	OPT	.20	.30	.40	.50	.60	.70	.80	.90
PERFORMANCE RESULTS:										
FIELD SIZE (1000 M**2)	750.	1000.	521.	812.	1109.	1454.	1899.	2515.	*****	*****
STORAGE SIZE (HRS)	.00	3.00	.00	.74	4.30	8.44	11.39	18.00	*****	*****
STORAGE CAPACITY (1000 KWH)	0.	993.	0.	246.	1427.	2809.	3800.	6036.	*****	*****
GENERATING CAPACITY (MW)	101.35	102.42	100.94	101.61	102.89	104.37	105.79	108.29	*****	*****
FIELD EFFICIENCY	.383	.379	.390	.382	.377	.372	.365	.359	*****	*****
TRANSPORT EFFICIENCY	.985	.986	.986	.985	.986	.986	.985	.985	*****	*****
STORAGE EFFICIENCY	*****	.956	*****	.236	.957	.959	.959	.951	*****	*****
ENERGY CONV. EFF. (FIELD)	.343	.345	.337	.343	.345	.346	.347	.347	*****	*****
ENERGY CONV. EFF. (STORAGE)	*****	.245	*****	.061	.246	.248	.249	.249	*****	*****
SYSTEM EFFICIENCY	.114	.113	.119	.114	.111	.107	.098	.086	*****	*****
CAPACITY FACTOR	.28	.37	.20	.30	.40	.50	.60	.70	*****	*****
ECONOMIC RESULTS:										
CONCENTRATOR (\$/M**2)	80.	80.	80.	80.	80.	80.	80.	80.	*****	*****
FRACTION OF LEC	.408	.417	.363	.408	.419	.421	.433	.428	*****	*****
RECEIVER (\$/M**2)	15.	14.	15.	14.	14.	13.	13.	12.	*****	*****
FRACTION OF LEC	.074	.073	.070	.073	.072	.070	.069	.066	*****	*****
TRANSPORT (\$/M**2)	2.2	2.1	2.3	2.2	2.1	2.0	1.9	1.8	*****	*****
FRACTION OF LEC	.011	.011	.011	.011	.011	.010	.010	.010	*****	*****
STORAGE (\$/KWH)	.0	3.3	.0	7.0	2.9	2.5	2.4	2.3	*****	*****
FRACTION OF LEC	.000	.017	.000	.011	.020	.025	.026	.029	*****	*****
ENERGY CONV. (\$/KW)	214.	217.	214.	215.	218.	221.	224.	229.	*****	*****
FRACTION OF LEC	.146	.113	.186	.135	.103	.080	.064	.049	*****	*****
BALANCE OF PLANT (\$/KW)	120.	146.	98.	127.	157.	192.	236.	298.	*****	*****
FRACTION OF LEC	.082	.076	.085	.080	.074	.070	.067	.063	*****	*****
INDIRECT/CONT. (\$/KW)	265.	339.	205.	286.	370.	467.	587.	757.	*****	*****
FRACTION OF LEC	.180	.177	.179	.180	.175	.169	.167	.161	*****	*****
TOTAL INITIAL CAP. (\$/KW)	1326.	1695.	1026.	1429.	1848.	2333.	2934.	3787.	*****	*****
FRACTION OF LEC	.901	.883	.893	.898	.873	.845	.835	.806	*****	*****
REPLACEMENT CAPITAL (\$/KW)	0.	42.	0.	6.	69.	174.	263.	493.	*****	*****
FRACTION OF LEC	.000	.025	.000	.005	.037	.072	.085	.120	*****	*****
OPER. AND MAINT. (1000 \$/YR)	987.	1192.	831.	1043.	1277.	1549.	1878.	2356.	*****	*****
FRACTION OF LEC	.099	.092	.107	.097	.089	.083	.079	.074	*****	*****
LEC (MILLS/KWH)	98.	97.	106.	98.	98.	102.	108.	124.	*****	*****

FIGURE A.11. ECON Program Output - Plant Configuration and Associated Costs

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