SERI/TP-351-464

SERI/TP-351-464
UC CATEGORY: UC-59B,59C,62A,62B,62C,
62D,62E

BALDR-1: A SOLAR THERMAL SYSTEM SYSTEM SIMULATION

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JANUARY 1980

PRESENTED AT THE SECOND ANNUAL SYSTEMS SIMULATION AND ECONOMICS ANALYSIS CONFERENCE, BAHIA HOTEL, SAN DIEGO, CALIFORNIA, JANUARY 23-25, 1980

PREPARED UNDER TASK NO. 3456.10

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A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG·77·C·01·4042

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ABSTRACT

A solar thermal system simulation (BALDR-1) has been written by a team of SERI engineers. This flexible simulation was written in a modular fashion to facilitate expansion and modification. The flexibility of the simulation is derived, in part, from the use of three separate models to constitute the system simulation: FIELD, POWER, and ECON. Each model can be run independently, or they may be coupled and run as a set.

The FIELD code models the optical and thermal performance of the collector field. It has separate optical and thermal performance routines for each generic collector type. Meteorological data is read in 15-minute or hourly increments.

The POWER code models the performance of power conversion and storage components. It calculates the total thermal and/or electrical energy produced during the year for a set of plant configurations comprised of different collector field sizes, thermal storage sizes, and electrical storage sizes. The POWER code allows the selection of one of several control strategies in the dispatch of thermal and electrical storage.

The ECON code calculates the initial capital cost of each power plant configuration modelled in POWER. This capital cost is combined with operations and maintenance costs to calculate a life-cycle busbar energy cost and simple payback period for each plant.

INTRODUCTION

A system simulation, BALDR-1*, was written to model the performance of solar thermal systems. The original application was to model the performance and economics of 0.1 - 10 MW_e solar thermal electric power plants (Ref. 1). It has subsequently been used in receiver selective surface value analysis and in thermal storage value analysis, and is being adapted currently to model industrial process heat systems.

The FIELD code models the optical and thermal performance of the collector field and thermal transport subsystems. The POWER code models the power conversion and energy storage subsystems. The ECON code determines the initial capital cost of the power plant and the life-cycle busbar energy cost. A flow chart of the system simulation is shown in Figure 1.

FIELD CODE

The FIELD code is a second-order simulation based on a similar code previously developed by the Aerospace Corporation with modifications by the Jet Propulsion Laboratory (JPL) (Ref. 2), and by Battelle Pacific Northwest Laboratories (PNL) (Ref. 3). The FIELD code uses meteorological data read in from SOLMET or TMY format weather tapes in 15-minute or hourly increments. Data used in the current version of FIELD are: direct normal insolation, solar time, global insolation, ambient temperature, dew point, and day of the year. The FIELD code models the performance of collector subsystems in four different ways depending on the type of collector subsystem being modelled. There are separate modules to calculate the optical and thermal performance of each generic collector type. If the need should arise to model other collector types, it is a simple matter to add additional optical and thermal performance modules.

For point focus central receiver systems (PFCR) and line focus central receiver systems (LFCR), the optical efficiency of the concentrator field is determined at each time step by a bivarient linear interpolation of tables of optical efficiency as a function of solar azimuth and zenith angles. These efficiency tables must be input and generally result from third-order simulation programs such as DELSOL (Ref. 4) and MIRVAL (Ref. 5).

The radiative losses from the receiver are calculated in the FIELD code based on the effective receiver temperature, the effective absorptivity and emissivity of the receiver and the effective normalized receiver area. The convective and conductive losses are assumed to be a constant fraction of the calculated radiative losses. The value of this fraction can be adjusted to yield receiver efficiencies similar to those predicted by third-order simulations and reconciled with experimental results. The energy incident on the receiver at each time step per unit area of collector is then equal to the product of the optical efficiency, direct normal insolation, and the time step. The energy collected at the receiver is this term minus the calculated thermal losses. The energy collected

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*In Scandanavian mythology, BALDR was the god of sunlight and the personification of wisdom, beauty and brightness. The version of the code is the original, hence "dash one".

in the collector field (ECF) is then equal to the product of the energy collected at the receiver and the thermal transport efficiency.

For the point focus distributed receiver systems (PFDR) e.g., paraboloidal dishes, and fixed mirror distributed focus systems (FMDF) e.g., hemispherical bowls, the optical efficiency is determined by explicit calculation at each time step. This calculation includes the effects due to solar azimuth, zenith, concentrator position, intercept factor, reflectivity, blockage, shadowing, edge losses and dust. The receiver thermal losses are calculated in a manner identical to that described above for the central receiver systems. The energy incident on the receiver at each time step per unit area is again equal to the product of optical efficiency, direct normal insolation and the time step. The energy collected at the receiver is the energy incident on the receiver minus the thermal losses. The energy collected from the field (ECF) is the product of the energy collected at the receiver and the thermal transport efficiency. This may be determined per unit area of concentrator or per unit collector module.

For the line focus distributed receiver systems (troughs) with either tracking collectors (LFDR-TC) or tracking receivers (LFDR-TR), the optical efficiency is determined by explicit calculation at each time step. This calculation includes the effects due to solar azimuth, intercept factor, reflectivity, blockage, shadowing, edge losses, dust, secondary concentrator efficiency and transmissivity of receiver cover. The thermal losses of the receiver are based on a selectable fraction of the thermal losses resulting from tests of the best receiver to date (Ref. 6). This fraction allows for future improvements in receiver design such as selective coatings, evacuated covers, etc. The energy incident on the receiver at each time step per unit area is once again equal to the product of the optical efficiency, direct normal insolation and the time step. The energy collected by the receiver is the energy incident on the receiver minus the thermal losses. The energy collected from the field (ECF) is equal to the product of the energy collected at the receiver and the thermal transport efficiency.

For low concentration non-tracking systems (LCNT) e.g., CPC collector, and shallow solar ponds (SSP), the total collector efficiency is determined from a linear relationship between total efficiency and $\Delta T\ (T_{collector} - T_{ambient})$. These relationships were based on plots of test data for advanced concept versions of each of the two collector types. (The y-intercept, $T=0$, is equal to the optical efficiency). The energy collected from the field (ECF) is equal to the product of the total collector efficiency (including thermal losses), insolation, the time step, and the thermal transport efficiency. For the LCNT, insolation was taken as the sum of direct normal plus diffuse divided by the concentration ratio. For the SSP, insolation was taken as direct normal plus diffuse, or global.

The variables passed to the POWER code include an array of values of ECF for each time step, dry-bulb and wet-bulb temperatures, and unit collector area.

POWER CODE

The POWER code is a second-order simulation based on the Aerospace computer code as modified by JPL (Ref. 2) and Battelle PNL (Ref. 3). POWER differs from the earlier codes primarily in that it provides the option of using different control algorithms for both the operation of power conversion equipment and the dispatch of electrical and thermal storage. There are currently two operational control algorithms: CNTRL2 and CNTRL3.

CNTRL2 models systems with storage of receiver fluid (e.g., salt, sodium, etc.) at approximately the same condition as it leaves the receiver, sometimes called series storage. CNTRL3 models systems with storage of an intermediate fluid (e.g., storage of oil for a steam receiver system). In this case, the temperature of storage is significantly below the receiver outlet temperature and a dual admission turbine is therefore modelled.

Both control algorithms share the following features not usually found in second order solar thermal system simulations.

1. Electrical and thermal storage may both be modelled for any power plant.
2. A weighting factor may be used to reduce the value of electricity delivered above plant rating to simulate hard or soft limits on plant output.
3. The decision of how to dispatch the energy from the collector field is made for the current time step; knowledge of future insolation is not used.
4. Depletion of thermal storage is limited to the value which will assure a hot start-up the following morning. The minimum allowable amount of heat in storage is then a function of the number of hours until the next anticipated morning start-up.

In addition, CNTRL2 incorporates the possibility of overload operation of the power conversion equipment for specified periods. While not currently incorporated into CNTRL3, this capability could easily be added.

CNTRL2 operates with priority on producing and delivering electricity. Thermal storage is used only when there is insufficient energy to start the engine or when there is more energy than required to produce rated power. If electrical storage is modelled it is used for leveling the plant output curve. When the engine generator output is below plant rating, the output is supplemented by energy from electrical storage.

In CNTRL3, there are three operating strategies available: electricity priority, storage priority, and peak load priority. The electricity priority strategy is identical to that used in CNTRL2. The storage priority causes thermal storage to be charged with the engine off until storage is filled to a specified fraction. Only then is the engine turned on, and the priority reverts to generation of electricity for the remainder of the day. The peak load priority option is similar to the storage charging priority except that storage is maintained at the specified fraction until a designated peak period occurs. During the peak period, the priority reverts to generation of electricity. When the peak period is over, any heat left in storage is retained for use during the following day.

Component models in POWER were written in several levels of detail according to their impact on plant performance. The engine efficiency model is a function of hot engine temperature, cooling tower temperature, and the load at each time step. The thermal and electrical energy storage residence losses are calculated based on the amount of energy in storage at each time step. The auxiliary electrical loads are calculated based on plant capacity and actual plant output at each time step. The electrical transport efficiency is based upon electrical current flow through the transport system. The component models for thermal and electrical storage charging and discharging, the electrical generator, power conditioning, the inverter and the converter currently use a constant average efficiency. The component models may be easily increased in accuracy if necessary or desirable for a particular application.

The POWER code calculates the electricity delivered to the grid at each time step and sums it for one year. The total electrical energy delivered during the year is divided by the total electricity which would have been delivered had the plant operated at rated capacity for the entire year. This yields the plant capacity factor.

This capacity factor is calculated for each plant described by an element of the three dimensional matrix of collector field sizes (AC), thermal energy storage sizes (ST), and electrical storage sizes (STE).

Matrices of the operating mode of the plant and the dispatch of electrical storage at each time step can be output. The calculated capacity factor, along with the corresponding collector field size, thermal storage size and electrical storage size, is output for use by the ECON code. In addition, the plant rated capacity and generator size are output for use by ECON.

ECON CODE

The ECON code includes two major subroutines (COST and BUSBAR) which are based on computer codes originally written by JPL (Ref. 2,7). Using the output from POWER, ECON determines a capital cost, a life cycle busbar energy cost, a simple payback period, and annual operations and maintenance (O&M) costs for each plant configuration based on either the thermal energy or the electrical energy produced.

Subroutine COST uses unit costs as inputs to determine the cost streams for both capital expenditures and O&M. Capital costs are determined for each of four subsystems: 1) collector and receiver, 2) electrical and/or thermal storage, 3) power conversion, and 4) miscellaneous (including land, thermal and electrical transport, and spares and contingencies). These costs are currently distributed over the plant construction period as a uniform series of payments. With slight modifications to the code, COST could create a nonuniform cost stream.

Operations and maintenance costs are also determined in COST. Currently, O&M is a uniform stream of annual costs for each year of the plant's lifetime. In case a specific schedule of required maintenance is known, COST can be modified to produce a nonuniform O&M cost stream. Alternatively, a periodic maintenance cost could be added onto the annual O&M cost stream currently produced by COST.

Subroutine BUSBAR is based on the Utility-Owned Solar Electric Systems (USES) model, a conventional present value analysis adapted for solar electric power plants by JPL (Ref. 8). It calculates that busbar energy cost in constant-year dollars which will generate system-resultant revenues equal to the system-resultant costs. The inputs for BUSBAR represent two types of information: system cost data and accounting information. The cost data as currently used consist of the arrays of capital costs and O&M costs which are generated in subroutine COST. Escalation rates are input for capital and O&M in addition to the general inflation rate. BUSBAR is written to handle separate maintenance charges, fuel costs and social benefits along with their appropriate rates of escalation. The ECON code also has the capability of doing only the busbar energy calculations if a net present value cost is input.

The second group of input data, the accounting information, represents the variables that are used to determine the cost of capital. From this data, the discount rate, the fixed charge rate, and the capital recovery factor are determined in BUSBAR.

An additional capability exists within ECON for producing plots of the data generated. Subroutine PLOTIT can be called to produce a graph of busbar energy cost versus capacity factor for each system. For the systems which use either thermal or electrical storage, but not both, the graph will have a set of curves, each of which represent a distinct value of collector area with points marked representing various amounts of storage (e.g., Figure 2). For the systems which use both electrical and thermal storage, a separate plot will be generated for each value of collector area. Each plot will consist of a set of curves, each representing an amount of thermal storage with points marked representing amounts of electrical storage.

COMPUTATIONAL TIME

To simulate the annual performance of a point focus central receiver system using 15-minute time steps, approximately 50 seconds of CPU time is required for FIELD and approximately 300 seconds of CPU time for POWER for a full matrix of collector areas and storage sizes for electrical output cases. ECON requires approximately 10 seconds of CPU time in the corresponding simulation.

SUMMARY

A system simulation has been written to model the performance of solar thermal power systems for both electrical and process heat applications. The models are modular allowing for easy use and modification. Annual performance and economics of most proposed solar thermal systems can be modelled by the simulation in its present form.

ACKNOWLEDGMENTS

The development of this simulation is the work of many SERI employees. The following people participated in the development of BALDR-1.

M. Buhl
S. Cronin
M. Edesess
A. Edgecombe
J. Finegold
A. Herlevich
M. Karpuk
J. Kowalik
L. Lacy
D. Madison
R. Mitchell
L. Morrison
R. O'Dougherty
J. Pagano

L. Morrison and A. Edgecombe are singled out for particularly important contributions in the early stages of model development. We also gratefully acknowledge the support of J. Thornton, Task Leader of the Small Power Systems Study, under whom this work was conducted. Funding was provided under DOE Contract EG-77-C-01-4042.

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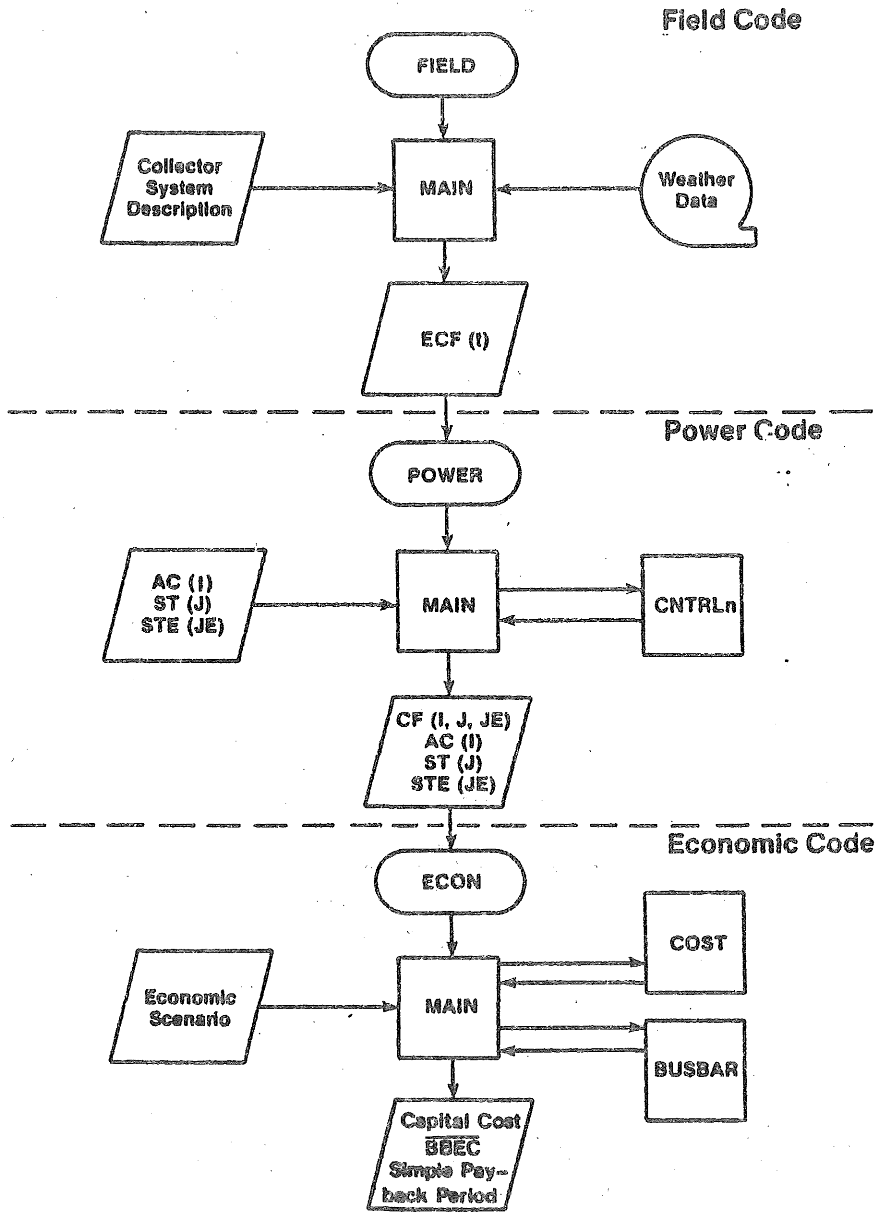

Figure 1 - Simplified flow chart for BALDR-1 performance and cost simulation codes

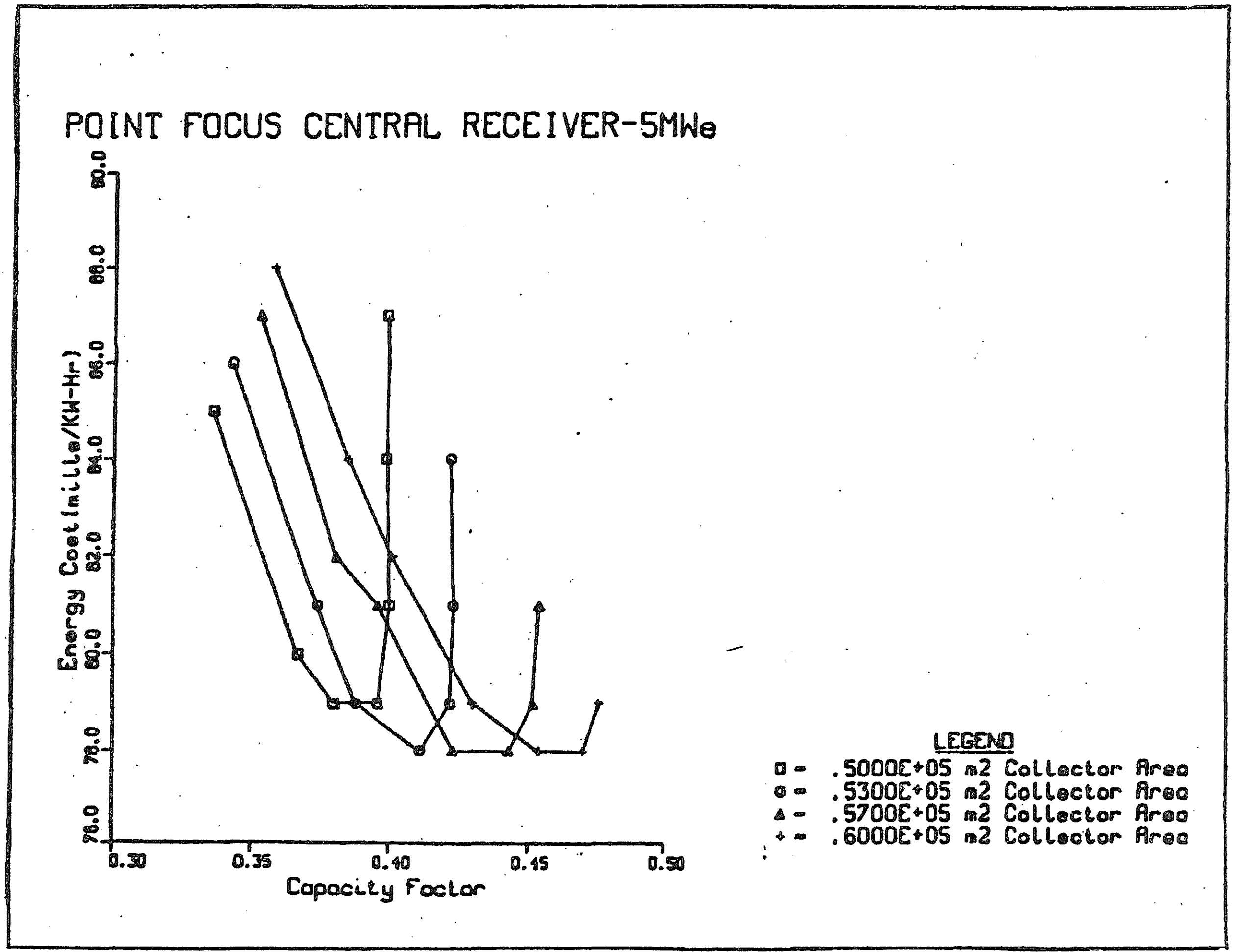

Figure 2 - Graphical Output from ECON
Each point marked on a curve represents a different amount of storage.

GPO: 1980-677-175-12