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July 1984

Industrial Process Heat Data Analysis and Evaluation

Allan Lewandowski
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Kenneth May

Solar Energy Research Institute
A Division of Midwest Research Institute

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Golden, Colorado 80401

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PREFACE

The Solar Energy Research Institute (SERI) has modeled seven of the Department of Energy (DOE) sponsored solar Industrial Process Heat (IPH) field test experiments and has generated thermal performance predictions for each project. Additionally, these predictions have been compared with actual performance measurements taken at the projects. This work was in support of the solar IPH project task being managed for DOE by Sandia National Laboratory, Albuquerque (SNLA).

This document consists of two volumes. Volume I contains the main body of work and includes an introduction, objectives, a description of the model, site configurations, model results, comparisons with reported data, and a summary. Volume II contains complete performance prediction results (both tabular and graphic output) and computer program listings.

The authors would like to especially thank Ed Harley of SNLA for funding this work and for his unwavering support of and confidence in the results presented in this report. We are grateful to Jerry Greyerbiehl of DOE Headquarters and George Pappas of the DOE Albuquerque Operations Office for their support. This document was improved considerably by the review process and we would like to acknowledge those people for their constructive technical contributions: Danny Deffenbaugh, Southwest Research Institute; Mitch Garber, Foster Wheeler Development Corp.; Ed Harley, SNLA; John Hoopes, Jacobs Engineering; David Kearney, Insights West; William Stine, California State Polytechnic University at Pomona; Lee Wilson, Energetics; and Meir Carasso, Chuck Kutscher, and John Thornton, SERI.

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SUMMARY

Objective

To model seven of the solar IPH field test experiments, generate performance predictions, and compare those predictions with reported data.

Discussion

Since 1977, DOE has funded a series of field tests of solar energy in industry. Several IPH applications have been utilized for these field tests, including hot water, hot air, low temperature (100°-175°C) steam, and intermediate temperature (175°-290°C) steam. Both small-scale and large-scale (up to 4680 m^2) systems have been built and monitored. In general, the earlier systems did not exhibit high levels of performance and reliability. The latest systems have fared better, but still have not met expectations. This is especially true in the area of energy delivery. In all cases, original performance predictions have been consistently overestimated due to a combination of inadequate weather data, optimistic component performance models, and low system reliability.

SERI has utilized its modeling capability to provide more realistic predictions of performance for seven of these field tests. The hour-by-hour simulation code, SOLIPH, was used to generate the performance predictions. Input data for each site was prepared and SOLIPH was coded with appropriate component subroutines to provide a complete system configuration. TMY solar irradiance and weather data were used to drive the simulations. Output for each site include annual and monthly summaries and monthly clear day data in both tabular and graphic form.

The performance predictions generated by SOLIPH were compared with the available measured data reported monthly by the seven site contractors. Comparisons were made on a system efficiency basis since long-term consistent data were rarely available for an entire month. Data gaps resulted primarily from solar system downtime and data acquisition system malfunctions. The comparisons produced an identification of the areas of field operation that were less than adequate and a recommendation of repairs or changes that might correct the problems. Also, as a result of the modeling effort certain design goals were generated which may help designers to improve system performance.

Conclusions

The SOLIPH code was shown capable to predicting performance for the seven solar IPH systems studied. When compared with the reported data from the field experiments, it appears that SOLIPH generally overpredicts slightly the system performance. However, the relatively low reliability and consistency of system operation in the field makes comparisons difficult. For the one system where high reliability and availability existed, SOLIPH predicted performance very well. Several areas within SOLIPH could be improved to provide a more accurate modeling tool. These include the effect of dust/dirt on

collector surface optical properties, transient system performance due to cloud cover, and the use of actual solar irradiance and other weather data. In addition to SOLIPH modifications, to improve predictive capabilities, changes in the field tests can improve the actual energy delivery of the systems. Most of these changes are related to the reduction of both heat losses and thermal capacitance. Many of the field experiments have initiated these design modifications to increase system performance. We hope future efforts can incorporate the field experiences and the modeling capabilities into improved solar IPH system designs that can provide industry with reliable systems delivering as much energy as designers predict.

ERRATA

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Page 9, Line 4: For "$1 - f \tan \Theta/[L(1 + W^2/48ft^2)]$, end loss factor"

substitute "$1 - f \tan \Theta (1 + W^2/48 f^2)/L$, end loss factor"

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SECTION 1.0

INTRODUCTION

Since 1977 the U.S. Department of Energy (DOE) has funded a series of field tests of solar energy systems in industry. These field tests have been conducted in phases, with the earliest projects supplying low temperature process heat below 100°C. Numerous design and operational problems kept these first systems from performing at expected levels of energy delivery (Kutscher and Davenport 1980a). This initial round of hot water/hot air projects was closely followed by a number of low temperature (100°-175°C) steam systems. Several of these systems are still operational and continue to deliver energy to the industrial partner. Levels of energy delivery were and are, however, still below those orginally predicted during the design phase. The next project phase concentrated on intermediate temperature (175°-290°C) systems. Of the four systems actually built, three are still operating with DOE funds. One has ceased operation by request of the industrial partner at the expiration of the DOE contract. The latest and last phase of government-funded projects consists of two large scale (4650 m^2), cost-shared systems, both of which continue to operate. A complete description of all the DOE funded projects can be found in two conference proceedings (SERI 1979 and SERI 1980) that deal specifically with solar industrial process heat.

Generally, the reliability of these solar industrial projects has not been good, with a variety of problems preventing many systems from operating continuously. While none of these problems have been or should be particularly difficult to correct, the end result, until very recently, has been that useful data on performance and operation and maintenance (O&M) costs are largely unavailable. In recent years DOE has provided additional funds, with technical support from Sandia National Laboratories, Albuquerque (SNLA), to upgrade equipment at several of the Industrial Process Heat (IPH) sites. As a result of the upgrades and of increased emphasis on reporting of experiment results, availability and reliability of the remaining operational sites have improved.

1.1 OBJECTIVES

The beginning of FY 1983 saw eight active solar IPH projects under funding by DOE. Table 1-1 lists the current status of these systems. Since previous experiences with the field experiments had universally shown that actual performance fell far short of original predictions, SNLA wanted to determine a realistic goal for system performance. The effort reported here was to utilize the best available predictive tools and data and provide an unbiased, independent estimate of theoretical energy deliveries. Actual performance of the field test was to be compared with the estimates and would be, in part, a measure of the success of the project. The expertise and tools to accomplish this task were available at the Solar Energy Research Institute (SERI), and thus SNLA requested SERI's participation in the project along with other national labs and support contractors.

Table 1-1 Active DOE Funded IPH Projects (as of 11/82)

Project	Contractor	Contract Start Date	Acceptance Test	End of Contract	Current Status
Capital Concrete Topeka, KS	Applied Concepts	1/81	8/82	12/82	Operational under site owner control
Caterpillar Tractor San Leandro, CA	Southwest Research Institute	9/79	2/83	9/84	Operational
Dow Chemical Dalton, GA	Foster Wheeler Development Corporation	9/78	11/81	3/84	Operational, system improvements underway
Home Laundry Pasadena, CA	Jacobs Engineering	9/77	4/82	9/83	Operational
Lone Star Brewery San Antonio, TX	Southwest Research Institute	9/78	1/82	11/84	Ceased operation, pending modifications to water preheat system
Ore-Ida Foods Ontario, OR	TRW	9/78	6/81	3/83	Ceased operation
Southern Union Refining Lovington, NM	Energetics	9/78	1/82	4/84	Operational, system modifications underway
USS Chemicals Haverhill, OH	Columbia Gas System	9/79	5/82	7/84	Operational

The prime SERI objective was to provide performance predictions for seven of the projects. The DOE funding for the eighth expired prior to SERI involvement. These predictions were to include annual, monthly, and daily performance estimates, using at best actual reported weather data for inputs. Once these estimates were generated, a detailed comparison of actual performance with predictions was to be undertaken. The specific objective of the comparison was to identity those areas of field operation that were deficient and to recommend repairs or changes to correct the problems. To insure that reported data were accurate, a review of the site instrumentation and data acquisition systems (DAS) was also included in the SERI scope of work. Data-reporting uniformity among the various contractors was to be accomplished through a set of guidelines previously developed by Kutscher and Davenport (1980b). These guidelines were accepted by the site contractors with only minor exceptions. Thus, two main objectives were established: to model the designated sites and generate performance predictions and to compare those predictions with reported data.

1.2 METHODOLOGY

In order to adequately model system performance and at the same time interpret the results at the component level, an hour-by-hour simulation was required. Numerous computer codes that are capable or could be made capable of IPH type component modeling exist. However, during previous work to develop a design handbook for solar IPH systems, Kutscher et al.(1982) wrote a computer code that had the versatility and ease of use needed for this task. This code, SOLIPH, uses an hour-by-hour simulation scheme that calculates average system conditions during the hour based on input data from the system configuration and from weather tapes for the appropriate site locations.

Each generic type of solar IPH system, e.g., unfired boiler, flash tank, hot water preheat, etc., requires a separate configuration of the code. To simplify input data SOLIPH is written so that each configuration has its own main routine within which a series of component subroutine calls are sequenced. The sequence of calls represents, as closely as possible, the physical configuration of components at a field experiment. The code and numerous modifications made to it for this application are described in greater detail in Section 2.0.

Data used to compile the complete set of inputs for each field experiment came from several sources. The source of initial information describing the site, collector, and energy delivery systems was usually obtained from the various contractor reports. Typically, at the completion of both the design and construction phases, a report was written by the contractor to document activities, decisions, and costs for that phase of the project. These reports provided important generalized data used for the model inputs. Specific data on sizes, lengths, capacities, etc., of individual components were obtained from specifications and drawings.

Confirmation and clarification of the documented information was then obtained during a site visit. These visits were especially important in that additional, undocumented information was available only by visual inspection. For example, to obtain the complete data on pipe subsystems, not only were the pipe length, size, and insulation thickness necessary, but also the quality of installation could and often did result in additional insight into the piping subsystem description. In some instances, changes had occurred that had not yet been documented.

The site visit also provided additional system information, such as operational characteristics, including start-up conditions, set points for various automatic system functions, and plant process schedule. In all cases, the site visit provided an invaluable experience, not just for data collection purposes, but to obtain a "feel" for the system. While these qualitative data were not applicable to the code inputs, they did provide a basis for later evaluation of system problems and differences between reported and predicted data.

The driving forces for system operation are the solar radiation and ambient weather conditions that exist at each site. Obviously, the preferable source of these data would be the data recorded by the site data acquisition system (DAS). Unfortunately, none of the seven sites have a consistent or continuous record of data collection for sufficiently long periods. There are many reasons why the site data are inadequate: DAS hardware and software problems, system or row downtime (where twin pyranometers are used), shading losses, power failures, and instrumentation failures. The end result is that the site data could not be used for annual simulation runs at any project site.

Hourly weather and solar radiation data for many sites around the country have been archived by the National Climatic Data Center (1981). This data has been manipulated to form a record of "typical" years. This Typical Meteorological Year (TMY) information is available for 26 of the original SOLMET data-gathering sites. More recently, many other sites have been included by synthetically generating the "typical" years' data. ERSATZ TMY (ETMY) data are available for 208 sites. The original version of the SOLIPH code utilized this TMY (or ETMY) data base and thus for both practical and necessary reasons, the data base was employed in the present SOLIPH application. While neither the TMY nor ETMY data contain actual direct normal irradiance measurements, they are generally considered to be the best irradiance data base currently available.

SECTION 2.0

SOLIPH

The SOLIPH code, as previously mentioned, is an hour-by-hour simulation program that uses TMY data for solar radiation and ambient weather condition inputs. An early version of SOLIPH was described by Kutscher (1983). This reference contains a basic description of how the code operates and derivations for the basic component models. This section will focus only on those general changes to the code that were necessary to model the field experiments. Since the code was originally developed to aid in preparation of a solar IPH design handbook (Kutscher et al. 1982) and not to model actual installations, some changes and additions were necessary.

The code was originally written in FORTRAN IV for a CDC 7600 main frame computer, which could no longer be supported at SERI and hence was removed. A CDC 720, a much slower machine, was available for use, but computation costs were potentially very high due to the execution time of the code. A new version of the code was written in FORTRAN V, which was streamlined to optimize compilation and execution time. This effort resulted in a 70% reduction in run time compared with benchmark runs of the original code on the CDC 720. Additionally, new output format options (including graphics) and file manipulation procedures were written to enhance the program user's ability to generate data from the code.

2.1 SOLIPH ROUTINES

2.1.1 Main Routine

To configure the program for a specific field experiment, a series of calls to the appropriate component subroutines are coded or edited into the main routine. The main routine has both data input and output sections, which are essentially unchanged from configuration to configuration, sandwiched around the subroutine call sequence. Essentially all variables are passed between routines via common blocks to simplify subroutine calls. Any other site-specific information (e.g., process schedule, energy accounting procedures, and additional program variables) was added in the main routine. Of the five systems using unfired boilers, four were configured identically with differences in input data only. For these four systems (Dow, Lone Star, Southern Union, and USS Chemicals) a single main routine was adequate. Each of the other systems required its own main routine. Complete listings of the main routines can be found in Volume II of this report.

2.1.2 Subroutines

Component subroutines have been written for a number of typical IPH hardware elements.

Table 2-1. IPH Hardware Component Subroutines

Subroutine Name	Component	Comments
FPLATE	Nontracking collectors	Flat plate and evacuated tube
TROUGH	Single axis tracking collectors	All orientations
PIPE	Pipe	Operating and nonoperating losses
HX	Heat exchanger	
HX2	Heat exchanger	Includes capacitance
LOADS	--	Load schedule and flows
STORE	Storage tank	Single node
TCSTORE	Storage tank	Two node (thermocline)
FLASH	Flash tank	Includes throttling valve, flash tank, and make-up valve
BOILER	Unfired boiler	
BOILER2	Unfired boiler	With preheater
DEBUG	--	Detailed daily output

Some of these routines had to be written to accommodate those components found in the field that had not been modeled previously. The unfired boiler was one such component for which a new routine (BOILER) was written. The analysis of the unfired boiler is fairly straightforward. Details of the analysis can be found in Appendix A. The routine is broken into two basic parts: boiler warm-up and steam generation. During periods of warm-up, boiler mass, skin losses, and tube side supply temperature all contribute to the net temperature increase (or decrease) of the boiler water. Once steam generation has begun, feedwater heating must also be accounted for. In order to satisfy energy balance criteria, it was necessary to break the hourly time steps into smaller increments. A criterion of approximately 1% convergence was established as a goal for energy balances in the unfired boiler subroutine.

The analysis for a heat exchanger with capacitance is nearly identical to the unfired boiler analysis during warm-up periods. The major difference is the addition of a shell-side flow at a given (constant) inlet temperature. Appendix B contains the analysis for this component.

Minor modifications were made to several other existing subroutines, mostly to enhance the speed of execution. For example, all possible trigonometric calculations were made outside subroutines so that calculations for angles that did not change were not repeated. The ability to calculate incident angles for an arbitrarily oriented, single-axis tracking collector was added to the TROUGH subroutine. This was necessary because many of the site collector fields were not oriented either strictly north-south (N-S) or east-west (E-W). The analysis for incident angles is given in Appendix C. A complete listing of all subroutines is contained in Volume II of this report.

2.2 ASSUMPTIONS AND LIMITATIONS

There are, by necessity, a number of assumptions that limit a code of this type from truly representing "reality." Many of these stem from the use of an hourly time step. A compromise between shorter time steps, which would more realistically simulate the system operation but require large amounts of data (not available for annual simulations), and longer time steps requiring less data but more inaccuracies generally resolves in favor of the hourly time step. This is the most practical solution when greater accuracy and more detail are the primary considerations.

The availability of actual hourly data discussed previously remains a major stumbling block for precise comparisons between predictions and actual performance. While some dynamic system response can be accounted for in hourly time steps, e.g., boiler warm-up and steam generation within a hour step, the transient performance due to variable cloudy weather cannot. The code assumes the collector field to be either on or off for the whole hour depending on the critical or start-up intensity of the control system. No other system control functions are or can be modeled for an hourly time step. Klein, Duffie, and Beckman (1974) studied the numerical effects of rapidly changing solar radiation on the performance of flat plate collectors. Their conclusion for a multi-node model was that "...fluctuations in solar radiation lead to a transient loss of less than 0.5 percent of the useful energy gain." Since concentrating collectors will generally have very low time constants and less thermal mass per unit area than flat plates, a reasonable argument could be made to extend their conclusion to concentrators. However, when the consideration of control strategies for single-axis trackers is added, drawing any conclusions becomes more difficult. This area is certainly a candidate for further study and analysis.

Another collector-related limitation is the use of collector module test data to represent full field thermal performance. Generally, the module level tests were conducted with carefully selected collector components so that optimum performance could be measured; i.e., the unit tested would not necessarily represent production line unit performance. The tests were also run on new, clean reflectors and glazings, and thus the data denote performance that rarely, if ever, occurs in the field. An attempt to account for the degradation in "optical" performance of the collectors was made for the input data utilized in the SOLIPH simulations. Three sources of information were used to estimate the effects of dirt and dust accumulation on reflectors and glazings. First, Morris (1982) has provided measured specular reflectance and transmittance data for several materials at many IPH sites. Using this data, plus reflectance measurements from site visits, reasonable estimates for average "optical" degradation factors were made. In some cases, fluctuations in reported collector performance from month-to-month and contractor-reported reflectance data were also utilized for these estimates. The optical efficiency input data are constant over the year; no attempt to match the data to washing cycles, rain, or other modifiying factors was attempted.

The pipe routine has two operating modes, one during operation and one during shut-down periods. During operation, only steady-state losses are calculated; no thermal capacitance effects are considered, because the pipe code does not include capacitance effects. Capacitance effects during operation are accounted for by using a storage node that contains pipe capacitance summations plus collector capacitance (collector heat loss is accounted for in the performance curve). This node is set up by a call to STORE with appropriate input parameters. For example, overnight cooldown losses in the various pipes and collector field lower this storage node's temperature on system start-up. While this storage node could be eliminated by incorporating its features into the pipe routine, there is little incentive to do so as overall accuracy would not necessarily be improved.

In addition to the various limitations that are inherent in the analytical basis for the model, the output can be only as accurate as the inputs. While the authors strove to maintain a consistent approach and methodology to input data generation, undoubtedly some deficiencies exist in the result. Efforts to improve both the model and the input data have hopefully resulted in an objective, realistic picture of each of the field experiments.

2.3 INPUT DATA

There are a large number of required inputs to characterize the configured system. The number and type of inputs also change from system to system. Within the code, the input data are provided to the program using a NAMELIST statement. In the NAMELIST declaration, all possible variables are listed. Each system configuration then has a separate data file containing only those necessary to describe its configuration. There are several other components or routines that are not described here because they were not used: flat plate collectors, load schedules, 2-node storage tank, and unfired boiler with preheater. Several other miscellaneous input variables are not utilized in the present analysis and are also not described. Each of the generic component inputs required for the system configurations studied is described in the following subsections.

2.3.1 Collector Field

Collector performance depends on many characteristics. Location, area, orientation, row spacing, optical and thermal performance data, physical dimensions, flow rate, and working fluid are the significant inputs. Table 2-2 includes all the inputs for the single-axis tracking parabolic trough collector fields at the site studied.

The collector performance equation utilized is reviewed here for clarification of the above list. The equation used is based on the analysis given by Tabor (1980) to account for nonlinear heat losses in a physically correct fashion. The performance equation is

$$\eta = \eta_o K \gamma - C_1 \frac{\Delta t}{I} - C_2 \frac{\Delta t^2}{I} , \qquad 2\text{-}1$$

where

η = collector efficiency based on radiation in the aperture plane

η_o = optical efficiency (modified for dust build-up)

K = incident angle modifier = $B_1 + B_2\theta + B_3\theta^2 + B_4\theta^3$

B_1, B_2, B_3, B_4 = coefficients of polynomial fit

θ = incident angle

$\gamma = 1 - f \tan\theta/[L(1 + W^2/48ft^2)]$, end loss factor

f = focal length

L = drive string length (gaps between modules ignored)

W = module width

C_1, C_2 = coefficients of regression fit (units appropriate to I and Δt)

$\Delta t = t_{av} - t_a$, ^oC

t_{av} = average of fluid inlet and outlet temperatures, ^oC

t_a = ambient temperature, ^oC

I = direct beam radiation in aperture plane, (kJ/hr-m^2).

Table 2-2. Inputs for Single-Axis Tracking Parabolic Trough Collector Fields

Variable	Units	Comments
Latitude	^{o}	
Area	m^2	Aperture area
Ground cover ratio		Used for shading loss calculations
Drive string length and width	m	Used for end-loss calculation
Focal length	m	Used for end-loss calculation
Orientation		Flag for E-W, N-S orientation
Tilt	^{o}	Nonhorizontal fields
Azimuth	^{o}	Axis azimuth, positive means CCW from S
Receiver mass	kJ/^{o}C	Used in nonoperational cooldown calculations
Critical intensity	kJ/hr-m^2	Control system start-up threshold
Optical efficiency		Modified for average dust and dirt accumulation
Loss coefficients		See explanation below
Incident angle modifier		See explanation below
Field mass flow rate	kg/hr	Calculated at average system operating temperature
Working fluid specific heat	kJ/kg-^{o}C	Calculated at average system operating temperature

Where published raw data were not available to perform regression analysis using Eq. 2-1, manipulation of available performance curve coefficients was necessary. When polynomial curves in $\Delta t/I$ were available, the third term (containing $(\Delta t/I)^2$) was modified by taking the known or estimated value of I during the test and dividing the third term coefficient by that I value, thus modifying the variable to $\Delta t^2/I$. The form of Eq. 2-1 results:

$$C_2' \left(\frac{\Delta t}{I}\right)^2 = \frac{C_2'}{I_{test}} \frac{\Delta t^2}{I} = C_2 \frac{\Delta t^2}{I}$$

and

$$C_2 = \frac{C_2'}{I_{test}} .$$

This approach was evaluated for a collector tested where both raw and polynomial curve fit data were available, and was found to be acceptable.

2.3.2 Pipe

The analytical approach in the pipe routine is quite straightforward, but the input data is relatively cumbersome and time consuming to generate. Steady-state heat losses are included as well as losses from all types of other hardware items. Handbook data exist for heat losses from uninsulated valves of various sizes, but the primary reference for heat loss from piping components was the recent work at SNLA by Harrigan and Meyer (1983). The data presented in SNLA's work were generalized to cover the range of component sizes necessary for this study. Heat losses from the various components can be a significant fraction of the total piping heat loss.

The piping system can be modeled in several sections. Collector supply and return lines are usually considered separately and broken into either inside or outside sections. Piping located outdoors loses heat to the environment at the ambient temperature; indoor piping loses heat to a fixed 25°C environment. Each pipe then has input parameters that describe its heat loss characteristics or overall UA (summation of all component UAs), thermal capacitance, and a flag for either indoor or outdoor location. The thermal capacitance includes working fluid, pipe, insulation, and pipe support mass and heat capacity. As mentioned previously, thermal capacitance during operational periods is handled using a single node, lumping all piping and collector mass together in a zero heat loss storage tank.

2.3.3 Storage

The storage routine is also straightforward and requires the thermal capacitance of the tank (including fluid and tank masses) and a skin heat loss UA.

2.3.4 Heat Exchanger (without capacitance)

The only input requirement for a simple heat exchanger is the effectiveness. Both stream outlet temperatures can be calculated knowing flow rates and inlet temperatures.

2.3.5 Boiler

The boiler analysis can be found in Appendix A. Input requirements are relatively easy to develop and include the skin heat loss coefficient, overall UA between tube and shell-side fluids, thermal capacitance (including a factor to account for supports, instrumentation, relief valves, etc.), blowdown requirements (minimum steaming rate for blowdown and blowdown rate), and a flag for whether the boiler is inside or outside. This input data plus the required steam temperature and available feedwater temperature are all that is necessary to calculate boiler performance.

2.3.6 Heat Exchanger (with capacitance)

Inputs and analysis (see Appendix B) are similar to those for the boiler during warm up. The shell-side fluid is assumed to have a fixed inlet temperature and flow, therefore the shell-side outlet temperature varies with tube side temperature and flow. In order to calculate performance it is necessary to know the skin UA and tube-to-shell side UA, heat exchanger thermal capacitance, shell side flow and inlet temperature, and whether the exchanger is indoors or outdoors.

2.3.7 Miscellaneous

Several more variables for program control should be mentioned. Any simulation can be limited to a time period less than a year by a flag indicating how many hours to run. A double check of the TMY site by an identification code number is also utilized. A flag for each month indicates which julian day to choose for the "clear" day outputs. A clear day is chosen prior to run time by the day in a month with the highest direct normal total. This will not always result in the highest delivered energy in the month because previous days' output will affect daily performance; e.g., a cloudy day before will result in lower system temperatures and therefore require longer warm-up time. Any of 12 days in the year can be output on a detailed basis (all system temperatures and energy flows) for debugging or further analysis by using another flag. Output can be generated for later plotting by setting a flag. Pump seal cooling losses, if any, can be added and parastic power requirements are also included. Electric power consumption is based on reported site data and is accumulated at an average hourly value whenever the circulating pump is on. A complete list of inputs for each site can be found in Tables 3.1 and 3.2.

2.4 OUTPUT

Output can be generated in three forms: tabular, graphical, and debug. Both the tabular and graphical output include an annual summary with breakdowns by month, a monthly summary with daily breakdowns, and a "clear day" output for each month with hourly breakdown.

The debug output shows detailed system flows and temperatures, ambient conditions, and energy flows for each hour for selected days. This feature was primarily used to debug new system configurations or subroutine modifications.

The tabular monthly and annual output include data for horizontal surface, direct normal and collector plane solar radiation (including row-to-row shading losses), collected energy, collector efficiency, delivered energy, system operating and nonoperating losses, system efficiency, and parasitic power requirements. Energy values are expressed in gigajoules (GJ) and efficiencies in percent, based on incident energy in the collector plane. The daily "clear day" output is similar and includes, in addition, hourly ambient temperature, flow rate, and collector inlet and outlet temperatures.

The graphical output for annual and monthly summaries is a series of bars showing incident energy in the collector plane, collected and delivered energy. Daily graphics include plots of direct normal irradiance, incident energy in the collector plane, and collected and delivered energy for each "clear" day selected.

Examples of each output form, except debug, can be found in Section 3.0, and complete system output data can be found in Volume II of this report.

SECTION 3.0

SOLIPH RESULTS

3.1 CATERPILLAR TRACTOR

3.1.1 System Description

The Caterpillar Tractor solar system is 4684 m^2 (50,400 ft^2) and interfaces directly with the plant's process water system. Chemically treated water under pressure, typically at 90°C, enters the collectors and is heated to a maximum collector outlet temperature of 113°C. The heated water flows through a conventional water heater and then through heat exchangers to provide hot wash water for cleaning mechanical parts. At start-up, the flow is reduced to prevent excessive thermal shock (near-ambient temperature fluid in the collector field) to the systems.

The collector system (Solar Kinetics T-700A) is roof mounted and comprises two distinct collector fields, one of 22 rows and the other of 8 rows. The circulating pumps and the manifold piping are housed in the building under the collector field. Roof penetrations are made for the collector risers and downcomers for each collector row. Thus only the collectors, flex hoses, and a minimal amount of piping and fittings are exposed to the outside environment.

The collector system was designed to provide process heat on a six-days-per-week basis. However, the plant has been running at such a low production level that the solar system output can exceed the total energy requirement for hot water. The maximum collector outlet temperature is maintained by shutting down collector rows by utilizing a desteering mechanism that defocuses the collectors for short time periods. Details of the collector system are shown in Tables 3-1 and 3-2. The use of water at the San Leandro site is particularly advantageous as freezing temperatures are uncommon. The row spacing was dictated by the location of the roof support beams.

Thermal characteristics of the solar system are illustrated in Table 3-3. The system is well insulated, and since most piping is indoors and operating temperatures are low, thermal losses should be small. However, the thermal capacity of the system is large. This results from the use of water as the working fluid, from the additional piping needed for the reverse return header configuration, and from the size of main pipelines.

3.1.2 SOLIPH Configuration

The main SOLIPH routine for Caterpillar is unique in that it is the only system with an open loop configuration. All the others have a closed collector loop and therefore require an iterative approach for each hourly solution. For this system, the code generates results (outlet temperatures) without iteration inputs and therefore runs very quickly. Some changes were necessary to determine if the collectors would operate (solar irradiance greater than the threshold) so that initial calls to PIPE would have the correct inputs.

Table 3-1. System Description

	Caterpillar Tractor	Dow Chemical	Home Laundry	Lone Star Brewery	Ore-Ida	Southern Union	USS Chemicals
Location	San Leandro, CA	Dalton, GA	Pasadena, CA	San Antonio, TX	Ontario, OR	Lovington, NM	Haverhill, OH
Latitude*	37.7	34.8	34.2	29.5	43.6	32.8	30.6
TMY site*	Oakland, CA	Chattanooga, TN	Los Angeles, CA	San Antonio, TX	Boise, ID	Roswell, NM	Cincinnati, OH
Collector area (m^2)*	4684	923	604	878	927	937	4680
Orientation*	NS	NS	NS	NS	11° W of N	EW	25° E of N
Tilt*	0	10° to S	0	0	0	0	0
Number of rows	30	15	58	15	14	6	60
Row length (m)	73.1	24.4	18.3	27.4	24.4	73.1	110
Row spacing (m)	4.1	5.5	1.37	4.1	4.6	4.9	6.1
Ground cover ratio*	0.525	0.44	0.405	0.525	0.60	0.434	0.35
Process type	Hot water preheat	Steam-unfired boiler	Steam-unfired boiler/DHW-heat exchanger	Steam-unfired boiler	Steam-flash tank	Steam-unfired boiler	Steam-unfired boiler
Plant schedule	24 hr/day, 6 day/wk	24 hr/day, 365 day/yr	7:00-3:30, 5 day/wk	24 hr/day, 365 day/yr	24 hr/day 365 day/yr	24 hr/day 365 day/yr	24 hr/day, 365 day/yr
Delivery temperature (°C)*	113	187	166/66	177	174	191	151
Feedwater temperature (°C)*	91	96	82/9.4	88	149	82	135
Collector fluid	Water	Dowtherm LF	Water	Therminol 55	Water	Texatherm	T-60
Specific heat (kJ/kg°C)*	4.20	2.22	4.21	2.37	4.60	2.54	2.08
Flow rate (kg/hr)*	98,320	11,270	15,840	13,200	10,500	17,900	72,450
Parasitic energy (kJ/hr)*	$6.4 \cdot 10^4$	$7.0 \cdot 10^3$	$2.6 \cdot 10^4$	$5.3 \cdot 10^3$	$2.5 \cdot 10^4$	$5.7 \cdot 10^4$	$7.3 \cdot 10^4$

*SOLIPH input data.

Table 3-2. Collector Characteristics

	Caterpillar Tractor	Dow Chemical	Home Laundry	Lone Star	Ore-Ida	Southern Union	USS Chemical
Collector width W (m)*	2.13	2.4	0.51	2.13	2.4	2.13	2.13
Drive string length L (m)*	18.3	24.4	18.3	13.7	21.3	18.3	18.3
Focal length F (m)*	0.53	0.61	0.12	0.53	0.61	0.53	0.53
Optical efficiency %*	0.66	0.638	0.575	0.59	0.674	0.59	0.63
C_1 (kJ/m^{2}h^{o}C)*	0.616	1.89	-0.133	0.839	1.89	0.839	0.616
C_2 (kJ/m^{2}h^{o}C^2*	0.00652	0.0	0.00384	0.00477	0.0	0.00477	0.00652
B_1*	1.007	1.007	1.013	1.007	1.007	1.007	1.007
B_2 (× 10^{-2})*	-0.296	-0.296	-0.422	-0.296	-0.296	-0.296	-0.296
B_3 (× 10^{-3})*	0.178	0.178	0.150	0.178	0.178	0.178	0.178
B_4 (× 10^{-5})*	-0.289	-0.289	-0.252	-0.289	-0.289	-0.289	-0.0289
Start-up intensity (kJ/m^{2}h)*	720	720	1134	720	720	720	1135

*SOLIPH input.

SERI

Table 3-3. System Thermal Characteristics

	Caterpillar Tractor	Dow Chemical	Home Laundry	Lone Star	Ore-Ida	Southern Union	USS Chemicals
Pipe UA (kJ/hr°C)*							
1	1119	459	212	222	938	188	921
2	646	160	107	58	130	28	17
3	646	381	68	92	166	142	72
4	568	564	374	215	835	358	1212
$\sum$ Pipe UA/area (kJ/hr °C m^2)	0.636	1.69	1.26	0.669	2.21	0.764	0.475
Pipe Mc_p (kJ/°C)*							
1	18565	544	874	531	3899	572	6859
2	804	653	481	244	653	160	152
3	804	1232	230	322	763	648	1696
4	6229	574	1727	528	3352	1780	14413
$\sum$ Pipe Mc_p/area (kJ/°C m^2)	5.30	3.25	5.48	1.85	9.25	3.37	4.94
Receiver Mc_p (kJ/°C)*	7643	1362	673	1400	1420	1493	6551
Pump cooling (kJ/hr)*	0	14,000[1]	0	0	1900	1900	0[4]
Boiler tube UA (kJ/hr°C)*	NA	66,000	22140/ 6467[2]	77,900	NA	77,900	372,000
Boiler skin UA (kJ/hr°C)*	NA	71.5	19.4/ 62.1[2]	52	32[3]	59	96.8
Boiler Mcp (kJ/°C)*	NA	2832	1594/ 1443[2]	3787	3176[3]	5256	14,484

1: Includes expansion tank losses
2: Boiler/DHW heat exchanger
3: Flash tank
4: Pump cooling included in Pipe 4 UA

*SOLIPH Input.

It was also necessary to artificially zero the solar radiation inputs one day per week to reflect plant schedule. Radiation values are not accumulated in monthly and annual totals for the plant non-operational days. A schematic of the code configuration is shown in Figure 3-1.

The initial subroutine call is to the storage node representing the system thermal capacity. This node's temperature is lowered at time steps when the system starts up to account for overnight cooldown type losses. No attempt to model actual system start-up flow reductions is made. Some days, after long nonoperational periods or particularly cold nights, will indicate a negative energy delivery. This occurs on five days during the modeled year. The energy delivered is determined by the Pipe 4 outlet temperature (representing upstream injection temperature) minus the system inlet temperature (a constant) times the mass flow-specific heat product. Energy collection, as in all the systems, does not include any flex hose or row interconnect piping losses.

Collector performance for the T-700A is taken from Dudley and Workhoven (1982). The modification process is somewhat different for this collector since the data presented in the reference are in nearly the same form as required. An additional term representing increased heat loss due to nonzero irradiance is included in the performance curve by Dudley and Workhoven. However, a curve fit of the raw data in the form required by SOLIPH yields residual errors that are nearly identical to the reported fit. The coefficients determined from the raw data curve fit in the form of Eq. 2-1 are utilized for both Caterpillar Tractor and USS Chemicals.

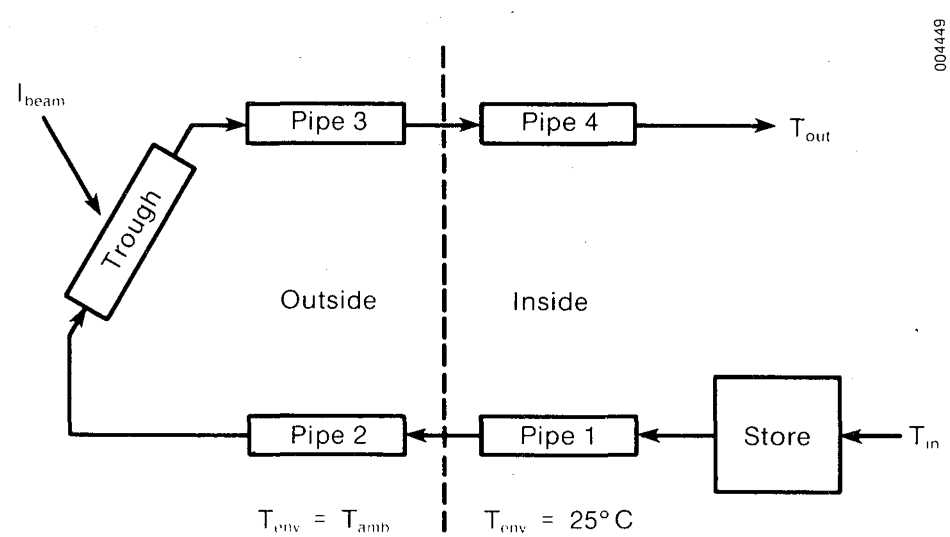

Figure 3-1. SOLIPH Configuration for Caterpillar Tractor

3.1.3 Results and Discussion

The Caterpillar Tractor solar system has a higher predicted annual energy delivery per unit of collector area, 2.4 GJ/m^2, than any of the other six systems studied. This is so in spite of the fact that irradiation availability is only slightly above average. The chief reason for this is that the operating temperature is low. The average collector operating temperature is only about $100^{o}C$. This low operating temperature has two very beneficial effects: first, the collectors operate at higher efficiency than for any of the other systems; second, energy transport losses are very low.

Energy transport operating losses are only 4.1% of energy collection. Along with the low operating temperature advantage, the system is well insulated and most of the piping is contained within the Caterpillar plant rather than outdoors. The piping system UA per unit of collector area is quite low in comparison to the other systems.

The thermal capacity of the piping system, however, is quite large. On a per unit collector area basis, only the Ore-Ida plant has a larger thermal capacitance. The large thermal capacitance results from the use of large (up to 6 inch) headers, the use of extra piping for reverse return flow, and the use of water rather than a heat transfer oil (with a lower specific heat) within the loop. While the thermal capacitance of the energy transport system is large, only 3.9% of energy collection goes to nonoperating losses.

The annual system efficiency is 51.8% (which is very good for reasons discussed above). This shows the distinct advantage of water preheat systems operating at low temperatures. The annual performance is summarized in Table 3-4 and shown graphically in Figure 3-2. Several features of this system can be seen in the clear day performance graphic for February in Figure 3-3. First, the low solar altitude in the winter months is reflected in the large difference (primarily cosine loss) between the direct beam and incident energy curves. The N-S orientation causes morning and afternoon peaks instead of the noon peaks of an E-W system.

It was recently determined that the building and consequently the collector axis was not true N-S but 22^{o} east of north. Because the system was modeled as true N-S, some of the results provided in this report are slightly in error. Daily profiles of incident, collected, and delivered energy will be affected with higher afternoon peaks and lower morning peaks. The daily, monthly, and annual summaries of energy delivery should not be significantly changed. Negative energy deliveries as during hour seven are caused by low available and incident energy coupled with large overnight cooldown losses. Generally, however, the low heat losses in this system are clearly seen in the small difference between collected and delivered energy for the remaining hours of the day. The complete set of SOLIPH output for Caterpillar is given in Volume II of this report.

Table 3-4. Caterpillar Tractor (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM OPERATING LOSSES GJ	SYSTEM NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	960.9	1278.8	748.1	348.7	46.6	289.9	24.9	33.7	38.8	7.2
FEBRUARY	1257.7	1460.8	1029.0	521.0	50.6	459.8	30.4	30.0	44.7	8.8
MARCH	1934.5	1848.2	1473.3	807.9	54.8	728.1	38.1	41.8	49.4	10.9
APRIL	2596.2	2488.9	2213.9	1273.7	57.5	1181.2	49.2	43.1	53.4	14.0
MAY	3236.4	3020.2	2878.7	1686.0	58.6	1585.4	59.1	41.5	55.1	16.9
JUNE	3188.1	2857.5	2717.1	1628.4	59.9	1534.5	53.3	40.6	56.5	15.2
JULY	3133.3	2915.9	2747.3	1640.4	59.7	1545.2	53.4	42.6	56.2	15.4
AUGUST	3003.5	3024.9	2824.4	1643.3	58.2	1540.6	58.0	43.9	54.5	16.9
SEPTEMBER	2290.8	2472.4	2124.6	1228.1	57.8	1141.1	45.6	42.2	53.7	13.5
OCTOBER	1732.6	2081.3	1526.9	822.3	53.9	738.5	40.0	43.2	48.4	11.9
NOVEMBER	1091.1	1539.0	942.1	454.4	48.2	383.7	30.1	40.7	40.7	8.9
DECEMBER	914.9	1464.6	842.2	368.6	43.8	298.4	32.1	38.1	35.4	9.4
TOTALS/AVERAGES	25340.2	26452.5	22067.5	12422.7	56.3	11426.4	514.1	481.4	51.8	149.1

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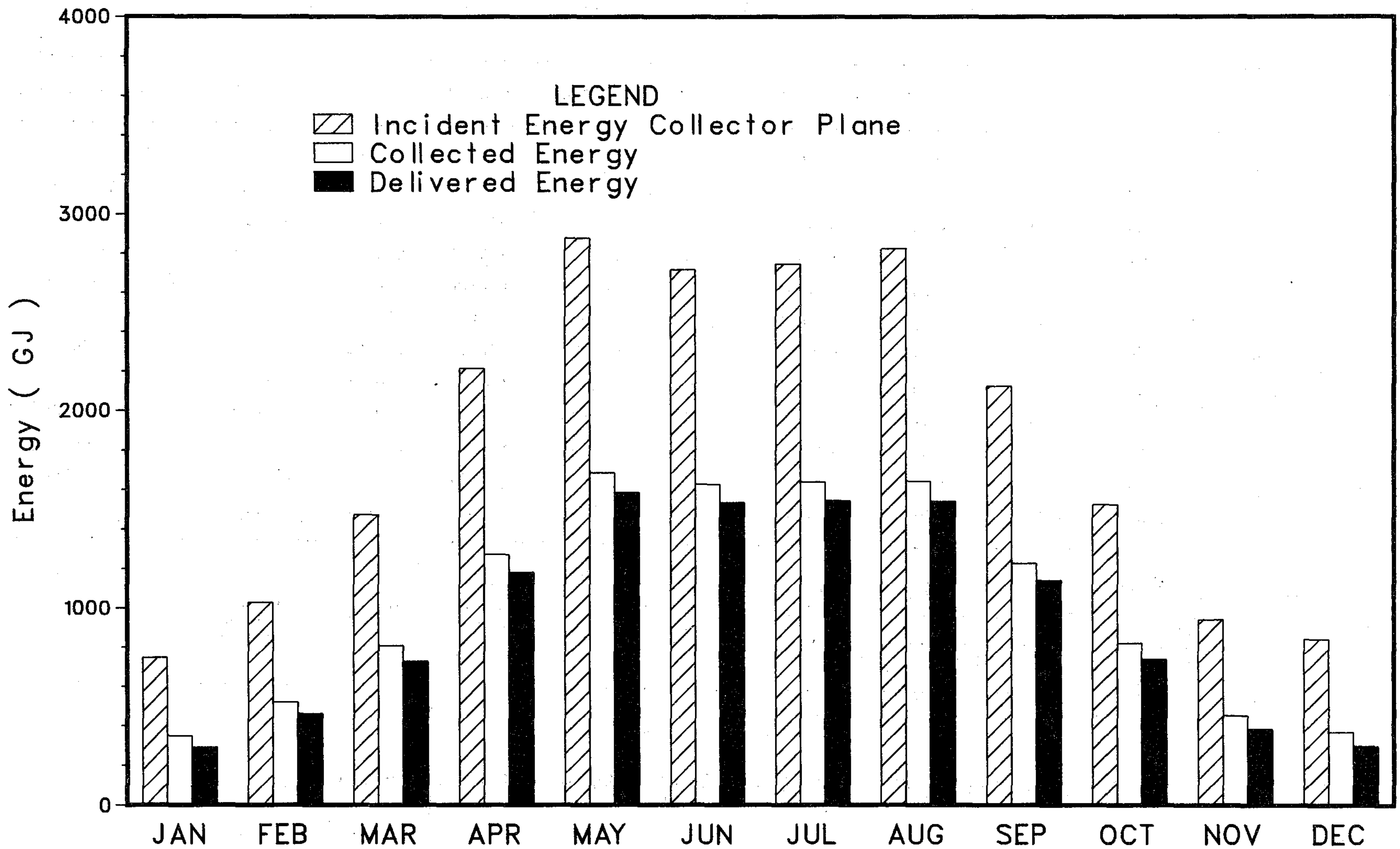

Figure 3-2. Annual Performance Summary: Caterpillar Tractor

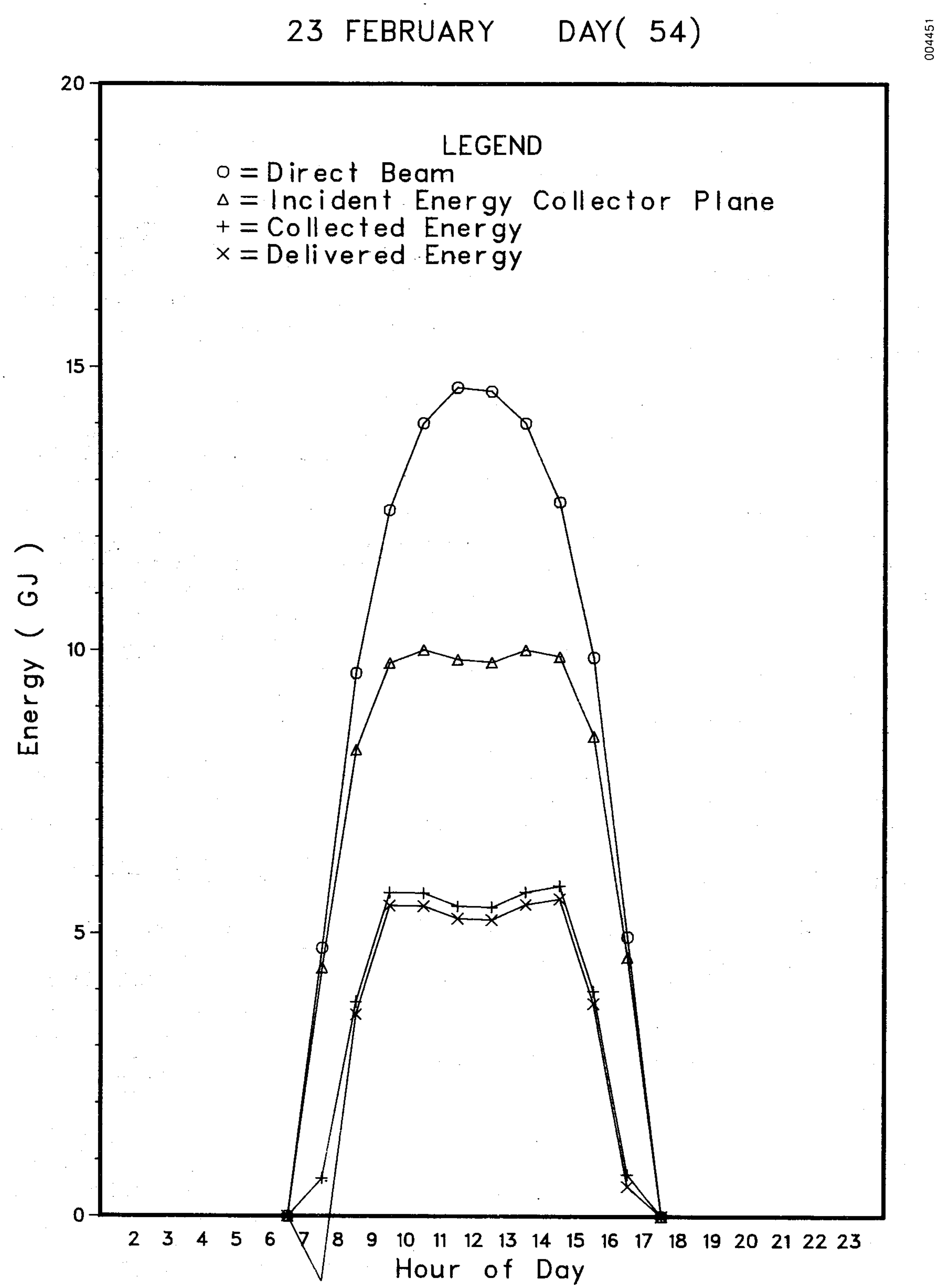

Figure 3-3. Clear Day Performance: Caterpillar Tractor

3.2 DOW CHEMICAL

3.2.1 System Description

This solar thermal system is designed to provide more than 7% of the required process steam for the continuous (24 hr/day, 7 days/week) stripping operation of Dow Chemical Company's latex manufacturing plant in Dalton, Ga.

The system consists of 15 rows of SUNTEC SH1655 parabolic trough collectors with a net aperture area of 922 m^2. The collector field is oriented N-S with a tilt of 10^o to the south. The heat transfer fluid is Dowtherm LF, which is used to provide energy to a kettle-type boiler producing steam at 187^oC and 1034 kPa pressure.

The entire system including the unfired boiler, expansion tank, and circulating pump is located outdoors. The unfired boiler is situated directly adjacent to the chemical plant boiler room, and thus boiler feedwater and the steam delivery lines are very short (about 10 m). However, it is more than 60 m (200 ft) from the unfired boiler to the nearest point in the collector field. All field piping except the connections to the collectors themselves consists of 2-in. pipe covered with 2-1/2 in. of calcium silicate insulation. The plastic jacket covering the insulation has deteriorated due to the weather, and many instances of water penetration into the insulation exist. The 2-in. piping is supported approximately every 3 m (10 ft) by fixtures that provide direct metal contact of the pipe to the environment.

Similarly, the in-line circulating pump is rigidly anchored to a metal base plate, and the pump is not insulated. Seal cooling also removes heat from the pump. The expansion tank is sized to hold the total field inventory of organic working fluid. Consequently, it is a large source of heat loss, particularly as piping forms a direct thermosyphon heat loop. Valves and fittings throughout the system are generally only partially insulated or not insulated at all. Details of the system are shown in Tables 3-1 and 3-2.

The SUNTEC absorber is insulated on the back half, and the front is covered with a glass half cylinder. This arrangement provides an imperfect environmental seal, and much dust had accumulated on the black chrome reflective surface at the time of the site visit. Thermal expansion of the receiver is accommodated by sliding through metal receiver support arms. This arrangement caused abrasion of the receiver tube and rusting along the tube near each support.

At the end of each collector row there is about 0.5 m (3 ft) of downcomer that is only half insulated. This downcomer is rigidly attached to the collector support pylon. The entire assembly acts as a large heat fin and is a considerable source of heat leakage. To ensure balanced collector flow in the reverse return piping configuration, restrictive orifices were employed at the inlet to each collector row. The thermal characteristics of the Dow solar system are illustrated in Table 3-3.

Near the end of the period covered by this report many of the deficiencies described were corrected. Piping was reinsulated with fiberglass; the steel pipe supports were removed and a reduced number of supports with calcium silicate saddles were installed; the pump, steam values, and miscellaneous uninsulated system elements were insulated.

3.2.2 SOLIPH Configuration

The main routine for Dow Chemical is identical to the other three unfired boiler systems. In fact, the only difference among the unfired boiler systems is the input data. Since these systems have a closed collector loop an iterative approach to converge on the average hourly operating temperatures was required. Typically, the heat balances are within 1% with a convergence criterion of 0.1°C. As with the other systems a storage node has been added to account for thermal capacitance and overnight cooldown losses.

The storage node and the remainder of the coded configuration are shown in Figure 3-4. Note that all components are outside, including the boiler. Energy delivery is computed as the difference in enthalpy between steam produced and feedwater inlet conditions. Steam enthalpy is determined at the boiler outlet and does not include any line losses to the plant steam header. Collector performance data are taken from Dudley and Workhoven (1978). Heat loss appears from the reported data to be linear when reviewing the efficiency data and slightly nonlinear when reviewing separate heat loss data. For consistency with the other systems, the reported efficiency data are utilized for the program inputs. Since the heat loss is linear, the third term in the efficiency equation is zero and no modifications to it are required.

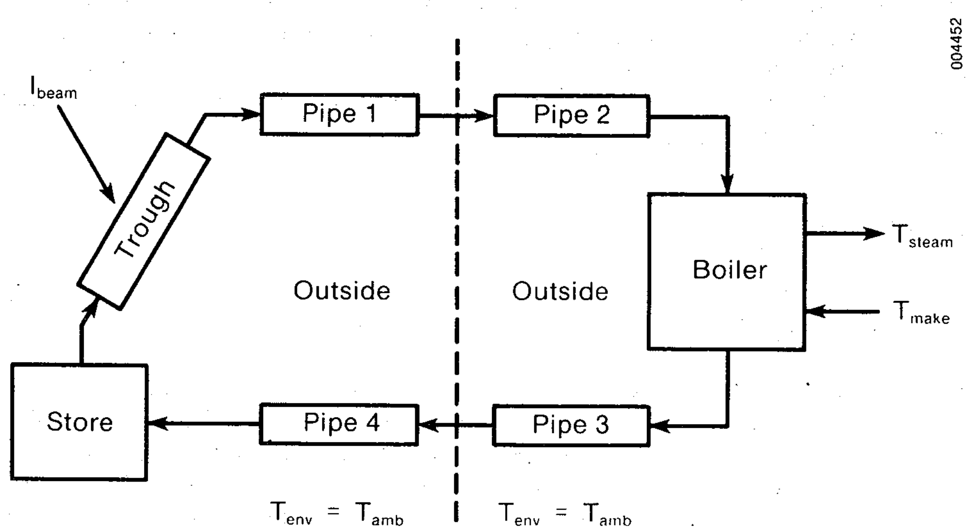

Figure 3-4. SOLIPH Configuration for Dow Chemical

3.2.3 Results and Discussion

The Dow Chemical system has the lowest expected energy delivery per unit of collector area, 0.86 GJ/m^2, of all seven field experiments. Two basic reasons lead to this result: available direct irradiance is very low, and the energy transport system is inefficient.

The available direct normal irradiation at the Dow site, based on ETMY weather data for Chattanooga, TN averages only 4.41 GJ/m^2. This irradiation level is less than half of the irradiation available at a good solar location such as the Southern Union site.

Before the system was upgraded the energy transport system suffered from a number of problems: the pipes lost heat easily because they directly contacted the pipes supports; valves and fittings were poorly insulated; the pump was not insulated; and the expansion tank lost considerable heat. All of these components are located outdoors and are thus subject to ambient temperatures. For these reasons the energy transport UA per unit area was a very high 1.70 kJ/hr^{o}C m^2, and 33% of the energy collected was lost during system operation. The thermal capacitance of the energy transport system was 3.25 kJ/hr^{o}C, and an additional 15% of the energy collected was lost during nonoperating hours.

The warm-up losses of the system are very evident in the clear day performance graphics. For example, the November clear day graphics in Figure 3-5 show energy collection beginning at approximately 7:00 a.m. However, no steam is delivered until more than two hours later. The 10^{o} tilt of this system makes the incident energy curve much smoother than for a horizontal NS orientation. This results in more constant energy collection through the middle hours of the day.

The annual efficiency of this system was only 25%, which is low due to the large heat losses within the piping and components. The annual performance prior to the upgrade is summarized in Table 3-5 and is shown graphically in Figure 3-6. The complete set of SOLIPH output data for Dow Chemical is given in Volume II of this report.

3.3 HOME LAUNDRY

3.3.1 System Description

The solar thermal system consists of 406 DEL linear parabolic trough collectors, in 59 rows, with a total aperture area of 603.5 m^2. The collectors are mounted on the roof of the laundry in a N-S orientation on a specially built support structure. The collected energy is supplied to an unfired boiler to produce 740 kPa saturated steam. Production of domestic hot water at 66^{o}C is an optional operation mode. Water is circulated at a constant flow rate between the collector array and either the 1) steam generator, 2) domestic hot water tank, or 3) high temperature storage tank. The storage tank is used as a buffer tank for closed-loop over-temperature protection, or for collector preheating during start up, or production of domestic hot water during periods of low irradiance. The system is designed to produce 20% of

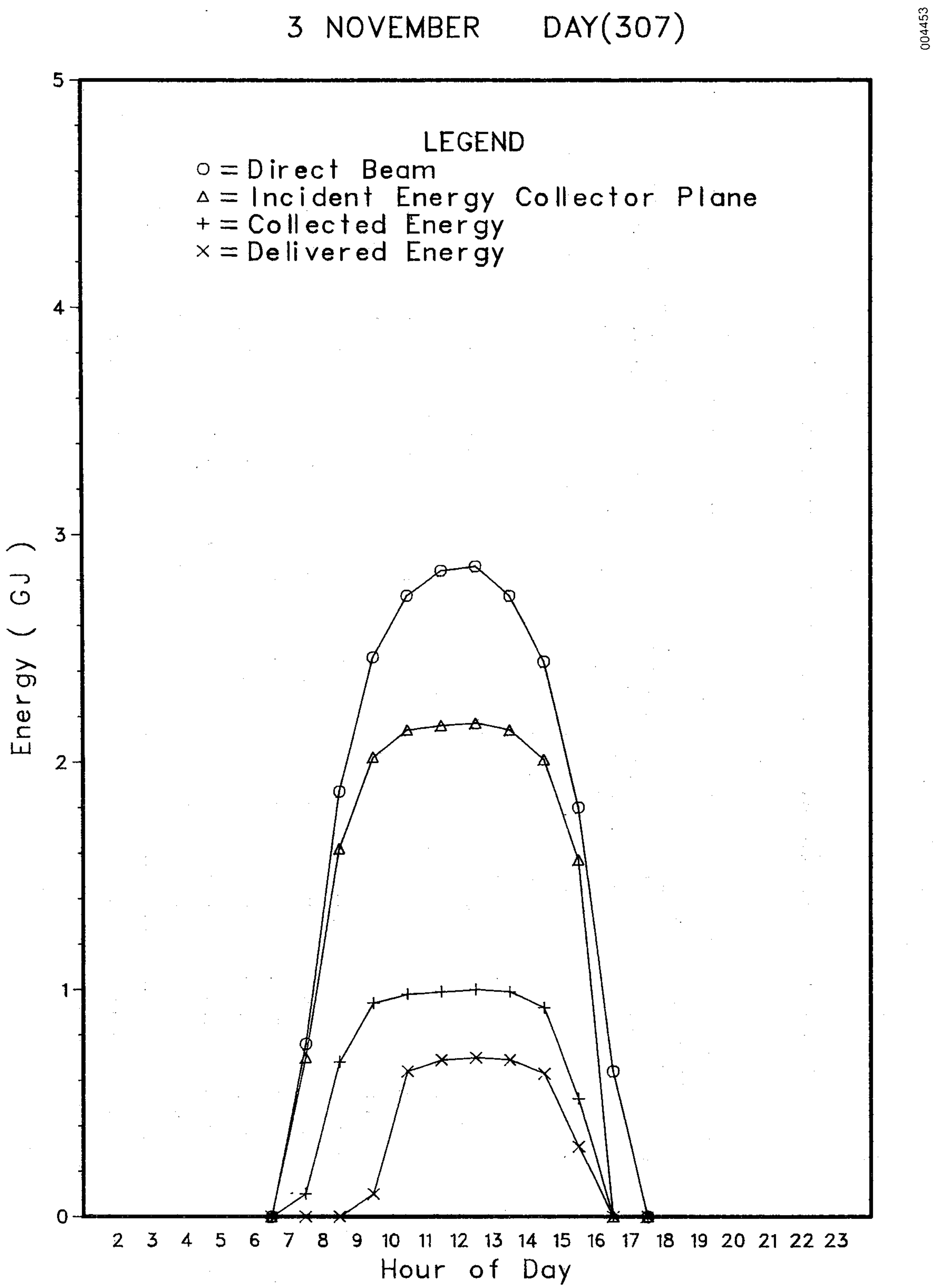

Figure 3-5. Clear Day Performance: Dow Chemical

Table 3-5. Dow Chemical (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM OPERATING LOSSES GJ	SYSTEM NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	213.5	252.1	175.8	68.0	38.7	22.5	28.6	16.6	12.8	.8
FEBRUARY	260.0	265.9	208.4	87.4	41.9	40.8	31.5	14.8	19.6	.8
MARCH	369.4	305.3	262.1	115.9	44.2	58.4	38.4	19.4	22.3	1.0
APRIL	504.5	387.6	348.3	161.1	46.3	89.5	49.6	21.7	25.7	1.3
MAY	546.6	384.6	363.7	169.9	46.7	99.5	52.1	18.1	27.4	1.4
JUNE	570.8	392.4	364.5	168.2	46.1	90.4	55.5	22.1	24.8	1.6
JULY	551.5	374.3	333.4	155.3	46.6	82.4	50.7	22.3	24.7	1.4
AUGUST	525.7	418.3	386.6	182.5	47.2	100.5	55.6	26.1	26.0	1.5
SEPTEMBER	415.9	350.3	319.4	147.2	46.1	83.6	44.3	19.3	26.2	1.2
OCTOBER	357.6	381.8	306.6	136.2	44.4	71.7	44.2	20.6	23.4	1.2
NOVEMBER	253.6	325.7	233.6	95.7	40.9	41.9	35.5	18.1	17.9	1.0
DECEMBER	186.1	223.1	144.0	53.7	37.3	13.1	25.6	14.9	9.1	.7
TOTALS/AVERAGES	4755.2	4061.3	3446.4	1541.0	44.7	794.4	511.6	233.9	23.0	14.0

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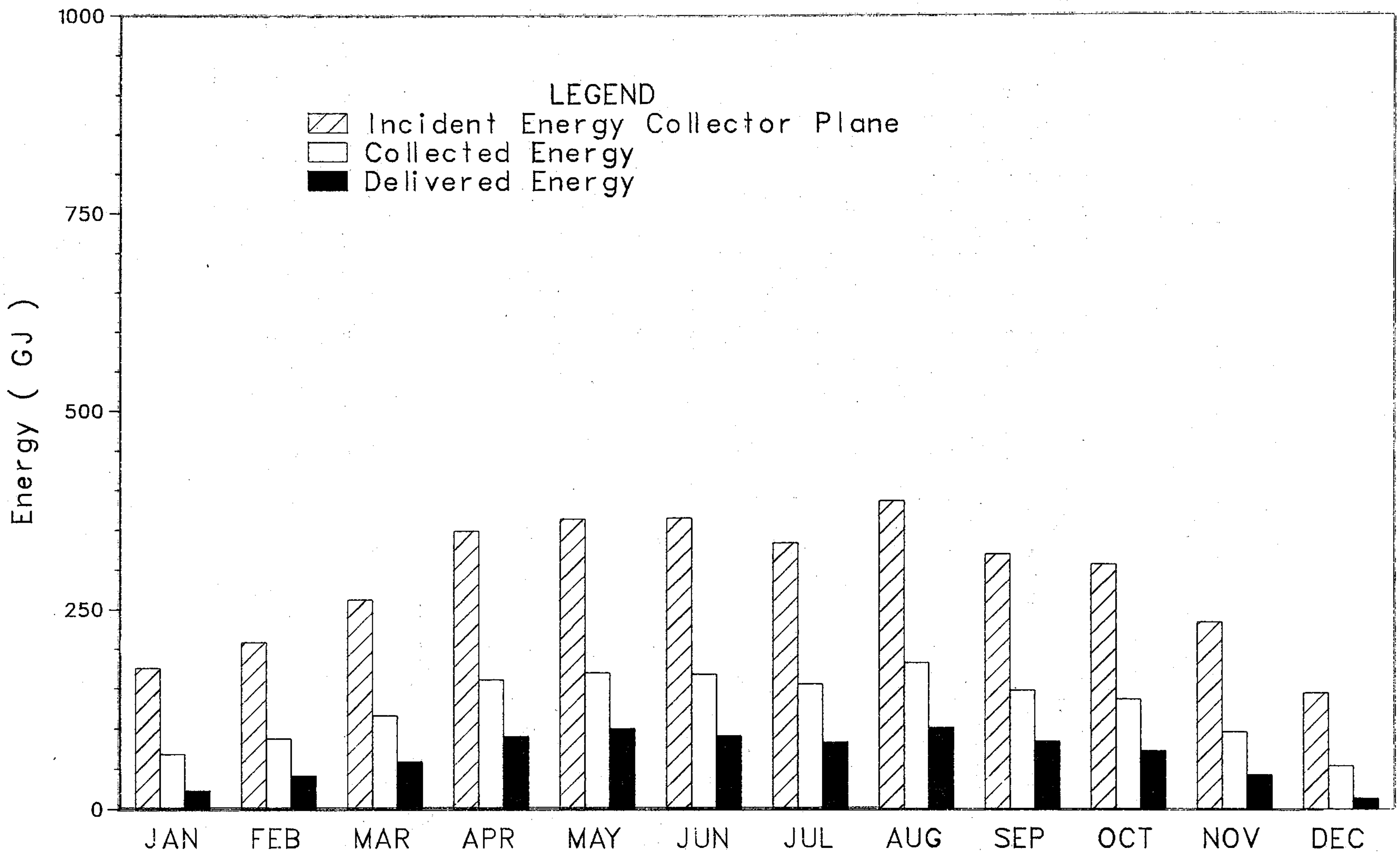

Figure 3-6. Annual Performance Summary: Dow Chemical

the laundry's annual steam demand. Additional system details are provided in Table 3-1 and details of the SOLIPH collector inputs are provided in Table 3-2.

At Home Laundry, the solar process equipment is located in the same room with the plant steam boiler. Collector supply and return lines run up through the roof to the solar field. The existing domestic hot water tank was retrofitted with a multiple-pass, tube type heat exchanger to provide the additional system capability noted previously. The data acquisition and control equipment are located in a separate room.

The system is generally well insulated with a minimum of exposed pipe and fittings. Two inches of fiberglass is standard throughout the system. Piping is arranged to minimize thermosyphoning between hot process lines, the storage tank, and the expansion tank. The expansion tank is utilized to maintain sufficient pressure (via a nitrogen supply) to prevent boiling of the working fluid. An inspection of the tank piping and daily records during the site visit indicates that both the expansion tank and storage tank (when bypassed) do not drain energy from the process piping.

While the indoor piping has fairly low heat loss characteristics, the outside piping, namely collector field supply and return lines, has fairly large heat losses. This is primarily due to the long lengths and large number of pipe supports that exist. Since the DEL collector modules are quite small in aperture, there is correspondingly a higher number per unit roof area. This results in a large number of header connections, more expansion loops and more opportunities for energy to be lost. The thermal characteristics, including the higher than average piping mass and losses, are shown in Table 3-3. Additionally, the use of water increases the system thermal capacitance.

The operating schedule at the Home Laundry is 7:00-3:30. Early plant shutdown results in a loss of potentially collectable energy in the late afternoon hours. In actual practice, much of that available energy is routed to a storage tank and utilized the next day.

3.3.2 SOLIPH Configuration

Generally, the nominal operating mode at Home Laundry includes both steam and domestic hot water production. Recently, domestic hot water has been the primary mode (as per the laundry's request), with steam production occurring only after the DHW load has been saturated. This type of operation is very difficult to model and is further complicated when the storage tank is utilized after both loads have been saturated. To avoid the difficulty of accurately modeling the actual operations, the two main operating nodes were split into two distinct simulations and not intermixed.

The domestic hot water configuration is similar to the unfired boiler except that a heat exchanger with thermal capacitance is utilized. The outlet temperatures of the heat exchanger both to the load and to the collector field float with the supply from the collector field. The load inlet is fixed at the average city water supply temperature. Again the storage node is utilized to account for piping and collector thermal capacitance. A schematic of the coded configuration is shown in Figure 3-7.

The laundry's operating schedule imposes a modification to the program. Since there is a daily limitation in operation time (7:00-3:30), the routine is set to ignore any hours outside this range when solar irradiance is above the threshold for operation. The irradiance that is ignored is accumulated and counted in daily, monthly, and annual summaries. The laundry does not operate on weekends; therefore, every two days out of seven the irradiance values are artificially zeroed and not counted in energy summations. The program operates on solar time only and will result in mismatches between actual and program operating time.

The amount of energy delivered to the load side fluid is the system energy delivery. This is different from that measured at the laundry: energy delivery is measured as that amount delivered to the heat exchanger. The difference will be skin losses and internal energy change in the heat exchanger.

The collector performance data are derived from early test data taken at SNLA (Dudley and Workhoven 1979). Unfortunately, complete test data are not published, therefore estimation of some data from the reported curve was necessary. The resulting curve fit has one unique aspect. Since the data do not include very low temperature points, an anomaly of the regression due to the distribution of points results in the second coefficient being negative. This implies a slight rise in efficiency at very low temperatures before the third term begins to dominate, and results in more realistic performance. Fortunately, this anomaly does not affect the simulation results significantly as the collector field generally operates at higher temperatures. When the collector cools to near ambient temperatures overnight, in some cases there will

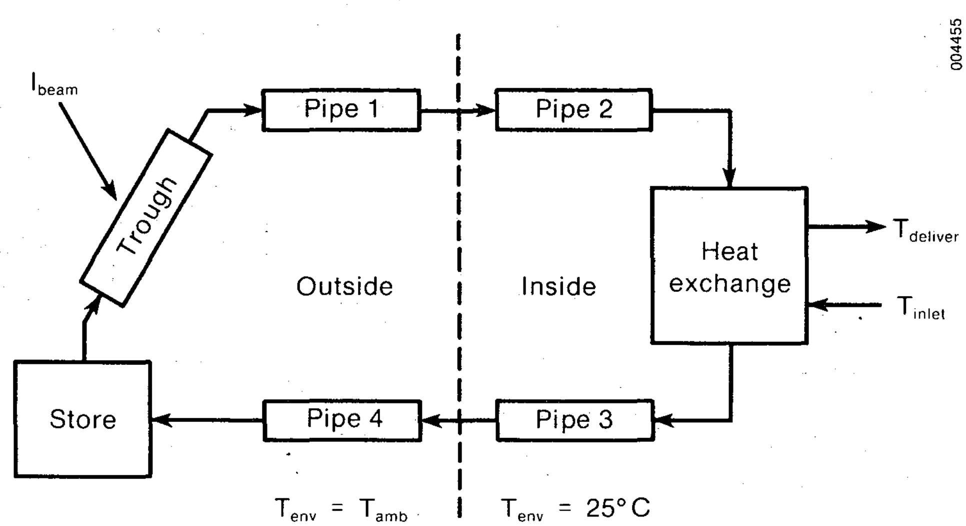

Figure 3-7. SOLIPH Configuration for Home Laundry (DHW)

be a slight heat gain instead of a loss. This happens rarely, however, and will not significantly affect the results.

With the exception of the operating time modifications, the steam configuration is identical to the other unfired boiler routines. At the laundry, there is a bypass valve at the boiler inlet, which is controlled by the steam outlet pressure to prevent overpressure in the boiler. This feature is not modeled, however, since there is no possibility for any overpressure in the boiler model and the bypass value rarely activates in practice. A schematic of the coded configuration is shown in Figure 3-8. Energy delivery is calculated, as at Dow, by the difference in enthalpy between steam outlet and feedwater inlet conditions.

3.3.3 Results and Discussion

While the energy transport system at Home Laundry has higher than average thermal losses and relatively large thermal mass resulting in higher system losses, the collector performance is higher than average. The piping UA is 1.26 kJ/hr°C m^2 while the piping thermal mass is 5.48 kJ/°C m^2, both higher than average. The operating and nonoperating losses represent 11% and 8%, respectively, of the energy collected. The collector field performs at an annual efficiency of 53%. When the collector performance and higher than average losses are combined, the annual energy delivery, in terms of system efficiency, becomes 43%, about average for this type of system.

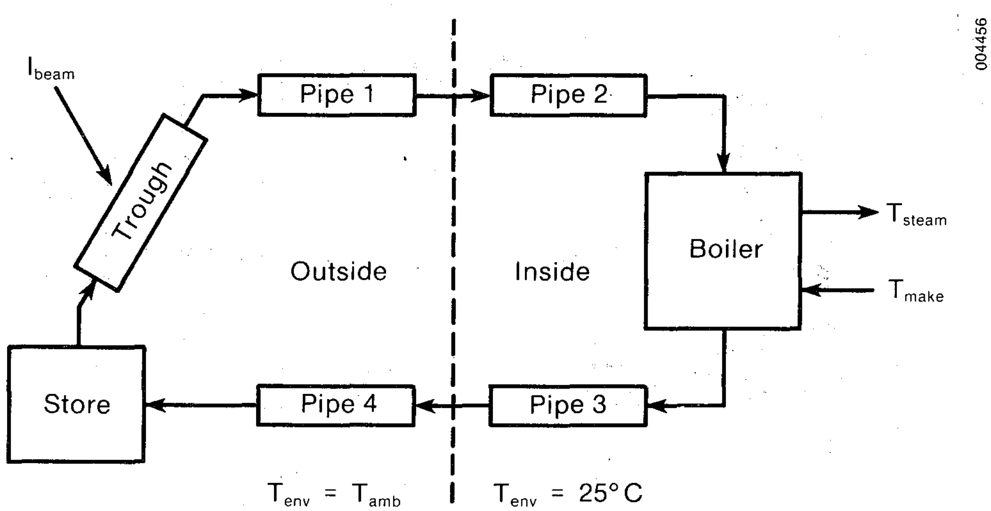

Figure 3-8. SOLIPH Configuration for Home Laundry (Steam)

Due to the lower operating temperature in the domestic hot water mode, losses are lower and performance higher than in the steam mode. While only 5% more energy is collected in the DHW mode, almost 28% more energy is delivered. This result shows the dramatic improvement in expected performance between steam and preheat systems. The annual performance is summarized in Table 3-6 and shown graphically in Figure 3-9. Effects of the large volume of water in the DHW heat exchanger are illustrated in the clear day performance curves for June shown in Figure 3-10. At startup, more energy is delivered than collected due to the large internal energy in the tank. This is quickly dissipated by the load. As can be seen, the thermal mass of the now cooled tank has to be overcome by the collected energy, which takes several hours.

The higher losses in the steam operation mode are due to the higher system temperatures. Operating and nonoperating losses represent 18% and 14%, respectively, of the energy collected. Since the same piping configuration is utilized for the steam mode, the thermal loss and capacitance figures are the same as for the DHW mode. Annual system efficiency for steam production is 33%, about 10 percentage points lower than for DHW.

Since the storage tank can be automatically or manually charged and discharged and this feature was not incorporated into the SOLIPH configuration, the predicted performance could be slightly low. If the effect of the storage tank had been accounted for, small increases in energy delivery could have resulted. Annual performance is summarized in Table 3-7 and shown graphically in Figure 3-11. Clear day performance for June is shown in Figure 3-12. High solar altitudes in the summer months result in low day-long incidence angles and hence maximize summer daily energy collection compared with an E-W orientation. System thermal mass is seen in the lag between collected and delivered energy. Early plant shutdown in the afternoon is tempered in practice by routing the collected energy to a storage tank, as in DHW operations. Complete SOLIPH output data for Home Laundry for both steam and DHW modes can be found in Volume II of this report.

3.4 LONE STAR BREWERY

3.4.1 System Description

This system consists of 878 m^2 of SKI T-700 collectors (the same as used at Southern Union), roof mounted and oriented N-S in 15 rows. The system is designed to produce 860 kPa saturated steam at a maximum rate of 544 kg/hr. Therminol 55 is circulated through the collector field producing steam in an unfired boiler. The brewery operates continuously. Tables 3-1 and 3-2 provide additional details of the solar system.

The solar system is located on the roof of a warehouse building housing the heat transfer equipment. The main collector inlet and outlet headers pass through the roof in a direct-return configuration. The boiler makeup water is piped from a distant central plant treatment facility, but steam feeds directly into an adjacent plant header. The steam generator is maintained at a minimum pressure of 100 kPa (15 psi) by the plant steam line to prevent any possible leakage of collector heat transfer fluid into the steam system.

Table 3-6. Home Laundry (DHW) (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY: HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY: DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY: COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM: OPERATING LOSSES GJ	SYSTEM: NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	144.7	225.4	141.5	66.7	47.1	54.4	7.1	4.3	38.4	3.7
FEBRUARY	171.2	215.4	145.2	74.1	51.0	59.9	8.1	5.5	41.2	3.3
MARCH	248.0	258.0	194.4	101.6	52.2	81.3	11.2	8.3	41.8	3.9
APRIL	276.8	255.2	204.6	110.1	53.8	87.6	12.2	9.3	42.8	3.5
MAY	343.7	298.1	237.7	130.0	54.7	104.2	14.3	10.7	43.8	4.1
JUNE	308.4	252.3	192.9	106.4	55.1	84.3	11.5	10.0	43.7	3.3
JULY	362.6	354.4	295.2	162.1	54.9	132.1	18.1	11.1	44.7	4.7
AUGUST	343.3	345.1	285.1	154.9	54.3	125.7	16.9	11.5	44.1	4.7
SEPTEMBER	241.8	245.8	198.3	105.7	53.3	85.3	11.3	8.6	43.0	3.7
OCTOBER	205.5	235.1	164.7	85.6	52.0	68.6	9.0	7.3	41.7	3.6
NOVEMBER	151.5	216.4	135.8	65.8	48.4	54.0	6.9	4.3	39.8	3.5
DECEMBER	120.1	188.7	113.5	52.0	45.8	42.3	5.3	3.8	37.3	3.3
TOTALS/AVERAGES	2917.5	3089.8	2309.1	1215.0	52.6	979.7	131.9	94.6	42.4	45.2

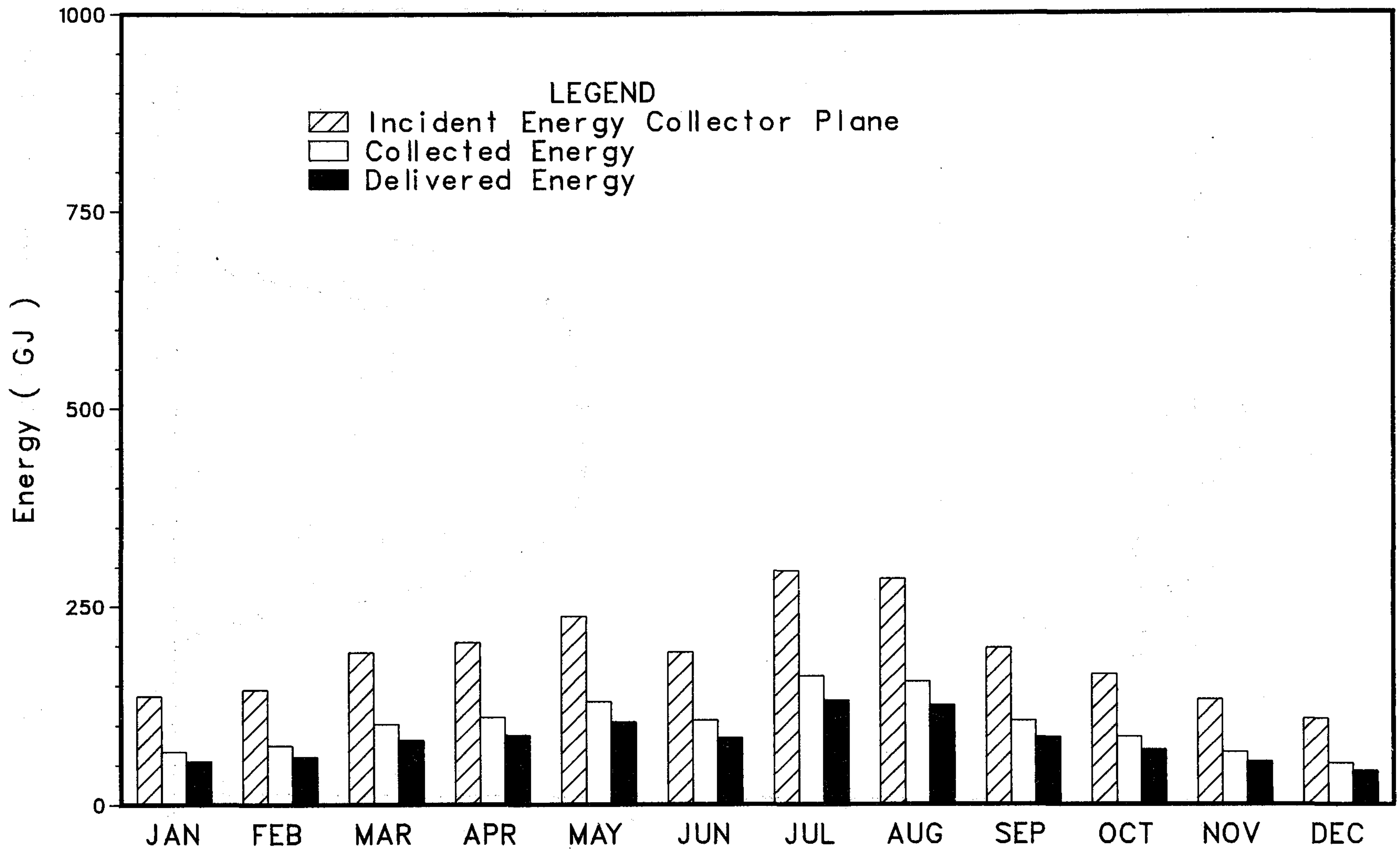

Figure 3-9. Annual Performance Summary: Home Laundry (DHW)

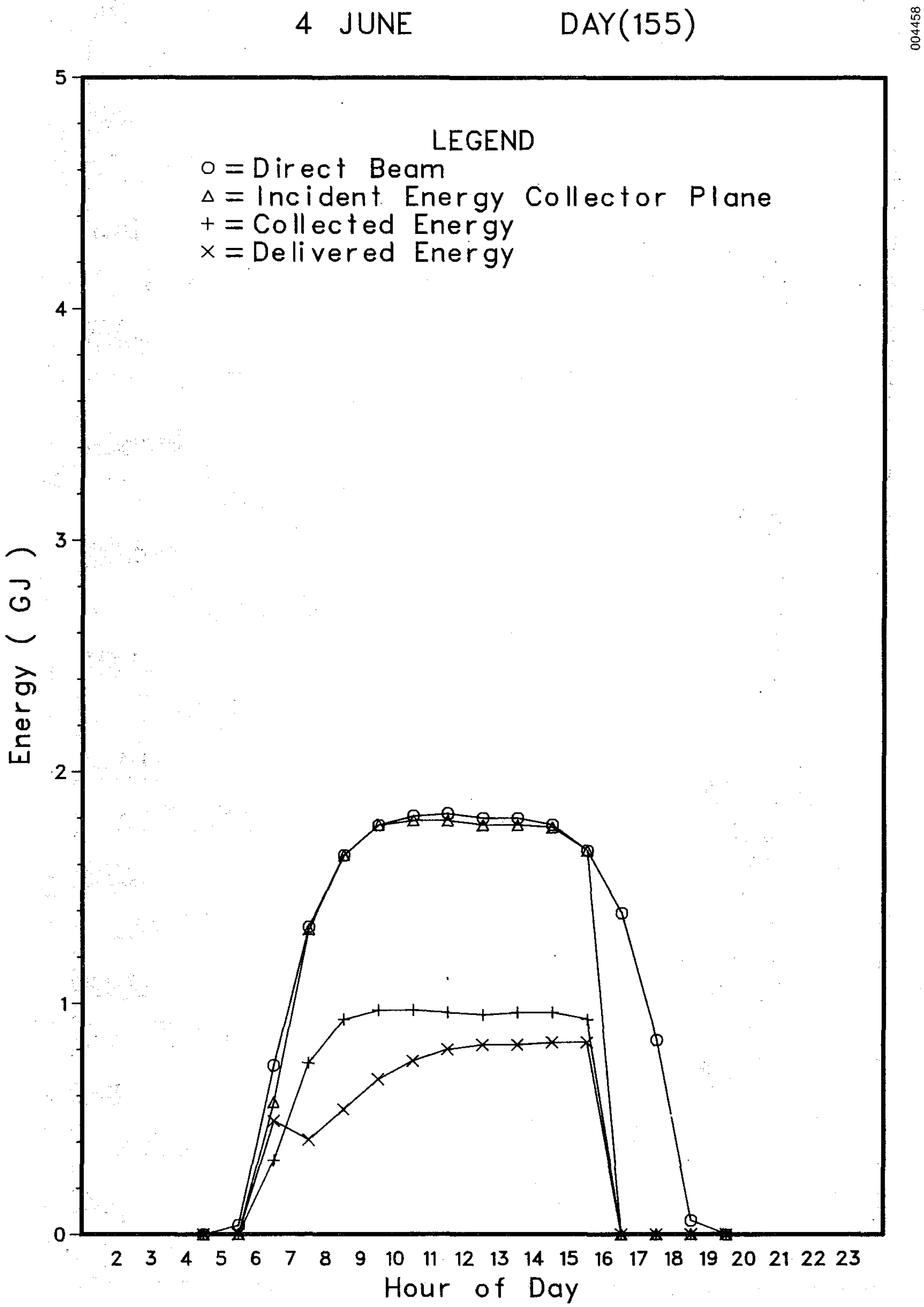

Figure 3-10. Clear Day Performance: Home Laundry (DHW)

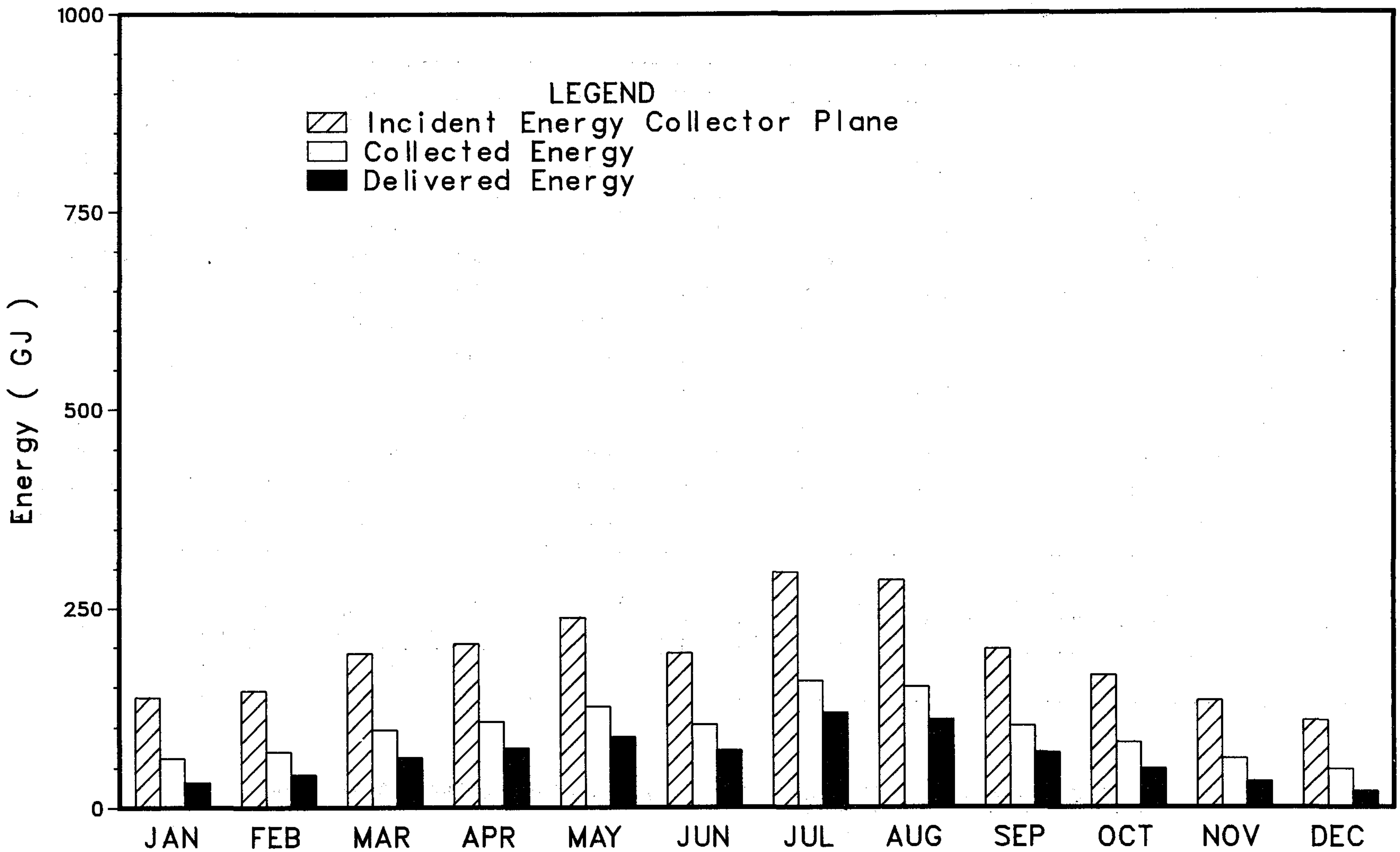

Figure 3-11. Annual Performance Summary: Home Laundry (Steam)

Table 3-7. Home Laundry (STEAM) (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM OPERATING LOSSES GJ	SYSTEM NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	144.7	225.4	141.5	61.4	43.4	32.2	16.6	11.6	22.8	3.7
FEBRUARY	171.2	215.4	145.2	69.5	47.8	41.9	15.6	11.5	28.8	3.3
MARCH	248.0	258.0	194.4	96.6	49.7	63.4	18.6	14.1	32.6	3.9
APRIL	276.8	255.2	204.6	106.3	51.9	75.1	17.4	13.2	36.7	3.5
MAY	343.7	298.1	237.7	125.6	52.8	89.2	20.4	15.4	37.5	4.1
JUNE	308.4	252.3	192.9	103.0	53.4	72.2	16.3	14.1	37.4	3.3
JULY	362.6	354.4	295.2	157.6	53.4	118.6	24.0	14.1	40.2	4.7
AUGUST	343.3	345.1	285.1	150.0	52.6	110.2	23.5	15.5	38.7	4.7
SEPTEMBER	241.8	245.8	198.3	101.3	51.1	69.6	17.9	13.4	35.1	3.7
OCTOBER	205.5	235.1	164.7	80.9	49.1	49.5	16.6	13.9	30.1	3.6
NOVEMBER	151.5	216.4	135.8	60.9	44.8	33.3	15.8	11.2	24.5	3.5
DECEMBER	120.1	188.7	113.5	47.5	41.9	20.7	14.1	12.0	18.3	3.3
TOTALS/AVERAGES	2917.5	3089.8	2309.1	1160.5	50.3	776.2	216.9	160.2	33.6	45.2

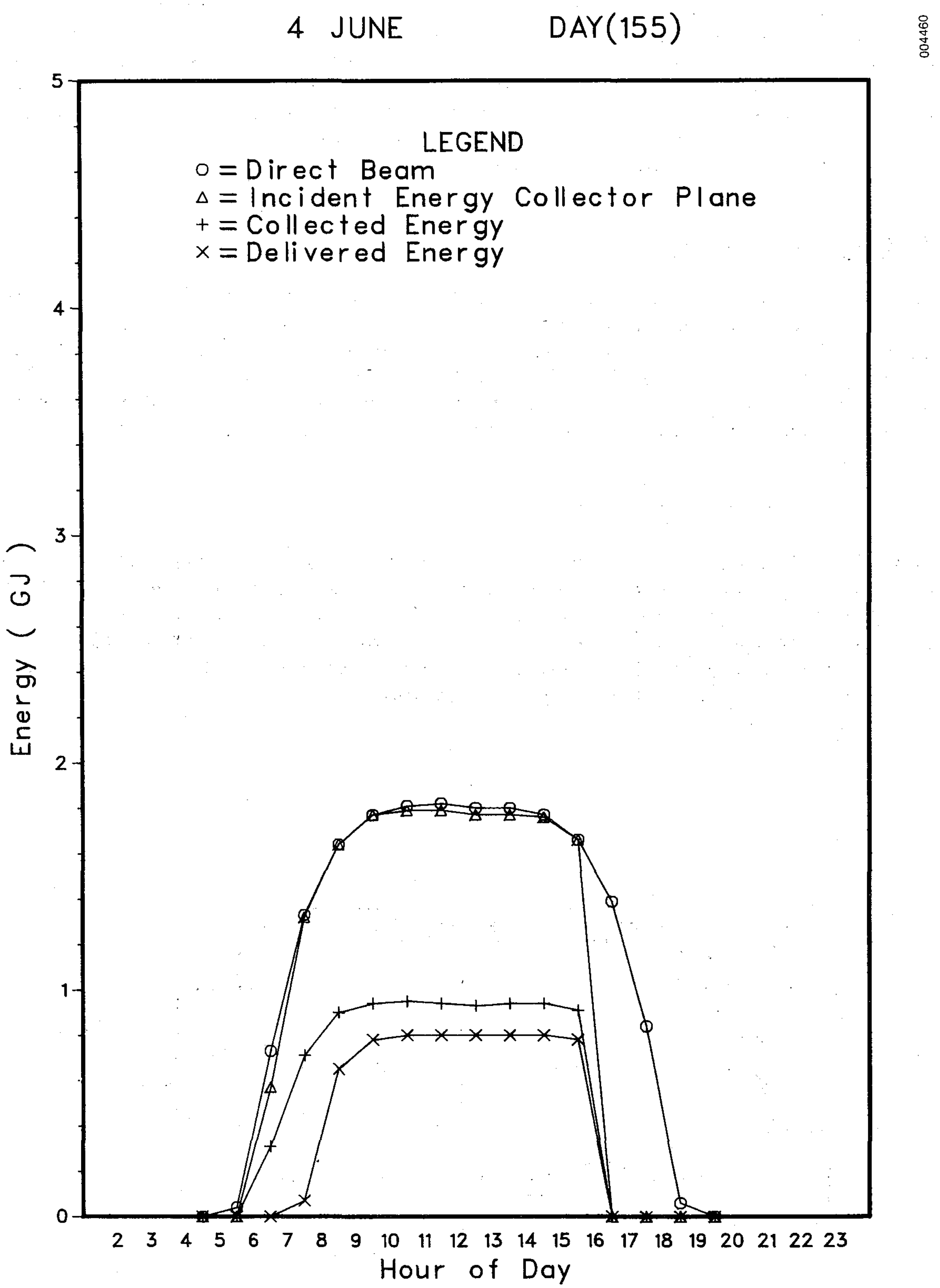

Figure 3-12. Clear Day Performance: Home Laundry (Steam)

By using small diameter piping and stepping down the pipe sizes along the collector header, the thermal capacity of the piping system was kept low. Insulating this piping system with a reasonable amount of insulation (2 in. of fiberglass insulation on a 2-in. pipe) resulted in a low heat loss coefficient. The expansion tank is thermally isolated from the piping system by the use of a long small-diameter connecting line. Valves and fittings are fully insulated, leaving only handles exposed.

3.4.2 SOLIPH Configuration

The Lone Star Brewery system is identical in configuration to the other unfired boiler systems that operate without interruption due to plant schedule. The schematic of the coded configuration is shown in Figure 3-13. Collector performance data for the T-700 are taken from Harrison (1980), and are the same as used for the Southern Union system. The same modifications mentioned in Section 2 have been applied to the reported data.

3.4.3 Results and Discussion

The Lone Star Brewery solar system has a very efficient energy transport subsystem. On a per unit of collector area basis the energy transport UA is only 0.669 kJ/hr^{o}C m^{2}, well below average for the systems studied. This small UA is the result of small, well-insulated piping and valves, a thermally isolated expansion tank, and a fully insulated circulation pump. On an annual basis, operating losses are 14% of energy collection.

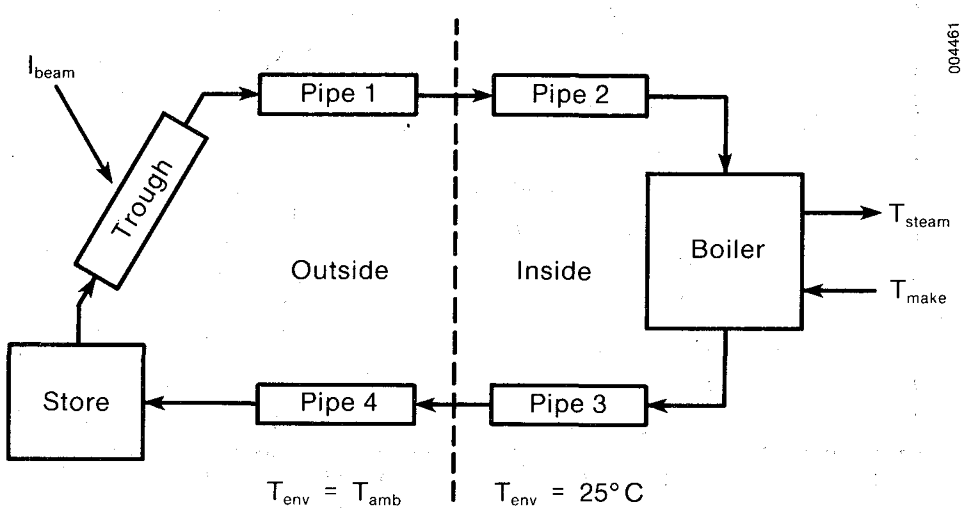

Figure 3-13. SOLIPH Configuration for Lone Star Brewery

The thermal capacitance of the energy transport system is very low: more than 50% lower than any of the other six systems. The thermal capacitance was kept low by using small-diameter, stepped-down piping. The largest header size is 2-in. pipe. Header lengths are also reasonably short since the boiler is just one floor below the roof-mounted solar collectors. The thermal capacitance of the system could have been even further reduced had both headers been run on the same side of the collector field (the side immediately above the unfired boiler) with adjacent row pairs connected to form "U-loop" temperature strings. The thermal capacitance on a per unit collector area basis is only 1.86 kJ/^{o}C m^{2}. Annual nonoperating losses are 10% of the energy collected.

Direct normal irradiation available in the San Antonio, TX area is surprisingly low, only 65% of what is available at the Southern Union site. The annual energy delivery is only 1.47 GJ/m^{2}; however, the sytem efficiency is 31.8% or about average for a well-designed and installed steam system. Annual performance is summarized in Table 3-8 and shown graphically in Figure 3-14. The clear day performance for June shown in Figure 3-15 exhibits a typical summer weather pattern, at least according to the TMY data. There is a distinct afternoon decrease in the direct beam irradiance, probably as a result of hazy cloud conditions or high humidity. Note that the direct beam irradiance curve is nearly coincident with the incident energy curve. This is so because during the summer incident angles are very low for N-S oriented parabolic trough collectors. The low thermal capacitance of this system results in very short lag in energy delivery compared with the other steam systems. Complete SOLIPH output data for Lone Star can be found in Volume II of this report.

A proposal to DOE to convert the Lone Star system from a steam system using oil as the working fluid to a feedwater preheat system using water as the working fluid has been funded. The collected energy will be transferred to the feedwater through a heat exchanger. This new application and configuration will result in a lower operating temperature and lower system thermal capacitance for a significant increase in performance. A preliminary SOLIPH run of the proposed system indicates an annual system efficiency of 50% for a nearly 60% improvement in delivered energy compared with the steam system.

3.5 ORE-IDA FOODS

3.5.1 System Description

This system was designed to supply saturated steam at either 2.1 MPa (300 psia, 417^{o}F) or 0.86 MPa (125 psia, 345^{o}F) to heat cooking oil for potato frying. The plant operates continuously. The solar system is comprised of 14 rows of SUNTEC SH1655 parabolic trough collectors with an area of 937 m^{2}. The collector array is oriented 11^{o} off N-S with a row spacing of 4.6 m.

This system uses water as the collector working fluid. Boiling in the collector field is suppressed by a back-pressure valve located at the inlet of a steam-separator or flash tank. As pressure falls across the back-pressure valve, some of the water flashes to steam, is separated from the water flow, and delivered to the plant system. Liquid water is recirculated through the collector field together with makeup feedwater supplied at the pump suction to

Table 3-8. Lone Star Brewery (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY: HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY: DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY: COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM: OPERATING LOSSES GJ	SYSTEM: NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	288.8	396.4	259.9	90.6	34.9	58.6	15.6	15.9	22.5	.9
FEBRUARY	315.5	342.5	262.1	98.4	37.5	68.5	15.6	14.0	26.1	.8
MARCH	453.4	410.4	345.9	144.7	41.8	111.3	18.4	14.8	32.2	1.0
APRIL	466.1	329.3	284.9	122.5	43.0	90.2	15.9	16.3	31.6	.9
MAY	573.3	440.4	417.3	182.5	43.7	142.8	23.1	16.4	34.2	1.2
JUNE	621.9	497.7	477.8	214.5	44.9	171.3	26.9	16.1	35.9	1.5
JULY	672.0	586.3	564.0	255.5	45.3	208.6	30.5	16.3	37.0	1.6
AUGUST	583.8	511.2	477.9	214.1	44.8	171.3	25.8	16.9	35.8	1.4
SEPTEMBER	497.5	457.2	409.0	176.8	43.2	137.2	23.5	16.1	33.5	1.3
OCTOBER	409.0	447.2	361.6	145.6	40.3	109.1	20.6	16.1	30.2	1.1
NOVEMBER	296.5	363.0	250.2	93.0	37.2	62.2	15.0	15.5	24.8	.8
DECEMBER	264.0	356.5	228.1	76.7	33.6	47.4	14.6	14.3	20.8	.8
TOTALS/AVERAGES	5441.9	5138.0	4338.7	1814.8	41.8	1378.5	245.4	188.9	31.8	13.3

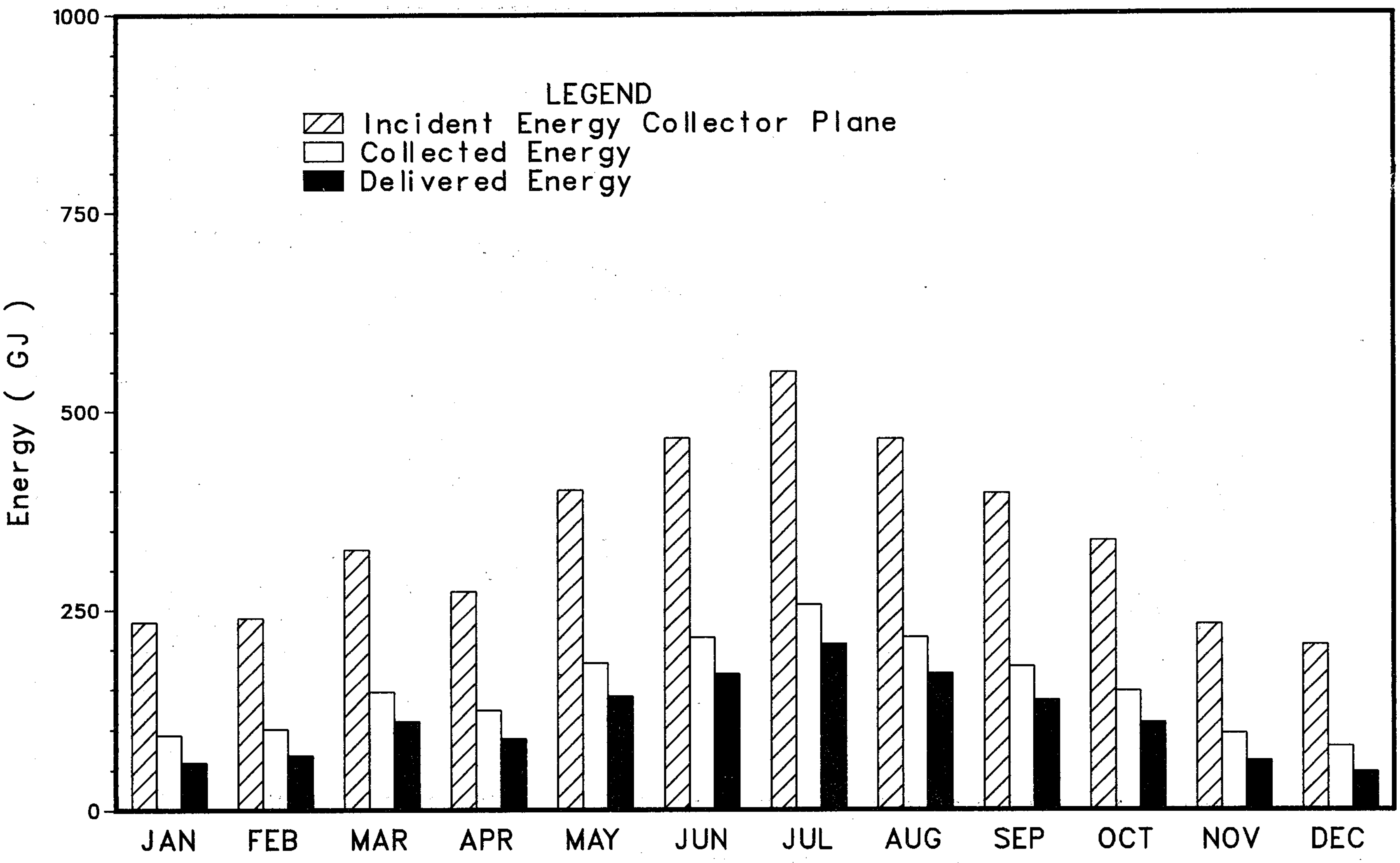

Figure 3-14. Annual Performance Summary: Lone Star Brewery

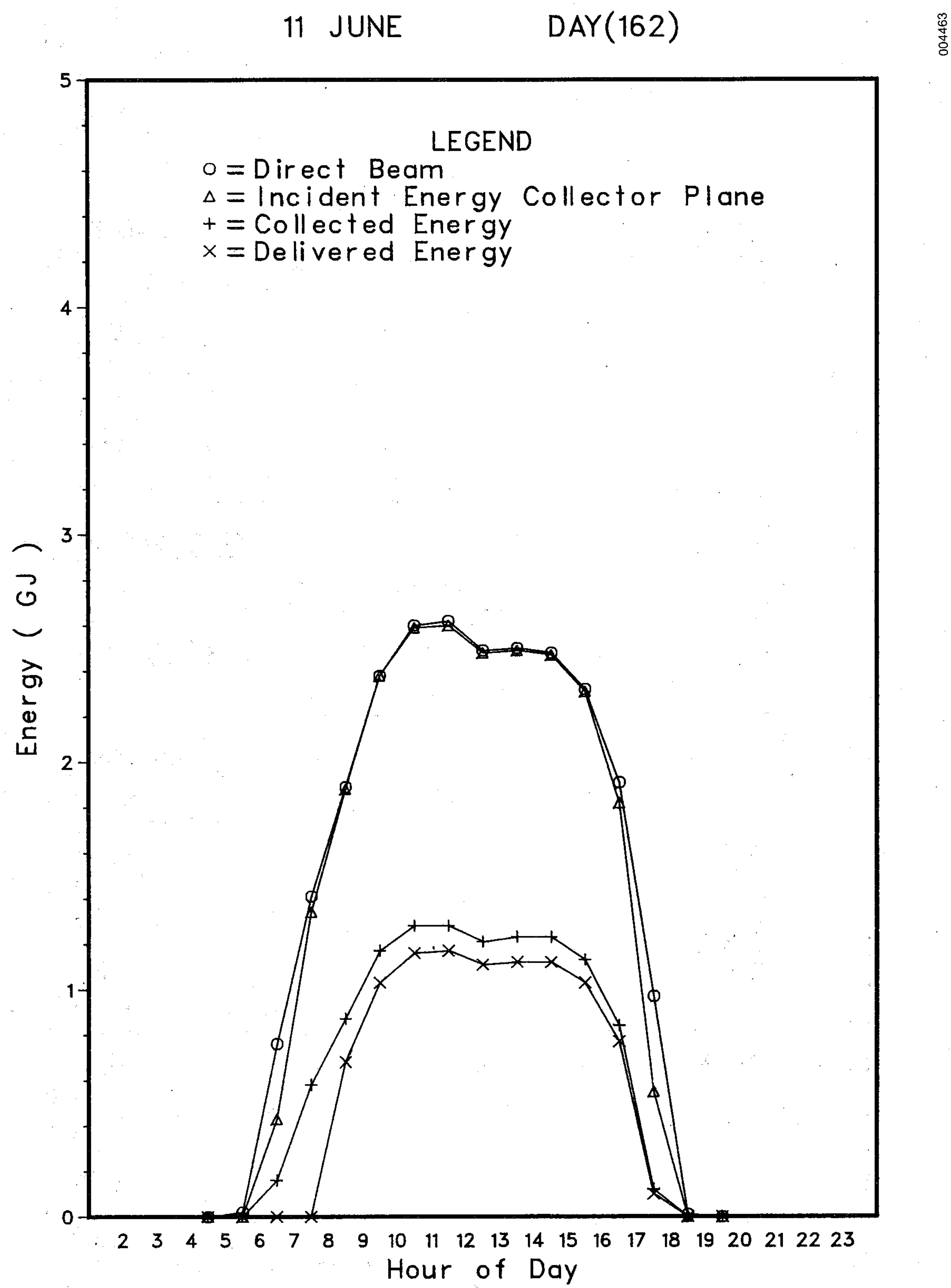

Figure 3-15. Clear Day Performance: Lone Star Brewery

maintain the system inventory. At the upper steam delivery pressure the pressure drop across the flash valve is as high as 2 MPa (300 psi). Consequently, electric power consumption is high and the circulating pump has a 40-hp rating.

An attempt is made to minimize electrical parasitics by modulation of the back-pressure valve. The collector outlet temperature is transmitted to a computer containing stored-steam data. The steam saturation pressure at 6°C (10°F) higher than the collector outlet temperature is computed and used as a control point for the valve. Because of variations in field pressure drop, the circulating flow rate varies from about 10,000 to 20,000 kg/hr.

The collectors of the Ore-Ida solar system in the original design were located on the roof of the main production building, allowing an efficient interface with the plant steam system. Collector row spacing was determined by the spacing of the roof support beams. However, when structural considerations precluded a roof-mounted array, a new location at ground level was selected. Unfortunately, this location is over 200 m (600 ft) from the flash tank and circulating pump, which are located inside, close to the plant steam and water lines.

Characteristics of the system are shown in Tables 3-1 and 3-2. The collector ground cover ratio, 0.60, dictated by the original roof-mounted design, is high for a site at this north (43.6°) latitude. Considerable row-to-row shading results, particularly in the winter months.

Data in Table 3-3 show the system having a high heat capacity and high heat loss coefficient. This results partly from the long pipe lengths to and from the flash tank. In addition, a reverse return system is used in the collector field to promote flow balancing. The collector outlet piping (279 m) is longer than the colder inlet piping (249 m). Schedule 80 pipe is used throughout the system and the use of water with its high density and specific heat adds to thermal heat capacity. Heavy duty roller pipe supports that provide a large exposed heat transfer surface are used every 3.7 m (12 ft) along the long pipe lengths. Most valves and fittings are only partially insulated and many smaller fittings are uninsulated. Lengths of the collector riser pipe are bare and insulation on the flex hoses has deteriorated.

Another source of heat loss is blowdown from the steam separator. This is controlled automatically depending on chemical content of the water, and is estimated to total 16% of the steam production rate. During the winter months, warm water is circulated intermittently through the collector field from the steam separator. If this source of heat is depleted a standby electric heater is activated. Such freeze-protection heat loss is not accounted for in the numerical simulation.

3.5.2 SOLIPH Configuration

A unique feature of this system is the use of a flash tank for steam production. The flash tank subroutine operates very nearly like the control system at Ore-Ida. However, the flow rate variation is not modeled and assumed to be constant based on an average value taken from reported data. The steam supply pressure modeled was fixed at the lower of the two operating pressures since this represented the better performance mode; i.e., lower operating temperatures. The configuration is shown schematically in Figure 3-16.

As mentioned, the freeze protection system was not modeled and therefore winter results may be overestimated. Collector performance data was taken from the same source as for Dow (Dudley and Workhoven 1978). A slightly different dust/dirt factor was applied to Ore-Ida based on site visit reflectivity data and data from Morris (1982).

3.5.3 Results and Discussion

The Ore-Ida solar system has a number of design problems that greatly inhibit the system thermal performance. Nearly all of these problems stemmed from the relocation of the collector field away from its originally intended roof-mounted location.

Due to structural considerations the collector field was relocated very distant from the flash tank. As a result, piping is very long and both the thermal capacitance and UA of the energy transport system are very high. Aggravating this situation are the use of extra piping to provide reverse return flow, the use of pipe supports that lose excessive thermal energy, and the only partial insulation of many valves and fittings. On a per unit of collector area basis, the piping system UA is 2.42 kJ/hr°C m^2 and the piping thermal capacitance is 10.1 kJ/°C m^2. Both of these values are higher than

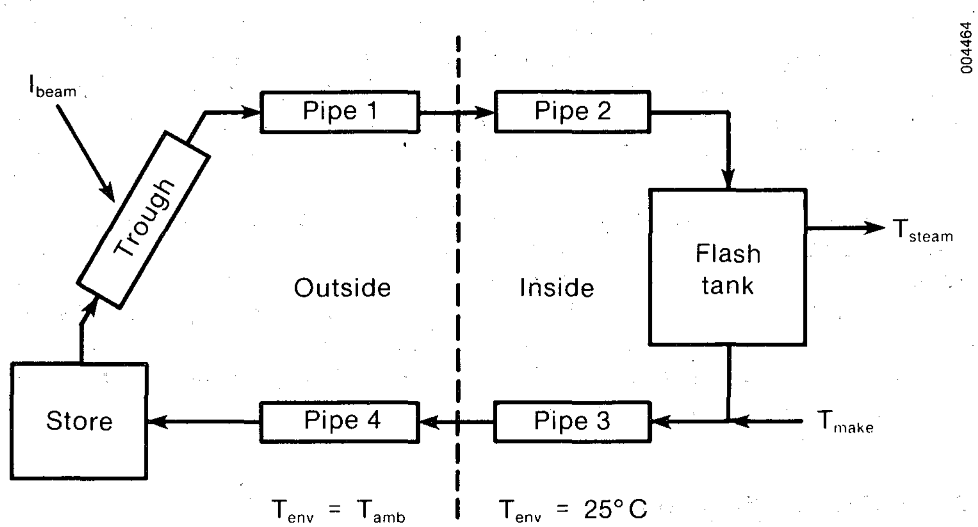

Figure 3-16. SOLIP Configuration for Ore-Ida Foods

for any of the other six systems. One additional problem is the high row-to-row shading losses that result from the close row-to-row spacing at the site. Shading losses for this system amount to about 14% of energy collected on an annual basis.

Predicted annual energy delivery on a per unit of collector area basis is only 1.24 GJ/m^2, below average for the systems studied. This low performance contrasts with the fact that Ore-Ida has the second highest average annual direct normal irradiance of all seven sites. Operating losses consume about 34% of energy collection and non-operating losses account for almost 20%.

Due to the collector field orientation and the high latitude of this location, the month-to-month variations in energy delivery are great. Summer energy delivery is high but winter energy delivery is low. In fact, no energy will typically be delivered between mid-November and early February. Hence, the system can be shut down during this period. Water can be drained from the collector field so that freeze protection is not needed during this time.

The clear day performance graphics show the long warm-up time required every morning to bring the system up to temperature. For example, see the clear day graphic for February in Figure 3-17. The collector system begins operating before 7:00 a.m., but no energy is delivered until nearly noon. One other interesting feature is apparent in the graphic: the double peak of energy collection during the day. This is a characteristic of N-S parabolic troughs that occurs because incidence angles are lower (i.e., closer to normal incidence) away from noon than at noon. This effect is very apparent for the Ore-Ida system during the winter because of its high latitude and resulting large variation of incidence angles during the day. The afternoon peak is higher than the morning peak because the collector rows are skewed 11^{o} west of south.

The annual efficiency of this system is 22%, a fairly low value caused primarily by the high system losses. Annual performance is summarized in Table 3-9 and shown graphically in Figure 3-18. Complete SOLIPH output data for Ore-Ida can be found in Volume II of this report.

3.6 SOUTHERN UNION REFINING

3.6.1 System Description

This solar thermal system is designed to generate dry saturated steam at a peak rate of 816 kg/hr to supplement the refinery's current usage of 9070-13,600 kg/hr. Steam is produced continuously at the plant in two natural gas or No. 5 fuel oil boilers. The solar facility provides up to 9% of the refinery's minimum steam requirement.

The solar system's 72 parabolic trough collectors (SKI T-700) are ground mounted in six parallel rows, oriented E-W. Total collector area is 937 m^2. A high temperature oil (Texatherm) is circulated through the receiver tubes and then fed to an unfired steam generator, where refinery feedwater is converted to steam at 190^{o}C and a pressure of 1.28 MPa. The refinery feedwater is supplied at 82^{o}C (104^{o}C after warm up). Additional details for the system

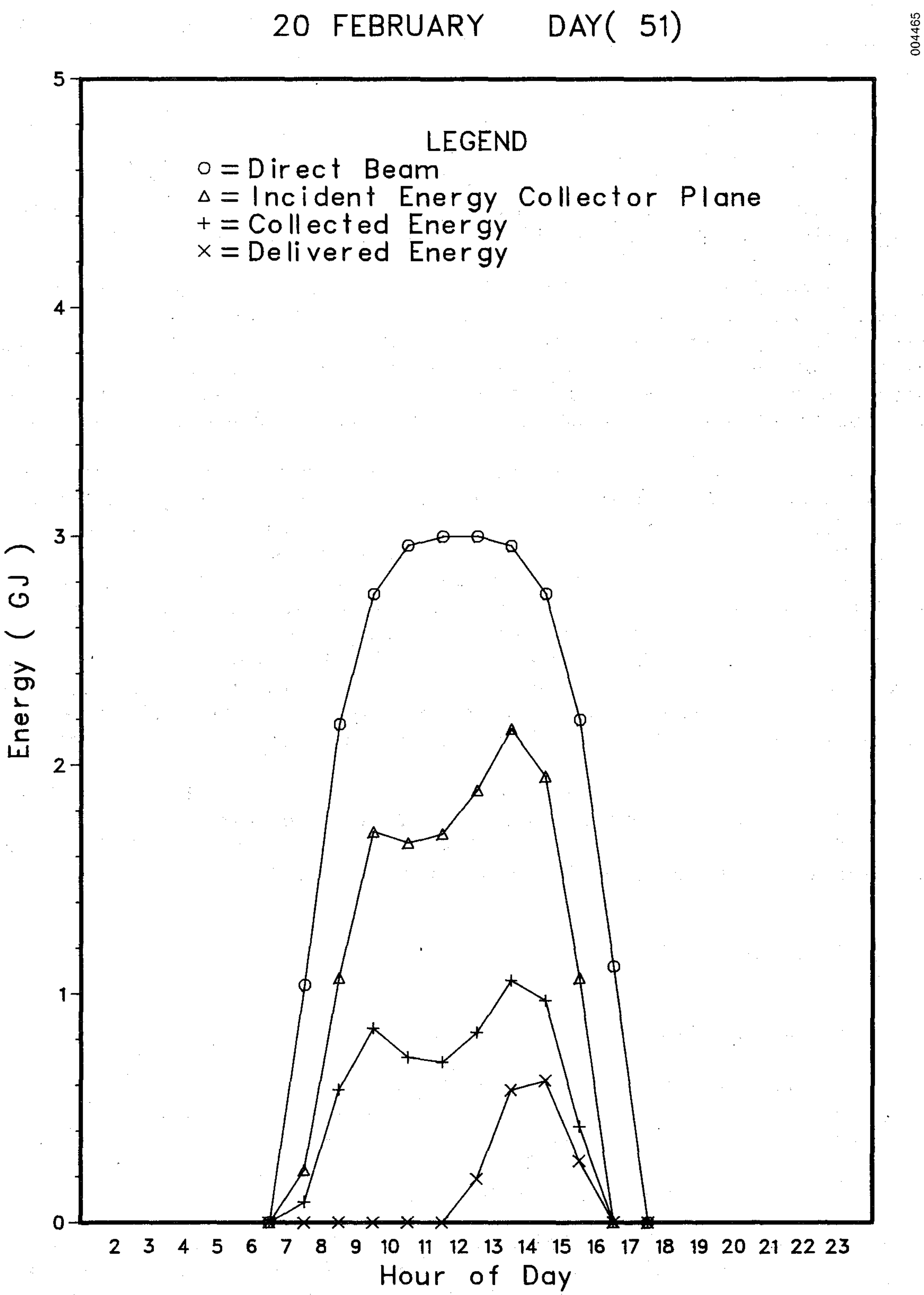

Figure 3-17. Clear Day Performance: Ore-Ida Foods

Table 3-9. Ore-Ida Foods (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY			ENERGY COLLECTED	COLLECTOR EFFICIENCY BASED ON (*)	ENERGY DELIVERED	SYSTEM		SYSTEM EFFICIENCY BASED ON (*)	PARASITIC ENERGY
	HORIZONTAL SURFACE GJ	DIRECT NORMAL GJ	COLLECTOR PLANE (*) GJ	GJ	%	GJ	OPERATING LOSSES GJ	NON-OPERATING LOSSES GJ	%	GJ
JANUARY	149.4	222.2	108.0	37.6	34.8	-.2	15.6	21.6	-.2	2.3
FEBRUARY	239.5	352.4	214.0	80.1	37.4	9.3	40.5	33.9	4.4	3.9
MARCH	380.0	419.1	311.7	130.5	41.9	35.5	58.9	38.9	11.4	4.9
APRIL	541.1	555.3	480.8	220.5	45.9	100.6	79.2	44.2	20.9	6.4
MAY	675.9	686.2	621.3	303.3	48.8	162.5	94.6	49.4	26.2	7.8
JUNE	730.4	763.2	708.1	352.8	49.8	198.2	105.4	52.4	28.0	8.8
JULY	794.1	898.4	832.2	425.6	51.1	264.7	114.0	50.2	31.8	9.1
AUGUST	671.6	793.1	725.4	351.7	48.5	200.7	105.9	48.6	27.7	8.7
SEPTEMBER	499.9	623.0	507.4	236.5	46.6	114.9	80.3	45.4	22.6	6.7
OCTOBER	343.1	520.9	353.5	144.2	40.8	42.4	60.3	45.0	12.0	5.4
NOVEMBER	176.8	264.5	146.4	53.3	36.4	2.9	26.6	27.2	2.0	3.0
DECEMBER	131.5	209.9	95.3	31.8	33.3	-.2	16.6	18.9	-.2	2.5
TOTALS/AVERAGES	5333.2	6308.2	5104.1	2368.0	46.4	1131.3	798.0	475.7	22.2	69.3

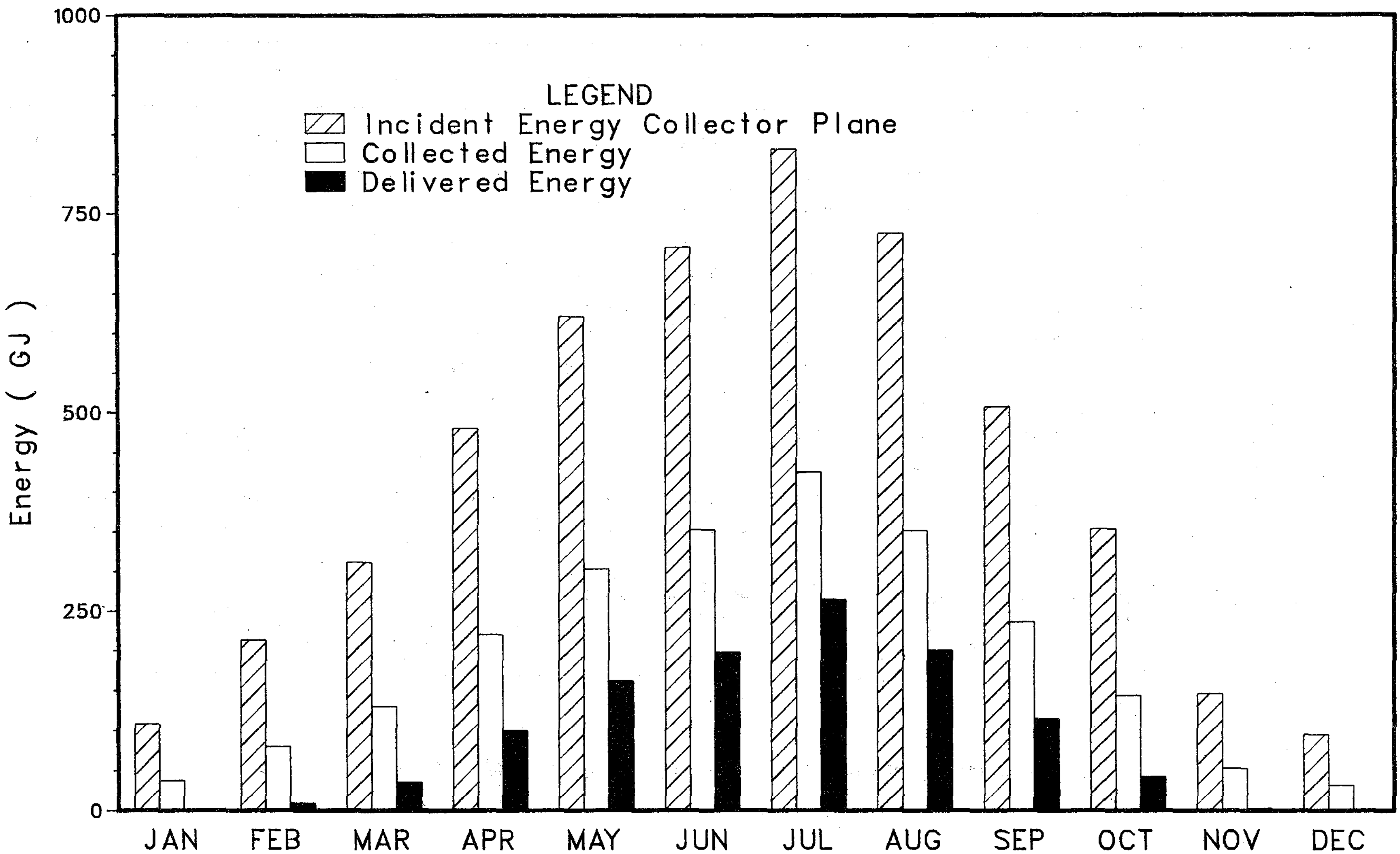

Figure 3-18. Annual Performance Summary: Ore-Ida Foods

are provided in Table 3-1. Characteristics of solar collectors used are shown in Table 3-2.

The heat transfer equipment, including the unfired steam generator, the expansion tank, the circulating pump, and much of the instrumentation, is located in a small building that can be heated if necessary. The collector system is located immediately adjacent to the heat transfer equipment. However, feedwater and steam must be transported to and from refinery headers that are located more than 300m from the solar system. Thermal losses in this transport piping are not accounted for in the system model since the actual data measurements are taken next to the unfired boiler.

To inhibit scaling in the steam generator, water was originally "blown down" at a rate of 10% of the steam flow whenever the steam flow exceeded 227 kg/hr. Present procedures call for boiler blowdown manually during cloudy days. Since blowdown and makeup occurs on an intermittent basis under the control of solenoid valves, the sudden input of cold feedwater to the boiler does result in some unsteadiness in the steam production rate.

All piping is thoroughly insulated with fiberglass covered with a waterproof aluminum jacket. However, pipe supports are directly connected to the pipe. Fittings such as valves, strainers, and checks are partially insulated. Seal cooling is provided to the pump, with a measured heat loss of 0.7 kW (2250 Btu/hr). The pump itself is not insulated to allow easy access. There is some thermosyphoning between transport piping and the uninsulated expansion tank.

The thermal characteristics of the system are shown in Table 3-3. The heat loss coefficients are fairly low because of the large thickness of insulation (for example, 3 in. of insulation on the 3-in. main headers). However, thermal mass is large because of the large main header lines, and because the main inlet line runs the total length of the field. All of these thermal losses will be eliminated or substantially reduced as a result of the system upgrade and repair currently being considered.

3.6.2 SOLIPH Configuration

The configuration at Southern Union, identical to those at Dow, Lone Star, and USS Chemicals, is schematically shown in Figure 3-19. Performance data for the T-700 collectors are again taken from Harrison (1980) and modified as previously discussed.

3.6.3 Results and Discussion

The Southern Union solar system is basically well designed and has received high quality maintenance to work out operation difficulties and to improve performance. Some areas of further improvement (currently in the planning process) are redesigned pipe supports, improved insulation of valves and instrumentation, redesign of the expansion tank piping to eliminate thermosyphoning, and redesign of the header line piping to reduce the size of one of the headers. With these improvements the energy transport UA and thermal

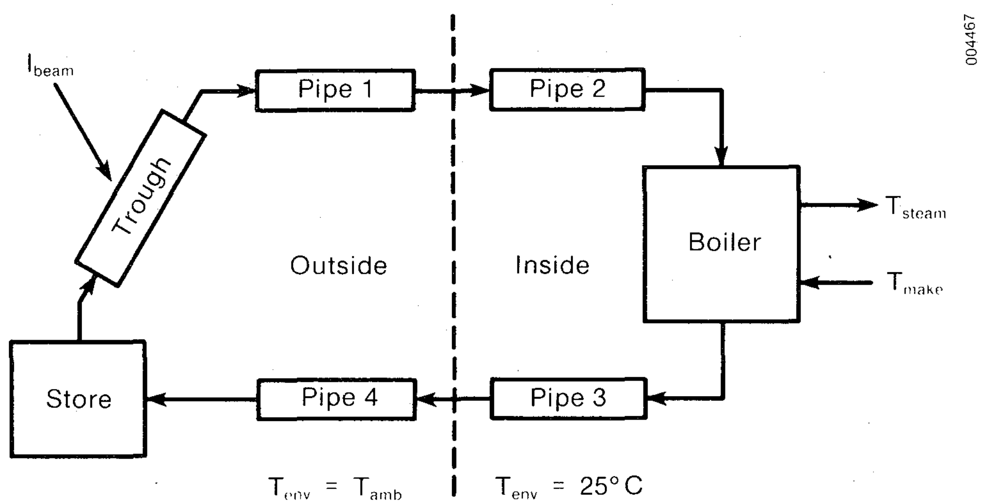

Figure 3-19. SOLIPH Configuration for Southern Union

capacitance should be reduced. Currently, the transport system UA on a per unit collector area basis is a respectable 0.76 kJ/hr°C m^2. The energy transport thermal capacitance on a per unit collector area basis is also quite low at 3.37 kJ/°C m^2. The annual operating losses represent 15% of energy collection. This is somewhat high, but of the seven systems studied Southern Union operates at the highest temperature and should hence have higher relative losses. Annual nonoperating losses are 11% of energy collection.

The expected annual energy delivery for Southern Union is very high at 2.06 GJ m^{-2}. A key reason for this high expected total is the very high direct normal irradiance available at this site, the highest available at any of the seven sites. The annual performance of the system could have been even higher, by about 15%, if the collector rows were aligned N-S rather than E-W. Note though that the expected month-to-month energy delivery variations are much smaller for this system than for any of the other solar systems due to the E-W orientation. Also note from the clear day graphic for May (Figure 3-20) how the energy collection peaks markedly at noon, whereas the other N-S systems have much flatter energy collection profiles during the day. The peak in energy collection is due to the impact of incidence angles on collector performance. East-west oriented troughs obtain normal incidence at solar noon, which maximizes both collector efficiency and energy available to the collectors. Thermal lag due to system capacitance is indicated clearly in the morning hours after start up.

Annual system efficiency is predicted to be 31.7%. A summary of annual performance is shown in Table 3-10 and graphics in Figure 3-21. Note the very even distribution of energy delivery throughout the year. The summer peak is due primarily to the longer days and correspondingly higher available solar

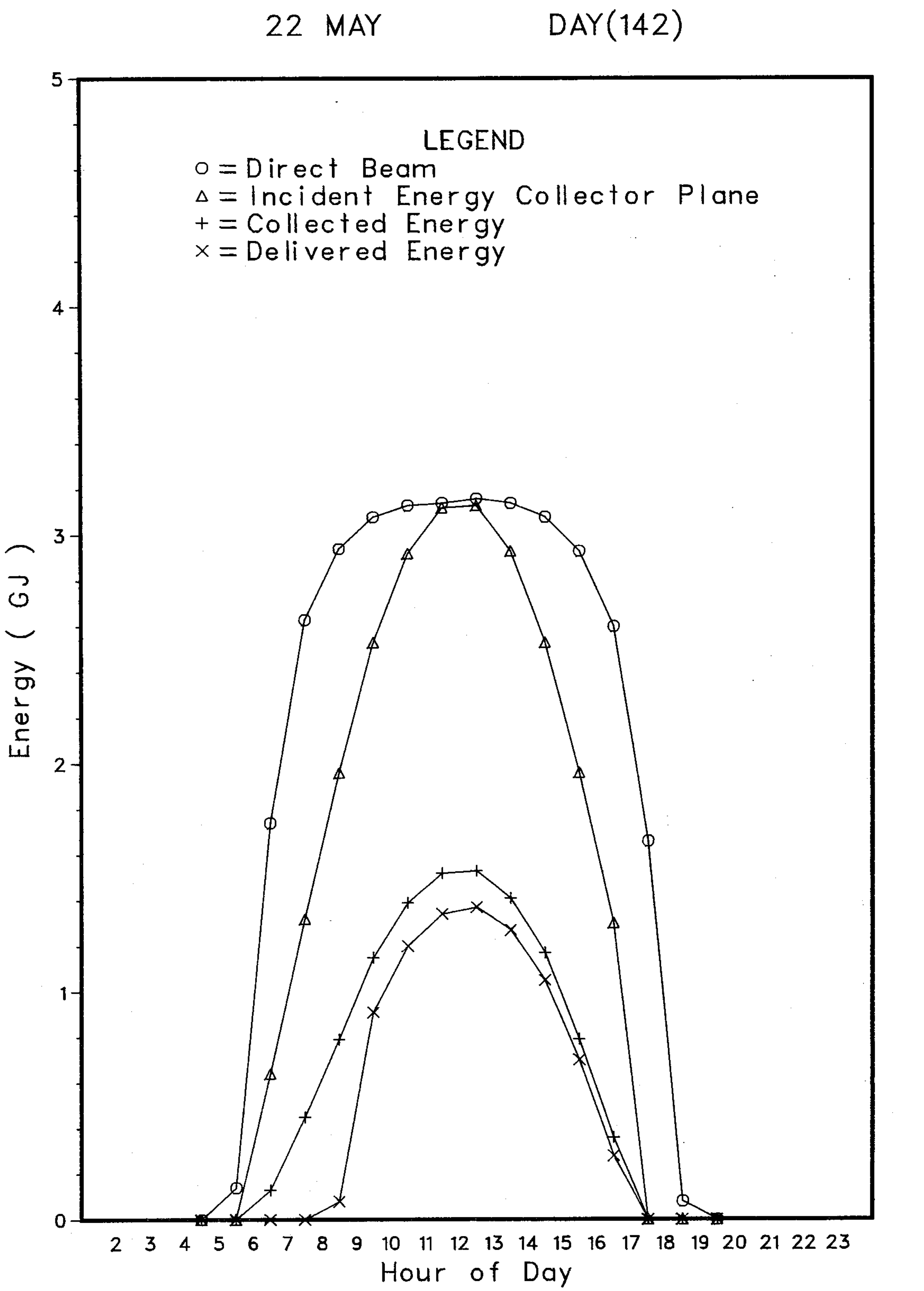

Figure 3-20. Clear Day Performance: Southern Union

Table 3-10. Southern Union (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM OPERATING LOSSES GJ	SYSTEM NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	349.1	604.5	495.7	217.8	44.0	156.8	31.8	28.2	31.6	12.3
FEBRUARY	411.6	597.9	470.8	204.5	43.4	148.2	31.3	24.8	31.5	12.6
MARCH	604.7	706.0	526.3	226.8	43.1	164.5	35.3	26.7	31.3	14.3
APRIL	708.1	765.4	536.4	229.7	42.8	166.3	35.8	27.4	31.0	14.6
MAY	807.4	814.3	585.5	249.0	42.5	181.1	41.1	26.3	30.9	17.6
JUNE	825.2	833.3	624.8	269.2	43.1	200.7	43.0	25.3	32.1	18.1
JULY	821.1	838.9	635.4	277.8	43.7	208.3	43.1	26.0	32.8	18.4
AUGUST	724.0	758.8	563.4	246.5	43.8	180.7	38.0	27.6	32.1	16.2
SEPTEMBER	613.0	690.9	526.1	227.5	43.2	165.9	35.8	25.6	31.5	15.0
OCTOBER	487.7	667.6	524.2	231.0	44.1	171.1	34.2	25.5	32.6	14.1
NOVEMBER	370.0	608.9	497.3	219.4	44.1	158.8	32.6	27.9	31.9	13.0
DECEMBER	312.4	558.2	469.8	203.3	43.3	143.5	30.7	29.0	30.5	11.8
TOTALS/AVERAGES	7034.2	8444.8	6455.7	2802.7	43.4	2046.0	432.7	320.4	31.7	178.0

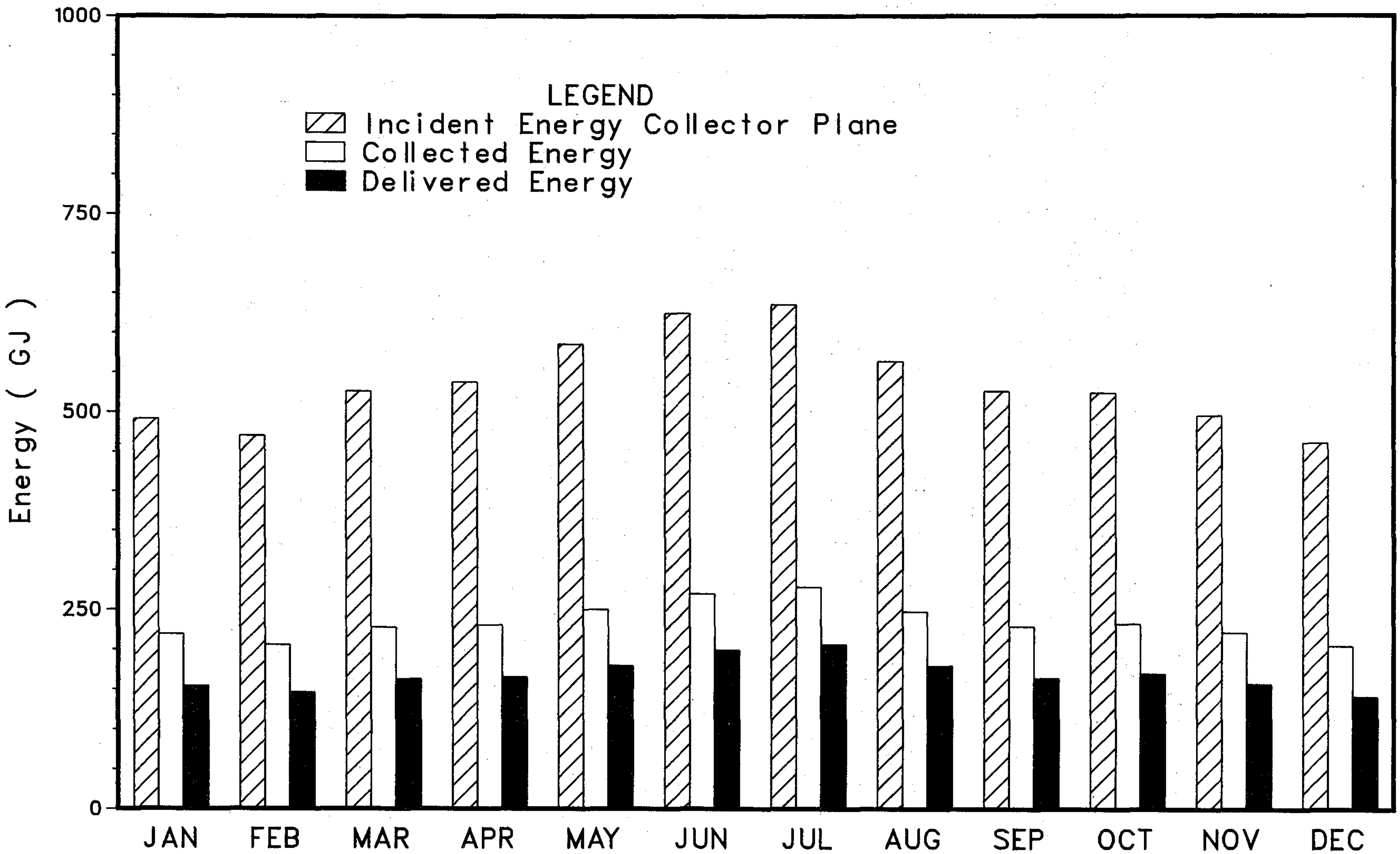

Figure 3-21. Annual Performance Summary: Southern Union

irradiance. Complete SOLIPH output data for Southern Union can be found in Volume II of this report.

3.7 USS CHEMICALS

3.7.1 System Description

The solar system at the USS Chemicals plant in Haverhill, OH supplies saturated steam at 151°C for continuous production of industrial chemicals used in the manufacture of a variety of products. The system consists of 60 rows, oriented 25° west of south, of SKI T-700A trough collectors. Honeywell suntrackers and controllers are used. Therminol 60 is circulated through the collectors and then fed to an unfired boiler where the steam is produced. Boiler feedwater is supplied at 135°C.

The 60 rows of collectors are each 110 m long and consist of 3 drive strings. Row-to-row spacing is 6.1 m (20 ft). All 60 rows are fed in parallel from a header that runs along the edge of the collector field. A return header runs along the other edge of the collector field and supplies the steam generator with the heated oil. Both the supply and return headers are stepped down in size along their lengths.

The headers step down from 6-in. piping to 4-in., then 3 in. and then 2.5 in. The headers are connected to the collector rows through 1.5-in. piping. At the end of each row at the collector outlet a pressure relief valve, shutoff valve, and drain valve are provided. The pressure relief valve is plumbed so that should it be activated, the relieved fluid goes to the outlet header. Along the collector inlet side of each row a shutoff valve is provided. All of these valves and pipes are extremely well insulated. No bare insulated metal surfaces exist at all within the collector field. Even the valve hand wheels have removable insulated coverings. Pipe anchors are insulated to ground level. Pipe supports are constructed to completely eliminate metal-to-metal contact and thereby minimize thermal loss. All pipes are covered with 10.2 cm (4 in.) of insulation and a waterproof aluminum jacket.

The unfired steam generator and expansion tank are contained within a mechanical room adjacent to the collector field. The unfired boiler and expansion tank are both covered with 5 cm (2 in.) of insulation. The circulation pumps are not contained within the mechanical room because of USS Chemicals policy. Instead, they are located outdoors immediately next to the mechanical room. Seal cooling of the pumps is provided continuously and the pumps are well insulated.

The thermal characteristics of the system are shown in Table 3-3. The heat loss coefficients are very low because the system is so well insulated. The thermal mass, however is quite large because the collector field headers are large (up to 6 in.).

3.7.2 SOLIPH Configuration

The code configuration of USS Chemicals is, again, identical to the other unfired boiler systems with continuous plant operation. Figure 3-22 shows the schematic of the system as coded. The system has a valve to allow heated collector fluid to bypass the boiler until a set fluid temperature has been reached. The heated fluid is then routed through the boiler. This feature was coded into the boiler routine. However, when runs were made with the bypass enabled, convergence did not occur. Repetitive cycling between the bypassed and unbypassed modes prevented the boiler temperatures from stabilizing in the model and therefore this feature was not utilized for USS Chemical. The advantage of this type of bypass is not clear and it is expected that very little difference in energy collection or delivery would result from its use.

As at Caterpillar, collector performance for the T-700A is taken from Dudley and Workhoven (1982), using the same modification process as previously described.

3.7.3 Results and Discussion

The USS Chemicals solar system is a well-designed and well-installed system. All outdoor piping and valves are extremely well insulated, including even the valve stems and hand wheels. Pipe anchors are also insulated and pipe supports were designed to eliminate direct contact of the pipes to the supports.

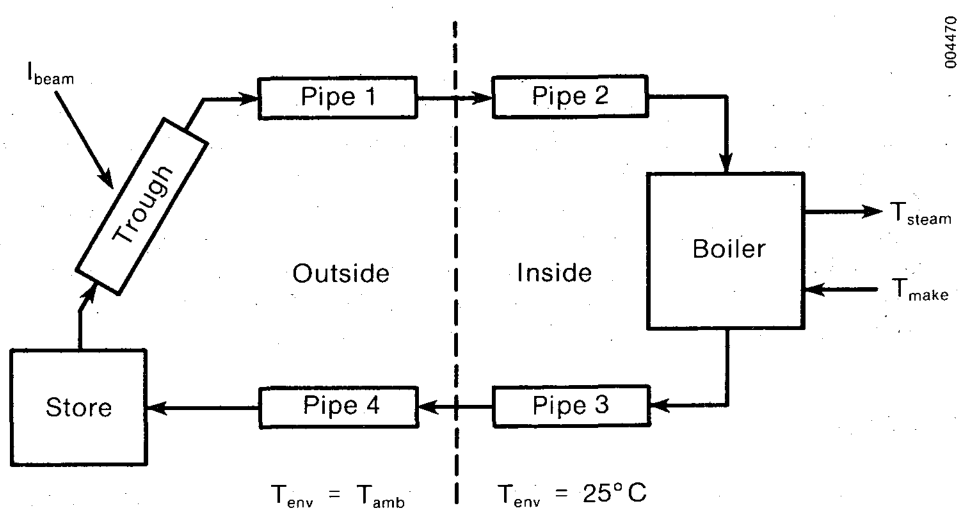

Figure 3-22. SOLIPH Configurations for USS Chemicals

Because the USS Chemicals energy transport system has by far the lowest UA value per unit area, 0.47 kJ/hr^{o}C m^2 (the Dechow factor), of all the systems studied, the system has relatively low annual operating thermal losses. As a percentage of annual energy collected, the operating losses represent only 8.2%.

Although the energy transport UA is very low, the thermal capacitance of the system is not. On a per unit of collector area basis, the thermal capacitance of the system is above average at 4.94 kJ/^{o}C m^2. Smaller pipe headers would have reduced this value. The annual nonoperating losses are more than 90% higher than the operating losses and represent 15.8% of the energy collected. This is the only system where nonoperating losses exceed operating losses.

While the system is basically well designed and has been installed with great care, the energy delivered by the system on a per unit area basis is very low: only 0.93 GJ/m^2. The reason that such a well-designed system performs relatively poorly is the low beam irradiance available at the solar site. In comparison, the average annual TMY direct normal irradiance available at a good solar site (such as Southern Union) is almost 2.5 times greater than the direct normal TMY irradiance available at the USS Chemicals site.

Note from the clear day graphic for June (Figure 3-23) that energy collection in the afternoon is much greater than in the morning. One reason for this is of course the system warm up that occurs every day as the system comes up to operating temperature. The other reason is that the collectors are oriented 25^{o} west of north, which enhances afternoon performance at the expense of morning performance.

The annual efficiency of this system is 36.1%, the highest of all the steam systems. Annual performance is summarized in Table 3-11 and shown graphically in Figure 3-24. Complete output data for USS Chemical can be found in Volume II of this report.

An interesting sensitivity analysis was performed for the USS Chemicals system because of the high start-up intensity that is utilized by the control system. The start-up intensity is set at 315 W/m^2, a higher value than is used by most parabolic trough systems. The sensitivity of solar system annual energy delivery and parasitic losses to start-up intensity was examined and is shown graphically in Table 3-12. Note that about 6% more energy delivery is possible from the USS Chemicals system if the start-up intensity were lowered to about 720 KJ/m^2-hr. This thermal energy gain of course should be weighed against the expected increase in electric parasitics.

3.8 IDEAL SYSTEMS

Since all of the systems modeled have some undesirable characteristics, it would be interesting to surmise the performance of a steam system that combined the most desirable characteristics. This 'ideal' system would have those attributes from the field sites that would approach the best possible system. The performance of the 'ideal' system might then represent a goal for future systems to achieve.

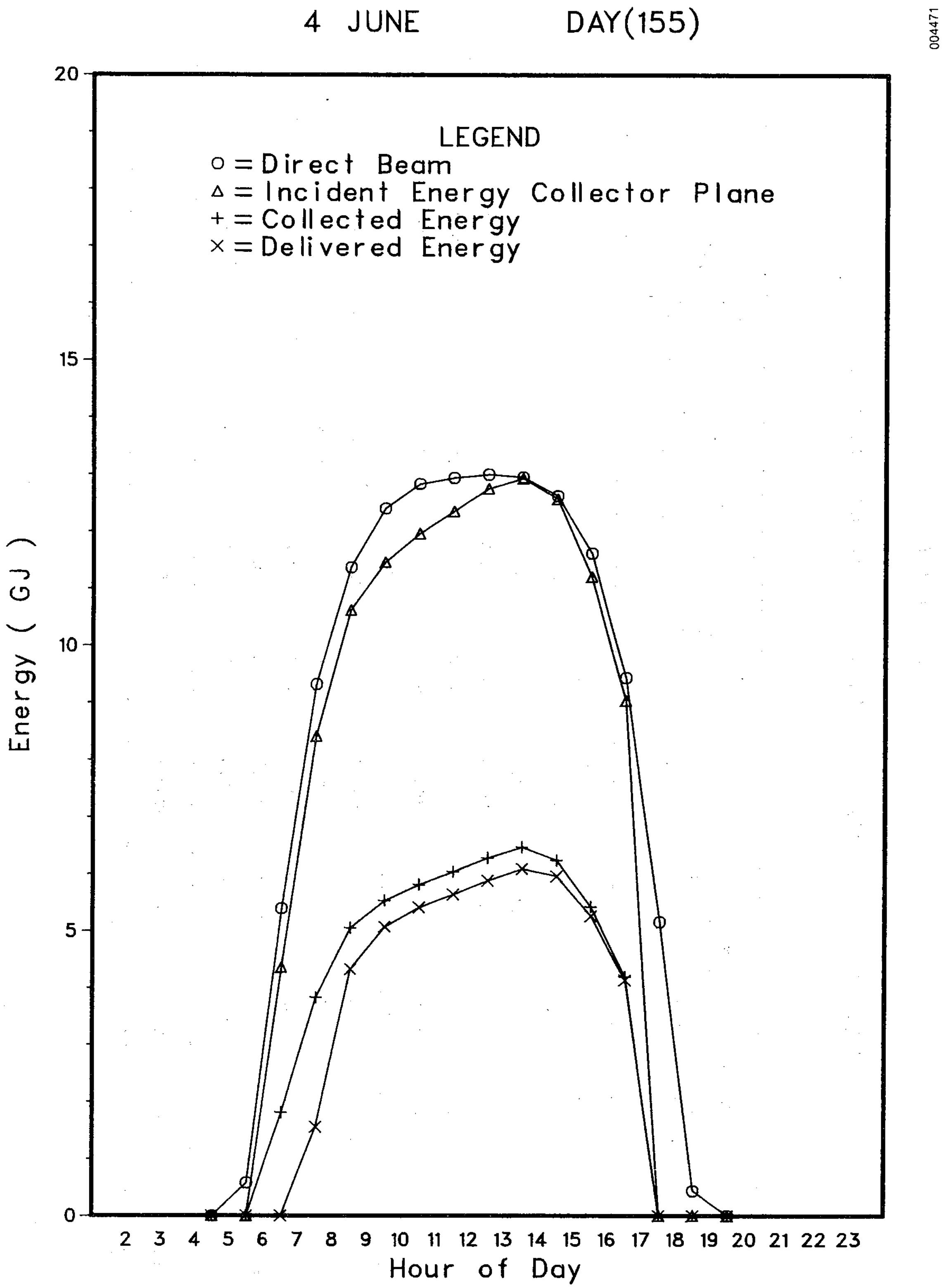

Figure 3-23. Clear Day Performance: USS Chemicals

Table 3-11. USS Chemical (Annual Performance Summary Table)

MONTH	INCIDENT SOLAR ENERGY HORIZONTAL SURFACE GJ	INCIDENT SOLAR ENERGY DIRECT NORMAL GJ	INCIDENT SOLAR ENERGY COLLECTOR PLANE (*) GJ	ENERGY COLLECTED GJ	COLLECTOR EFFICIENCY BASED ON (*) %	ENERGY DELIVERED GJ	SYSTEM OPERATING LOSSES GJ	SYSTEM NON-OPERATING LOSSES GJ	SYSTEM EFFICIENCY BASED ON (*) %	PARASITIC ENERGY GJ
JANUARY	789.0	845.5	473.8	187.7	39.6	93.7	22.4	69.7	19.8	5.4
FEBRUARY	1123.4	1054.0	604.6	250.6	41.4	152.8	28.0	67.2	25.3	6.3
MARCH	1672.9	1184.4	760.4	353.2	46.5	250.2	31.4	71.0	32.9	6.9
APRIL	2176.3	1504.4	1152.1	566.4	49.2	444.9	43.0	78.1	38.6	9.2
MAY	2888.4	2134.6	1748.2	870.9	49.8	707.6	65.1	100.1	40.5	14.5
JUNE	3029.7	2162.5	1740.3	883.0	50.7	725.8	61.3	92.6	41.7	14.0
JULY	2893.3	2034.2	1567.3	785.5	50.1	621.9	58.4	105.1	39.7	13.4
AUGUST	2662.3	2191.9	1784.1	890.6	49.9	725.2	67.1	97.8	40.7	15.4
SEPTEMBER	1911.0	1537.7	1132.8	555.5	49.0	428.7	43.4	84.9	37.8	10.0
OCTOBER	1576.6	1748.9	1174.2	541.8	46.1	404.0	47.0	88.8	34.4	10.8
NOVEMBER	896.7	975.8	530.8	213.7	40.3	120.5	25.3	68.9	22.7	6.4
DECEMBER	735.5	829.2	408.6	161.3	39.5	77.0	19.4	63.9	18.8	5.0
TOTALS/AVERAGES	22355.2	18203.1	13077.2	6260.1	47.9	4752.3	511.8	988.0	36.3	117.3

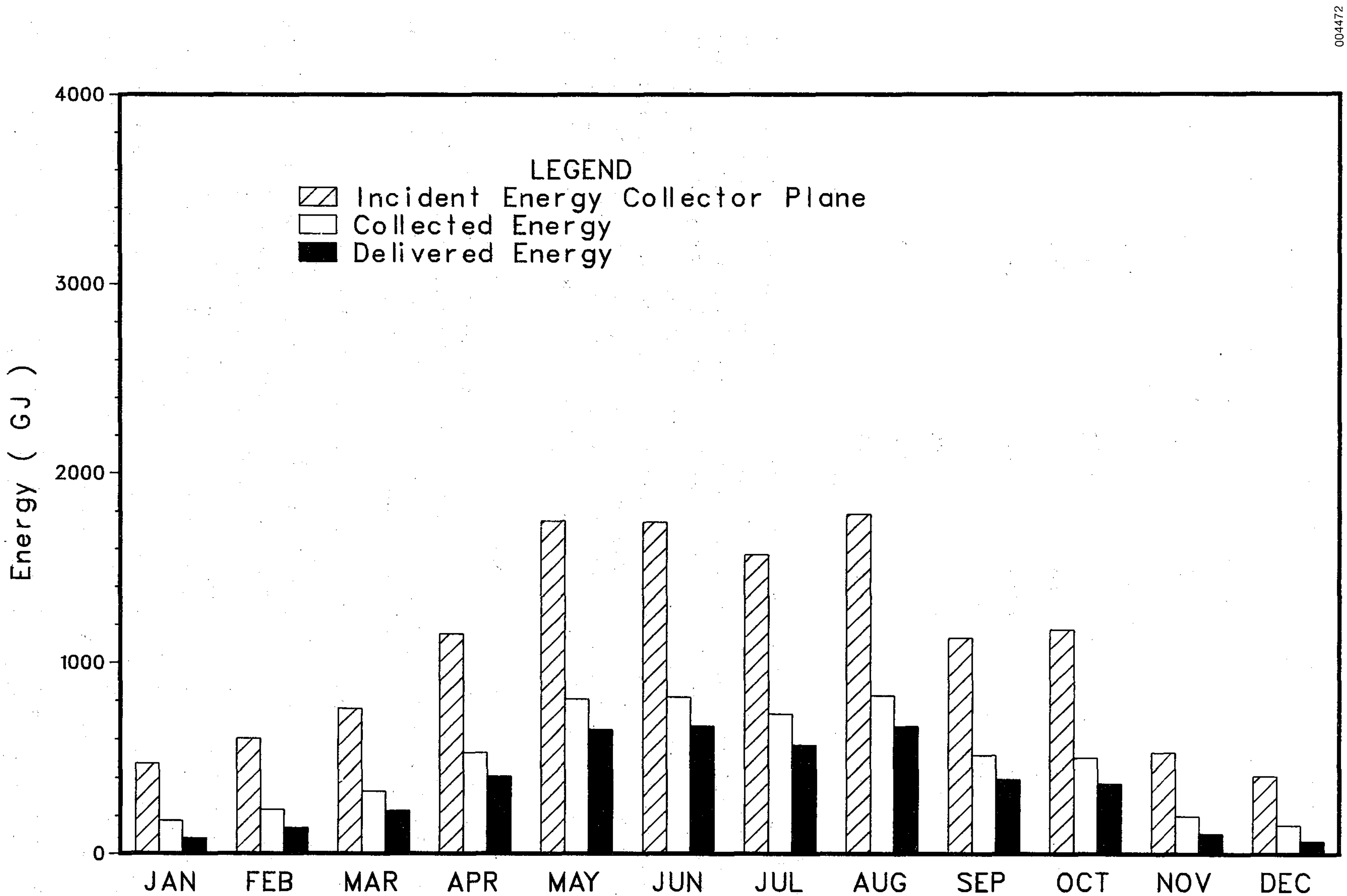

Figure 3-24. Annual Performance Summary: USS Chemicals

Table 3-12. Sensitivity of Annual Energy Delivery at USS Chemicals to Start-up Intensity

Start-up Intensity (kJ/m^2-hr)	Incident Energy (GJ)	Delivered Energy (GJ)	Parasitic Energy (GJ)
75	15085	4669	179
180	15037	4685	172
360	14899	4687	163
720	14236	4609	140
1135	13077	4331	117
1440	12024	3999	102
1800	9881	3241	79
2160	7167	2287	54

Available irradiance at Southern Union is the greatest of any current IPH site, therefore the system would be located in southern New Mexico. For convenience, the collector area of Southern Union would also be used. However, the field orientation would be N-S to maximize annual energy delivery. The collectors chosen would be the SKI T-700A with heat loss data identical to that at USS chemicals. The optical efficiency would be modified by the same factor as at Southern Union. Although the latest generation of trough collectors has better performance characteristics than the T-700A, the primary goal was to estimate the effects of other design characteristics on the system.

Choice of working fluids is somewhat arbitrary. Both water and oil could be utilized, and each will affect the remainder of the parameters. The flow rate and specific heat for oil would be the same as Southern Union (Texatherm). For water, the flow rate-specific heat product is assumed to be the same as for oil, therefore the flow rate is about 0.6 that of oil.

In terms of achievable goals for the heat loss coefficient and thermal mass of the ideal system, it is instructive to analyze the best case for each factor. At USS Chemicals a UA of 0.47 $kJ/^oC\ h\ m^2$ of aperture was calculated. The amount of insulation may have exceeded the economic optimum, but if smaller headers had been used a lower value would have resulted. Overall, then, a reasonable goal for an oil-based system might be 0.5 $kJ/^oC\ h\ m^2$. Due to smaller piping sizes for a water system a reduction in UA to possibly 0.4 $kJ/^oC\ h\ m^2$ might be achievable. To reach these goals would require careful design and fabrication, with the boiler located in close proximity to the collector field. The "ideal" boiler might have increased insulation levels or more thermal isolation to reduce its UA value by 75%.

The thermal mass of the ideal system would be optimized by minimizing the pipe sizes and stepping piping wherever possible. At Lone Star, where this approach was utilized, a system Mc_p of 1.86 kJ/^{o}C m^2 was calculated. A reasonable goal for an oil-based system would be 2 kJ/^{o}C m^2. Using water, smaller pipe sizes could be used; however, the thermal mass of water-filled pipes would be about twice that of oil-filled pipes. Overall, a thermal mass goal for a water system would be 3.0 kJ/^{o}C m^2.

To use these goals in the ideal system at Southern Union, the UA and Mc_p values for individual pipe sections were apportioned by the ratio of individual-to-total values for the calculated parameters of the Southern Union system. Additionally, the water system receiver mass was increased by 3/2, the ratio of water-to-oil thermal mass goals.

Two runs were made, one for an ideal water system and one for an ideal oil system, using the same steam delivery temperature and feedwater supply temperature as at Southern Union. The results of these runs are shown in Table 3-13. There is very little difference in annual performance for the oil and water systems. The oil system has higher operating losses (due to higher UA's) and lower nonoperating losses (due to lower Mc_p's). The increase over the predicted performance for Southern Union is between 18% and 19%. This represents a substantial improvement if the goals established here are reasonable. Given that both UA and Mc_p goals have actually been achieved or nearly achieved at different field tests suggests that the performance predicted for these "ideal" systems is realistic.

Table 3-13. Annual Performance Summary for Ideal Water and Oil Systems Located at Southern Union

System	Incident Energy in Collector Place (GJ)	Energy Collected (GJ)	Collector Efficiency (%)	Energy Delivered (GJ)	Operating Loss (GJ)	Nonoperating Loss (GJ)	System Efficiency (%)
Oil	7183	3256	45.3	2714	294	244	37.8
Water	7180	3261	45.4	2685	239	333	37.4

Steam delivery temperature: 191°C

Feedwater supply temperature: 82°C

SECTION 4.0

COMPARISON OF SOLIPH RESULTS WITH REPORTED DATA

The results of any model must be viewed suspiciously until they are compared or validated against real performance data. However, SOLIPH has been verified against other simulation programs (TRNSYS, DOE-2, etc). In this section the data reported on a monthly basis by the field site contractors are compared with SOLIPH predictions. Generally, SOLIPH overpredicts system performance (when compared to measurements). Another interpretation is that the systems are underperforming compared to design expectations. It is very difficult to determine the source (or sources) of the differences between predictions and actual performance due to the large number of possible causes.

While most of the sites have collected and reported data over the past year, much of the system operation has been inconsistent. Considerable hardware downtime, either in the collector field or energy delivery system, DAS problems, and in some cases, industrial process limitations have resulted in variable system performance. These site-related problems make actual performance versus prediction comparisons in terms of absolute energy collection and delivery difficult at best.

In order to take system downtime or partial field operation into account, a slightly different approach is necessary. To normalize the differences in solar energy available between the TMY data used by SOLIPH and the actual energy available, comparisons based on collector and system efficiencies are utilized. In the SOLIPH output, efficiency is based on the energy incident in the plane of the collector when the system is tracking. All contractor data are now reported in this manner. If part of the field is down, an attempt to modify the reported data is made in the following fashion. The fraction of the field operating is determined from the monthly reports. It represents an 'availability' when the system is operating and is given the variable name "A" in the tables in the following sections. Both reported collector and system efficiencies are divided by "A" to give an approximation of the efficiency should the full field be operating. This is only an approximation, since additional heat lost from the nonoperating rows is not accounted for in the model. Some of the systems have reported efficiencies based on actual operating area, therefore A = 1 for those comparisons even though part of the field is not operating.

In addition to the collector and system efficiency comparison, both the actual and TMY energy incident in the collector plane are given in the tables. It is interesting to note that only rarely does the reported incident energy exceed the TMY based calculation. A number of explanations for this can be postulated. A primary contributing factor for those systems with inconsistent operation is system downtime. For those that do operate whenever there is energy available, the explanation may lie in weather patterns, which this year have resulted in somewhat lower insolation levels. In some cases, a good match between available TMY sites and actual location may not exist. Figure 4-1 shows the total horizontal and direct normal irradiance annually for each of the seven sites. This figure illustrates the large differences between the various sites in terms of available energy on a per unit area basis.

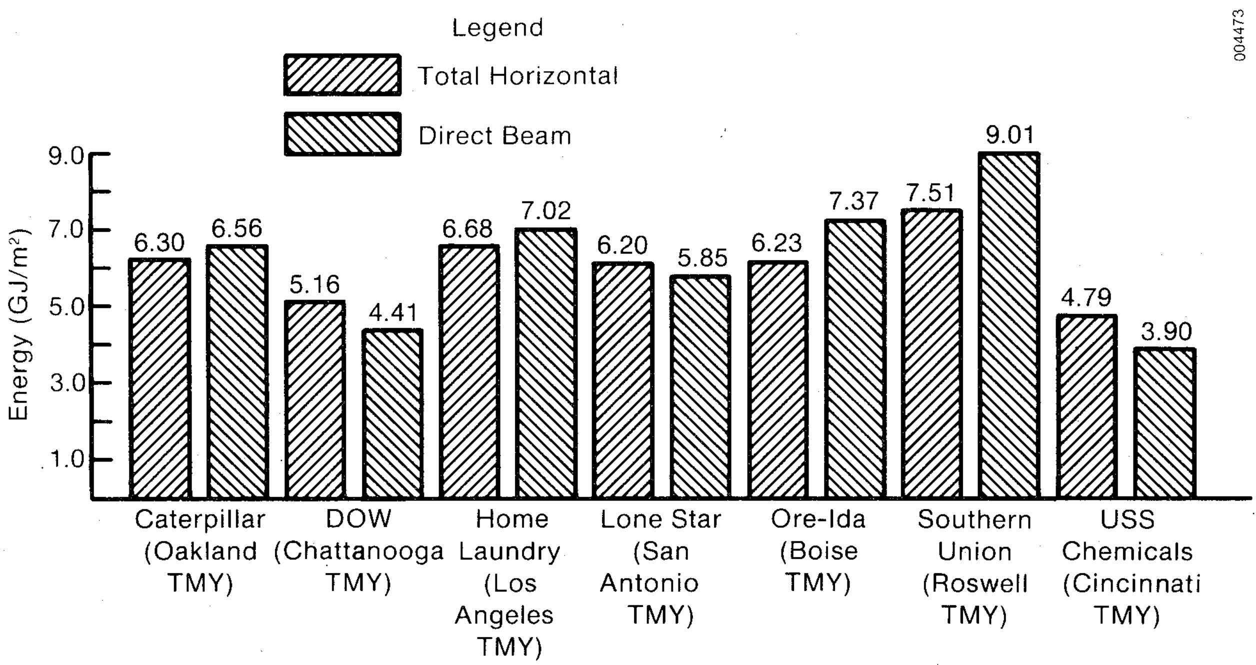

Figure 4-1. Annual Site TMY Irradiance for Various IPH Field Test Sites

The following sections present and discuss the comparisons for each site. Both monthly and clear day comparisons are made for those months where data have been reported and reports were available.

4.1 CATERPILLAR TRACTOR

A unique problem at Caterpillar Tractor renders comparisons extremely suspect. The hot water load has been consistently lower than the amount of energy the solar system can deliver due to reduced production levels. Various schemes to control the output of the field to match the load have been tried, including defocusing parts of the field and more recently shutting down rows with fluid flow valved off. The system has never been able to operate at full output for any length of time due to the decrease in demand.

The reported data does not include system efficiency because instrumentation is set up so that energy collection and delivered energy are identical. In SOLIPH energy collection does not include flex hose or interconnect piping losses and therefore in this configuration (as for all the configurations) there will be a decrease from collected to delivered energy.

Since SOLIPH uses an average dirt/dust accumulation factor to reduce collector optical efficiency, the month-to-month variation in collector efficiency will be smooth. As can be seen in Table 4-1, the monthly variation in reported data is quite large. This is due to cleaning schedules and to load supply problems mentioned previously. There have also been some central tracking control problems, which have resulted in many rows losing the sun in partially cloudy weather and never being able to re-acquire. Note that the actual

Table 4-1. Monthly Performance Comparison for Caterpillar Tractor

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Oct. 1983[a]	606.9	1.0	20	20	1527	54	48
Sept.	475	1.0	30	30	2125	58	54
April[a]	582	1.0	33	33	2214	58	53
March	435[b]	.97[c]	23	23	1473	55	49
Feb.	310	.99	19	19	1029	51	45
Jan. 1983	87[d]	.98	15	15	748	47	39
Dec. 1982	120[e]	1.0	26	26	842	44	35
Nov.	187[f]	1.0	36	36	942	48	41

[a]Based on active area only.

[b]Based on entire field aperture area.

[c]Two drive strings reported down and assumed down entire month.

[d]DAS not operational Jan 1-10.

[e]DAS down Dec. 22-31.

[f]DAS operational beginning Nov. 13.

incident energy is far less than TMY. Again, a meaningful comparison is not possible here because of the operational control of the system.

The clear day comparison exhibits the same characteristics as the monthly comparison. However, the expectation that clear day efficiencies should match better than shown in Table 4-2 is not realized. Especially during the recent months when rows are stowed, effectively removing them from the system, it was expected that better comparisons would result. With a system operating at lower temperatures like this one the collector efficiencies should be higher than those reported. The maintenance staff at Caterpillar has little incentive to clean the collector field under the present operating conditions and therefore the real dirt/dust accumulation is certainly not as modeled. Tracking problems may also be the source of the difference in this case. To be fair to both the operation at Caterpillar and to the SOLIPH predictions, meaningful comparisons cannot be made until the system can operate at full capacity and with control functions providing their full capability.

4.2 DOW CHEMICAL

The Dow Chemical system has operated fairly reliably since the beginning of the 1983 calendar year. Some data have been lost due to DAS and pyrheliometer problems, but generally data availability has been high. Until recently, energy delivered referred to delivered energy to the boiler water and not to steam delivery. This form was reported until May 1983 when software was modified to correctly calculate net energy delivered to the process as steam.

Table 4-2. **Clear Day Performance Comparison for Caterpillar Tractor**

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Oct. 1983[a]	42.3	1.0	23	-	90.6	55	51
Sept.	38.7	1.0	37	37	113.2	59	55
April[a]	48.4	1.0	40	40	132.3	57	54
March	34.4[b]	.97[c]	37	38	106.6	57	53
Feb.	52.9	1.0	25	25	85.0	51	46
Jan. 1983	31.1	.98	29	29	60.9	49	43
Dec. 1982	25.4	1.0	23	23	50.6	44	37
Nov.	40.0	1.0	36	36	63.4	51	45

[a]Based on active area only.

[b]Based on entire field aperature area.

[c]Two drive strings reported down and assumed down entire month.

The SOLIPH modeling of the Dow system attempted to include insulation degradation factors to account for the poor condition of the pipe insulation. Comparing the monthly system efficiencies in Table 4-3 it is clear that SOLIPH overpredicts performance. It is possible that continued degradation of the insulation has caused the very poor performance at Dow. An upgrade of the insulation is currently in progress and should result in much improved system performance. The large difference in collector efficiencies is postulated to be due primarily to the instrumentation at Dow, which includes all flex hoses and the field header piping in the calculation. Clear day comparisons in Table 4-4 show somewhat better agreement. Note that in both tables the agreement in incident energy is good. However, the reported incident energy is higher in many cases, indicating that the Chattanooga TMY site may not be an entirely satisfactory choice. The next closest TMY site, Atlanta, has a significantly higher available energy and probably is not appropriate for the Dow site.

4.3 HOME LAUNDRY

Data reporting at Home Laundry has been very consistent, as has the operation of the solar system. Since the laundry operation requires both DHW and steam at various times throughout the month and throughout any given day, the comparison with predictions is very difficult.

The data presented in the monthly comparisons, Table 4-5, attempt to identify and compare the major operating modes of the month. In Table 4-5 the operating modes are noted after the month. When both steam and DHW have been utilized the primary mode is listed first. When one mode dominated the month it is listed alone. Note the fairly consistent collector and system efficiency through June 1983 and good agreement with SOLIPH. Performance drops

Table 4-3. Monthly Performance Comparison for Dow Chemical

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Oct. 1983[a]	259.6	1.0	27	-	306.6	44	23
Sept.	b,c	--	--	--	319.4	46	26
August	c	--	--	--	386.6	47	26
July	c	--	--	--	333.4	47	22
June	334.4	1.0	23	16[d]	364.5	46	25
May	451.2	.97	22	16[d]	363.7	47	27
April	467.9	.87	23	23[e]	348.3	46	26
March	187.0[f]	.97	26	15[e]	262.1	44	22
Feb.	219.4	1.0	19	15[e]	208.4	42	20
Jan.	202.5	1.0	16	10[e]	175.8	39	13

[a]Upgrades complete 9/14.

[b]System down for upgrade 8/15.

[c]No pyrheliometer available.

[d]Energy delivered to process.

[e]Reported as energy delivered to water; does not include boiler warm-up or skin losses.

[f]DAS down 3/22-31.

Table 4-4. Clear Day Performance Comparison for Dow Chemical

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Oct. 1983	23.0	1.0	30	-	17.9	46	26
Sept.	a	--	--	--	21.4	47	30
August	a	--	--	--			
July	a	--	--	--			
June	31.8	1.0	30	25[b]	23.6	48	31
May	34.1	1.0	27	20[b]	26.1	48	32
April	32.1	.93	32	25[b]	25.5	49	34
March	23.3	1.0	27	21	22.0	45	28
Feb.	23.3	1.0	26	20	20.4	44	26
Jan.	18.2	1.0	23	15	15.6	38	17

[a]No pyrheliometer available.

[b]Reported as energy delivered to water; does not include boiler warm-up or skin losses; includes overnight losses.

Table 4-5. Monthly Performance Comparison for Home Laundry

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Sept. 1983 (DHW & Steam)	87.0[b]	1.0	34	27	198.3	51/5[a]	35/43[a]
Aug. (Steam & DHW)	172.1	1.0	37	30	285.1	53/54[a]	39/44[a]
July (Steam & DHW)	202.0	1.0	37	31	295.2	53/55[a]	40/45[a]
June (DHW & Steam)	105.1	1.0	45	36	192.9	53/55[a]	37/44[a]
May (Steam)	120.4	.97	42	34	257.7	53	38
April (Steam)	95.4	.97	45	41	204.6	52	37
March (DHW)	77.3	1.0	42	36	194.4	52	42
Feb. (DHW)	39.8	1.0	44	41	145.2	51	41

[a]Steam/DHW

[b]Laundry operations have been terminated and moved to another location. Solar system operated for data collection purposes only.

off from July through September 1983. Reduced utilization by the laundry resulted in more frequent system saturation and consequently lowered efficiencies during the last 8-10 weeks of operation. Collector washing was performed monthly during this period. The incident energy is considerably less than expected by the TMY data. It should be noted that an error in the DAS software calculating incident from direct normal irradiance was discovered, which would make some difference in the reported data.

Comparisons of the clear day performance in Table 4-6 also show good agreement through June 1983, with the exception of March 1983, which has an unusually low reported value not at all consistent with the monthly values. It is hard to determine how clear day performance could be lower than the monthly for any set of circumstances.

4.4 LONE STAR BREWERY

The system operation at Lone Star has been fairly consistent; however, there often has been at least two rows not functioning. A continuing flex hose leakage problem has been responsible for some of the row shutdown and, in fact, has increased to the point where the entire system has been shut down at the request of the Lone Star management. A system configuration change to a feedwater preheat system using water as the working fluid has been proposed and recently accepted by all involved parties. The system has been shut down since June pending resolution of the leakage issue. The deterioration of the system can be seen in Table 4-7 as the decrease in "A" with time over the March-May reporting periods.

Agreement between system efficiencies reported and SOLIPH is spotty with some months having good agreement and some very poor. Cleaning cycles could cause some of this. However, some months reported data seem inconsistent with other months; e.g., November 1982 with an extremely low system efficiency. It is not clear, however, from the reports what causes these inconsistencies. It is clear that the available irradiance, even when corrected for full field operation, is not close to the average year reported in the TMY data.

Examination of the clear day comparisons in Table 4-8 yields no new observations. The collectors were cleaned in February 1983 (among many other times) and the improvement in performance can be clearly seen in the collector and system efficiencies.

Table 4-6. Clear Day Performance Comparison for Home Laundry

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col}[a] (%)	η_{del}[a] (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Sept. 1983 (DHW)	8.3		39	34	9.2	52/54[b]	35/42[b]
Aug. (DHW/Steam)	10.6	1.0	37	30	15.3	55/53[b]	44/41[b]
July (Steam)	13.1	1.0	32	29	15.5	54	41
June (Steam)	11.8	1.0	42	36	16.0	53	40
May (Steam)	11.0	1.0	43	40	15.9	53	40
April (Steam)	10.1	1.0	44	39	14.9	53	39
March (Steam)	8.8	1.0	31	20	12.7	50	35
Feb. (DHW)	5.5	1.0	44	41	9.9	51	42

[a]Hours when excessively high system and collector efficiencies reported are not included.

[b]DHW/Steam.

Table 4-7. Monthly Performance Comparison for Lone Star Brewery

Month	Reported Data				SOLIPH		
	Q_{inc}[a] (GJ)	A	η_{col}[c] (%)	η_{del}[c] (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
May 1983	53.3[b]	.67	38	19	417.3	44	34
April	266.2	.72	48	29	284.9	43	32
March	196.6	.81	46	29	345.9	42	32
Feb.	199.8	.86	45	24	262.1	38	26
Jan 1983	127.7	.87	40	18	259.9	35	23
Dec. 1982	152.7	.87	24	5	228.1	34	21
Nov.	76.2	.86	26	5	250.2	37	25
Oct.	136.1	.86	32	19	361.6	40	30
Sept.	195.2	.83	46	32	409.0	43	34
Aug.	258.0	.84	45	34	477.9	45	36
July	251.5	.84	42	28	564.0	45	37
June	125.4	.85	38	20	477.8	45	36

[a]Based on operable area of collector field.

[b]System shutdown 5/7.

[c]Energy collected and delivered not counted for those days when row with twin pyranometers did not track the sun.

Table 4-8. Clear Day Performance Comparison for Lone Star Brewery

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
May 1983[a]	22.9	.67	30	19	25.5	45	38
April	22.6	.73	39	27	24.7	44	37
March	18.8	.87	40	26	23.5	43	36
Feb.	16.1	.87	45	26	19.2	38	30
Jan. 1983	13.7	.87	31	18	15.5	35	25
Dec. 1982	13.5	.87	28	15	14.3	35	25
Nov.	12.3	.87	25	10	17.8	37	28
Oct.	18.1	.87	41	28	20.0	42	35
Sept.	22.5	.87	43	31	20.8	44	36
Aug.	19.2	.87	42	37	24.7	45	38
July	20.7	.87	42	30	23.7	47	40
June	15.2	.87	42	25	24.2	46	39

[a]System shutdown 5/7.

4.5 ORE-IDA FOODS

The Ore-Ida system has had an extremely poor operating record. Pump cooling problems and DAS failures have been the primary causes of system downtime. The management at Ore-Ida has decided not to maintain the system due to its poor operational history. Data for system performance is generally not available, especially for operation at 125 psi (the mode modeled by SOLIPH). In fact, only a single month's data (August 1982) are available at that operating steam pressure.

Since the amount of data available for comparison is so scant, any comparison based on it is not considered meaningful. The data for August 1982 is presented for information in Table 4-9 and Table 4-10.

4.6 SOUTHERN UNION

The Southern Union system is fortunate to be situated in a near ideal solar environment. Available direct irradiance is higher here than for all the other sites (see Figure 4-1). Unfortunately, the system performance has not reached its potential due to relatively low utilization of the system. Lack of fully automatic mode operation has reduced the number of days the system actually functions.

Table 4-9. Monthly Performance Comparison for Ore-Ida Foods

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
August 1982	320.6[a]	1.0	6[b]	4[b]	793.1[a]	44	25

[a]Direct beam.

[b]Based on direct beam.

Table 4-10. Clear Day Performance Comparison for Ore-Ida Foods

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
August 1982	31.5[a]	1.0	21[b]	17[b]	27.7[a]	42	25

[a]Direct beam.

[b]Based on direct beam.

The low utilization and generally below average available energy have combined to reduce the amount of energy incident in the collector plane. This can be seen in Table 4-11 for the year of data reported. The early operational history during the summer of 1982 included a number of tracker and drive related problems, which are reflected in the poor performance during that period. Performance has improved since then, but not to the point expected from the SOLIPH predictions.

Agreement is much better on the clear days, as indicated in Table 4-12. Since February 1983 agreement has been quite good with SOLIPH, generally 2-4 percentage points high. This gives somewhat more confidence in the ability to model a clear day at Southern Union, although it does not help much in explaining the differences in the monthly values.

Table 4-11. Monthly Performance Comparison for Southern Union

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Oct. 1983[a]	94.4	.97	-	-	524.2	44	33
Sept.	System Down for Upgrade				526.1	43	32
Aug.	86.6[b]	.83	c	18	563.4	44	32
July	244.9[d]	.83	c	22	635.4	44	33
June	155.4	.83	c	19	624.8	43	32
May	246.3	.83	c	25	585.5	43	31
April	177.4[e]	.83	c	26[e]	536.4	43	31
March	190.9	.99	35	24	526.3	43	31
Feb.	149.5	.90	32	18	470.8	44	32
Jan. 1983	205.8	.83	33	17	495.7	44	32
Dec. 1982	74.3[f]	.94	38	21	469.8	43	31
Nov.	193.7	.92	36	22	497.3	44	32
Oct.	255.9	.93	37	23	524.2	44	33
Sept.	177.0	.92	30	18	526.1	43	32
Aug.	68.4[g]	1.0[h]	22	9	563.4	44	32
July[i]	5	--	--	--			

[a]Repairs complete 9/13; instrumentation problems caused uncertainty in energy collection and delivery.

[b]System up only 9 days, down for upgrade and repair the remainder.

[c]Collector field instrumentation down due to drive string failure.

[d]For entire field on days when system is up.

[e]Wind damage to two drive strings.

[f]System down 12/18-31

[g]System down 7/11-26.

[h]Unable to determine number of drive strings inoperable.

[i]Numerous drives inoperable, system generally unreliable.

Table 4-12. Clear Day Performance Comparison for Southern Union

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del} (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Oct. 1983[a]	18.1	.96	-	34	21.8	44	34
Sept.	System down for upgrade				21.9	44	34
Aug.	17.6	.83	b	28	23.2	44	34
July	15.6	.83	b	32	24.7	44	34
June	18.8	.83	b	30	25.2	43	34
May	20.2	.83	b	30	24.4	44	34
April	19.5	.83	b	29	23.8	44	34
March	18.9	.92	42	34	22.6	43	33
Feb.	16.9	1.0	39	32	22.4	43	33
Jan. 1983	16.7	.83	37	23	21.5	45	34
Dec. 1982	12.6	.92	37	23	20.3	45	34
Nov.	17.8	1.0	35	24	21.4	44	34
Oct.	18.0	1.0	36	26	21.8	44	34
Sept.	17.6	1.0	35	30	21.9	44	34
Aug.	13.8	1.0	25	12	23.2	44	34

[a]Repairs complete 9/13; energy delivery counted only after start-up due to transient measurement problem in energy collection.

[b]Collector field instrumentation down due to drive string failure.

4.7 USS CHEMICALS

With the exception of some early DAS reliability problems, the system at USS Chemicals has been very reliable. The solar system itself has ad relatively few problems, resulting in both high availability and high utilization. The instrumentation is quite extensive and placed in such a manner as to closely approach the SOLIPH configuration. For example, the collector field performance is determined by temperature probes mounted very near the row inlet and outlets, excluding a large portion of the headers. Since SOLIPH models the collector field without flex hoses, interconnect piping or headers included, the measurements at USS chemicals are closer to SOLIPH than any of the other systems.

Good agreement is exhibited in the monthly comparisons shown in Table 4-13. Note also that the agreement when averaged over the months reported is very good. The differences in monthly comparisons are dependent on the cleaning cycle, which for such a large field cannot be very often due to cost. The improvement in performance with cleaning is dramatic as evidenced by the change from April to May 1983 when the collectors and receivers were washed. The collectors were washed at the end of August, as indicated by the September 1983 performance improvement. Again, incident irradiance is low compared to TMY data with the exception of July and September 1983.

Table 4-13. Monthly Performance Comparison for USS Chemicals

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del}[a] (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Sept. 1983	1377	1.0	54	42	1133	49	38
Aug.	1200	.97	47	35	1784	50	41
July	1658	.93	52	43	1567	50	40
June	1283	1.0	53	40[b]	1740	51	42
May[c]	1027	1.0	60	51	1748	50	41
April	809	1.0	46	33	1152	49	39
March[d]	335	1.0	42	32	760	47	33
Feb.[e]	293	1.0	42	28	600	41	25

[a] $\eta_{del} = \frac{Q_{steam} - Q_{FW}}{Q_{inc}\ A}$, Q_{steam} and Q_{FW} as reported.

[b] Feedwater flow measurement error suspected by Columbia Gas.

[c] Reflectors and receiver glazings washed May 5 and 6.

[d] System down from March 9-31 for receiver tube seal replacement.

[e] DAS down Feb. 1-13.

Comparisons of clear day performance in Table 4-14 are as equally encouraging as the monthly comparisons. Unfortunately, clear day performance was not reported until June 1983. The available irradiance figures are very close as well, indicating that any underprediction overall would stem from a larger number of overcast or partly cloudy days than expected from the TMY data.

Table 4-14. Clear Day Performance Comparison for USS Chemicals

Month	Reported Data				SOLIPH		
	Q_{inc} (GJ)	A	η_{col} (%)	η_{del}[a] (%)	Q_{inc} (GJ)	η_{col} (%)	η_{del} (%)
Sept. 1983	103.1	1.0	61	52	96.6	50	43
Aug	93.9	.97[b]	47	39	101.0	51	44
July	118.1	.93[b]	56	48	112.1	52	45
June	113.0	1.0	56	49[c]	117.6	52	45

[a] $\eta_{del} = \frac{Q_{steam} - Q_{FW}}{Q_{inc} \cdot A}$, Q_{steam} and Q_{FW} as reported.

[b] Assumed; no specific information available in report.

[c] Feedwater flow measurement error suspected by Columbia Gas.

SECTION 5.0

SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY OF ACCOMPLISHMENTS

The two main objectives of this work were both completed successfully. Models of the seven sites were prepared, input data were developed, and performance predictions were generated to complete the first objective. Comparisons of those predictions with reported performance data were then conducted with varying degrees of agreement.

Excellent agreement was achieved for the USS Chemicals system. Other comparisons were not as close, ranging from good to fair. Generally, SOLIPH predicted more efficient systems than actual performance indicates. This could be due to limitations in the analytical methods utilized or inaccurate input data. Two specific areas of concern in the model are the estimation of dirt/dust effects on collector performance and accurate quantification of system heat loss characteristics.

It certainly appears that at USS Chemicals, the SOLIPH model does an excellent job of performance prediction. To say, however, that the model is validated is premature. Considering the results from the other sites, it generally appears that the model overpredicts performance. Why this is not true at USS chemicals is not clear and conversely, why the model does not do better at the other sites is also not clear. A significant difference between USS Chemicals and the other sites is the overall reliability of the system. It has operated for far longer periods without failure than any other. As system reliability improves for the other systems, it will be interesting and important to compare SOLIPH with the hopefully improved performance and to update SOLIPH input data and methodology to better reflect actual performance.

It is clear, additionally, that the systems do not always perform as expected. Besides downtime, which limits delivered energy, operational deficiencies that tend to reduce efficiency include tracker and control system problems, dirt/dust buildup on reflective surfaces and glazings, working fluid leaks, deterioration of insulation and jacketing, and lack of adequate or timely maintenance. No matter where the source of discrepancies exists, improvements in the model can be made and continuing efforts to improve system performance and reliability should result in confidence in both the model's ability to predict performance and the system's ability to achieve it.

5.2 RECOMMENDED IMPROVEMENTS

5.2.1 SOLIPH

Several areas within the code could be improved and/or evaluated. The modeling of transient performance due to both weather and control system functions should be evaluated to determine the extent of errors introduced by steady-state model assumptions.

Since dirt/dust effects are so site specific, both environmentally and in relation to maintenance schedules, a more rigorous approach should be utilized. A relatively simple method such as estimation of optical performance degradation from reported data could yield a significant improvement (as it did for USS Chemicals) in comparisons of predicted and actual data. There certainly are other methods that could improve the estimates used in this report.

It is also possible that heat loss calculations for pipes and fittings are low due to differences between assumed (or handbook) thermal conductivities and actual values. Calculation of pipe UA is at best approximate, especially estimates for values and fittings that are partially exposed. Insulation installation techniques can also have an effect on subsequent heat losses; i.e., it is easy to install insulation poorly and more difficult to do the job properly. While quantitative evaluation of material properties is difficult in the field, there may be some methods that would allow more accurate heat loss determination.

Finally, although not inclusively, a better method for providing input solar irradiance data is needed. If site data reliability and accuracy could be improved to provide consistent hourly data, then this would be the preferred source. Alternately, TMY data should be evaluated for their validity compared to actual long-term averages. There is a study ongoing at SERI in the Renewable Resource Assessment and Instrumentation Branch to test TMY data generation algorithms against actual site data. Preliminary results indicate that TMY data tend to be slightly (up to 5%) high. As IPH contractor reports continue to build a solar radiation data base it may be possible to incorporate those data into the SOLIPH modeling effort.

5.2.2 Field Tests

All of the remaining operational field tests are currently undergoing upgrades. These system improvements have been designed to increase reliability and performance. All have occurred or been planned primarily as a result of the operating experiences at the sites and secondarily as a result of the SOLIPH modeling effort. For example, piping insulation improvements at DOW were certainly indicated by simple observation, but the SOLIPH model results clearly show the significance of losses in that system and the corresponding potential energy savings. At Southern Union, the reduction in thermal mass by piping changes will definitely improve the performance of the system. A change from steam to feedwater preheat configuration at Lone Star has been modeled (preliminarily) showing a significant increase in performance potential. Hopefully, the continued use of the reported SOLIPH data will, by itself, aid in determining potential system improvement areas. Additionally, the comparison with reported data can continue to identify system performance deficiencies that may require attention.

5.2.3 Design

A number of design guidelines can be identified that would improve the ultimate performance of IPH solar systems. While many of these ideas are common sense, the SOLIPH modeling effort has served to reinforce their validity and potential as well as quantifying their impacts. Most of these guidelines have been generated from the thermal point of view and do not necessarily represent economic optima. System designers will, of course, have to make the final decisions.

Design features to consider when selecting collector systems for IPH applications include many ideas currently under development. Tracking problems have been significant and therefore deserve considerable attention. Search-mode trackers are an absolute necessity as evidenced at Caterpillar. Drive system reliability must be improved to reduce current maintenance requirements. New receiver designs that eliminate glass breakage and working fluid leaks are essential. Flex hose failures, especially with oils at higher temperatures, must be eliminated to prevent problems such as occurred at Lone Star. Rotary joints could be a solution, both for oil and water systems, but this hardware has not completed evaluation. While these features do not have a direct connection to the SOLIPH modeling efforts, they will affect the thermal output of the system. It is, however, the thermal transport system that is more directly connected to the modeling effort and it is here that the SOLIPH results can be especially well utilized to make significant recommendations.

Since the operating and nonoperating heat losses consume approximately 10%-50% of the energy collected for the field tests modeled in this report, it is important to consider ways to reduce them. A common problem was long pipe lengths, which increase both heat loss and thermal capacitance. Minimizing the pipe lengths by locating boilers, heat exchangers, etc., close to the collector field is very important. Performance benefits are achieved by using flow balancing valves as opposed to reverse return piping to equalize collector row flowrates. Pipe supports should be eliminated where possible and always isolated from direct connection to the pipe. Pipe sizes should be minimized consistent with pressure drop requirements. This reduces both heat loss (allowing smaller insulation thickness) and thermal capacitance through lower system fluid inventory and smaller pipe mass. Insulation should be applied to all fittings to the extent economically feasible.

Vessels and tanks should also be well insulated. Thermosyphoning can be easily eliminated with traps and other piping design features. Pumps, although more difficult to insulate, can represent large heat losses, especially if continuous seal cooling is required.

Lowering the operating temperature of systems by providing energy to process hot water or boiler feedwater will pay significant dividends. IPH system designers should look for lower temperature applications that take advantage of the increased system efficiency and lower losses inherent in these applications.

While it appears that significant improvements in system performance are being made, it is clear that continued improvement is necessary for commercial market penetration by solar IPH systems. It is expected that through continued system modeling efforts to identify problem areas, potential energy deliveries, design trade-offs, etc., system designers will have the tools necessary to bring solar IPH technology into its place in the industrial energy market.

SECTION 6.0

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APPENDIX A – UNFIRED BOILER SUBROUTINE

A new unfired boiler routine was added to SOLIPH to improve modeling accuracy. This new model includes the thermal capacitance of the boiler.

During warm up (when the boiler has cooled below the steam saturation temperature) the unfired boiler model assumes that the shell side of the boiler is at one mixed temperature. The 1-hour time step that is being considered is divided into 10 smaller time steps. Over these smaller time steps the shell-side (water/steam side) temperature is assumed to be constant. The heat given up by the working fluid circulating through the tubes (which is equal to the heat gained by the shell-side water) is calculated based on the log-mean temperature difference. After each small time step a new shell-side temperature is calculated. No steam is generated during the warm-up period.

Once the boiler has reached the steam saturation temperature, the energy flows are based on steady-state steam generation for the remainder of the hour.

Figure A-1 shows the schematic representation of the unfired boiler model.

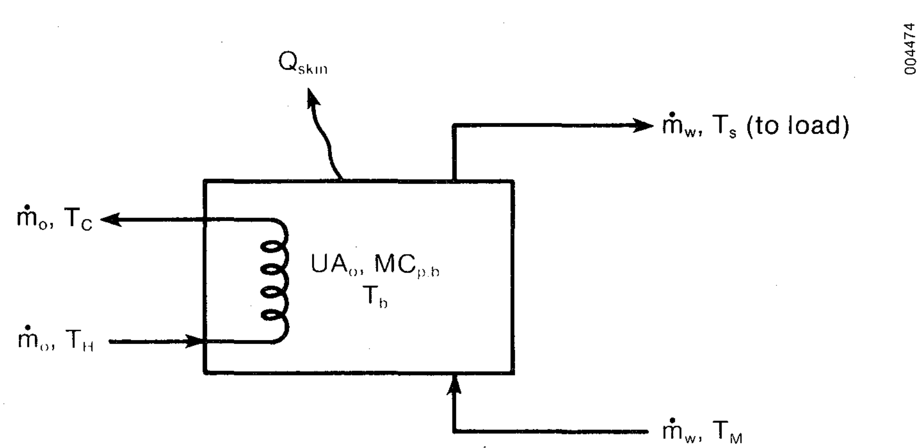

Figure A-1. Unfired Boiler Schematic

A.1 NONOPERATION

If the boiler is not being supplied with hot oil from the collectors, the bulk boiler temperature is reduced due to skin losses. The final bulk temperature is

$$T_b = T_{env} + (T_o - T_{env}) \exp \left[\frac{-(UA)_{skin}}{(Mc_p)_{boiler}} t\right] , \quad \text{A-1}$$

where T_o = bulk boiler temperature at beginning of hour,

$T_{env} = T_{amb}$ if outside, 25°C if inside, and

t = time step.

Skin losses during this time are:

$$Q_{skin} = (Mc_p)_{boiler} (T_o - T_b) \quad \text{A-2}$$

A.2 OPERATIONAL

If the boiler is being supplied with hot oil, the subroutine models the boiler in two distinct sections: warm-up and steady-state steam generation. The algorithms used for each are described below.

Warm up

During warm up of the boiler the overall energy balance is

Heat Loss Rate From Fluid Within Boiler Tubes =
Heat Transfer Rate From Boiler Tubes to Shell-Side Water

$$\dot{m}_o c_p (T_H - T_C) = (UA)_{boiler} \frac{T_H - T_C}{\ln \dfrac{T_H - T_b}{T_C - T_b}} , \quad \text{A-3}$$

where T_b = bulk boiler temperature.

Solving for the oil return temperature,

$$T_c = T_b + (T_H - T_b) \exp \left(-(UA)_{boiler}/\dot{m}c_p\right) . \quad \text{A-4}$$

For small time steps dt, the energy transferred during this time is:

$$\dot{Q}_{dt} = \dot{m}_o c_p (T_H - T_C) dt . \quad \text{A-5}$$

Now, the new (end of time step) bulk tank temperature is calculated from the following energy balance:

Heat Loss Rate From Fluid Within Boiler Tubes =
Heat Loss Rate From Tank + Heat Gain Within Boiler

$$\dot{m}_o c_p \ (T_H - T_C) = (UA)_{skin} \ (T_b - T_{env}) + (Mc_p)_{boiler} \frac{\Delta T \ bulk}{dt} \ . \qquad A-6$$

Solving for ΔT bulk,

$$\Delta T_{bulk} = [\dot{m}_o c_p \ (T_H - T_c) - (UA)_{skin}(T_b - T_{env})] \frac{dt}{(Mc_p)_{boiler}} \ . \qquad A-7$$

For the next time step, a new bulk boiler temperature is assumed and the calculations are repeated.

The total boiler skin loss during warm up is a summation over the n smaller time steps.

$$Q_{skin,warm\ up} = \sum_{i}^{n} (UA)_{skin} \ (T_{b,i} - T_{env}) \ dt \ . \qquad A-8$$

The final bulk boiler temperature is the T_{new} that results from the last time step, or until the steam saturation temperature is reached. The average boiler tube outlet temperature (collector field return temperature) is the arithmetic average of T_C for the time steps.

Steady-State Steam Generation

Once the bulk fluid temperature within the boiler reaches the steam saturation temperature, steam is generated. The boiler feedwater that is supplied to the unfired boiler is assumed to be "instantly mixed" upon its introduction into the shell side of the boiler.

The overall energy balance during steady-state steam generation is thus:

$$\dot{m}_o c_p \ (T_H - T_C) = (UA)_{boiler} \ \Delta T_m \ , \qquad A-9$$

where the log-mean temperature difference for the unfired boiler is

$$\Delta T_m = \frac{T_H - T_C}{\ln \left(\frac{T_H - T_s}{T_C - T_s}\right)} \ . \qquad A-10$$

Solving for T_C,

$$T_C = T_s + (T_H - T_s) \exp \left(-(UA)_{boiler}/\dot{m}_o c_p\right) \ . \qquad A-11$$

Skin losses during steam generation are calculated based on a constant boiler operating temperature:

$$Q_{skin,ss} = UA_{skin} \ (T_s - T_{env}) \ (1 - t_{warm\ up}) \ , \qquad A-12$$

where $t_{warm\ up}$ = fraction of the hour needed to warm up the boiler.

The average return temperature to the collectors is calculated based on the time weighted average during both warm-up and steam generation. The boiler skin loss is the total of the warm-up skin losses and the steady-state skin losses.

The energy delivered to the load in the form of saturated steam is equivalent to the energy provided to the boiler during the steam generation time period minus skin losses during this time.

$$Q_{del} = \dot{m}_o c_p \,(T_H - T_c)\,(1 - t_{warm\ up}) - Q_{skin,ss} \,. \qquad \text{A-13}$$

The steam delivery mass flow rate is calculated as

$$\dot{m}_w = \frac{Q_{del}}{h_{fg} - c_{pw}\,(T_s - T_m)} \,. \qquad \text{A-14}$$

Blowdown losses, if any, are calculated as

$$Q_{blowdown} = f_{blowdown}\,\dot{m}_w\, C_{pw}\,(T_s - T_m)\ , \qquad \text{A-15}$$

where $f_{blowdown}$ = fractional blowdown rate,

and is subtracted from the delivered energy in the main routine.

APPENDIX B

HEAT EXCHANGER WITH CAPACITANCE

This routine was added to SOLIPH to allow configurations that use domestic hot water heat exchangers with large storage volumes on the load side.

The analysis of this component is similar to the warm-up phase of the unfired boiler in Appendix A. The addition of a known load side flow with a fixed inlet temperature is the only difference. Both nonoperational (collector side pump off) and operational (collector side pump on) modes are included. Energy is delivered to the load whenever the collector pump is on, therefore the load supply temperature floats with the collector temperatures. The schematic of the heat exchanger is shown in Figure B-1.

B.1 NONOPERATION

If the collector pump is not on, the bulk temperature of the heat exchanger is reduced due to skin losses. The final bulk temperature is

$$T_b = T_{env} + (T_o - T_{env}) \exp\left(-(UA)_{skin}/(Mc_p)_{exchanger}\right) , \qquad \text{B-1}$$

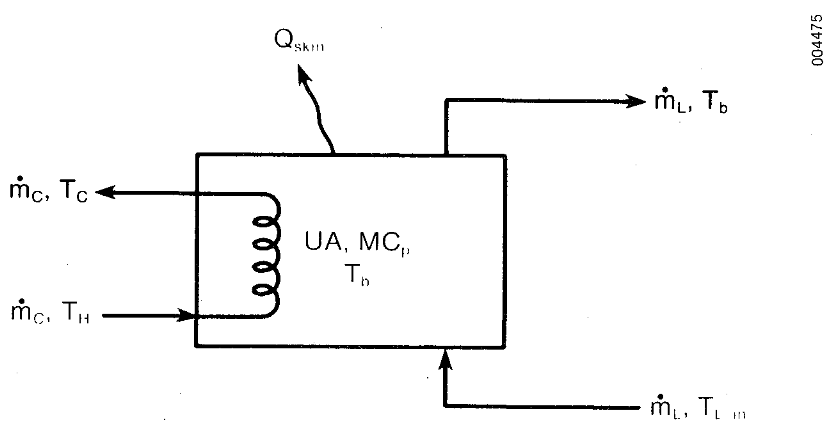

Figure B-1. Heat Exchange with Capacitance Schematic

where T_o = bulk heat exchanger temperature at beginning of hour,

T_{env} = T_{amb} if outside, 25°C if inside, and

t = time step.

Skin losses during the time step are

$$Q_{skin} = (Mc_p)_{exchanger} (T_o - T_b) \ . \qquad \text{B-2}$$

B.2 OPERATIONAL

The overall energy balance is:

Heat Loss Rate For Fluid With Heat Exchanger Tubes =
Heat Transfer Rate From Tubes to Bulk (Shell-Side) Water,

$$\dot{m}_c c_p (T_H - T_c) = (UA)_{exchanger} \frac{T_H - T_c}{\ln \dfrac{T_H - T_b}{T_c - T_b}} \ , \qquad \text{B-3}$$

where T_b = bulk exchanger temperature.

Solving for the collector return temperature,

$$T_c = T_b + (T_H - T_b) \exp\left(-(UA)_{exchanger}/\dot{m}_c c_p\right) \ .$$

For small time steps dt, the incremental bulk temperature increase is calculated from the following energy balance:

Heat Loss Rate from Fluid With Exchanger Tubes =
Heat Gain Rate for Load Side Fluid + Heat Loss Rate from Tank
+ Heat Gain Within Exchanger.

$$\dot{m}_o c_p (T_H - T_c) = \dot{m}_L (T_b - T_{L,in}) + (UA)_{exchanger} (T_b - T_{env}) + (Mc_p)_{exchanger} \frac{\Delta T}{dt} \text{ bulk} \ . \qquad \text{B-4}$$

Solving for ΔT_{bulk},

$$\Delta T_{bulk} = \left[\dot{m}_c c_p (T_H - T_c) - \dot{m}_L (T_b - T_{L,in}) - (UA)_{skin} (T_b - T_{env})\right] \frac{dt}{(Mc_p)_{exchanger}} \ . \qquad \text{B-5}$$

For the next incremental time step, a new bulk temperature is calculated ($T_b = T_b + \Delta T_b$) and the calculations are repeated.

The total skin loss is the summation over the n incremental time steps:

$$Q_{skin} = \sum_{i=1}^{n} (UA)_{skin} (T_{b,i} - T_{env}) dt \ . \qquad \text{B-6}$$

The total energy delivered is also the summation over the n incremental time steps:

$$Q_{del} = \sum_{i=1}^{n} \dot{m}_L c_p \left(T_{b,i} - T_{L,in}\right) dt \ . \tag{B-7}$$

The final bulk temperature is the T_b that results from the last incremental time step. The average tube side outlet temperature is the arithmetic average of T_c over the time step.

APPENDIX C

INCIDENT ANGLES FOR A HORIZONTAL, ARBITRARY RECEIVER AXIS, LINE FOCUS COLLECTOR

For an arbitrarily oriented receiver axis with a horizontal receiver and a known solar altitude and azimuth, the incident angle is relatively easy to calculate. Figure C-1 shows the geometry of collector-sun relationship.

Solar position is calculated with these well-known equations:

$$\sin(h_s) = \sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(H), \text{ and} \qquad \text{C-1}$$

$$\sin(az_s) = \frac{\cos(\delta)\sin(H)}{\cos(h_s)}, \qquad \text{C-2}$$

where h_s = solar altitude

L = latitude

δ = solar declination

H = hour angle

az_s = solar azimuth

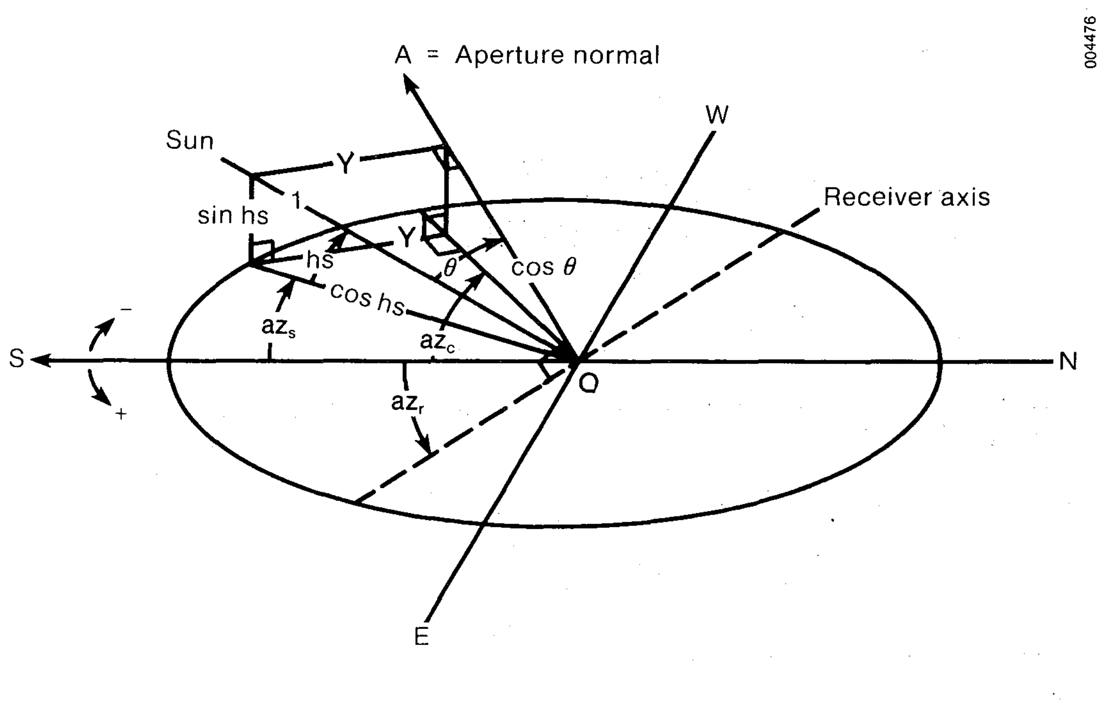

Figure C-1. Geometry of Sun-Collector Relationship

From the geometry in Figure C-1,

$$|y| = \cos(h_s)\ \sin\ (az_c - az_s), \qquad \text{C-3}$$

$$\cos^2(\theta) = 1 - \cos^2(h_s)\ \sin^2(az_c - az_s),$$

$$\cos(\theta) = [1-\cos^2(h_s)\ \sin^2(az_c - az_s)]^{1/2}, \qquad \text{C-4}$$

where

az_r = receiver azimuth

az_c = collector aximuth az_r-90

θ = incident angle.

The equations can be simplified to the well-known forms for N-S and E-W collectors. For a N-S collector,

$az_r = 180^o$

$az_c = 90^o$

$$\cos(\theta) = [1 - \cos^2(h_s)\ \sin^2(90 - az_s)]^{1/2}$$

$$= [1 - \cos^2(h_s)\ \cos^2\ (az_s)]^{1/2}\ . \qquad \text{C-5}$$

For an E-W collector,

$az_r = 90^o$

$az_c = 0^o$

$$\cos(\theta) = [1 - \cos^2(h_s)\ \sin^2(az_s)]^{1/2}$$

$$= (1 - \cos^2(h_s)\ \frac{\cos^2(\delta)\ \sin^2(H)}{\cos^2(h_s)}]^{1/2}$$

$$= [1 - \cos^2(\delta)\ \sin^2(H)]^{1/2}. \qquad \text{C-6}$$

The SOLIPH code is written with input data in terms of az_r, the receiver orientation from true south. Equation C-4 can be rewritten as

$$\cos(\theta) = [1-\cos^2(h_s)\ \sin^2(az_r-az_s-90)]^{1/2}$$

$$= [1-\cos^2(h_s)\ \cos^2(az_r-az_s)]^{1/2}\ . \qquad \text{C-7}$$

This is the equation used in the TROUGH subroutine in SOLIPH to calculate incident angles for horizontal fields.

APPENDIX D

UA AND Mc_p CALCULATIONS

D-1 Caterpillar Tractor

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Inside, Collector Inlet)				
Manifold (South)				
6" pipe, 2-1/2" insulation, 20.3 m	2.1	89.1	42.6	1809
pipe supports (3)	4.0	3.0	12	9
4" pipe, 2" insulation, 39.8 m	1.8	41.1	71.6	1636
pipe supports (2), anchors (1), guides (2)	3.0	2.0	15	10
3" pipe, 2" insulation, 20.3 m	1.5	24.9	30.5	505.5
pipe supports (1), anchors (1)	2.5	1.2	5	2.4
2" Pipe, 2" insulation, 12.2 m	1.2	11.8	14.6	144
pipe supports (2)	1.8	0.8	3.6	1.6
Inlet Riser (22) (South)				
1" pipe, 1" insulation, 6.1 m	1.2	3.7	161	496.5
pipe supports (1)	1.5	0.5	33	11
Branch to Field (South)				
6" pipe, 2-1/2" insulation, 79.2 m	2.1	89.1	166.3	7056.7
pipe supports (11), anchors (1),	4	3	48	36
flange, drain valve	6	8	6	8
Manifold (North)				
3" pipe, 2" insulation, 16.2 m	1.5	24.9	24.3	403.4
pipe supports (2), anchors (1)	2.5	1.2	7.5	3.6
2" pipe, 2" insulation, 12.2 m	1.2	11.8	14.6	144
pipe supports (2)	1.8	0.8	3.6	1.6
Inlet Riser (8) (North)				
1" pipe, 1" insulation, 6.1 m	1.2	3.7	58.6	180.6
pipe supports (1)	1.5	0.5	12.0	4
Branch to Field (North)				
4" pipe, 2" insulation, 101.2 m	1.8	41.1	182.2	4159.3
pipe supports (12), anchors (2), guides (2)	3.0	2.0	48	32
strainer and valve	4	5	4	5

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Inside, Collector Inlet) (cont'd)				
Expansion loops (8) (North)*				
1" pipe, 1" insulation, 12.8 m	1.2	3.7	61.4	189.4
drain valve	4	8	16	32
Common Piping				
Pumps (2)	30	40	60	80
6" pipe, 2-1/2" insulation, 17 m	2.1	89.1	35.7	1514.7
4" pipe, 2" insulation, 4.9 m	1.8	41.1	8.8	201.4
6" bell valve, insulated (2)	4	8	8	16
4" bell valve, insulated (2)	3	6	6	12
strainer, drain valve	6	8	6	8
instrumentation (4)	1.5	0.5	6	2
			1173	18715

*50% to inside, 50% to outside

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 2 (Outside, Collector Inlet)				
Inlet Riser (22) (South)				
flex hose, 1.5 m	3.4	3.7	112.2	122.1
supports (1)	2.0	0.4	44	8.8
1" ball valve, insulated	0.7	0.3	15.4	6.6
1" pipe, 1" insulation, 1.5 m	1.4	3.7	46.2	122.1
Expansion loops (22) (South)*				
flex hose (2), 1.5 m	3.4	3.7	112.2	122.1
plug/safety valve	1.4	0.4	15.4	4.4
pipe hangers (3)	2.0	0.5	66	16.5
1" pipe, 1" insulation, 5.3 m	1.4	3.7	81.6	215.7
Inlet Riser (8) (North)				
flex hose, 1.5 m	3.4	3.7	40.8	44.4
supports (1)	2.0	0.4	16	3.2
1" ball valve, insulated	0.7	0.3	5.6	2.4
1" pipe, 1" insulation, 1.5 m	1.4	3.7	16.8	44.4

Item/Description	UA/L (kJ/h °C m)	Mc$_p$/L (kJ/°C m)	UA (kJ/h °C)	Mc$_p$ (kJ/°C)
Expansion loops (8) (North)*				
flex hose (2), 1.5 m	3.4	3.7	40.8	44.4
pipe supports (2)	2.0	0.4	16	3.2
1" pipe, 1" insulation, 3.0 m	1.4	3.7	16.8	44.4
			646	804

Pipe 3 (Outside, Collector Outlet)

Item/Description	UA/L (kJ/h °C m)	Mc$_p$/L (kJ/°C m)	UA (kJ/h °C)	Mc$_p$ (kJ/°C)
Outlet Riser (22) (South)				
flex hose, 1.5 m	3.4	3.7	112.2	122.1
supports (1)	2.0	0.4	44	8.8
1" ball valve, insulated	0.7	0.3	15.4	6.6
1" pipe, 1" insulation, 1.5 m	1.4	3.7	46.2	122.1
Expansion loops (22) (South)*				
flex hose (2), 1.5 m	3.4	3.7	112.2	122.1
plug/safety valve	1.4	0.4	15.4	4.4
pipe hangers (3)	2.0	0.5	66	16.5
1" pipe, 1" insulation, 5.3 m	1.4	3.7	81.6	215.7
Outlet Riser (8) (North)				
flex hose, 1.5 m	3.4	3.7	40.8	44.4
supports (1)	2.0	0.4	16	3.2
1" ball valve, insulated	0.7	0.3	5.6	2.4
1" pipe, 1" insulation, 1.5 m	1.4	3.7	16.8	44.4
Expansion loops (8) (North)*				
flex hose (2), 1.5 m	3.4	3.7	40.8	44.4
pipe supports (2)	2.0	0.4	16	3.2
1" pipe, 1" insulation, 3.0 m	1.4	3.7	16.8	44.4
			646	804

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°Cm)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Inside, Collector Outlet)				
Manifold (South)				
6" pipe, 2-1/2" insulation, 20.3 m	2.1	89.1	42.6	1809
pipe supports (3)	4.0	3.0	12	9
4" pipe, 2" insulation, 39.8 m	1.8	41.1	71.6	1636
pipe supports (2), anchors (1), guides (2)	3.0	2.0	15	10
3" pipe, 2" insulation, 20.3 m	1.5	24.9	30.5	505.5
pipe supports (1), anchors (1)	2.5	1.2	5	2.4
2" Pipe, 2" insulation, 12.2 m	1.2	11.8	14.6	144
pipe supports (2)	1.8	0.8	3.6	1.6
Outlet Riser (22) (South)				
1" pipe, 1" insulation, 6.1 m	1.2	3.7	161	496.5
pipe support (1)	1.5	0.5	33	11
Return Piping (South)				
6" pipe, 2-1/2" insulation, 6 m	2.1	89.1	12.6	534.6
strainer, drain valve	6	8	6	8
Manifold (North)				
3" pipe, 2" insulation, 16.2 m	1.5	24.9	24.3	403.4
pipe supports (2), anchors (1)	2.5	1.2	7.5	3.6
2" pipe, 2" insulation, 12.2 m	1.2	11.8	14.6	144
pipe supports (2)	1.8	0.8	3.6	1.6
Return Piping (North)				
4" pipe, 2" insulation,	1.8	41.1	10.8	246.6
strainer, drain valve	4	5	4	5
Outlet Riser (8) (North)				
1" pipe, 1" insulation, 6.1 m	1.2	3.7	58.6	180.6
pipe supports (1)	1.5	0.5	12.0	4

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Inside, Collector Outlet) (cont'd)				
Expansion loops (8) (North)*				
1" pipe, 1" insulation, 12.8 m	1.2	3.7	61.4	189.4
drain valve	4	8	16	32
			620	6378
Receiver, 1-1/2" Pipe, 2196 m	-	3.48	-	7643

D-2. Dow Chemical

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Outside, Collector Outlet/Manifold)				
Risers (15)				
3/4" flex hose, 1" insulation, 1.5 m	2.5	1.6	56.3	36
1-1/2" pipe, 0.46 m	10.8	4.4	74.5	30.4
1" pipe, 1-1/2" insulation, 1.35 m	1.6	3	32.4	60.8
1" gate valve	4	1	60	15
pipe support (1)	1	0.2	15	3
Manifold				
2" pipe, 2-1/2" insulation, 78 m	1.72	9.3	134.2	725.4
pipe supports (20)	2.9	4	87	120
			459	991
Pipe 2 (Outside, Field to Boiler)				
2" pipe, 2-1/2" insulation, 62.5 m	1.72	9.3	107.5	581.3
pipe supports (18)	2.9	4	52.2	72
			160	653
Pipe 3 (Outside, Boiler to Field)				
2" pipe, 2-1/2" insulation, 114 m	1.72	9.3	196.1	1060.2
pipe supports (30)	2.9	4	87	120
gate valve, insulated body (5)	7.6	1.9	38	9.5
pump (1)	32.4	37.6	32.4	37.6
instrumentation (1)	10	2	10	2
1" vent valve (2)	7	1	14	2
orifice flange	4	0.2	4	0.2
			382	1232

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Outside, Collector Inlet/Manifold)				
Risers (15)				
3/4" flex hose, 1" insulation, 1.5 m	2.5	1.6	56.3	36
1-1/2" pipe, 0.46 m	10.8	4.4	74.5	30.4
1" pipe, 1-1/2" insulation, 1.35 m	1.6	3	32.4	60.8
1" gate valve, insulated body	4	1	60	15
1/2" vent valve	5	1	75	15
safety valve	2	1	30	15
pipe support	1	0.2	15	3
Manifold				
2" pipe, 2-1/2" insulation, 78 m	1.72	9.3	134.2	725
pipe supports (20)	2.9	4	87	120
			564	1020
Receiver, 1-1/2" pipe, 366 m	-	3.72	-	1362

D-3. Home Laundry

Item/Description	UA/L (kJ/h ^oC m)	Mc_p/L (kJ/^oC m)	UA (kJ/h ^oC)	Mc_p (kJ/^oC)
Pipe 1 (Outside, Collector Outlet)				
flex hoses (58), 0.51 m	.75	2	22.1	59
pipe anchors (43)	1	0.2	43	21.5
2" pipe, 2" insulation, 101.3 m	1.31	7.8	132.8	790.1
2" globe valves (2), insulated	1.6	1	3.2	2
1/2" valve (1), insulated	0.5	0.3	0.5	0.3
safety valve (1)	10.0	1	10	1
			222	874
Pipe 2 (Inside, Collector Outlet)				
2" pipe, 2" insulation, 60.4 m	1.31	7.8	79.1	471.1
pipe anchors (4)	1	0.2	4	0.8
2" globe valves (5), insulated	1.6	1	8	5
control valves (3), insulated	4	1	12	3
instrumentation (7)	0.5	0.2	3.5	1.4
			107	481
Pipe 3 (Inside, Collector Inlet)				
2" pipe, 2" insulation, 23.4 m	1.31	7.8	30.7	182.5
3/4" pipe, 2" insulation, 3.0 m	.75	1.5	2.3	4.5
pump, insulated	19.4	38	19.4	38
anchors (6)	1	0.2	6	1.2
2" valves, insulated (2)	1.6	1	3.2	2
control valve (1), insulated	4	1	4	1
instrumentation (5)	0.5	0.2	2.5	1
			68	230

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Outside, Collector Inlet)				
2" pipe, 2" insulation, 209.4 m	1.31	7.8	274.3	1633.3
anchors (64)	1	0.2	64	32
flex hoses (58), 0.51 m	0.75	2	22.1	59
2" globe valve (2), insulated	1.6	1	3.2	2
1/2" valve (1), insulated	0.5	0.3	0.5	0.3
safety valve (1)	10	1	10	1
			374	1728
Receiver, 3/4" pipe, 1106.4 m	-	0.61	-	672.8

D-4. Lone Star Brewery

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Outside, Collector Outlet)				
Manifold				
2" pipe, 2" fiberglass, 40.3 m	1.31	7.1	53	286.1
anchors (2), guides (2)	2.9	0.4	11.6	1.6
1-1/2" pipe, 2" insulation, 18.7 m	1.14	4.8	10	41.7
1-1/4" pipe, 2" insulation, 13 m	1.06	3.8	13.8	49.6
guides (2)	2.2	0.3	4.4	0.6
1" pipe, 2" insulation, 8.7 m	0.93	2.6	8.1	22.5
anchors (1)	2.0	0.3	2	0.3
pipe supports (8)	2.0	0.5	16	4
Risers (15)				
flex hose, 1.2 m	3.4	2.6	61.2	46.8
1" pipe, 2" insulation, 1.8 m	0.93	2.6	25.1	70.2
1" ball valve, insulated (1)	0.64	0.3	9.6	4.5
thermowell, 1/4" vent valve	0.5	0.2	7.5	3
			222	531
Pipe 2 (Inside, Collector Outlet)				
2" pipe, 2" insulation, 33.5 m	1.2	7.1	40.2	238
2" gate valves (3)	1.6	1	4.8	3
check valve	2	2	2	2
flow meter/flanges	10.6	1	10.6	1
			58	244
Pipe 3 (Inside, Collector Inlet)				
2" pipe, 2" insulation, 39.6 m	1.2	7.1	47.5	282
control valve	12	4	12	4
2" gate valves, insulated (5)	1.	1	8	5
flow meter, insulated	3.2	1	3.2	1
pump, insulated	2	2	2	2
			92	332

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Outside, Collector Inlet)				
Manifold				
2" pipe, 2" insulation, 40.3 m	1.31	7.1	53	286.1
anchors (2), guides (2)	2.9	0.4	11.6	1.6
1-1/2" pipe, 2" insulation, 18.7 m	1.14	4.8	10	41.7
1-1/4" pipe, 2" insulation, 13 m	1.06	3.8	13.8	49.6
guides (2)	2.2	0.3	4.4	0.6
1" pipe, 2" insulation, 8.7 m	0.93	2.6	8.1	22.5
anchors (1)	2.0	0.3	2	0.3
pipe supports (8)	2.0	0.5	16	4
Risers (15)				
flex hose, 1.2 m	3.4	2.6	61.2	46.8
1" pipe, 2" insulation, 1.8 m	0.93	2.6	25.1	70.2
1" ball valve, insulated (1)	0.64	0.3	9.6	4.5
			215	528
Receiver, 1-5/8" pipe, 411.5 m	-	3.4	-	1400

D-5. Ore-Ida Foods

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Outside, Collector Outlet)				
Manifold/Piping				
2-1/2" S80 pipe, 2" insulation, 238 m	1.7	15.5	405	3689
pipe supports (65)	4.8	0.5	312	32.5
Risers (14)				
1-1/4" S80 pipe, 1-1/2" insulation, 0.75 m	1.1	5.3	11.9	46.2
flex hose, 1.4 m	1.2	3.3	23.5	64.5
3/4" valve	5.7	0.3	79.8	5.2
3/4" drain valve	5.7	0.3	79.8	5.2
supports	1	-	14	-
3/4" S80 pipe, 1-1/2" insulation	0.85	7.3	11.9	46.2
			938	3899
Pipe 2 (Inside, Collector Outlet)				
2-1/2" S80 pipe, 2" insulation, 41 m	1.4	15.5	57.4	635.5
check valve, insulated	2	2	2	2
Orifice flange	4	1	4	1
gate valve (3)	6	2	18	6
instrumentation	6	1	6	1
flash valve (1)	4	2	4	2
pipe supports (11)	3.5	0.5	38.5	5.5
			130	653
Pipe 3 (Inside, Collector Inlet)				
2-1/2" S80 pipe, 2" insulation, 46 m	1.4	15.5	64.4	713
pump	25	20	25	20
pipe supports (12)	3.5	0.5	42	6
gate valve (3)	6	2	18	6
strainer (1), insulated	2	2	2	2
gate valve (4), insulated	1.8	2	7.2	8
bellows, 0.5 m	15	16	7.5	8
			166	763

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Outside, Collector Inlet)				
Manifold/Piping				
2-1/2" S80 pipe, 2" insulation, 203 m	1.7	15.5	345.1	3146.5
pipe supports (56)	4.8	0.5	268.8	28
Risers (4)				
1-1/4" S80 pipe, 1-1/2" insulation, 0.75 m	1.1	5.3	11.6	55.7
3/4" S80 pipe, 1-1/2" insulation, 1 m	0.85	3.3	11.9	46.2
flex hose, 1.4 m	1.2	3.3	23.5	64.5
3/4" valve	5.7	0.3	79.8	5.2
3/4" drain valve	5.7	0.3	79.8	5.2
supports	1	-	14	-
			835	3352
Receiver, 1-1/4" S80 pipe, 341 m	-	4.17	-	1420.3

D-6. Southern Union Refining

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Outside, Collector Outlet)				
Manifold/Field Piping				
3" pipe, 4" insulation, 18.3 m	1.09	15.6	19.9	285.5
anchors (2), supports (4), guides (1)	2.9	0.4	20.3	2.8
2" pipe, 3-1/2" insulation, 27.4 m	0.95	8	25.9	219
anchors (2), supports (8), guides (2)	2.9	0.4	34.8	4.8
Risers (6)				
1" pipe, 2" insulation, 1.1 m	0.93	2.5	6.1	16.5
flex hose, 1.3 m	3.4	2.5	26.7	19.5
1" gate valve, insulated	1.3	0.3	7.8	1.8
support	2	0.2	12	1.2
safety valve and instrumentation	1.3	0.3	7.8	1.8
Expansion loop (6)				
flex hose, 1.3 m	3.4	2.5	26.7	19.5
			188	572
Pipe 2 (Inside, Collector Outlet)				
3" pipe, 3" insulation, 9.1 m	1.2	15	11.1	136
3" check, insulated	6	10.5	6	10.5
thermowells (2)	1.5	-	3	-
3" gate valve, insulated	8	13.3	8	13.3
			28	160
Pipe 3 (Inside, Collector Inlet)				
3" pipe, 3" insulation, 22.9 m	1.2	15	27.4	342.9
control valve	12	4	12	4
3" gate valve (6), insulated	8	13.3	48	79.8
strainer, insulated	6	10.5	6	10.5
pump/safety valve	20	38	20	38
expansion tank piping	-	-	29	173
			142	648

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Outside, Collector Inlet)				
Manifold/Field Piping				
3" pipe, 4" insulation, 94.5 m	1.09	15.6	103.4	1472
pipe supports (22), guides (2)	2.9	0.4	69.6	9.6
anchors (2)	2.9	0.4	8.7	1.2
2" pipe, 3-1/2" insulation, 27.4 m	0.95	8	25.9	219
pipe supports (8), guides (2), anchors (2)	2.9	0.4	34.8	4.8
2" drain valve	11.4	1	11.4	1
Risers (6)				
1" pipe, 2" insulation, 2 m	0.93	2.5	31.1	30
flex hose, 1.3 m	3.4	2.5	26.7	19.5
1" gate valve, insulated	1.3	0.3	7.8	1.8
support	1.3	0.2	12	1.2
Expansion loop (6)				
flex hose, 1.3 m	3.4	2.5	26.7	19.5
			358	1780
Receiver, 1-1/2" pipe, 439.9 m	-	3.4	-	1493

D-7. USS Chemicals

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°Cm)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 1 (Outside, Collector Outlet)				
6" pipe, insulated, 92.2 m	2.05	13.0	189	1199
4" pipe, insulated, 43.4 m	1.59	7.4	69	320
3" pipe, insulated, 15.3 m	1.37	5.3	21	81
2-1/2" pipe, insulated, 9.0 m	1.22	4.3	12	39
flex hoses (60), 1.4 m	3.4	-	282	-
1-1/2" piping, 2" insulation, 116 m	1.4	-	167	-
safety valve (20), insulated	6.5	2.0	130	39.6
1-1/2" drain valves, insulated (41)	1.1	2.0	45	81
anchors (3)	1.9	0.6	6	1.8
fluid volume, 2149 kg	-	2.08 kJ/kg °C	-	4471
insulation, 1498 kg	-	0.84 kJ/kg °C	-	626
			921	6859
Pipe 2 (Inside, Collector Outlet)				
6" pipe, insulated, 0.6 m	2.05	13.0	1.2	7.9
4" pipe, insulated, 3.8 m	1.59	7.4	6.1	28.2
6" valves (2), insulated	3.1	10.5	6.2	20.9
instrumentation	3	-	3	-
fluid volume, 38 kg	-	2.08 kJ/kg °C	-	79
insulation, 19 kg	-	0.84 kJ/kg °C	-	16
			17	152
Pipe 3 (Inside, Collector Inlet)				
6" pipe, insulated, 15 m	2.05	13.0	31	191.5
4" pipe, insulated, 6.2 m	1.59	7.4	10	45.7
expansion tank	5	-	5	-
air separator, 1.4 m	3.6	-	5.1	53.6
control valve (1), insulated	6	5.6	6	5.6
4" valves (2), insulated	2	5.6	4	11.2
6" valves (2), insulated	3	10.4	6	20.9
2" valves (2), insulated	1.5	-	3	-
instrumentation	2	-	2	-
fluid volume, 618 kg	-	2.08 kJ/kg °C	-	1285
insulation, 97 kg	-	0.84 KJ/kg °C	-	81.3
			72	1696

Item/Description	UA/L (kJ/h °C m)	Mc_p/L (kJ/°C m)	UA (kJ/h °C)	Mc_p (kJ/°C)
Pipe 4 (Outside, Collector Inlet)				
6" pipe, insulated, 243 m	2.05	13.0	498	3163
4" pipe, insulated, 48 m	1.59	7.4	76	356
3" pipe, insulated, 18 m	1.37	5.3	25	95
2-1/2" pipe, insulated, 6.5 m	1.22	4.3	8	25
flex hoses (60), 1.4 m	3.4	-	282	-
1-1/2" piping, 2" insulation, 110 m	1.4	-	158	-
1-1/2" valves, insulated (41)	1.4	2.0	45	81
anchors (3)	1.9	0.6	6	1.8
pumps (2), insulated, cooled	58	-	104	-
4" valves (4), insulated	1.8	5.5	7	22
1/4" valves (6)	0.5	-	3	-
fluid volume, 4495 kg	-	2.08 kJ/kg °C	-	9350
insulation, 1548 kg	-	0.84 kJ/kg °C	-	130
			1212	14394
Receiver, 1-1/2" pipe, 2274 m	-	2.88	-	6551

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16. Abstract (Limit: 200 words)

The Solar Energy Research Institute (SERI) has modeled seven of the Department of Energy (DOE) sponsored solar Industrial Process Heat (IPH) field experiments and has generated thermal performance predictions for each project. Additionally, these performance predictions have been compared with actual performance measurements taken at the projects. Predictions were generated using SOLIPH, an hour-by-hour computer code with the capability for modeling many types of solar IPH components and system configurations. Comparisons of reported and predicted performance resulted in good agreement when the field test reliability and availability was high. Volume I contains the main body of the work: objective model description, site configurations, model results, data comparisons, and summary. Volume II contains complete performance prediction results (tabular and graphic output) and computer program listings.

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