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End-Use Matching for Solar Industrial Process Heat

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Shirley A. Stadjuhar
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Golden Colorado 80401

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FOREWORD

Assistance in analysis and preparation of this report was provided by many members of the SERI staff. The authors wish to acknowledge with appreciation the contributions of: Solar Thermal Conversion Branch--Frank Kreith (Branch Chief), David Kearney, Chuck Benham, Jim Castle, Paul Bendt, and Bimleshwar Gupta; Systems Analysis Branch--Carl Bingham; Energy Resource Assessment Branch--Roland Hulstrom; Economic Analysis Branch--Sam Flaim and Susan Christmas. Particular recognition should be given to Frank Kreith, whose ideas on energy utilization and the Second Law led to the original concept of end-use matching. Gerard F. Lameiro of Colorado State University is recognized for his contributions to the initial framework and direction of this study. The authors are also grateful to the Agricultural and Industrial Process Heat Branch of the Office of Solar Applications (Department of Energy) for the support that made this project possible.

David W. Kearney
Program Leader

Frank Kreith
Branch Chief
Solar Thermal Conversion Branch

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

K. J. Touryan
Assistant Director for Research

SUMMARY

The particular requirements and energy use patterns of end-use demand sectors are receiving increasing attention. The industrial sector, which annually consumes 37% of the nation's gross energy demand and upon whose vitality much of the U.S. economy must rely, is of special interest. A large portion of the industrial energy demand is for thermal energy for use in the processing of goods, known in general terms as industrial process heat (IPH). This heat is utilized at temperatures from 140 F to over 3000 F in thousands of manufacturing processes. Over one-quarter of the total industrial process heat requirements are at temperatures below 550 F; thus, a significant fraction of industrial processes are potential near-term applications of solar thermal technology.

An advantage of solar thermal technology is the capability to control output temperatures over a fairly broad range. Solar thermal process heat systems can be designed with specific end uses in mind and therefore efficiency of energy conversion can be maximized with respect to the Second Law of Thermodynamics. Second Law optimization is currently of little economic advantage but is directly related to the effectiveness with which our nation's limited energy supplies are used.

In order to identify the proper matches of solar collector technology and industrial process needs, various combinations of collectors, processes, and locations are evaluated using the method of "end-use matching." Information on the nature and location of processes is obtained and various solar collector options are tested against load requirements in order to determine which systems will deliver the required energy at the lowest cost. The solar systems are designed to operate as closely to process-required temperatures as possible so that wasted energy is minimized. Finally, viable near-term solar applications are identified by comparison of solar system costs with local fuel costs.

Performance and cost evaluation codes and attendant data bases were developed for the end-use matching. Data for industrial process requirements and plant locations, meteorological conditions, solar equipment, and economic factors are assembled in data bases that may be accessed from the performance code PROSYS and the cost and economic evaluation code ECONMAT. PROSYS is based upon a long-term average performance methodology developed by Collares-Pereira and Rabl. With this code, collector performance in specified operating conditions can be rapidly determined. The rapidity of the calculation allows an exhaustive search of all feasible collector/system/process combinations. The evaluation code ECONMAT uses site- and industry-specific economic factors to determine energy costs for various system sizes. Minimum-cost combinations can then be selected. ECONMAT may also be used in sensitivity studies and in evaluations of the distribution and ranking of application costs in given locations.

The concept and methods of end-use matching were tested in a study of industrial processes in six U.S. cities: Fresno, Calif.; Denver, Colo.; El Paso, Tex.; Bismarck, N.D.; Brownsville, Tex.; and Charleston, S.C. The results indicate the near-term importance of low-temperature industrial processes and

the advantage of southwestern locations for delivering solar energy at low costs. As expected, some collectors have advantages over others in the various operating temperature ranges, but this segmentation of the temperature scale varies significantly with location. This study found relatively few competitive applications for solar industrial process heat in the six cities given the current state of solar technology and current fossil fuel costs. However, other applications will become competitive as fuel costs increase and solar technology improves.

To evaluate the effectiveness of the end-use matching methodology, case studies of two industries were performed. The case studies indicate that more accurate and complete data on industrial processes are needed in order to achieve reliable results with end-use matching. PROSYS and ECONMAT were shown to be effective in performing detailed studies of applications for solar industrial process heat. The case studies offer a wealth of information and improved understanding of the industrial market. For example, industry will undoubtedly view its options for energy supply from the broadest possible perspective; solar energy utilization is only a part of this perspective. In these two case studies several options became apparent for energy conservation that could be adopted at little cost and offer significant energy savings (for example, 42% of the energy in one process could be saved by simply turning off a switch at night). It is important that solar applications be designed for processes in which conservation measures have already been incorporated; such measures may often dramatically affect the design of the solar systems. The results of the case studies point out the usefulness of solar energy in preheating, particularly when preheated fluids (such as boiler feedwater) can be circulated directly in the collector field. Results also point to the importance of low-temperature hot air applications in industry and to the advantages of displacing expensive or poorly utilized fuels with solar energy.

The success of the end-use matching methodology as a valuable tool in assessing the worth of solar industrial process heat applications encourages expansion of this effort. Future emphasis will be placed on improvement of the PROSYS and ECONMAT routines and on utilization of these codes in studies of particular industries for which detailed process characterizations can be obtained. With improved input data, PROSYS/ECONMAT can offer valuable service in planning and evaluation in the increasingly important area of solar process heat.

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SECTION 1.0

INTRODUCTION

Energy is universally acknowledged to be the mainstay of an industrial society. Without an adequate supply of energy the social, economic, and political structures of the society are in jeopardy. As the world's supply of inexpensive but nonrenewable fossil energy sources decreases, the need for developing alternative energy sources and conserving existing supplies becomes critical.

The energy crisis in the United States today results from the divergence between America's historically increasing energy demand and its decreasing supplies of oil and gas. At this point it is believed that no single energy source will replace oil and gas in the near future. Solar energy is the only renewable resource available on a large scale, but the country must prepare for a period in which many different energy sources will be used and each one is selected for its most appropriate application.

In the current transition it is expected that scientific and technological innovations will motivate the development of conservation measures and renewable energy sources. However, in view of the fact that the current transition is not towards a single plentiful source but rather towards a combination of several different energy sources, the suitability of each of these sources for a given task must be determined. In this selection process, energy conservation will play the same role as an energy source; in many cases the most logical alternative to a solar technology will be a conservation measure.

The choice among available energy sources for a given task will require technical and economic trade-offs on the part of the individual investor. From the national perspective, however, the effectiveness with which a given energy source is utilized may well become an overriding consideration. Since the energy supply will be limited in the future, it will become increasingly important to achieve the highest possible energy conversion efficiency and to minimize energy waste. It is with this outlook that the following report addresses the development of a methodology to determine the most appropriate industrial process heat applications for solar thermal energy in the near term.

1.1 INDUSTRIAL ENERGY USE IN THE UNITED STATES

A number of studies have investigated the division of energy demand among the three major end-use sectors of the economy: residences and commercial establishments, transportation, and industry. The industrial sector is the largest consumer of energy in the United States. In 1977, it accounted for nearly 37% of U.S. energy consumption (U.S. Department of Energy 1978) as shown in Fig. 1-1. In contrast, combined residential and commercial consumption was approximately 37% of the total while transportation accounted for 26% of U.S. consumption. Energy demand in the United States during 1977 totaled 80×10^{18} joules (75.8 quads). Thus, it is apparent that industrial applications represent an enormous potential for solar technology.

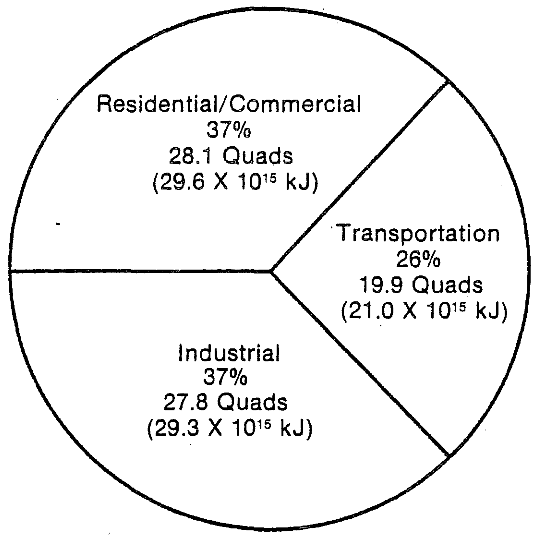

Figure 1-1. Approximate Distribution of 1977 U.S. Energy Consumption by End-Use Sector

Energy for consumption by industry is supplied from a wide variety of sources. Currently, energy is supplied to industry via natural gas (29.8%), distillate and residual oil (24.9%), coal (12.9%), and electricity (32.4%). Certain sources of renewable energy are also utilized as industrial fuels but are small percentages of the total. (Most notably, the paper and pulp industry in the United States supplies approximately 40% of its demand through the use of wood byproducts.)

Energy consumed by industry is used in a number of ways. These uses can be grouped into four major categories: process heat, electrical/mechanical power, electric process energy, and feedstocks. The distribution of energy consumption* among these categories, as given in Table 1-1, is subject to some uncertainty, even on an aggregate basis. It is equally important to identify energy usage within particular industrial sectors. Figure 1-2(a) shows the

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*These consumption figures also include energy wasted in all steps of industrial production, as well as energy wasted or lost in the production and transmission of electrical power from utilities. In addition, the figures include equivalent energy used in the form of chemical, refining, and metal processing feedstocks, such as petroleum and coke. A fifth category--building space heating, cooling, lighting, and domestic service energy--might also be added. However, data on energy demand for these auxiliary uses are not readily available at this time.

distribution of industrial energy consumption for the six largest energy consumers by major SIC (Standard Industrial Code) categories. These six industrial groups collectively account for approximately 80% of the total U.S. industrial energy demand.

Table 1-1. INDUSTRIAL ENERGY USE BY FUNCTIONAL REQUIREMENT[a]

	Percentage of 1968 Industrial Energy Use[b]
Process heat-total	68.4
(Process steam)	(40.6)
(Direct heat)	(27.8)
Electrical/mechanical power	19.2
Electrical process energy	2.8
Feedstocks	8.8
Unaccounted energy	0.8

[a]From SRI 1972.
[b]Total 1968 energy use = 25 quads.

Process heat is defined to be the thermal energy used directly in the preparation and/or treatment of goods produced by manufacturing processes (normally associated with industrial goods produced by SIC categories 20 through 39). It is clear from Table 1-1 that process heat requirements constitute the largest use of current industrial energy consumption. This energy can be supplied either by means of a heat transport fluid or by direct heating. In practice, heat is most often supplied via hot water, low-pressure steam, or hot air. While recent evidence suggests that furnaces and direct-heat devices are responsible for nearly 60% of process heat consumption, there continues to be a substantial requirement for indirect heating by steam and hot water at more moderate temperatures (Hamel and Brown 1976). Figure 1-2(b) shows the distribution by major SIC group of process heat consumption. Figure 1-3 shows a more detailed breakdown of process heat energy requirements for the total U.S. market.

1.2 SOLAR POTENTIAL FOR INDUSTRIAL PROCESS HEAT

The technical and economic feasibility of supplying industrial process heat (IPH) from a solar collector to a specified task depends on four factors. First, there must be an adequate quantity of heat. Heat quantity can be calculated from the first law of thermodynamics and depends on available land area and the climate. Second, the heat must be of adequate quality for the purpose. Heat quality from solar equipment depends mainly on the type of collector. For example, heat available from a flat-plate collector at 200 F

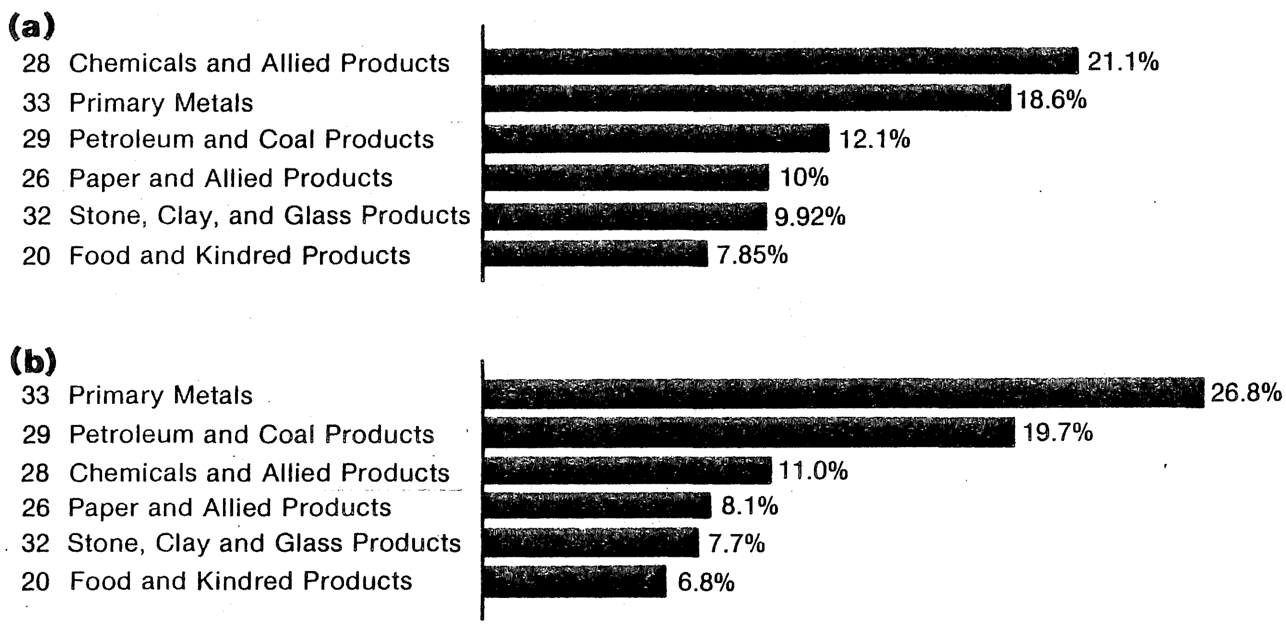
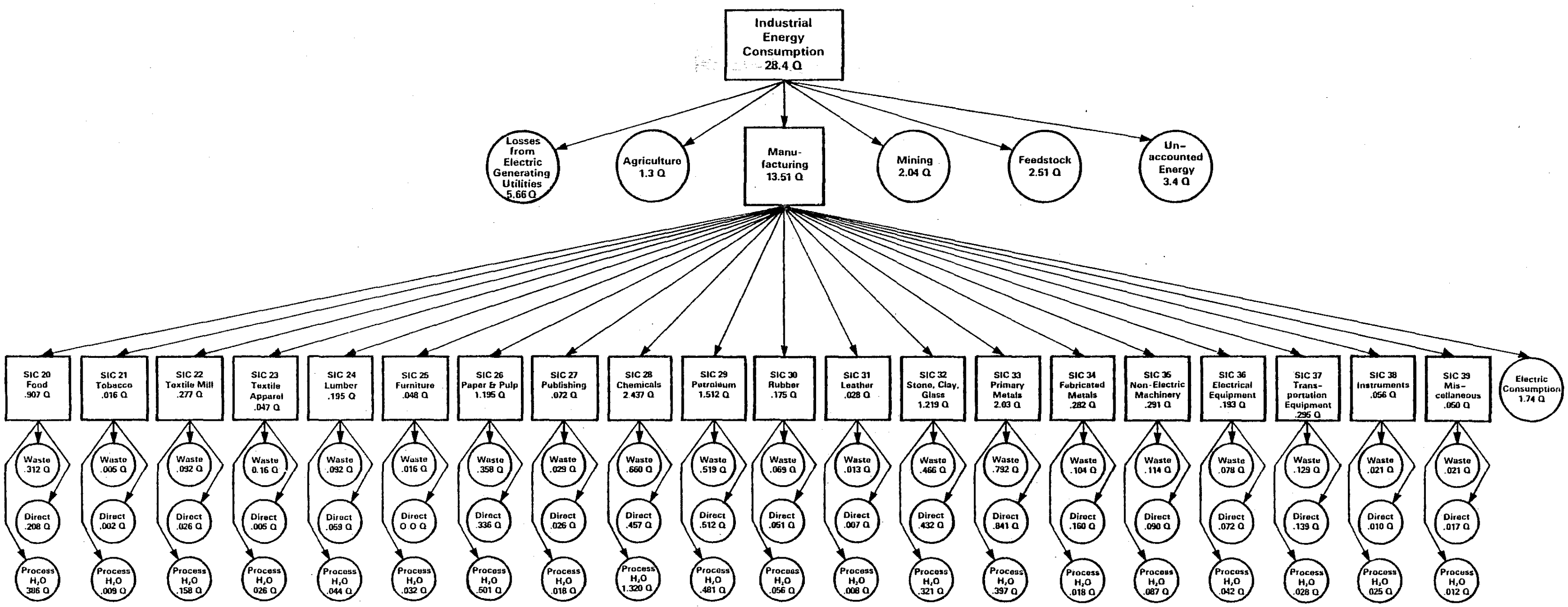


Figure 1-2. Approximate Distributions of (a) Industrial Energy Consumption and (b) Process Heat Consumption Among the Six Largest Energy-Consuming Industries



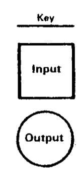
Total Manufacturing Energy Wasted	=	3.906 Q
Total Manufacturing Energy Requirement for Direct Heat	=	3.450 Q
Total Manufacturing Energy Requirement for Process Hot Water and Steam	=	3.969 Q
		11.325 Q

Details may not add to totals due to independent rounding.

Data for Agriculture, Mining, Feedstock, Electric Generating Losses, and Unaccounted Energy from Planning Research Corp./Energy Analysis Co. from meeting at D.O.E. (report to be released soon).

Data for individual SIC's are from *Survey of Manufacturers*, U.S. Bureau of the Census, 1972. *Fuels and Electric Energy Consumed* – Special Report, July, 1973.

Percentages for the breakdown of individual SIC energy consumption into waste, direct heat, and process hot water and steam were taken from *Industrial Waste Energy Data Base/Technology Evaluation*, Drexel University, December, 1976, CONS/2862-1.



Q = 10^{15} Btu/year

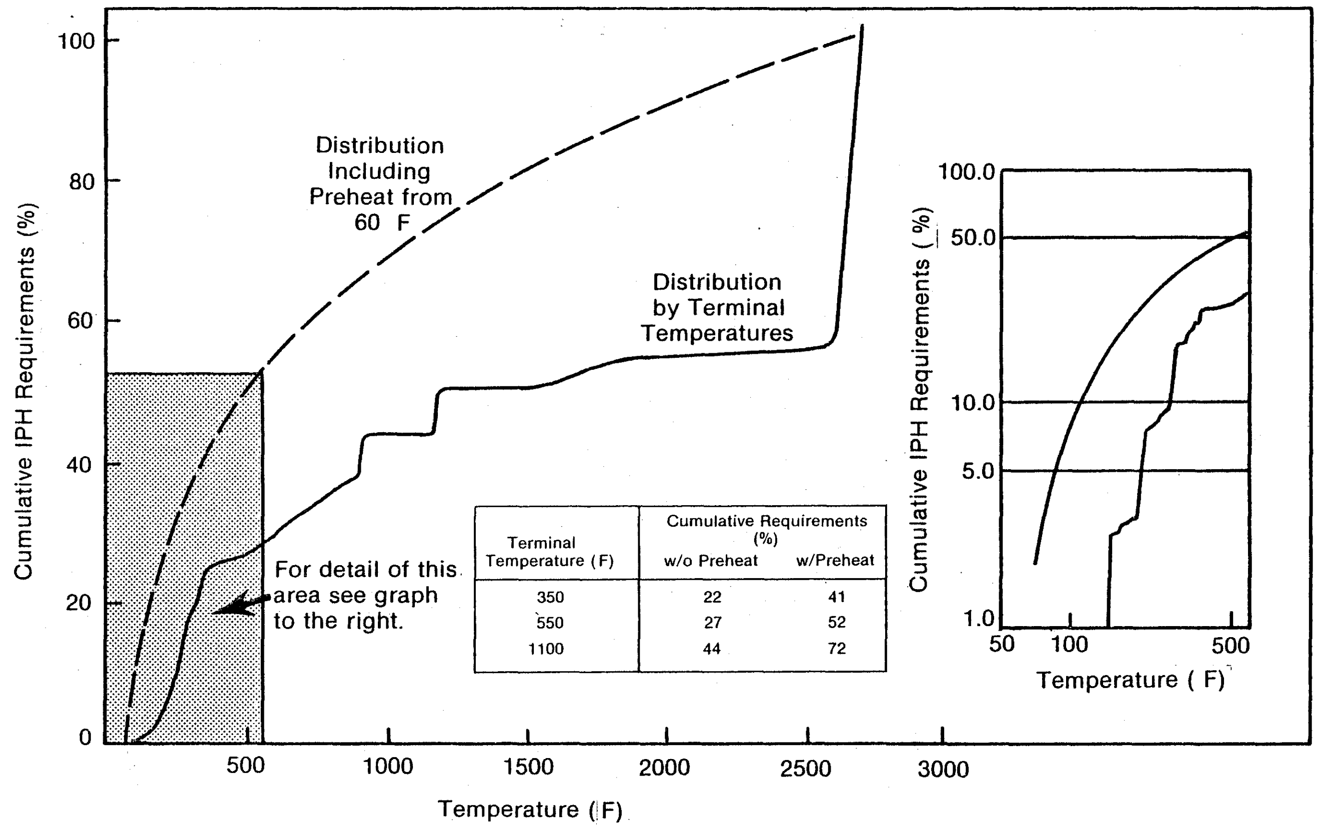
Compiled by Harry W. Gaul

Figure 1-3. 1972 Industrial Energy Consumption by Major Industry Groups
(Standard Industrial Classification (SIC) 2-digit groups)

cannot be used directly to heat steam to 250 F. Problems of heat quality and availability are treated by means of the second law of thermodynamics. Third, the heat must be transferred from the collector to the working fluid passing through the collector and, unless the task is to heat this fluid, heat must then be transferred from the fluid stream to the process or material where it is to be used. This is ordinarily a problem in heat transfer, but because of the peculiar characteristics of solar energy conversion equipment this step may also require a reexamination of the process requirements in order to optimize the availability of solar energy. Finally, the solar energy must be used profitably; this is a question of economics.

A study by the InterTechnology Corporation (Fraser 1977) describes the distribution of the total U.S. process heat requirements as a function of the temperature at which the energy is used. The results are summarized in Fig. 1-4. According to this study, at least 28% of industrial process heat is required at supply temperatures below 415 C (550 F), a temperature level that can be supplied by currently available line-focusing concentrating solar collectors. Half of industrial process heat requirements are for end-use temperatures below 1100 F. The technical viability of both distributed and central solar thermal collectors at these temperatures has been demonstrated. It may be concluded that solar thermal systems are potentially applicable to a substantial fraction of industrial process needs and that the fraction potentially amenable to currently available solar equipment is significant. The fraction that may be amenable in the future (50%) comprises a market larger than the total thermal consumption of the entire residential sector.

Two aggregate market studies were carried out to quantify the potential of solar industrial process heat (Fraser 1977; Hall 1977). In addition, solar industrial process heat was included in the more general market studies performed by Mitre Corporation (Rebibo et al. 1977), Stanford Research Institute International (1978), and the U.S. Energy and Research Development Administration (1977). The industrial process heat market was characterized where possible by industry, region, and temperature level. Solar system technology options were reviewed, analyzed, and then represented in the penetration modeling by generic systems operating in regionally "typical" climates. Therefore, the studies yielded aggregate potential markets by time and region that may be summed to indicate some future estimate of solar energy displacement impact. The results of these studies vary, depending not only on the typical costs and performances assumed for future solar industrial process heat systems, but also on assumed future costs of competitive fuels, incremental demand, and the strategies of market penetration. InterTechnology Corporation (Fraser 1977) estimated a market potential of 7.27 quads in 2000 with unconstrained market penetration; Mitre Corporation (Rebibo et al. 1977) estimated a market of 10 quads in 2020 under their "Recent Trends Scenario," and Stanford Research International (1978) estimated only 0.1 quad in 2020. By comparison, recent memoranda from the Domestic Policy Review committees cited an expected solar process heat impact of 0.2 to 1.4 quads in 2000 and a possible maximum potential of 2.0 quads. On a lesser scale, some field surveys have been carried out to examine the solar potential in selected industries and plants (see, for example, Jet Propulsion Laboratory 1978, Casamajor and Wood 1978).



Terminal Temperature (F)	Cumulative Requirements (%) w/o Preheat	Cumulative Requirements (%) w/Preheat
350	22	41
550	27	52
1100	44	72

Figure 1-4. Temperature Spectrum of Industrial Process Heat and Preheat Requirements
(From Fraser 1977; revised by Edelstein et al., PRC)

1.3 END-USE MATCHING

The aggregate industrial process heat market studies used SIC code data as a means of determining the required quality and quantity of energy. In contrast to the SIC code approach is the individual industrial case study that considers the details of a given process application. A compromise in the level of scope and detail between these two kinds of assessment studies is the goal of the "end-use matching" approach. This type of applications analysis refines the understanding of issues identified in the market studies while directing the emphasis and selection of case studies for more detailed analysis. In developing this methodology, a primary task is to determine the minimum degree of specificity required to obtain a reasonable accuracy for making predictions of the suitability of solar energy for various applications.

End-use matching takes into account the important factors affecting the applicability of solar thermal energy to generic industrial processes: namely, process energy needs, solar collector technology, geographic location, and economics. The result of the end-use matching procedure is an identification of the most cost-effective combinations of currently available solar system hardware and particular industrial processes within a given location. End-use matching is not intended to be a design tool for a specific plant, but rather a planning tool for determining where and for what general applications solar systems would seem to appear economically viable in the near- to intermediate-term. Consequently, it is important to recognize that end-use matching is not a system optimization procedure since it deals only with generic systems and because system optimization requires a closer look at given load and resource characteristics than undertaken here. Hence, the research objective is the development of a concept and a degree of detail that will allow for appropriate planning decisions and provide for comparisons among different applications and locations. It is too much to expect that end-use matching can analyze industrial plants as single entities. For example, the food industry includes too many different processes to be treated as one aggregate solar application. On the other hand, it may be possible to approach all milk pasteurization applications as one generic process in which the economic viability of solar energy can be studied. Once the end-use matching process is developed and applied, individual case studies can serve as a means of calibration and confirmation of the more general end-use matching approach.

1.4 METHODOLOGY

In order to arrive at reliable conclusions, appropriate analytical tools as well as data bases with requisite breadth and accuracy are required. Two tools were developed for this study: (1) a long-term average performance predictor for solar process heat systems, and (2) an economic/matching code for life-cycle cost comparison and selection of combinations from (1). These tools provide a means of testing the sensitivity of these combinations to the variation of several input parameters.

After considering several possible alternatives for solar system performance simulation, the method devised by Collares-Pereira and Rabl (1977) was adopted and modified for application to process heat systems, resulting in the long-term average performance prediction program, PROSYS. The output of PROSYS is an annual delivered energy value based on the total solar collector aperture area of various systems. It should be emphasized that no energy storage is included in the PROSYS model. The model assumes that all of the heat delivered by the solar system can be used in supplying heat to the load at the specified temperature level, an assumption that limits the maximum size of solar systems that can be used for any given task. This maximum size varies among applications, but in no case can it exceed the minimum load required at any time of year. Consequently, no optimization relative to solar system size can be made with the PROSYS model. Instead, the output of PROSYS is reported at ten increments of size based upon the maximum annual load. These size increments yield information on size-related cost variations.

While PROSYS does not yield output data suitable for design purposes, it is sufficiently accurate in predicting long-term (>15 years) annual solar system performance to be useful for the purpose of end-use matching. The model is flexible with respect to collectors, system designs, and operating conditions, and it offers rapid execution time for large-scale applications analyses.

The economic/matching code (ECONMAT) is a means of selecting economically attractive combinations. In order to separate life-cycle economic analysis from performance and initial cost calculations, the large file of combinations generated in PROSYS is screened first to select the least energy capacity cost* [$/(GJ/yr) or $/(Btu/yr)] for each process and system configuration. The results are screened further to print only those records at each site where energy capacity cost is found to be below an established critical level. This screened information can then be used to locate trends showing that particular sites, process industries, or collectors have special potential for near-term application.

Using PROSYS and ECONMAT, the technique of end-use matching consists of synthesizing and evaluating each possible combination of site, industrial process, system configuration, solar collector, and incremental system size. The study described in this report was carried out for six sites, with an average of 100 process plants per site, 3 allowable system configurations for any process, 8 collectors, and 10 system size increments, resulting in approximately 144,000 combinations to be tested. Consequently, a cost-limited evaluation requires both that the codes be efficient and that they utilize minimal computer time.

Input data are critically important to end-use matching but often are very difficult to obtain. (In particular, the assembly of representative industrial process heat data for particular plant types has only recently been initiated in solar energy studies.) Data for this study were collected in four major categories: (1) industrial process heat requirements and characterization, (2) solar collector equipment specifications, (3) site-specific insolation and climatological requirements, and (4) site-specific economic characterization.

*Capacity cost is defined as the total initial capital investment required per unit of energy delivered annually, and so it is closely related to the much-used $\$/kW_e$ term in electric power studies.

1.5 STUDY OBJECTIVES AND ORGANIZATION OF THE REPORT

In summary, this study was designed to meet the following objectives:

- Provide an applications analysis, through an end-use matching approach, for solar industrial process heat in six U.S. cities, and thereby provide a level of detail intermediate between aggregate market studies and case studies;
- Determine, using this analysis, the following:
  - the most promising industries for the near-term application of solar process heat technology,
  - the most likely locations for such a near-term market, and
  - an indication of the most appropriate equipment and systems now available for solar process heat;
- Provide analytical tools for performance and economic comparison of feasible alternative combinations and illustrate the utility of such tools for applications selection, applications comparison, and sensitivity studies.

Section 2.0 of this report describes the data bases utilized for the end-use matching. Section 3.0 outlines the simulation model PROSYS, which was developed for use in assessing the performance of various solar industrial process heat systems. Section 4.0 describes a separate form of life-cycle cost economic analysis and, in an associated appendix, outlines ECONMAT, the integrated economic and matching routine. The economic and matching analysis evaluated technically feasible system/process/location combinations and provided an economic ranking. The basis of this selection and a summary of these results are discussed in Section 5.0. Certain selected sensitivity studies are also described in Section 5.0. Section 6.0 presents the results of two case studies of the potential industrial application of solar energy; these case studies were performed primarily as special tests of the validity of data and methods used in end-use matching. General conclusions about the methodology of end-use matching and the results of our assessments are discussed in Section 7.0. For completeness, appendices are included giving the details of the data base contents, the methodology for collector performance evaluation, a detailed description of the economic matching code, and technical observations associated with the case studies.

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SERI

SECTION 2.0

DATA BASES

The value of the end-use matching process depends on the extent and validity of the data bases for industrial processes, meteorology, collector performance, and economics. The collection and expansion of these data bases is a continuing effort; the matching process is particularly difficult in some areas due to lack of data and inadequate accuracy and completeness. Nevertheless, sufficient information was available for this study to arrive at supportable conclusions. Moreover, the process of establishing these data bases has provided valuable insight regarding the steps necessary to develop more complete and useful data for future studies.

The following subsections describe the input data used in this analysis, delineating the sources of information and the restrictions and limitations of each data base. More detail on the contents of data bases is included in the appendices.

2.1 INDUSTRIAL PROCESS HEAT DATA BASE (IPHDB)

In order to determine the most economic match between currently available solar technology and industrial process heat requirements, a large data base is required. All relevant technical information regarding the industrial processes must be included in the data base. IPH needs have been studied only recently as industrial energy conservation has become an important issue. Data on process conditions are often proprietary or unknown even to plant personnel. The Standard Industrial Classification (SIC) code identifies approximately 1,500 industrial processes, and this listing could be expanded to 200,000 processes by matching SIC codes to a large industrial plant locator data base, such as the U.S. Census of Manufacturers Data Base. Thus, the assembly of a complete IPHDB for all industrial processes and locations is a very large, time-consuming task. For this study, the objective was to collect IPH data in sufficient detail for the end-use matching described in this report and also to allow future refinements in the analysis (such as the inclusion of thermal storage).

Process heat data were collected for selected industries in six cities: Bismarck, North Dakota; Brownsville, Texas; Charleston, South Carolina; Denver, Colorado; El Paso, Texas; and Fresno, California. These cities were selected because they represent large variations in geographical location, in major types of industrial activity, and in the annual amount of solar insolation. The data collected for the IPHDB represent an initial effort to provide sufficient information for assessment of solar IPH potential in these six cities. The IPHDB will be updated and expanded by staff at the Solar Energy Research Institute (SERI) when possible.

2.1.1 Requirements and Structure of IPHDB

To determine a good thermal and economical match between IPH requirements and solar equipment, several items of information are required: the industry and process type as identified by Standard Industrial Classification (SIC) (U.S. Executive Office of the President 1972), energy sources and heat transfer fluids used in the process, temperature and pressure, heat rate, and operating schedule.

The information categories of the IPHDB are shown in Table 2-1. A complete set of information for a particular industry, as indicated in this table, enables sizing of a solar IPH system and determination of the resulting system cost. Certain solar IPH system characteristics have not been evaluated, such as thermal storage requirements; only the data denoted by asterisks in Table 2-1 were collected. A list of the codes used for the information collected is given in Table 2-2.

2.1.2 Sources of Information

In compiling information for the IPHDB, data assembled during previous studies of IPH requirements was used in order to avoid unnecessary duplication and to best use existing resources. The first step in the data collection process was to determine which industries were present in each of the six cities and to classify each industry according to a four-digit SIC code. Table 2-3 lists all industries for which data were collected in the six cities. State Manufacturer's Directories were used to compile this information.*

Next, several sources were consulted to determine the IPH requirements listed in Table 2-2 for as many industries as possible in each city.** The IPH information, which was usually given as annual energy use for the total industry, was revised to indicate IPH requirements for an average-sized plant by normalizing the total annual energy use by the number of plants in the industry. To use the IPHDB, a SIC code for an industry located in a particular city is chosen from Table 2-3; the corresponding IPH data for an average-sized plant of that industry is then obtained from the IPHDB.

Therefore, when the systems code (PROSYS) is run with data from the IPHDB for a particular industry in a particular city, the results are indicative of a hypothetical, average-sized plant in that city, not an actual plant. The output from PROSYS for a particular industry will vary from city to city due to differences in local fuel costs, labor rates, insolation and other meteorological conditions, and other factors. If it is desired to run PROSYS with IPH requirements for an actual rather than hypothetical industrial plant, the actual data may be entered into PROSYS.

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*For the directories consulted, see the following references: California Manufacturers Register 1977, North Dakota Business and Industrial Development Department 1976, South Carolina Planning and Research Division 1976, U.S. Executive Office of the President 1972, University of Colorado 1977, and University of Texas 1977.

**The references consulted include: A. T. Kearney, Inc., 1976a; A. T. Kearney, Inc., 1976b; Byer et al. 1976; Casper 1977; Ford, Bacon, and Davis, Inc., 1976; Fraser 1977; Gordian Associates, Inc., 1976; Hall 1977; Hamel and Brown 1976; Lyman 1969; Rogan 1977; SCS Engineers, Inc., 1976; Schorr et al. 1976; and U.S. Department of Commerce 1973.

Table 2-1. INDUSTRIAL PROCESS HEAT DATA BASE

Item[a]	Description/Comments
Process Code	
SIC code*	Standard Industrial Classification code describing process
Process Data	
Fluid used*	1 - Air 2 - Water 3 - Steam 4 - Other
Direct heat*	0 - Direct (collector fluid direct to process) 1 - Indirect (intermediate heat exchanger)
Process description	Description of process (cooking, washing, etc.)
Temperature Data	
Temperature*	Maximum temperature required for process
Tolerance	Tolerance of temperature
Supply temperature	Minimum supply temperature
Heat Rate Data	
Heat rate*	Heat rate required for process
Tolerance	Tolerance of heat rate
Energy use*	Average annual energy required for process in a plant of "standard" size
Energy use - unit output	Average amount of energy required per unit of industrial output
Pressure Data	
Pressure	Pressure required for process
Tolerance	Tolerance of pressure
Electrical Data	
Peak electricity	Peak electrical power required for process
Average electricity	Average electrical power required for process

[a]Data items collected for current IPHDB indicated by asterisks.

Table 2-1. INDUSTRIAL PROCESS HEAT DATA BASE (Concluded)

Item[a]	Description/Comments
Operation Schedule	
Operation code*	0 - Continuous 1 - Batch or other
Seasonal operation	
Season beginning	Week season begins (0 if year-round)
Season ending	Week season ends (0 if year-round)
Weekly operation	
Monday-Friday shifts Saturday shifts Sunday shifts	0 - No shift 1 - Shift 1 2 - Shift 2 3 - Shifts 1 + 2 4 - Shift 3 5 - Shifts 1 + 3 6 - Shifts 2 + 3 7 - Shifts 1 + 2 + 3
Daily operation	Military time when each shift starts or ends (to nearest hour)
Shift 1 start	
Shift 1 end	
Shift 2 start	
Shift 2 end	
Shift 3 start	
Shift 3 end	
System Applicability	Possible systems in order of applicability:
1st applicable system* 2nd applicable system* 3rd applicable system*	1 - Direct hot water 2 - Heat exchanger/hot water 3 - Direct hot air 4 - Indirect hot air 5 - Flashed steam 6 - Steam generator
Process name	
Process name*	Name of process

[a]Data items collected for current IPHDB indicated by asterisks.

Table 2-2. CURRENT CONTENTS OF IPHDB

Label	Description/Comments
SIC	Standard Industrial Classification code describing process
ALPHA	Alphanumeric character to distinguish segmented process
NAME	Description of industry
TMP	Required process temperature (C or F)
HEATR	Required process heat rate (MW or MBtu/h)
FLOWR	Maximum required steam flow rate (kg/s or 10^3 lb/h)
SAE	Standard annual energy use [10^{13} J/yr or 10^{10} Btu/yr)
SYS	Possible solar systems, in order of applicability:
1	Direct hot water
2	Indirect hot water
3	Direct hot air
4	Indirect hot air
5	Steam flash
6	Steam generator
BF	Backup fuel:
1	Natural gas
2	Electricity
3	Oil
4	Coal
OP	Operation schedule:
1	Continuous process
2	Batch process
SOP	Seasonal operation:
0	Continuous
1	Seasonal
ENERGY	Energy required per unit of industrial output
UNIT	Unit of production for ENERGY

Table 2-3. INDUSTRIES CONTAINED IN IPHDB

SIC	Industry	Location					
		Bismarck	Browns-ville	Charles-ton	Denver	El Paso	Fresno
2011	Meat Packing Plant		x	x	x	x	
2013	Sausages/Prepared Meat				x		
2016	Poultry Dressing Plant				x		
2021	Creamery Butter	x			x	x	
2022	Nat. and Processed Cheese	x			x		
2023	Condensed/Evap. Milk					x	
2024	Ice Cream				x	x	
2026	Fluid Milk	x		x	x	x	
2032	Canned Specialties				x	x	
2033	Canned Fruit/Veg.				x	x	x
2034	Dried Fruits/Veg.				x		x
2035	Pickled Fruits/Veg.				x	x	x
2037	Frozen Fruit/Veg.		x			x	
2038	Frozen Specialties	x			x		
2041	Flour/Grains				x	x	x
2043	Cereal						x
2045	Flour/Grain Mixes				x		
2047	Pet Food				x		
2048	Animal Feed				x		
2051	Bakery Products	x		x	x	x	x
2052	Cookies/Crackers				x	x	
2065	Candy/Confections			x	x		
2066	Chocolate Products				x		
2077	Animal Fat/Oils				x		
2079	Shortening/Oils				x		
2084	Wines						x
2085	Liquors						x
2086	Soft Drinks	x	x	x	x	x	x
2087	Flavoring/Extracts				x	x	
2091	Canned Seafoods					x	x
2092	Fish/Seafood			x	x		
2095	Coffee				x		
2097	Ice			x	x		
2098	Macaroni				x	x	x
2099	Misc. Foods				x	x	x
2211	Cotton Weaving				x		
2241	Small Weave Fabric				x		
2253	Knit Outerwear				x		x
2261	Finishing Broad Cotton			x	x		
2262	Finishing Broad Fabrics				x		
2271	Woven Carpets/Rugs				x		x
2293	Upholstery Fillings				x		
2295	Coated Fabrics				x		
2311	Male Coats				x		
2321	Male Shirts		x	x	x		

Table 2-3. INDUSTRIES CONTAINED IN IPHDB (Continued)

SIC	Industry	Location					
		Bismarck	Browns-ville	Charles-ton	Denver	El Paso	Fresno
2327	Male Pants		x		x		
2329	Male Misc. Clothes				x		
2331	Female Tops				x		
2335	Female Dresses			x	x		
2339	Female Misc. Clothes				x		
2352	Hats/Caps		x		x		
2361	Girls Outerwear				x		
2369	Girls Misc. Outerwear				x		
2386	Leather/Sheep Clothes				x		
2387	Belts				x		
2389	Misc. Attire				x		
2392	House Linens				x		
2395	Decorative Adorning				x		
2396	Auto Apparel				x		
2399	Misc. Fabric Products				x	x	
2421	Saw Mills			x	x		
2426	Hardwood Floor Mills				x		
2431	Millwork	x	x	x	x	x	x
2436	Plywood			x			
2441	Wood Boxes			x	x		x
2491	Wood Preserving			x	x		
2499	Misc. Wood Products			x	x		x
2511	Wood Furniture		x		x		x
2512	Wood Furn. w/Upholstery				x		
2515	Mattresses			x	x		
2519	Misc. Furniture				x		
2521	Wood Office Furniture				x		
2522	Metal Office Furniture				x		x
2531	Public Office Furniture				x		
2541	Wood Partitions				x	x	
2542	Metal Partitions			x	x		
2591	Drapery Hardware		x	x	x		
2599	Misc. Furniture				x		
2631	Paperboard			x			
2641	Coated Paper				x		
2642	Envelopes				x		
2643	Bags			x	x		
2645	Die-Cut Paper				x		
2649	Converted Paper				x		
2651	Folding Paper Boxes				x	x	
2652	Set-Up Paper Boxes				x		
2653	Cardboard Boxes				x	x	
2655	Fiber Cylinders			x	x		
2661	Building Paper Mills				x		

Table 2-3. INDUSTRIES CONTAINED IN IPHDB (Continued)

		Location					
SIC	Industry	Bismarck	Browns-ville	Charles-ton	Denver	El Paso	Fresno
2711	Newspapers	x	x	x	x		
2721	Periodicals				x		
2731	Books				x		
2732	Book Printing				x		
2751	Letter Press		x	x	x	x	x
2752	Lithograph	x	x	x	x	x	
2761	Manifold Printing			x	x		
2782	Blank Books				x		
2789	Book Binding			x	x		
2791	Typesetting				x		
2793	Photoengraving				x		
2813	Industrial Gases	x	x		x		x
2819	Industrial Inorganics			x	x		
2821	Plastics				x		
2822	Synthetic Rubber				x		
2831	Biological Products				x		
2834	Pharmaceuticals				x		x
2841	Soaps/Detergents				x	x	
2842	Sanitation Goods	x			x	x	
2843	Surface Agents				x		
2851	Paints				x	x	
2865	Cyclic Organics				x		
2869	Industrial Organics				x		
2873	Nitrogenous Fertilizer			x			
2874	Phosphate Fertilizer			x			
2879	Pesticides				x	x	
2891	Glues/Sealants				x		
2892	Explosives				x		
2893	Ink				x		
2899	Misc. Chemicals		x		x		
2911	Oil Refining			x		x	x
2951	Paving Material			x	x	x	x
2952	Asphalt			x	x		
2992	Greases			x			x
2999	Petroleum/Coal Products	x					
3069	Misc. Rubber			x	x	x	
3079	Misc. Plastic				x		
3111	Leather Processing				x		
3161	Luggage				x		
3171	Handbags				x		
3199	Misc. Leather Goods				x	x	
3211	Flat Glass				x		
3229	Blown Glass			x	x		
3231	Glass Products		x		x	x	

Table 2-3. INDUSTRIES CONTAINED IN IPHDB (Continued)

		Location					
SIC	Industry	Bismarck	Browns-ville	Charles-ton	Denver	El Paso	Fresno
3241	Hydraulic Cement			x		x	
3251	Brick/Clay Tiles				x		x
3253	Ceramic Tiles		x		x		
3259	Misc. Clay				x		
3269	Pottery				x		x
3271	Concrete Blocks/Bricks			x	x	x	x
3272	Misc. Concrete	x		x	x	x	x
3273	Ready Mixed Concrete	x	x	x	x	x	
3274	Lime		x				
3275	Gypsum Products				x		
3281	Cut Stone Products			x	x	x	
3291	Abrasives				x		
3292	Asbestos			x	x	x	
3293	Gaskets/Seals			x	x		
3295	Ground Minerals		x		x	x	x
3296	Mineral Wool				x		x
3299	Nonmetal Minerals				x	x	x
3317	Steel Pipe/Tube				x		
3321	Gray Iron				x	x	
3333	Zinc Refining				x	x	
3334	Aluminum Refining				x		x
3339	Misc. Metals Refining				x		
3341	Alloys				x		
3356	Misc. Metal Forming				x		
3361	Aluminum Casting			x	x	x	
3362	Alloy Casting				x	x	
3369	Misc. Castings				x		
3411	Metal Cans				x		
3423	Hand Tools				x		
3429	Misc. Hardware				x		
3431	Enameled Iron Plumbing				x		
3432	Brass Plumbing				x		
3433	Fuel Heaters				x		
3441	Structural Metal		x	x	x	x	
3442	Metal Doors		x	x	x	x	
3443	Boiler Shops		x	x	x	x	x
3444	Sheet Metal Work		x	x	x	x	x
3449	Misc. Metal Work		x	x	x	x	
3451	Screw Machines				x		
3452	Nuts/Bolts/Screws				x		
3471	Metal Plating			x	x		x
3479	Misc. Metal Surface Treatment	x			x	x	
3493	Steel Springs				x		
3494	Pipe Fittings/Valves				x		x

Table 2-3. INDUSTRIES CONTAINED IN IPHDB (Continued)

		Location					
SIC	Industry	Bismarck	Browns-ville	Charles-ton	Denver	El Paso	Fresno
3496	Wire Products			x	x		
3499	Misc. Metal Products				x	x	
3519	Internal Comb. Engines			x	x		
3522	Farm Machinery	x	x				x
3524	Garden Machinery			x	x		
3531	Construction Machinery				x		x
3533	Oil Field Machinery				x		x
3541	Metal Cutting Tools				x		
3542	Metal Forming Tools				x		
3544	Tools			x	x		
3545	Machine Tool Access.		x				
3551	Food Products Machinery				x		x
3559	Special Machinery				x	x	x
3561	Pumps		x		x		x
3566	Gears				x		x
3568	Power Trans. Equipment			x			
3573	Computers				x		
3576	Weighing Devices				x		
3582	Ind. Laundry Machinery				x		
3585	Refrig./Heating Equipment				x		x
3589	Misc. Service Machinery	x			x		
3599	Misc. Machines		x	x	x		x
3612	Transformers				x		
3621	Motors/Generators				x		
3622	Industrial Controls				x		
3623	Welding Apparatus	x					
3629	Elect. Ind. Apparatus				x		
3641	Electric Lamps				x		
3643	Misc. Electrical Parts			x	x		
3644	Elect. Insul./Fittings				x		
3651	Radio/TV				x		x
3652	Phono Records/Tapes			x	x		
3661	Telephone Telegraph				x		
3662	R/TV Transmit			x	x		
3672	Cathode Ray TV Tubes				x		
3674	Semiconductors				x		x
3679	Misc. Elect. Components				x		
3691	Storage Batteries		x		x		
3694	Elect. I.C. Engine				x		
3711	Motor Vehicles				x		
3713	Trucks/Buses				x		
3714	Motor Vehicles Parts				x		x
3715	Truck Trailers				x		x
3721	Aircraft		x				

Table 2-3. INDUSTRIES CONTAINED IN IPHDB (Concluded)

SIC	Industry	Location					
		Bismarck	Brownsville	Charleston	Denver	El Paso	Fresno
3728	Aircraft Parts			x	x		
3731	Ship Building		x				
3732	Boats			x	x		x
3751	Motorcycles/Bicycles				x		
3811	Engineering Instruments				x		
3822	Automatic Controls				x		
3841	Medical Instruments				x		
3842	Medical Supplies				x		
3843	Dental Equipment				x		
3851	Ophthalmic Goods				x		
3861	Photo Equipment				x		x
3911	Jewelry				x		
3914	Silverware				x		
3931	Musical Instruments				x		x
3949	Sporting Goods				x		x
3951	Pens/Pencils				x		
3953	Marking Devices		x	x	x		
3955	Carbon/Paper Ink Ribbons				x		
3961	Costume Jewelry				x		
3962	Artificial Plants				x		
3964	Needles/Pins/Hooks				x		
3999	Misc. Manu. Products				x		
Number of industries for which data were collected		18	33	63	222	51	57
Total number of industries		21	42	75	294	60	80
Percentage of total industries for which data were collected		86	79	84	76	85	71

2.1.3 Contents of IPHDB

IPH data were collected for over 70% of all the industries in the six cities. As indicated in Section 2.1.2, data in the IPHDB for a particular industry are the same for each city in which the industry is located since the IPHDB is based upon hypothetical, average-sized industrial plants. Sample data from the IPHDB for selected industries are given in Table 2-4.

The complete IPHDB is listed in Appendix A according to SIC code. The data format and units are the same as those shown in Table 2-2. The IPHDB data reflect process characteristics for individual processes within an industry for which the necessary data were available (for example, SIC 2022 contains several entries, each representing a particular process in cheese production).

2.1.4 Limitations of IPHDB and Future Plans

There are certain limitations of the IPHDB which must be kept in mind in interpreting the results from PROSYS. First, the IPHDB is based entirely on previous IPH studies. We did not survey industrial trade associations, process heat engineering firms, or other potential sources of IPH data. Second, as previously discussed, the IPH data were redefined to describe a hypothetical, average-sized plant for each industry. Using the IPHDB in conjunction with PROSYS results in an overall assessment of the potential for solar IPH in each city. A case study, as described in Section 6.0, would be required to determine if a solar IPH system could be used economically for an actual plant.

The IPHDB could be extended in two areas. For further evaluation of end-use matching in the identification of viable economic industrial applications of solar energy in the near- to intermediate-term, the data base must be extended to additional cities and must cover more industries. Also, verification of the end-use matching approach and a more detailed evaluation of the industrial application of solar energy require more detailed process information. Both of these needs are being considered in the continuation of this study.

2.2 COLLECTOR DATA BASE (COLDAT)

2.2.1 Requirements and Structure of COLDAT

Matching of solar systems to specific industrial processes in the near term requires that the characteristics of currently available solar collecting equipment be modeled. Among the component subsystems that constitute a solar IPH system design, the collector subsystem has the greatest degree of sensitivity with regard to location, operating requirements, and cost. Therefore, it is important that all of the relevant performance and cost information available on currently manufactured collector subsystems be assembled in a data base for use in the analysis. While it is important to consider the cost and performance characteristics of the several other subsystem components in any particular solar process heat system, the PROSYS simulation model does not model discrete combinations of subsystem components. Instead, PROSYS calculates an approximate annual energy delivery based on collector performance and

Table 2-4. SAMPLE AVERAGE PLANT DATA FROM IPHDB FOR SELECTED INDUSTRIES

		Process Temperature		Heat Rate		Flow Rate		Standard Annual Energy Use		System Type[a]	Backup Fuel	Operation Schedule	Seasonal Operation	Energy/Unit	
SIC	Industry	C	F	MW	MBtu/h	kg/s	10^3 lb/h	10^{10} kJ/yr	10^{10} Btu/yr					kJ/kg	Btu/lb
2011	Fluid Milk	77	170	1.16	3.97	0.55	4.35	0.88	0.83	6 2 1	Nat. gas	1	0	25.3	24.0
2051	Bread/Baked Goods	232	450	0.84	2.89	0.10	0.77	0.95	0.90	4 3 2	Nat. gas	1	0	--	--
2086	Soft Drinks	77	170	0.91	3.11	0.18	1.42	1.02	0.97	2 6 0	Nat. gas	1	0	--	--
2431	Millwork	93	200	0.21	0.72	0.04	0.28	0.30	0.28	1 3 6	Nat. gas	0	0	--	--
2653	Cardboard Boxes	149	300	0.23	0.79	0.50	4.00	2.85	2.70	3 1 6	Nat. gas	0	0	--	--
3444	Sheet Metal Works	93	200	0.07	0.24	0.02	0.12	0.44	0.42	3 1 6	Nat. gas	0	0	--	--

[a]See Table 2-1 for identification of codes.

assumed system losses. Specific attention is given to capital cost estimates for the balance of the solar system beyond the collector field. It was not necessary, however, to collect technical data on nonsolar equipment items for incorporation in the data base.

The information on solar collectors required by the PROSYS model is listed in Table 2-5. Current cost and installation information is required in order to make accurate capital cost estimates for the solar collector subsystem.

Although preliminary data were collected on approximately 25 solar collectors during the course of this study, only 8 collectors were used in the final end-use matching analysis. The collectors used were selected on the basis of the following criteria:

- The collector is of a generic type amenable to modeling by the simulation procedure selected. Fixed flat-plate collectors, fixed compound parabolic collectors, one-axis tracking parabolic trough or fresnel lens collectors, and two-axis tracking parabolic dishes may be modeled.
- The collector must be currently manufactured.
- Only performance data collected in verifiable tests or verified in field applications are acceptable.
- Only collectors amenable to the assumptions made in system performance and cost estimates (which have been generalized) can be used. For example, results for parabolic dish collectors are subject to significant uncertainty because system models do not account for larger piping heat losses encountered in these systems.

It should be noted that although COLDAT solar collector data represent best estimates of the actual state of currently manufactured collectors, no manufacturers' names are reported. Collectors are identified only by generic type and by letter code.

2.2.2 Sources of Information

Collector specifications were acquired from a number of sources. In most cases, the optical efficiency, heat loss coefficients, and other physical characteristics were obtained from product literature provided by the manufacturer. When verified test results became available, the input data were modified to reflect test results. Usually, test results yielded physical characteristics that were less optimistic than manufacturers' first estimates. Most of the verified tests used to supplement the collector data base were performed by Sandia Laboratories, Albuquerque, as part of the Collector Module Test Facility program to characterize several selected collector modules (Dudley and Workhoven 1978).

Information on collector costs was obtained, where possible, from quotes given directly by current manufacturers. In certain cases quotes could not be obtained and collector costs were estimated from the information supplied in reports describing the installation of collectors as part of field engineering

Table 2-5. COLLECTOR DATA BASE CONTENTS

Label	Description/Comments
A	Shading and blockage factor
KMUG	Optical efficiency
PHI-AHA	Tracking efficiency, where applicable; acceptance half angle for CPCs (degrees)
CR	Concentration ratio
DTILT	Difference in tilt from a polar axis mounting (degrees) if = 999, collector is horizontal
$/SQM	F.O.B. cost per m^2 of collector ($)
A$/SQM	Auxiliary equipment cost per m^2 of collector ($)
B$/SQM	Special additional costs per m^2 of collector ($)
HR/SQM	Required hours of installation labor per m^2 of collector (person-hours)
M-AREA	Standard area of one collector module (m^2)
	Collector Type
0	Flat plate
1	Parabolic trough
2	Compound parabolic concentrator (CPC)
3	Parabolic dish
	Annotation of Data Origin
TEST	Data derived from test data
MFG	Data derived from manufacturer information
DES	Data derived from design information
EDNR	Performance efficiency data not verified
CDBE	Cost data are best estimate
U	Heat loss coefficient as a function of collector operating temperature (W/m^2 C)

tests. Installation labor (person-hours per unit area) was estimated from such reports. Where no adequate installation history was available, labor hours were estimated from data for similar collector designs.

2.2.3 Contents of COLDAT

Twenty collectors are carried in the data base currently on file. Only the eight collectors selected on the basis of the criteria given in Section 2.2.1 were used in the final end-use matching. These eight are denoted by asterisks in the complete listing of COLDAT given in Appendix B.

2.2.4 Limitations of COLDAT

While COLDAT contains a fairly complete listing of line-focusing concentrating collectors manufactured today, it is deficient in information on the wide variety of flat-plate collectors currently being manufactured. Only representative flat plates are included. COLDAT should be expanded to include at least ten of the best flat-plate collectors now manufactured and useful in industrial applications.

Nearly all solar system analyses suffer from the lack of adequate verified collector performance data. As more collectors undergo controlled performance tests, their physical specifications should be added to COLDAT. In particular, more reliable data on end losses, blockage losses, and shading losses are required for determination of daily cutoff times.

Actual F.O.B. collector equipment quotes can be included in COLDAT. However, the costs of special fittings, supports, etc. ($\$/m^2$); the costs of special additional items such as shipping ($\$/m^2$); and the number of labor person-hours required for installation (person-hours/m^2) are difficult to estimate. Substantially more experience in collector subsystem installation (particularly for concentrating collectors) is required for better estimates. Collector-specific estimates of operation and maintenance costs would also be useful and should eventually be included in COLDAT.

2.3 METEOROLOGICAL DATA BASE (METDAT)

2.3.1 Requirements and Structure of METDAT

In order to match industrial processes and solar systems throughout the United States, local meteorological data are needed for a number of representative sites. The meteorological data base (METDAT) was established using the following criteria:

- The data must contain the parameters required for the collector performance model.
- The data are to be available for a number of representative sites across the United States.
- The data should be accurate.

- The data base should be easy to access by the computer program, preferably by disk to avoid time-consuming magnetic tape manipulation.

A suitable collector performance model, such as that described in Appendix D, requires the site latitude and the following meteorological parameters for each month of the year:

- $\overline{\overline{HT}}$, long-term average daily total insolation on a horizontal surface (kJ/m^2 or Btu/ft^2);
- $\overline{\overline{KT}}$, long-term average cloudiness index (equal to $\overline{\overline{HT}}$/average daily extraterrestrial insolation); and
- $\overline{\overline{TA}}$, long-term average daytime ambient temperature (C).

Also included for calculating the annual efficiency of concentrating collectors is the parameter DIR, the average annual direct normal incident radiation.

In addition, the collector cutoff calculations require clear-day instantaneous profiles of direct normal and total radiation incident on a surface of given tilt. These parameters are generated by SIM, a solar irradiance computer model (Hulstrom et al. 1968) which requires the additional input of CLNO, the clearness number.

To provide the required parameters while meeting the criteria for accuracy and representative U.S. coverage, the SOLMET data network, consisting of 26 U.S. cities, was selected. Denver, Colo., was added to facilitate local case studies. A map of the 27 sites is shown in Fig. 2-1.

2.3.2. Sources of Information

The Department of Energy (DOE) has identified SOLMET data as the standard for solar energy studies; therefore, SOLMET insolation data was used for the 26 available sites (excluding Denver). The long-term average daily total insolation on the horizontal surface, $\overline{\overline{HT}}$, contained in the SOLMET data base is derived from 23 years of historical data (Schlagheck 1977).

Because the cloudiness index $\overline{\overline{KT}}$ is not contained in the SOLMET files the available values of $\overline{\overline{KT}}$ from the f-Chart data base (Beckman et al. 1977) were corrected by the ratio of the SOLMET total insolation to the respective f-Chart total insolation as follows:

$$\overline{\overline{KT}} = \overline{\overline{KT}}_{f\text{-Chart}} \frac{\overline{\overline{HT}}\ \text{SOLMET}}{\overline{\overline{HT}}\ \text{f-Chart}} .$$

For Denver, the total insolation $\overline{\overline{HT}}$ and cloudiness index $\overline{\overline{KT}}$ were taken from the f-Chart data base (Beckman et al. 1977).

The average daytime ambient temperatures for the 26 SOLMET sites are given by Liu and Jordan (1963), but this information is not available for Denver. The

Figure 2-1. SOLMET Sites

24-hour average ambient temperature for Denver is included in the f-Chart data. Temperature data for Grand Junction, Colo., are available from both Liu and Jordan (daytime average) and f-Chart (24-hour average). The monthly differences between average daytime and 24-h average temperatures were calculated for Grand Junction, and the f-Chart Denver averages were adjusted by these differences.

The clearness numbers for all sites were obtained from Threlkeld and Jordan (1958), with adjustments made by Hulstrom et al. (1968).

The annual average direct normal incident radiation was derived from SOLMET data by the Aerospace Corporation (Melton 1978) for all SOLMET sites. The SIM computer program (Hulstrom et al. 1968) was used to calculate this parameter for Denver.

2.3.3 Contents of METDAT

For each of the 27 sites, METDAT contains the site name, latitude, and annual direct incident radiation, as well as average monthly values for daily total insolation on a horizontal surface, cloudiness index, daytime ambient temperature, and clearness number. Complete METDAT contents are listed in Appendix C. Examples of typical METDAT values for Denver, Colo., and Brownsville, Tex., are shown in Table 2-6.

2.3.4 Limitations of METDAT and Future Plans

Perhaps the most limiting aspect of METDAT is the availability of information for only 27 sites. However, this number can be expanded by an additional 220 sites when the NOAA-ERSATZ data become available (Cinquemani 1978). The data base can also be improved by replacing the current daytime ambient temperature data with more accurate data calculated from the 23-year SOLMET data.

2.4 ECONOMIC DATA BASE (ECONDAT)

2.4.1 Requirements and Structure of ECONDAT

A complete site-specific analysis of the feasibility of solar process heat systems requires that site-related economic information be taken into account. For example, while the estimated time to assemble and interconnect solar collectors and interfield piping on the job site may be reasonably constant, the average cost of labor to perform this installation varies rather widely across the United States. This variation may make a significant difference in total system capital investment for large systems in which the collector subsystem cost is a substantial fraction of total system cost. Furthermore, fuel prices differ significantly by location. An analysis of 1975 No. 2 distillate oil prices showed a 33% price difference between two states located within the same region (New Mexico and Nevada). Even within one state, prices may differ by as much as 15% from city to city (Sherman H. Clark

Table 2-6. SAMPLE OF METDAT DATA FORMAT FOR BROWNSVILLE, TEX., AND DENVER, COLO.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Brownsville, Tex.												
(Latitude: 25.55°)												
$\overline{\overline{HT}}$ (kJ/m^2)	10373.00	12827.00	16834.00	19540.00	21696.00	24475.00	25630.00	23140.00	19462.00	16435.00	12169.00	9784.00
$\overline{\overline{HT}}$ (Btu/ft^2)	913.97	1130.19	1465.62	1721.67	1911.63	2156.49	2258.26	2038.87	1714.80	1448.09	1072.21	862.07
$\overline{\overline{TA}}$	0.44	0.46	0.51	0.53	0.55	0.61	0.65	0.61	0.57	0.56	0.50	0.44
$\overline{\overline{TA}}$ (C)	17.39	19.28	21.50	24.56	27.44	29.59	30.28	30.50	28.94	26.06	21.50	18.44
$\overline{\overline{TA}}$ (F)	63.30	66.70	70.70	76.21	81.39	85.10	86.50	86.90	84.09	78.91	70.70	83.19
Clearness number	0.76	0.76	0.76	0.76	0.81	0.81	0.81	0.81	0.81	0.81	0.76	0.76
Denver, Colo.												
(Latitude: 39.58°)												
$\overline{\overline{HT}}$ (kJ/m^2)	10676.00	14152.00	18247.00	21729.00	24367.00	27381.00	26502.00	24785.00	20682.00	15491.00	10970.00	9127.00
$\overline{\overline{HT}}$ (Btu/ft^2)	940.66	1246.93	1607.74	1914.54	2146.98	2412.54	2335.09	2183.81	1822.29	1364.91	966.57	804.18
$\overline{\overline{KT}}$	0.69	0.69	0.67	0.63	0.62	0.66	0.66	0.68	0.69	0.69	0.66	0.65
$\overline{\overline{TA}}$ (C)	-0.83	1.67	5.00	11.22	19.06	23.28	27.06	25.44	20.89	14.61	4.56	-3.33
$\overline{\overline{TA}}$ (F)	30.51	35.01	41.00	52.20	66.31	73.90	80.71	77.79	69.60	58.30	40.21	26.01
CLNO	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95

Associates 1978). These differences are very important in an economic analysis of fuel-saving solar process heat systems since the results depend directly upon the purchase cost of the displaced fuel. Many other cost and economic factors vary with respect to the location and type of industrial plant. It is important to supply several of these most critical parameters in a site-specific data base. Other parameters (such as required rate of return, tax rate, lifetimes) are difficult to specify by plant or site. Consequently, typical ranges of these parameters are specified. Specific values of the parameters may be selected by the analyst to replace "default" values and used to determine a multiplier for life-cycle cost, as shown in Section 4.0.

Two sets of economic information supplied to the end-use matching are presented in this section. First, the economic data base (ECONDAT) is described. ECONDAT is designed to be accessed when a net present value analysis (ECONMAT) is performed as an integral part of the end-use matching. ECONMAT contains default values of discount rate, fuel price escalation rate, and inflation but contains actual data on local fuel prices and labor rates. The second set of information concerns fuel prices and escalation rates alone. This information may be used to compare with solar costs derived using the multiplier described in Section 4.0. Ranges of value are also presented for investment parameters used in calculating the multiplier.

2.4.2 Contents of ECONDAT

The contents of ECONDAT (i.e., conventional fuel prices and average labor rates) are shown in Table 2-7. Other economic parameters required in the net present value analysis are shown in Table 2-8. In the program ECONMAT, each of these parameters is held constant for the six sites at a default value. While these parameters probably vary from site to site, it was not possible in this study to identify more specific investment parameters.

2.4.3 Economic Information for Separable Analysis

Since life-cycle economic analysis can be treated separately from capital cost and performance estimates, it is possible to calculate life-cycle costs by establishing economic parameters separately. This allows the analyst to select economic parameters on the basis of more detailed information. Table 2-9 lists the economic parameters that are required for life-cycle cost analysis and the typical range of values that can be assigned to these parameters under current conditions. Each item is denoted as site-specific, industry-specific, or nearly constant.

Table 2-10 presents projected conventional fuel costs (Sherman H. Clark Associates 1978) for the states in which this analysis was conducted. Note the difference between these costs and the calculated projected costs from ECONDAT in which the default real escalation rate of 0.05 is used. Table 2-11 shows the levelized cost of delivered conventional fuel energy over 20 years at two discount rates for several base years. These costs may be directly compared to implicit solar costs such as those given in Section 5.0.

Table 2-7. CONTENTS OF ECONDAT: FUEL COST AND AVERAGE LABOR RATE

City \ Average Conversion Efficiency[a]	Fuel Cost ($ per 10^6 Btu delivered heat equivalent) Natural Gas[b] 0.75	Residual Oil[c] 0.80	Coal[d] 0.75	Electricity[e] 1.00	Average Labor ($ per person-hour)[f]
Bismarck, N.D.	3.25	2.20	1.20	9.25	19.98
Brownsville, Tex.	3.20	2.40	0.96	8.50	15.00
Charleston, S.C.	2.00	2.80	1.55	8.15	14.63
Denver, Colo.	1.83	2.90	1.23	7.80	19.38
El Paso, Tex.	3.20	2.40	1.30	7.75	15.63
Fresno, Calif.	3.27	3.15	2.00[g]	9.64	23.44

[a]Efficiency estimates are for typical, noneconomized, industrial steam boilers. From Ver Schave 1974.
[b]Gas costs are by state for 1976, from AGA 1976. Costs in 1976 are extrapolated at recent rates to 1978.
[c]Oil costs are for residual fuel oil sold to utilities by census regions. From U.S. DOE 1978.
[d]Projected 1978 costs for delivered coal from regional sources to utilities. Prices are first-year prices for long-term contracts. From EPRI 1978.
[e]Electrical costs are typical for industrial customers. 1 kWh = 3412 Btu. Average of light and heavy industrial rates in 1976 escalated at 7% to 1978 by state except where specific data available. From EEI 1977.
[f]Rates given are for local union rates for pipefitters and plumbers; plus 30% for taxes, insurance, supervision, and small tools; plus 20% overhead. From Dodge Building Cost Services, and Wood and Tower, Inc., 1977.
[g]Equivalent cost of heat for "clean" coal due to air pollution regulations in California.

Table 2-8. CONTENTS OF ECONDAT: DEFAULT VALUES FOR ECONOMIC PARAMETERS

Symbol	Label	Description/Comments	Default Value
g	GIR	General inflation rate	0.06
e_E	FERE	Real fuel price escalation for electricity	0.05
e_O	FERO	Real fuel price escalation for oil	0.05
e_G	FERG	Real fuel price escalation for natural gas	0.05
e_C	FERC	Real fuel price escalation for coal	0.02
τ	TAXR	Composite income tax rate	0.50
B	OMPI	Fraction of initial cost applied to annual operation, maintenance, property taxes, and insurance	0.02
TC	TAXCR	Investment tax credit	0.20
R	ROR	Market rate of return required	0.12
N	NYR	System lifetime (yr)	20

Table 2-9. RANGES OF VALUES FOR ECONOMIC PARAMETERS USED IN CALCULATING A LIFE-CYCLE COST MULTIPLIER

Symbol	Item	Range	Remarks[a]
R	Market rate of return on equity capital	0.12-0.30	B
r	Market rate of return on debt capital	0.06-0.12	B,A
f	Fraction of initial cost financed by debt capital	0-0.80	B,A
τ	Composite income tax rate	0.49-0.51	C
TC	Composite income tax credit	0.10-0.50[b]	C
N	System service life or period of life-cycle cost analysis (yr)	10-20	B
LP	Loan repayment period (yr)	10-20	B,A
DP	Depreciation accounting lifetime (yr)	8-20	B
OMPI	Fraction of initial cost for annual operation, maintenance, property taxes, and insurance	0.02-0.06	A
g	General rate of inflation	0.06-0.12	C

[a]A indicates site-specific; B, industry-specific; C, nearly constant.
[b]Depends on pending legislation.

Table 2-10. FUTURE CONVENTIONAL FUEL COSTS

City	Source	Cost (1978 $ per 10^6 Btu delivered heat equivalent)											
		Natural Gas			Residual Oil			Coal			Electricity		
		1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
Bismarck, N.D.	S. H. Clark projection	3.31	7.05	9.28	3.94	5.38	6.79	1.63	2.38	2.97	9.93	12.57	15.29
	5% real escalation	3.58	5.84	9.51	2.43	3.95	6.43	1.32	2.16	3.51	10.20	16.61	27.06
Brownsville, Tex.	S. H. Clark projection	2.70	5.51	7.66	3.90	5.57	6.95	1.31	1.84	2.22	8.49	13.60	15.64
	5% real escalation	3.53	5.75	9.36	2.65	4.31	7.02	1.06	1.72	2.81	9.37	15.27	24.86
Charleston, S.C.	S. H. Clark projection	3.00	6.20	8.17	3.18	5.18	6.55	2.50	3.16	4.10	7.55	10.88	14.95
	5% real escalation	2.20	3.59	5.85	3.09	5.03	8.19	1.71	2.78	4.53	8.99	14.64	23.84
Denver, Colo.	S. H. Clark projection	2.13	5.51	7.63	3.88	5.38	6.73	1.23	1.42	1.76	8.09	11.90	14.95
	5% real escalation	2.02	3.29	5.35	3.20	5.21	8.48	1.36	2.21	3.60	8.60	14.01	22.81
El Paso, Tex.	S. H. Clark projection	2.70	5.51	7.66	3.90	5.51	6.95	1.31	1.84	2.22	8.49	13.60	15.64
	5% real escalation	3.53	5.75	9.36	2.65	4.31	7.02	1.43	2.33	3.80	8.54	13.92	22.67
Fresno, Calif.	S. H. Clark projection	3.26	6.03	7.73	3.87	5.44	6.82	2.16	2.57	3.16	9.21	12.57	15.64
	5% real escalation	3.61	5.87	9.56	3.47	5.66	9.21	2.20	3.59	5.85	10.63	17.31	28.20

Table 2-11. LEVELIZED FUEL COSTS (OVER 20 YEARS) FOR TWO DISCOUNT RATES R AND FOR BASE YEARS 1980, 1985, AND 1990

City	Discount Rate R	Levelized Fuel Cost[a] (1978 \$ per 10^6 Btu heat equivalent)											
		Natural Gas			Residual Oil			Coal			Electricity		
		1980	1985	1990	1980	1985	1990	1980	1985	1990	1980	1985	1990
Bismarck, N.D.	Base	3.58	4.57	5.84	2.43	3.10	3.95	1.32	1.68	2.16	10.20	13.02	16.61
	Levelized at R = 0.10	9.52	12.16	15.53	6.46	8.25	10.51	3.51	4.47	5.75	27.13	34.63	44.18
	Levelized at R = 0.15	8.27	10.56	13.49	5.61	7.16	9.12	3.05	3.88	4.99	23.56	30.08	38.37
Brownsville, Tex.	Base	3.53	4.51	5.75	2.65	3.38	4.31	1.06	1.35	1.72	9.37	11.96	15.27
	Levelized at R = 0.10	9.39	12.00	15.30	7.05	8.99	11.46	2.82	3.59	4.58	24.92	31.81	40.62
	Levelized at R = 0.15	8.15	10.42	13.29	6.12	7.81	9.96	2.45	3.12	3.97	21.64	27.63	35.27
Charleston, S.C.	Base	2.20	2.81	3.59	3.09	3.94	5.03	1.72	2.18	2.78	8.99	11.47	14.64
	Levelized at R = 0.10	5.85	7.47	9.55	8.21	10.48	13.38	4.55	5.80	7.39	23.91	30.51	38.94
	Levelized at R = 0.15	5.08	6.49	8.29	7.14	9.10	11.62	3.95	5.04	6.42	19.61	26.50	33.82
Denver, Colo.	Base	2.02	2.58	3.29	3.20	4.08	5.21	1.36	1.74	2.21	8.60	10.98	14.01
	Levelized at R = 0.10	5.37	6.86	8.75	8.51	10.85	13.86	3.62	4.63	5.88	22.88	29.21	37.27
	Levelized at R = 0.15	4.67	5.96	7.60	7.39	9.42	12.04	3.14	4.02	5.11	19.87	25.36	32.36
El Paso, Tex.	Base	3.53	4.51	5.75	2.65	3.38	4.31	1.43	1.83	2.33	8.54	10.90	13.92
	Levelized at R = 0.10	9.39	12.00	15.30	7.05	8.99	11.46	3.80	4.87	6.20	22.72	28.99	37.03
	Levelized at R = 0.15	8.15	10.42	13.29	6.12	7.81	9.96	3.30	4.23	5.38	19.73	25.18	32.16
Fresno, Calif.	Base	3.61	4.61	5.87	3.47	4.43	5.66	2.20	2.81	3.59	10.63	13.57	17.31
	Levelized at R = 0.10	9.60	12.26	15.61	9.23	11.78	15.06	5.85	7.47	9.55	28.28	36.10	46.04
	Levelized at R = 0.15	8.34	10.65	13.56	8.02	10.23	13.07	5.08	6.49	8.29	24.56	31.35	39.99

[a]Levelizing factor LF, which converts the base year cost into a levelized cost over 20 years, is given by: $LF = \frac{CRF(R,20)}{CRF(R''',20)}$, where $R''' = \frac{1 + R}{1 + g'} - 1$ for an inflation rate g of 6% and real fuel price escalation e of 5%; $g' = (1 + g)(1 + e) - 1 = 11.3\%$.

2.4.4 Sources of Information

Several sources were consulted to obtain the information shown in ECONDAT and in Table 2-10. Complete site-specific information was not available for all cities in certain references. In these cases, available prices for the nearest city or region were used.

ECONDAT fuel prices are expressed in dollars per delivered heat equivalent. To obtain these values, conversion efficiencies were assumed. For boiler systems, a conversion efficiency of 75% was assumed for natural gas, 80% for oil, and 75% for coal (VerSchave 1974). Electrically heated systems were converted at the rate of 1.0 kWh per 3412 Btu.

Base fuel costs are industrial average costs in 1978 dollars. AGA's Gas Facts (American Gas Assn. 1976) was the source of natural gas prices. The EEI Statistical Yearbook (Edison Electric Institute 1977) was used to define average industrial per-unit electrical costs. Oil costs were obtained from the EIA Monthly Energy Review (U.S. DOE 1978). Coal costs were taken from the EPRI Technical Assessment Guide (EPRI 1978) as first-year costs of long-term contracts, except in the case of Fresno, Calif., where equivalent "clean" coal fuel costs are cited due to restrictive air pollution regulations.

Labor rates for each city are from the 1978 Dodge Manual Dodge Building Cost Services (and Wood and Tower, Inc., 1977) and are a weighted average for labor teams consisting of laborers, pipefitters, plumbers, and foundation workers. Fifty-five percent is added for taxes, insurance, supervision, small tools, craft benefits, and other overhead items.

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SECTION 3.0

PERFORMANCE MODELING

The end-use matching analytical model was developed to meet the following needs:

- calculation of the performance of a variety of solar collectors and types of process systems;
- rapid analysis of many site/process/system collector combinations; and
- prediction of long-term average performance over a time span equivalent to the period of a typical economic analysis (~20 years).

3.1 SOLAR COLLECTOR ENERGY DELIVERY

The performance of solar collectors is usually specified by instantaneous or peak efficiency, based on clear days and normal incidence. In practical applications, however, the important conditions are long-term average energy delivery, cloud conditions, and incidence angles during the year; therefore, many researchers have advocated average diurnal efficiency as a collector performance measure. Unfortunately, such average efficiency curves depend strongly on weather peculiarities for the test day and location and are not suitable for long-term energy delivery prediction.

One approach to circumvent this problem is to input instantaneous efficiency and hourly insolation data to a computer program in order to predict long-term energy delivery. The results of this calculation are valid only if data are representative of long-term weather behavior. Various averaging approaches have been tried using several forms of data; for example, real hourly data for a single year, real hourly data for several years, averaged hourly data, and stochastic data. Use of real data for a specific place and year provides a performance simulation for that place and year, but its reliability as prediction for the long-term average is uncertain. Fluctuations in monthly total insolation from one year to the next commonly exceed ±10%, and the resulting output fluctuations for thermal collectors are even larger.

An alternative method has been developed by Colleras-Pereira and Rabl (1978), in which the Liu and Jordan method (Liu and Jordan 1963) for calculating long-term average energy collection of flat-plate collectors is generalized to concentrating collectors. The only meteorological inputs needed are the long-term average daily total hemispherical insolation $\overline{H}_h$ on a horizontal surface and the average ambient temperature. The collector is characterized by optical efficiency, heat loss (or U value), concentration ratio, and tracking mode. With this method, a factor is calculated that converts the daily total horizontal insolation $\overline{H}_h$ to yield the long-term average useful energy $\overline{Q}$ delivered by the collector. Although this factor depends on a large number of variables, such as collector temperature, optical efficiency, tracking mode, concentration ratio, latitude, clearness index, and direct-to-diffuse insolation ratio, it can be broken up into several components that depend on only two or three variables and can be presented in convenient graphical or analytical form. In general, the seasonal variability of the weather will necessitate a separate calculation for each month of the year; however, one calculation for the central day of each month is adequate for most purposes.

A detailed derivation and formulation of the analytical model for flat-plate collectors, compound parabolic concentrators, one-axis tracking concentrators (both N-S and E-W), and two-axis tracking concentrators is given in Appendix D. This model (via the computer code PROSYS discussed in Section 3.3) allows the end-use matching to proceed efficiently, with annual energy delivery predictions estimated to be within 5% to 10% accuracy.

3.2 SOLAR SYSTEM DESCRIPTION

A solar industrial process heat system includes the plumbing and equipment by which the energy gained by the solar collector working fluid is transferred to the process, as illustrated in Fig. 3-1. Obviously, in order to properly characterize the ability of collected solar energy to meet the end-use requirements of an industrial process, it is insufficient to estimate only the performance of the solar collector. Although a certain amount of solar energy is potentially deliverable from the solar collector field, the actual useful heat energy delivered at the process interface will depend upon losses in other parts of the system. Such losses include thermal losses in piping, valves, and equipment; losses in heat exchangers; and losses in steam production or heat conditioning.* Therefore, it is important that typical total system losses be included in PROSYS. For example, where saturated steam

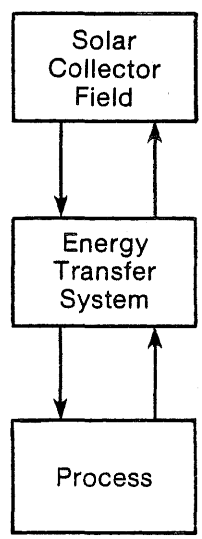


Figure 3-1. Relationship of Major Subsystems in Solar IPH Systems Modeled in PROSYS

*In addition, significant losses may result from diurnal warm-up and cool-down cycles and from collector field losses due to shading, as mentioned in Appendix D.

is required, it is important that the losses due to the production of steam (which may amount to as much as 15% of the collectible energy) and to the increased collection temperature required to allow steam flashing or steam generation at a lower required end-use temperature (perhaps a 50-F difference) be included in predictions of the long-term average performance of a solar process heat system.

System characteristics, such as parasitic heat losses and temperature differences required for heat exchange, influence the total performance of solar IPH systems. Realistic system models must therefore include these factors. The characteristics of the process (e.g., temperature, working fluid, configuration) will determine which systems are particularly suitable for solar applications. The simulation model developed for this study is not designed to evaluate explicitly all of these system characteristics since simplicity was a major factor in its development. Most of the important factors are accounted for, however, subject to the following assumptions and constraints:

(1) The number of system configurations provided in the model must be limited in order to limit the number of cases actually simulated in an extensive matching analysis. Otherwise, an inordinate amount of computing time would be required. This constraint thus forces us to find widely applicable general system configurations.

(2) System optimizations, including those for storage size, field layout, and multiple collector hybrids, are beyond the scope of the present effort.

(3) It is assumed that all (100%) energy delivered by the collectors and system can be used by the process; i.e., the process can absorb energy at the peak delivery rate of the solar system. Considerable detail on the dynamic behavior of the solar system and the process would be needed to use any other approach. If solar energy is used as a supplement to conventional energy sources rather than as a complete replacement, this assumption is reasonable provided that peak solar capacity does not exceed the maximum process load during periods of high insolation. This is expected to be the case for most solar industrial applications.

(4) Collector working fluid is maintained at a constant average temperature or constant unidimensional temperature distribution for which an average in each collector may be calculated.

(5) The system is supplemental; i.e., because of constant operating temperature requirements, system flow must be variable. Hence the percentage of load carried by solar energy will vary. Auxiliary capacity of up to 100% of load requirements generally will be required.

(6) No storage capability is included in PROSYS. The strict reliability requirements of industrial users probably will necessitate conventional backup capacity. It is likely that most near-term solar IPH systems will not include storage and will act as fuel savers by supplementing conventional systems. The third and fourth constraints listed above effectively limit PROSYS simulation of storage-coupled solar IPH systems; however, this is not a critical inability and attempts will be made to provide storage-coupled simulation capability in later program development.

In view of these constraints and of the need to uniformly calculate realistic solar IPH performance, six typical systems were selected that meet the majority of low- to intermediate-temperature IPH needs. Short descriptions of these systems are listed in Table 3-1, and schematics of the system configurations are shown in Figs. 3-2 to 3-7. Table 3-2 provides a summary of system specifications.

The six selected systems are deliberately simple in description and broad in applicability. Piping, controls, and mechanical equipment items shown in the schematics are for illustrative purposes only. The schematics indicate the typical placement of certain necessary items of major equipment. The equipment is not specifically sized for a given application. Instead, the modeled system is assumed to be designed for optimal thermal performance. Typical system loss characteristics are used to translate energy delivered from the solar collector field into useful energy delivered to the process interface (e.g., extractable energy in steam). This loss factor includes all system losses and is considered constant with respect to system capacity. These assumed loss factors and the corresponding balance-of-system efficiencies are shown in Table 3-3.

Assumptions about system temperatures affect overall solar IPH performance by influencing the average operating temperature of the collector, which in turn affects the collector thermal efficiency. The average collector operating temperature for collector performance calculations is the inlet temperature plus two-thirds of the temperature difference across the collector (outlet temperature minus inlet temperature). For direct systems (where air or water is heated, supplied to the process, and then discarded), the collector inlet temperature is 55 F for water (i.e., a feed water supply at 55 F is assumed) or ambient temperature from METDAT for air, and the outlet temperature is the same as the process temperature. This seems reasonable since a direct fuel-heated system would usually operate in the same way.

For exchange systems, the process fluid temperature of the inlet to the heat exchanger is 55 F for water or ambient temperature for air, and the outlet temperature is the process temperature. The solar collector fluid leaves the collector at 20 F (for water) or 30 F (for air) above the process temperature and leaves the exchanger at a temperature the same amount above the process fluid inlet temperature. Thus, for the same process temperature, the average collector operating temperature in an exchange system, as compared to a direct system, is 20 F greater for a water system or 30 F greater for an air system.

These assumptions were used for direct and exchange system simulations when details of the process were not known; they may not be adequate for all exchange systems. When a given amount of energy is exchanged between the solar working fluid and the process fluid, an equivalent amount of energy can be transferred to the process only if the fluid is cooled to its heat exchanger inlet temperature (55 F for water or ambient temperature for air). This seems unlikely for many processes. In most exchange systems it may be possible to recycle the process fluid through the heat exchanger. In such cases, the inlet temperature to the heat exchanger would generally be higher than is presently assumed, making the average collector operating temperature higher and the collector less efficient. On the other hand, recycling of process fluid means that its thermal energy is recovered, thereby reducing the amount of

Table 3-1. SELECTED SOLAR IPH SYSTEM CONFIGURATIONS

No.	PROSYS Label	Description
1	HW-DIRECT	Water heated in collector and delivered directly to process. Feed water assumed to be 55 F.
2	HW-XCHNG	Process water heated via heat exchange with collector-heated liquid. Collector fluid is in closed loop. Feed water assumed to be at 55 F.
3	HA-DIRECT	Air at ambient temperature heated in collector and delivered directly to process.
4	HA-XCHNG	Feed air (at ambient temperature) heated via heat exchange with collector-heated liquid and delivered to process. Collector fluid is in closed loop.
5	STEAM-FLSH	Steam produced via flashing of water heated in collector. Steam delivered to process, liquid returned to collector.
6	STEAM-GEN	Steam produced in unfired steam generator heated by collector-heated liquid. Steam delivered to process, condensate returned to steam generator. Collector liquid is in closed loop.

Table 3-2. SYSTEM SPECIFICATIONS

Assumptions
- Collector field operates at constant temperature: flow control
- No storage: 100% backup

Specifications Required
- Major items of auxiliary equipment
- Standards for piping and insulation
- Cost estimates: preferably with a size-to-total-cost correlation
- System heat loss estimates
- Required temperature margin (collector output to process input)

Flexibility
- Accepts any distributed collector field type in any field orientation
- Delivers process loads at any temperature and in any fraction of annual load requirements from 10% to 90% in 10% increments

Output Modifications
- Utilization losses due to operating schedules
- Utilization losses due to heat extraction efficiency

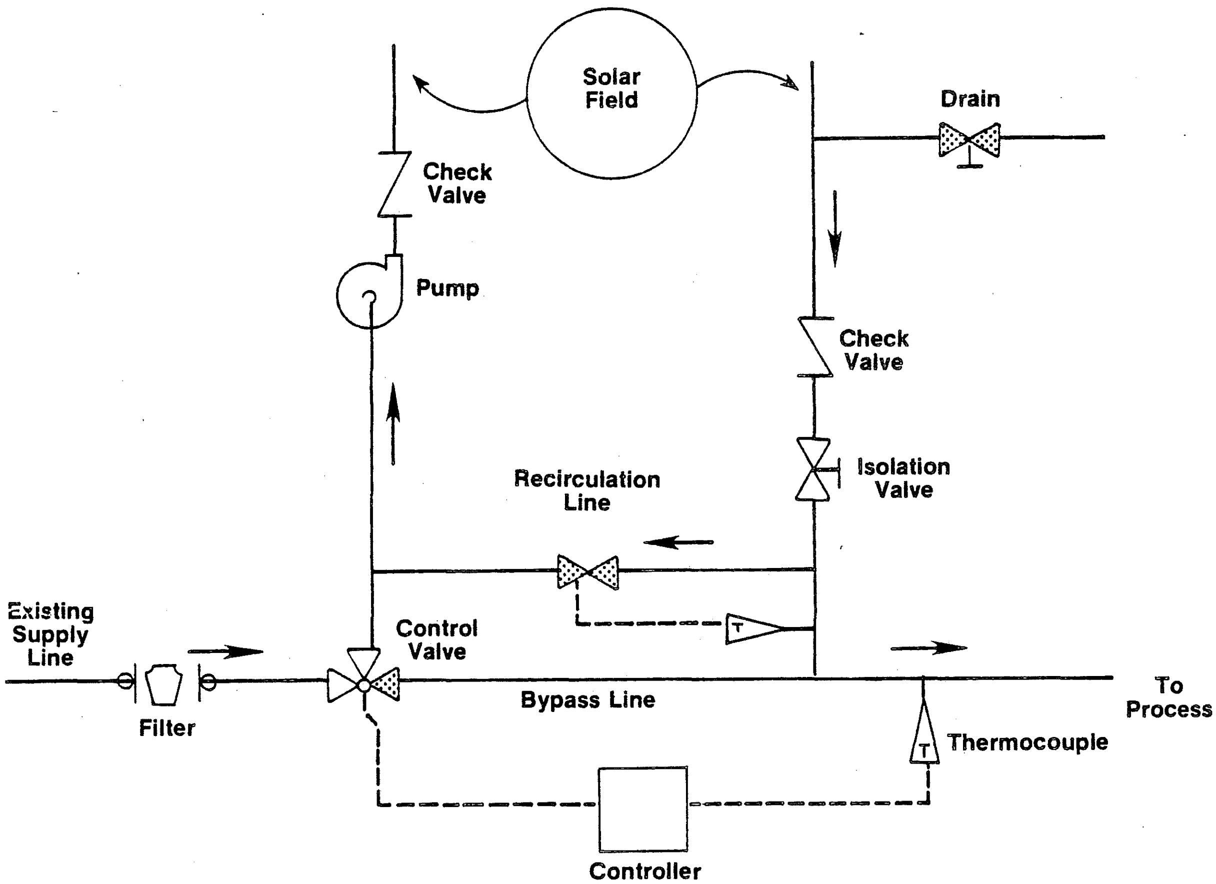


Figure 3-2. System No. 1: Direct Hot Water

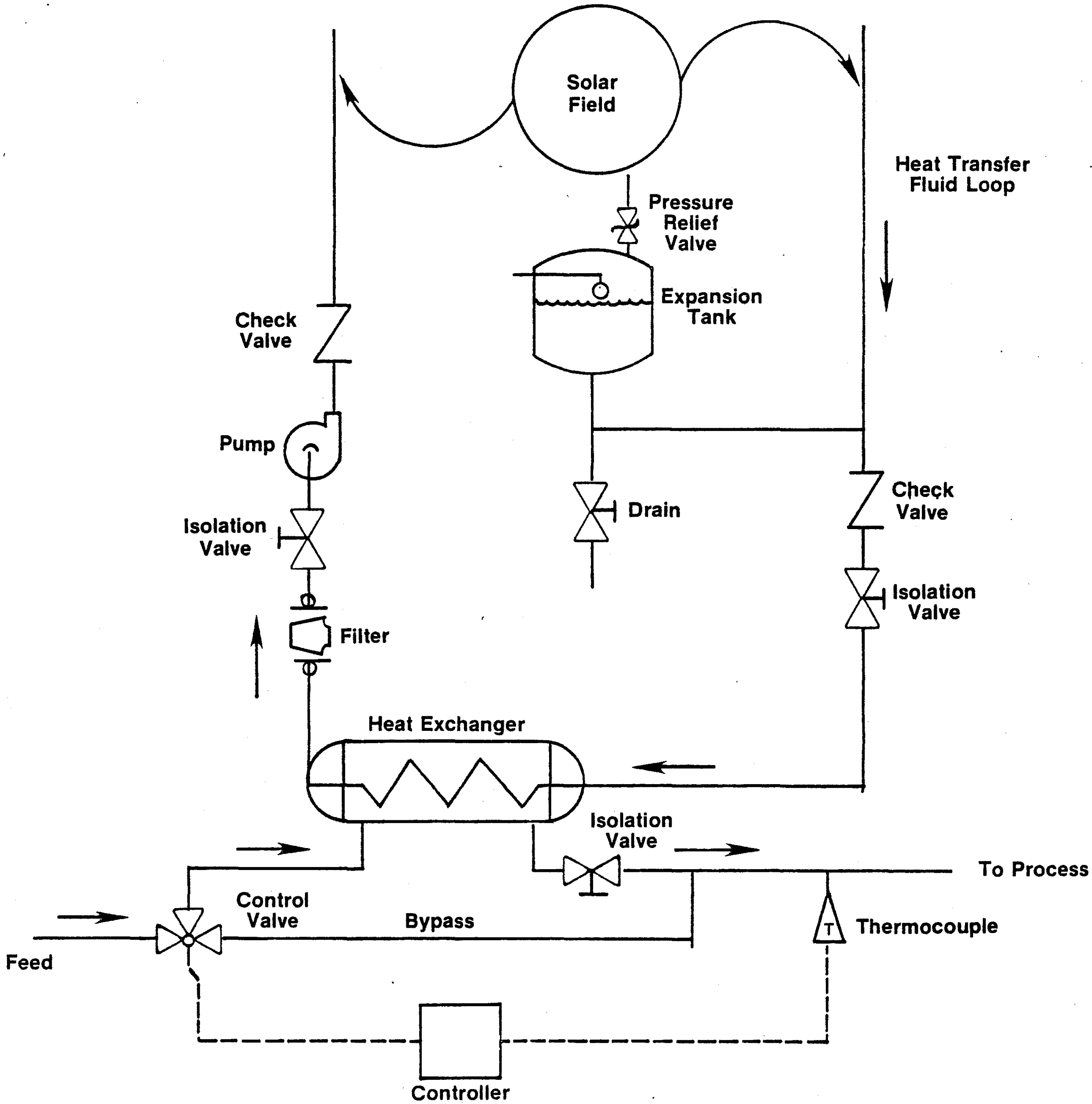


Figure 3-3. System No. 2: Hot Water Exchange

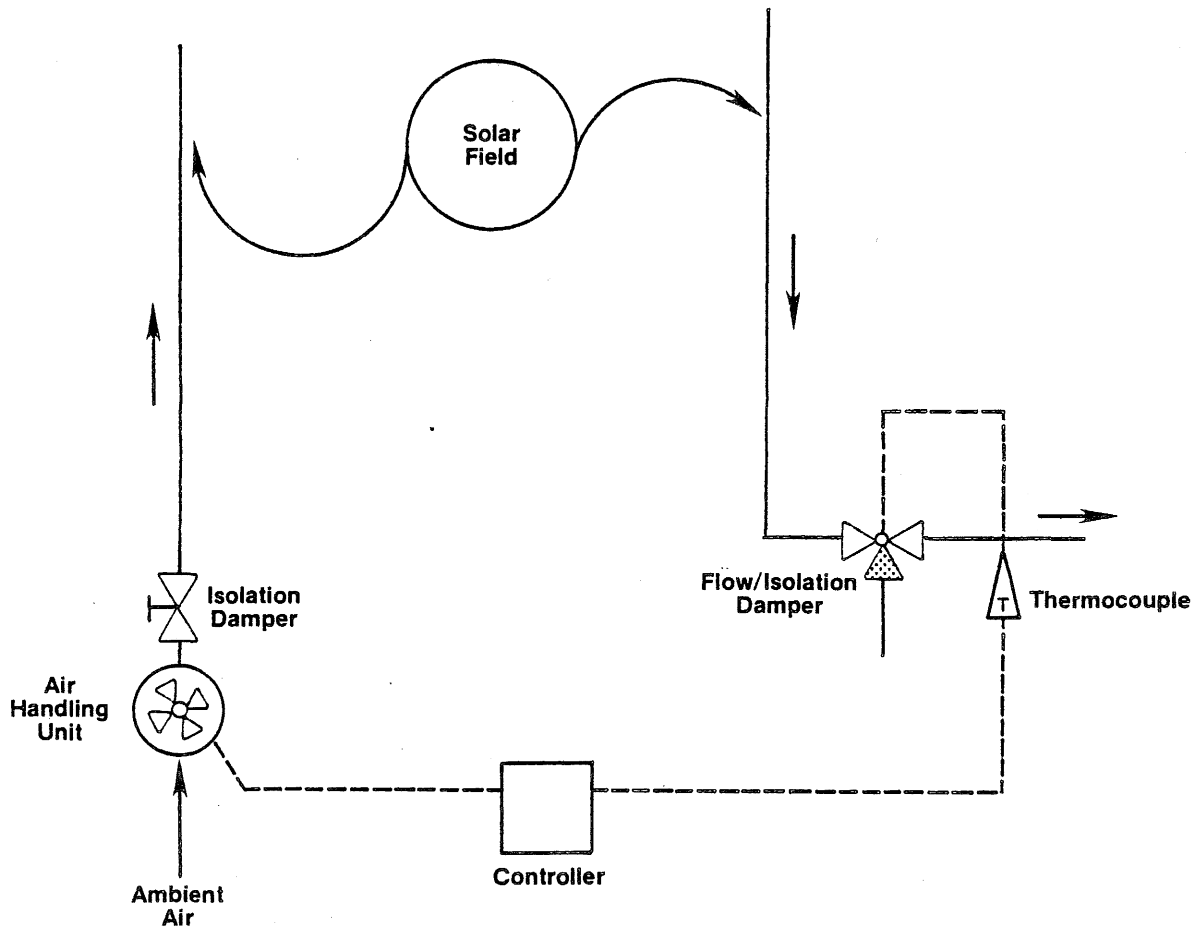


Figure 3-4. System No. 3: Direct Hot Air

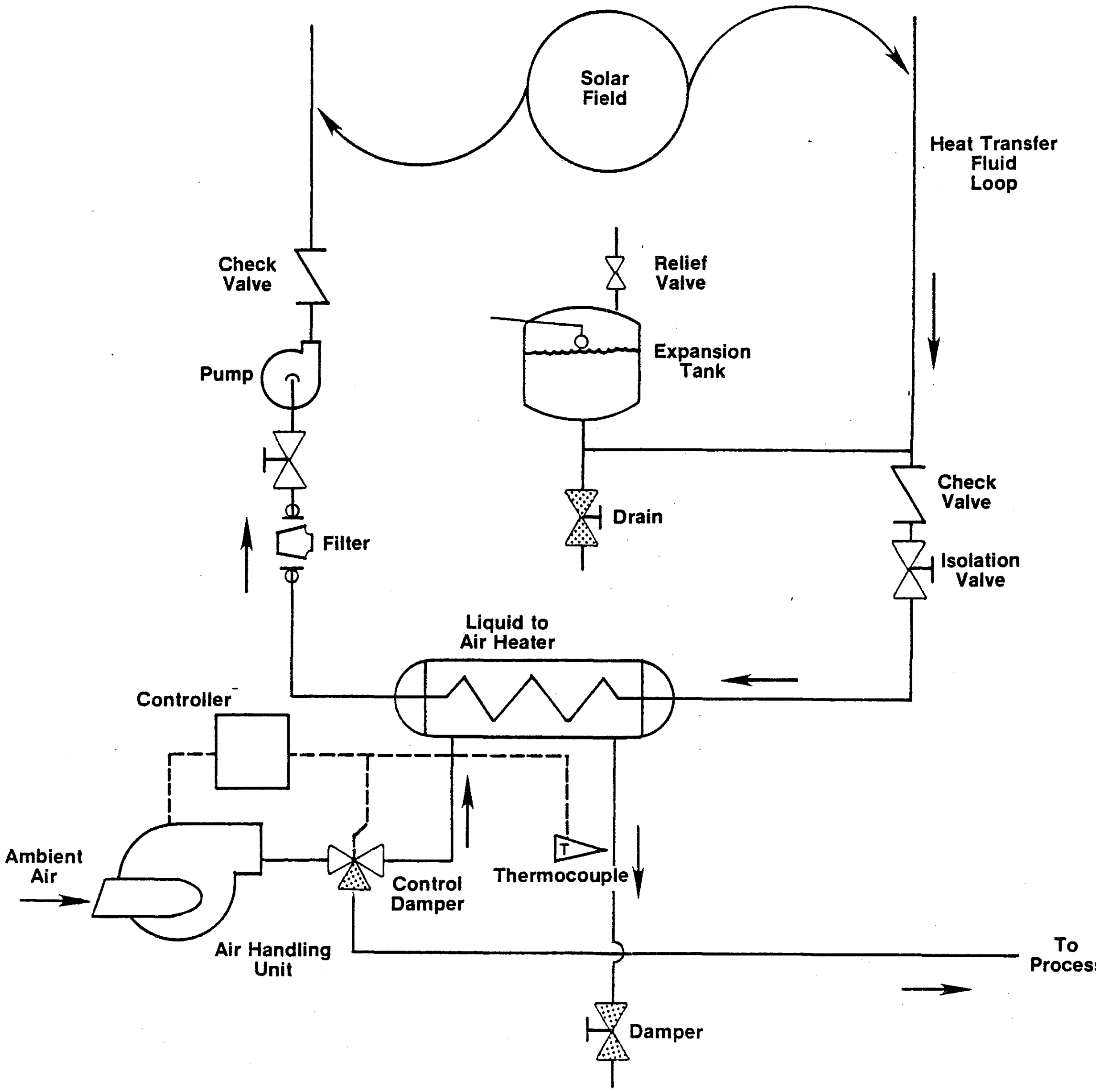


Figure 3-5. System No. 4: Hot Air Exchange

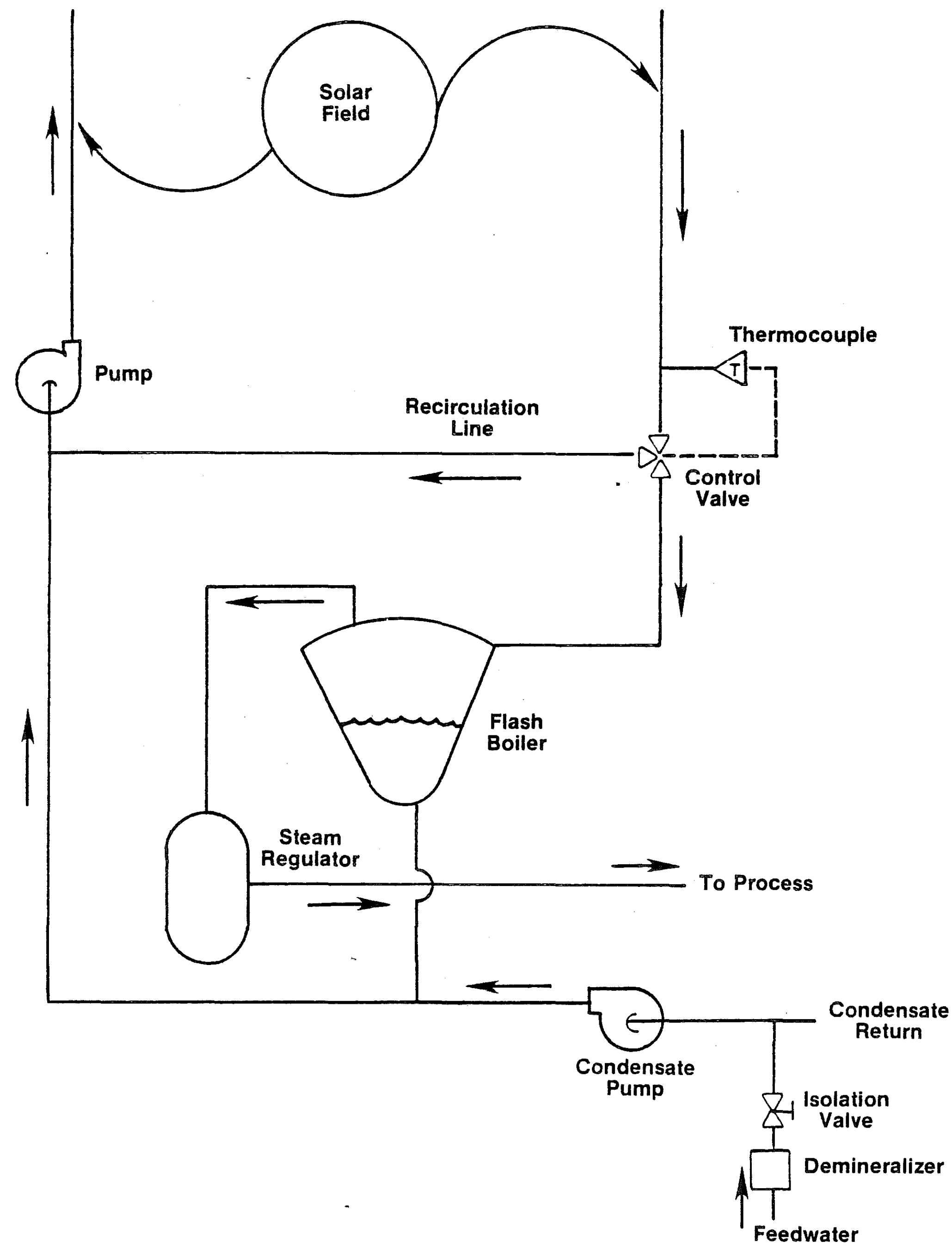


Figure 3-6. System No. 5: Steam Flash System

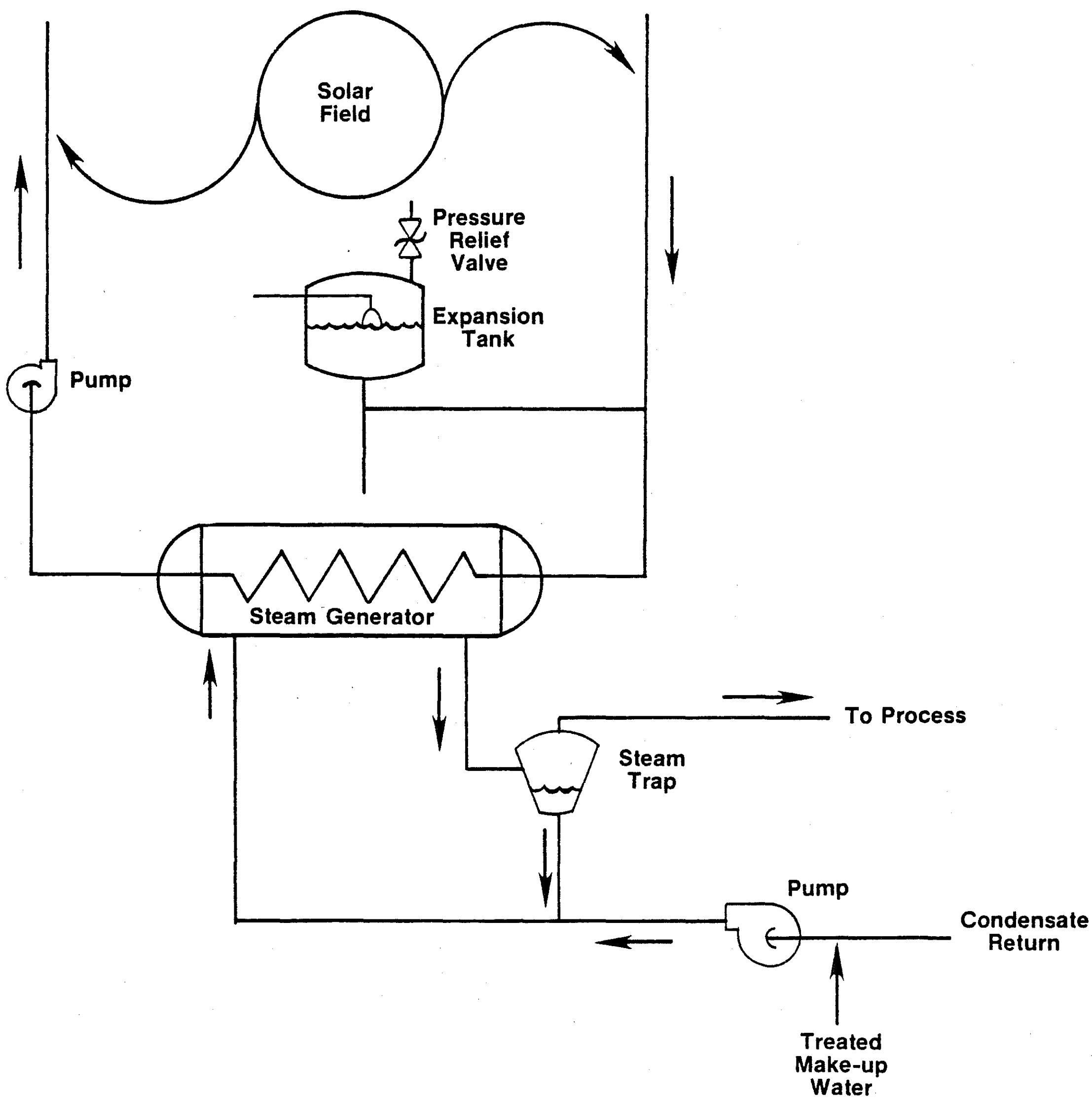


Figure 3-7. System No. 6: Steam Generation

Table 3-3. SYSTEM LOSS FACTORS

No.	PROSYS Label	Loss Factor	Efficiency (%)
1	HW-DIRECT	0.06	94
2	HW-XCHNG	0.08	92
3	HA-DIRECT	0.05	95
4	HA-XCHNG	0.10	90
5	STEAM-FLSH	0.09	91
6	STEAM-GEN	0.10	90

energy the collector must supply. The overall effect might be an increase or decrease of the collector area required, depending on the particular circumstances of the application; the case studies suggest that the required collector area will probably increase. Thus, PROSYS simulations of exchange systems do not always adequately reflect the coupling of the solar system to the process. The case studies provide guidance in approaching this problem.

3.3 THE PROSYS COMPUTER PROGRAM

The PROSYS computer program is an analytical tool that evaluates the abilities of various collector and system types to meet industrial process demands at selected sites. PROSYS uses information from the meteorological, industrial process heat, and collector data bases with the analytical performance model to calculate annual deliverable energy. The results are subsequently used in the economic analysis program ECONMAT. Figure 3-8 shows the basic relationship of the data bases and the computer programs PROSYS and ECONMAT. PROSYS is written in Fortran for the CDC 6000 series.

3.3.1 Program Logic

The main elements of the PROSYS program flow are presented in Fig. 3-9. PROSYS is designed to work with one site per computer run. For each run the identifying site number and the SIC codes for all processes at that site are user defined and are read from card input. The meteorological data for the selected site is then read from METDAT and additional site-dependent parameters are calculated, including midmonth values for sunrise time, noon solar elevation angle, and clear-day profiles for direct and total insolation. All information from the collector data base is accessed and stored.

The program then enters into a series of three nested loops: the outermost process loop, the middle system loop, and the inner collector loop. For each identified process the respective IPHDB information is accessed. Included in this information is the required process temperature and the identification of up to three applicable systems. For each system the system loop is entered and the average collector operating temperature required to meet the process

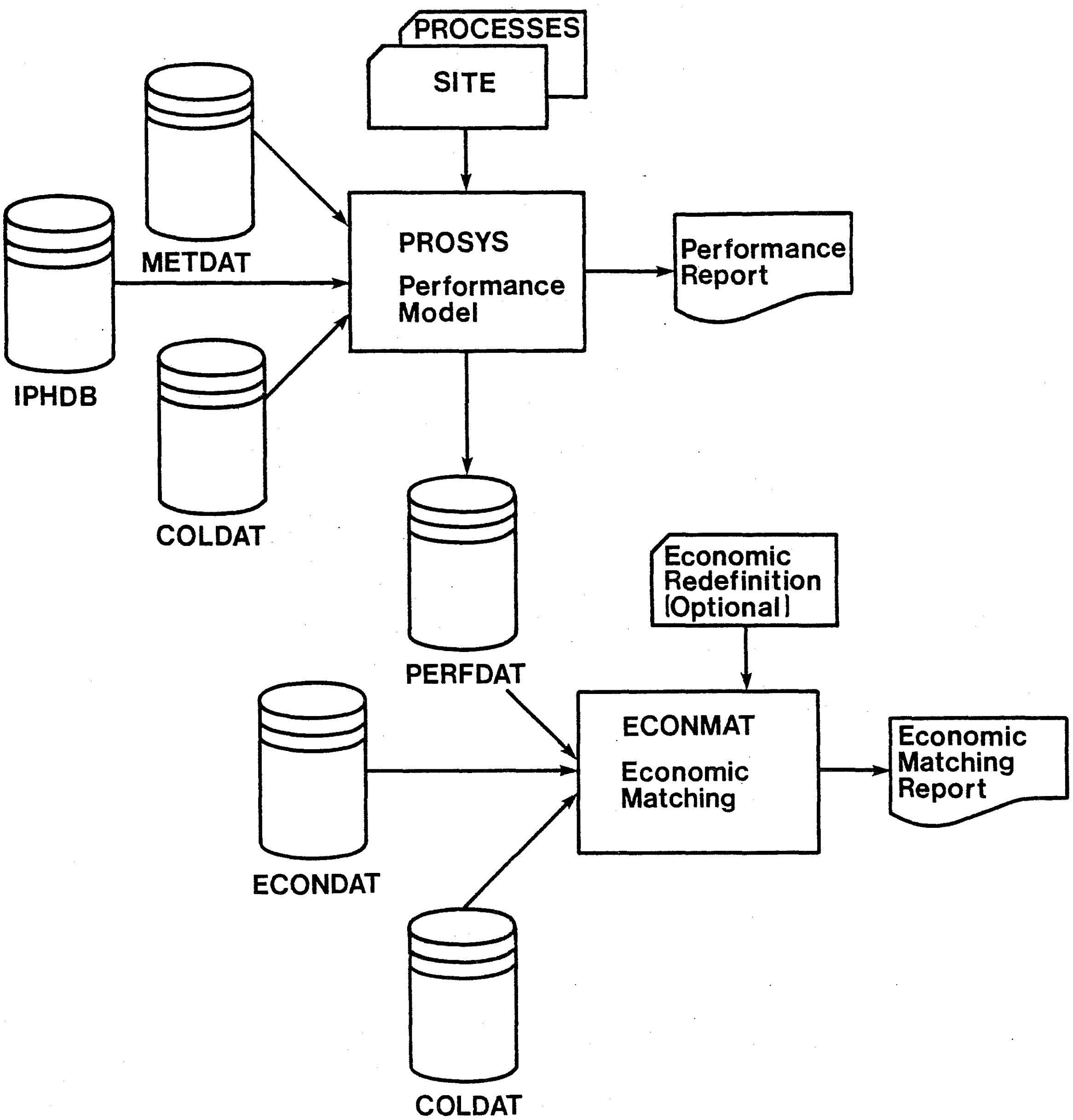


Figure 3-8. End-Use Matching Systems Flow Diagram

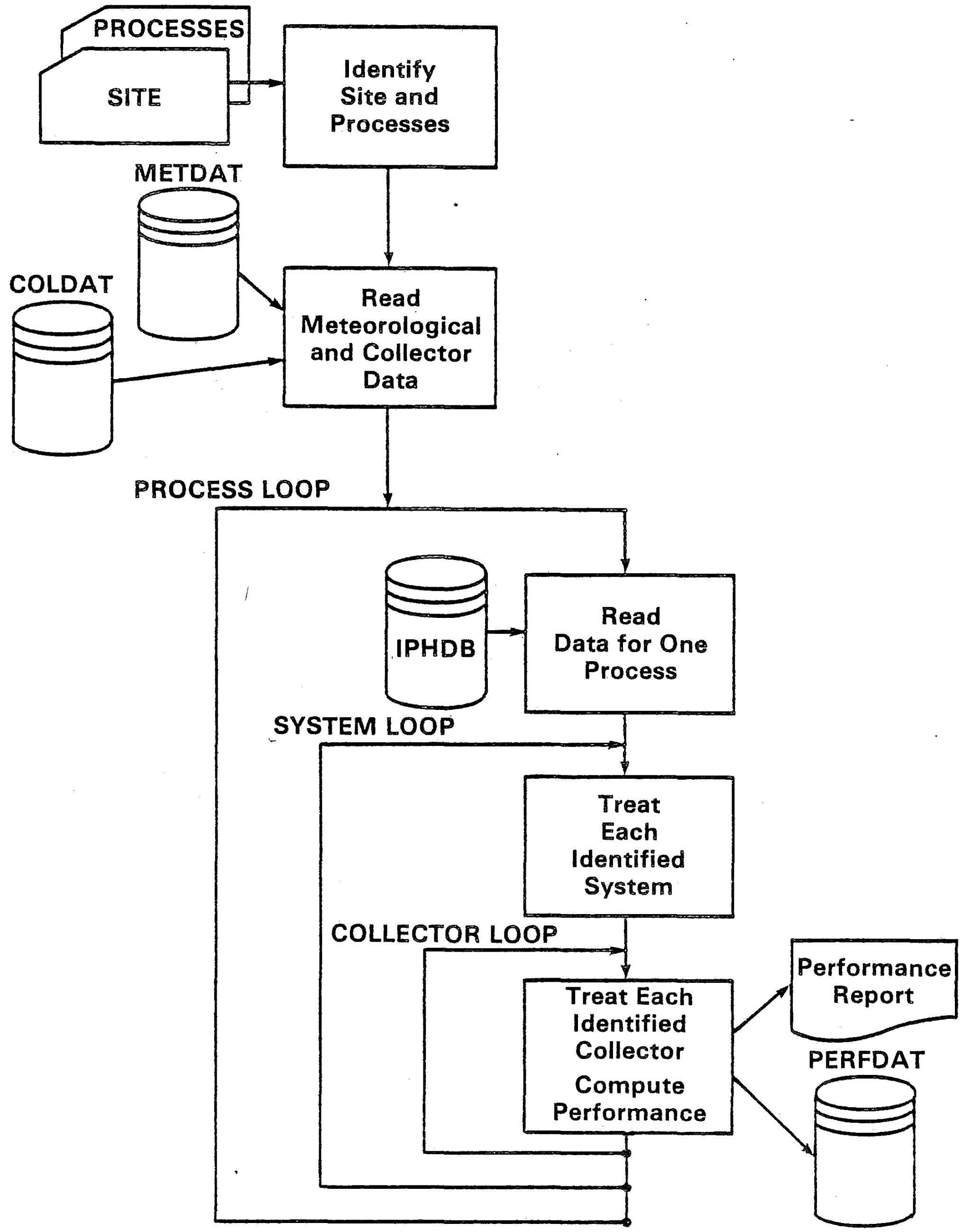


Figure 3-9. PROSYS Logic Flow Diagram

temperature is calculated. Internal to the program is a table that identifies the collectors suitable for each system. Accordingly, the inner collector loop is entered for each applicable collector. The major performance calculations are made in the inner loop and are a function of the specific collector parameters, the operating temperature, and the previously calculated meteorological parameters. The results of each collector's annual energy output in kJ/m^2 (Btu/ft^2) are printed and recorded in the performance data base PERFDAT.

3.3.2 Input

The normal operational mode of PROSYS requires only a few inputs from the user. This input is read from cards in namelist form and includes the site identification number and a list of the SIC codes for industrial processes. An optional parameter is IPTOR, a flag that describes the orientation for the parabolic trough collectors. The default value of 0 indicates a north-south (or polar) tracking axis; 1 indicates an east-west tracking axis; and 2 indicates both N-S and E-W. Sample input for Denver, Colo., is shown in Fig. 3-10.

```
$PRODAT
ISITE = 10,
NOPRO = 2016,2021,2024,2097,2491,2512,2653,
        3652,2655,3111,3429,3444,3851,
$END
```

Figure 3-10. PROSYS Sample Input

3.3.3 Output

PROSYS output is both a performance report and a disk file PERFDAT that records information for the companion economic analysis. The principal results of the performance report are the long-term average annual deliverable energy and annual efficiency for each process/system/collector combination. The report also includes a list of the collector data and meteorological parameters for the selected site. A portion of the performance report for Denver, Colo., is shown in Fig. 3-11. Useful for program verification or trouble-shooting, an optional printout shows month-by-month results for several intermediate performance parameters. The information recorded on PERFDAT includes process identification, required temperature, heat rate and steam flow rate, standard annual energy use, collector and system identification, and the resultant annual deliverable energy.

DENVER CO

PROCESS SIC -- 3111 LEATHER PROCESSING

ANNUAL LOAD = .334372E+11 KJ (.317000E+11 BTU)
PROC TMP = 60.00 C (140.00 F)

SYSTEM -- 3 HA-DIRECT OPR TMP = 44.14 C (111.46 F)

COLLECTOR	TYPE	TILT	QEFF	Q, BTU/SQFT	Q, KJ/SQM
FLAT PLATE E	FLAT PLATE	39.50	.38	.217216E+06	.246518E+07

SYSTEM -- 1 HW-DIRECT OPR TMP = 44.28 C (111.70 F)

COLLECTOR	TYPE	TILT	QEFF	Q, BTU/SQFT	Q, KJ/SQM
FLAT PLATE A	FLAT PLATE	39.50	.65	.364583E+06	.413765E+07
FLAT PLATE B	FLAT PLATE	39.50	.68	.384210E+06	.436040E+07
CPC 1.3X AHA=38.	CPC		.53	.297169E+06	.337257E+07
CPC 1.5X AHA=34.	CPC	~	.56	.313424E+06	.355705E+07
FRESNEL LENS A	PARA-T N-S	39.50	.66	.461064E+06	.523261E+07
PARABOLIC TROUGH D	PARA-T N-S	0.00	.56	.390416E+06	.443083E+07
PARABOLIC TROUGH E	PARA-T N-S	0.00	.55	.381565E+06	.433038E+07

SYSTEM -- 6 STEAM-GEN OPR TMP = 85.00 C (185.00 F)

COLLECTOR	TYPE	TILT	QEFF	Q, BTU/SQFT	Q, KJ/SQM
PARABOLIC TROUGH D	PARA-T N-S	0.00	.54	.356352E+06	.404424E+07
PARABOLIC TROUGH E	PARA-T N-S	0.00	.51	.341404E+06	.387460E+07

Figure 3-11. PROSYS Sample Output

3.3.4 Additional Uses

PROSYS was originally intended as a tool that in tandem with ECONMAT would facilitate end-use matching. The structure of PROSYS also lends itself readily to parametric sensitivity studies when temporary data bases are substituted in the appropriate formats. For example, in order to compare the performance of several collectors over a range of temperatures, only one data base must be substituted. A temporary version of the IPHDB is created using psuedo SIC codes for entries at the desired temperature values with all other process parameters held constant. The user input specifies the desired site and the psuedo SIC codes. A comparison of collector types on the basis of delivered energy per unit area is shown in Fig. 3-12. The analysis can be made for any of the 27 sites, yielding a three-way comparison of collector performance versus temperature versus geographic location.

The sensitivity of collector parameters can be similarly investigated by substituting a temporary collector data base. The data base contains repeated entries of the same collector with all parameters held constant except the one to be tested. In addition to the standard performance report, the optional debug printout is useful in this kind of sensitivity analysis.

PROSYS can be used for individual case studies. The standard IPHDB information for typical industrial processes can be supplemented by detailed information for a specific plant. This data can be added with a real or psuedo SIC code. Furthermore, many processes require heat at different temperature levels within the process sequence. Each level can be a separate data entry if the respective steam flow rate, heat rate, and annual energy use can be identified, can be analyzed with a substitute data base, or can be added to the standard IPHDB. Processes broken into temperature levels carry the same SIC code followed by a distinguishing alphanumeric character. Analysis of all levels is accomplished by repeating the SIC code as many times as there are IPHDB entries in the user input. The namelist input simplifies this analysis by allowing multiplicative definition of repetitive values (e.g., NOPRO = 5*9001, for five entries of SIC 9001).

3.3.5 Restrictions

Some restrictions intrinsic to PROSYS should be recognized in order to properly interpret the performance results. The annual deliverable energy from the solar system calculated by PROSYS is based on a collection time of seven days per week and the maximum possible hours per day. This approach is appropriate in comparing the deliverable energy to the load requirements of typical industrial processes contained in the IPHDB where a seven-day-per-week schedule is assumed. For specific case studies, however, the actual operating schedule can be approximated, thus yielding more accurate results. For example, for a plant that operates only five days per week, the optional input value NDPW (number of days per week) would be set to five and the annual deliverable energy would automatically be adjusted by a factor of five-sevenths. Similarly, the standard annual energy use of a plant operating 24 hours a day should be modified to reflect only the load demand during daylight hours since no storage capacity is assumed; at optimum conditions, solar supplementation could be used during only 10 hours.

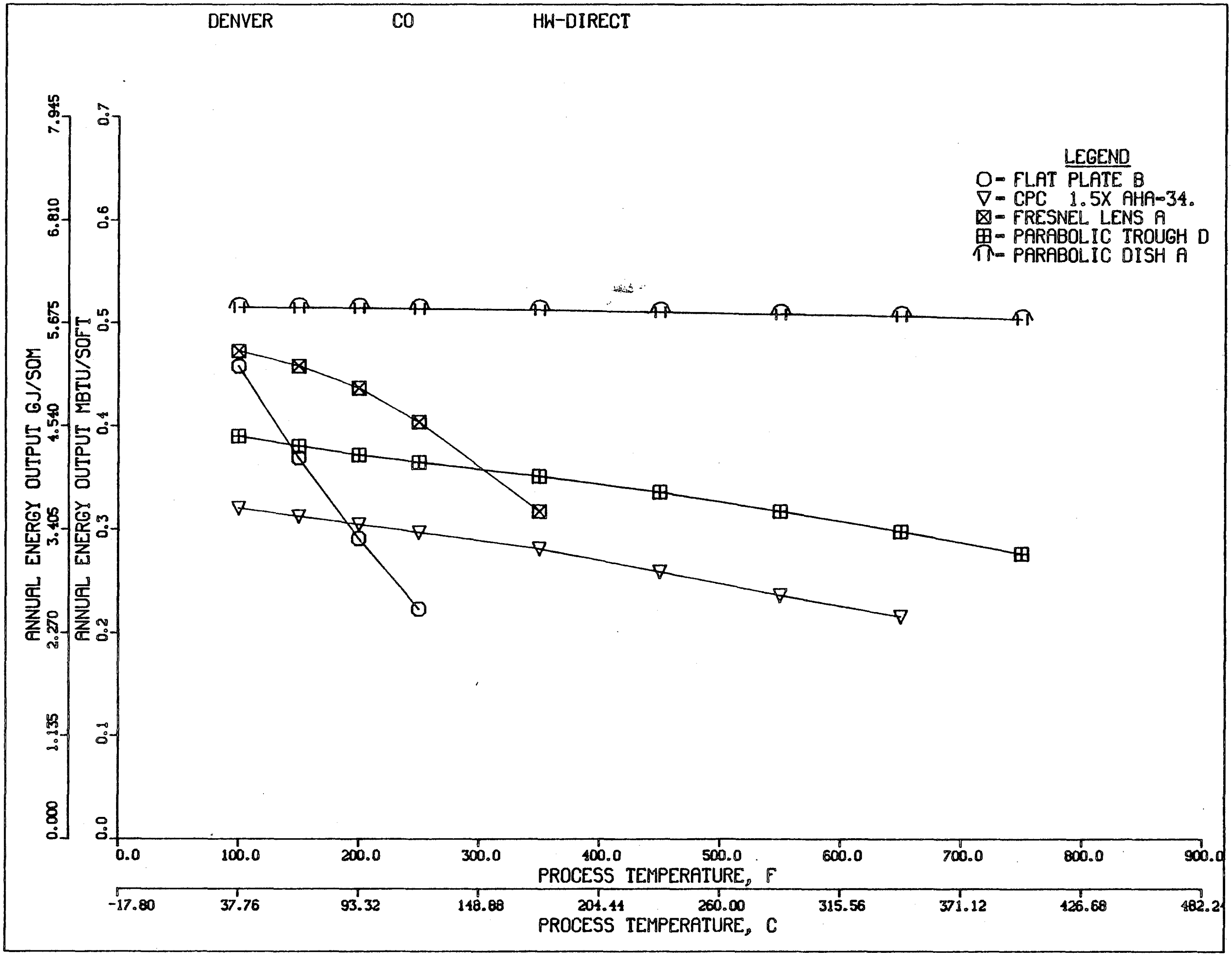


Figure 3-12. Annual Energy Delivered per Unit Area for a Direct Hot Water System in Denver, Colo.

The process temperature range analyzed by PROSYS is limited by individual collector characteristics. The IPHDB contains several processes whose temperatures are beyond those supplied by any collector contained in COLDAT. (The maximum temperature obtainable by these collectors is 540 C, or 1000 F.) These high-temperature processes are ignored in the PROSYS computations but are included in the data base. Case studies may indicate the need to evaluate preheat applications for such processes.

The deliverable energy per unit area of collector calculated by PROSYS is based on the output of a single collector module and does not include the effects of shading inherent in large collector array configurations. Shading on tracking collectors for some installations can lower the energy output 10% or more (Collares-Pereira and Rabl 1978). Future expansion of the PROSYS computer program should address collector array geometry and shading effects, as well as more details about the process system.

3.4 AN EXAMPLE OF PROSYS RESULTS

Although economic factors must be considered in meeting the end-use matching goals, performance analysis alone can contribute significant information. As an example of solar energy system performance analysis for industrial processes, PROSYS was run for SIC code 2051 (Bread and Baked Goods). The analysis was performed for all applicable systems and collectors for six cities. The complete PROSYS output for Denver is presented in Fig. 3-13. The output shows that one of the three applicable systems, direct hot air, is eliminated because the required temperature is too high for the only collector appropriate for this system. Tables 3-4 and 3-5 show the annual deliverable energy from the remaining system/collector combinations for all six cities. The hot-air and hot-water exchange systems (HA-XCHNG and HW-XCHNG) yield similar results, but the most applicable HA-XCHNG is lower in delivered energy than the third-choice HW-XCHNG. For both systems the parabolic trough has the greatest yield. This analysis concerns performance only; economics must be considered in selecting the most cost-effective collector/system combination.

Table 3-4. PROCESS SIC-2051 (BREAD/BAKED GOODS) HOT-AIR EXCHANGE SYSTEM

	Predicted Annual Deliverable Energy (GJ/m^2)					
Collector	Bismarck	Brownsville	Charleston	Denver	El Paso	Fresno
CPC 1.3X AHA = 38	1.67	1.86	1.50	2.42	2.78	2.32
CPC 1.5X AHA = 34	1.89	2.09	1.69	2.73	3.10	2.60
Parabolic trough D	2.51	2.97	2.34	3.64	4.40	3.69
Parabolic trough E	2.36	2.83	2.26	3.45	4.20	3.51

DENVER CO

PROCESS SIC -- 2051 BREAD/BAKED GOODS

ANNUAL LOAD = .949320E+10 KJ (.900000E+10 BTU)
PROC TMP = 232.22 C (450.00 F)

SYSTEM -- 4 HA-XCHNG OPR TMP = 175.68 C (348.23 F)

COLLECTOR	TYPE	TILT	QEFF	Q, BTU/SQFT	Q, KJ/SQM
FLAT PLATE A	REQUIRED TEMPERATURE TOO HIGH				
FLAT PLATE B	REQUIRED TEMPERATURE TOO HIGH				
CPC 1.3X AHA=38.	CPC		.40	.213467E+06	.242263E+07
CPC 1.5X AHA=34.	CPC		.44	.240135E+06	.272529E+07
FRESNEL LENS A	REQUIRED TEMPERATURE TOO HIGH				
PARABOLIC TROUGH D	PARA-T N-S	0.00	.48	.320533E+06	.363773E+07
PARABOLIC TROUGH E	PARA-T N-S	0.00	.46	.304047E+06	.345062E+07

SYSTEM -- 3 HA-DIRECT OPR TMP = 159.02 C (318.23 F)

COLLECTOR	TYPE	TILT	QEFF	Q, BTU/SQFT	Q, KJ/SQM
FLAT PLATE E	REQUIRED TEMPERATURE TOO HIGH				

SYSTEM -- 2 HW-XCHNG OPR TMP = 170.26 C (338.47 F)

COLLECTOR	TYPE	TILT	QEFF	Q, BTU/SQFT	Q, KJ/SQM
FLAT PLATE A	REQUIRED TEMPERATURE TOO HIGH				
FLAT PLATE B	REQUIRED TEMPERATURE TOO HIGH				
CPC 1.3X AHA=38.	CPC		.40	.222524E+06	.252543E+07
CPC 1.5X AHA=34.	CPC		.45	.247847E+06	.281281E+07
FRESNEL LENS A	REQUIRED TEMPERATURE TOO HIGH				
PARABOLIC TROUGH D	PARA-T N-S	0.00	.49	.330318E+06	.374877E+07
PARABOLIC TROUGH E	PARA-T N-S	0.00	.46	.313094E+06	.355331E+07

Figure 3-13. PROSYS Output for SIC 2051(Bread/Baked Goods) in Denver, Colo.

Table 3-5. PROCESS SIC-2051 (BREAD/BAKED GOODS) HOT-WATER EXCHANGE SYSTEM

Collector	Predicted Annual Deliverable Energy (GJ/m^2)					
	Bismarck	Brownsville	Charleston	Denver	El Paso	Fresno
CPC 1.3X AHA=38	1.74	1.98	1.59	2.53	2.91	2.43
CPC 1.5X AHA=34	1.95	2.19	1.76	2.81	3.21	2.69
Parabolic trough D	2.58	3.07	2.47	3.75	4.54	3.81
Parabolic trough E	2.42	2.92	2.34	3.55	4.34	3.63

The performance analysis is more appropriate for sensitivity studies examining collector performance. A comparison of energy per unit area delivered annually by several collector types and a comparison of the effects of variations in tilt and orientation of one-axis tracking concentrators are shown in Fig. 3-14. In all three cases, the flat plates are tilted at an angle equal to the latitude of the site, the CPCs are nonadjustable and tilted at an angle equal to latitude, and the parabolic dish has complete two-axis tracking. The orientation and tilt of the parabolic trough collector are varied as follows:

- tracking about N-S axis and tilted at an angle equal to the site latitude (N-S-T);
- tracking about N-S axis and placed horizontally (N-S-H); and
- tracking about E-W axis and placed horizontally (E-W-H).

A few observations can be made concerning the graph in Fig. 3-14. The flat-plate collectors excel only at very low temperatures, while the parabolic dish has excellent thermal performance over a large temperature range. The parabolic trough shows highest performance when tracking about the N-S axis and tilted at an angle equal to the latitude. However, even when the collector is horizontal, tracking about the N-S axis yields a higher performance than does tracking about the E-W axis. The nonadjustable CPC (with evacuated tube receiver), tilted at an angle equal to the latitude, is competitive in performance with the E-W-oriented one-axis tracking concentrators. Thermal performance alone, however, is not a sufficient criterion for selecting a collector array. Because of shading effects, field layout, plumbing connections, and line losses, the E-W tracking axis orientation is often more practical for large collector array installations than is the N-S orientation. In addition, line losses and parasitic power requirements for the parabolic dish system may significantly reduce the overall thermal performance of this system. A great deal of work remains to ensure that PROSYS accurately reflects these losses in evaluating the parabolic dish system. Complete results of the end-use matching analysis are presented in Section 5.0.

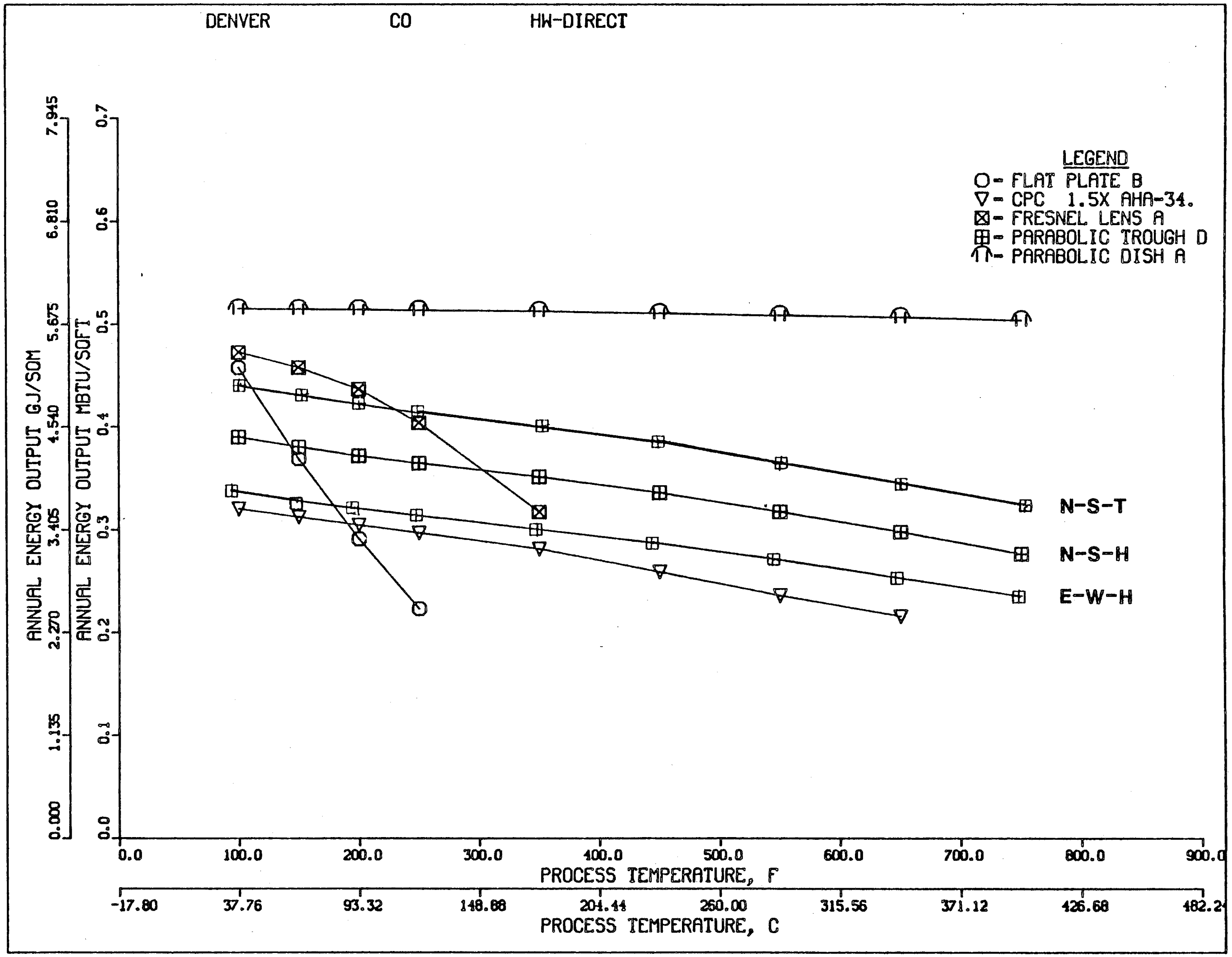


Figure 3-14. Annual Delivered Energy per Unit Area

3.5 References

Collares-Pereira, Manuel; Rabl, Ari. 1978. Simple Procedure for Predicting Long-Term Average Performance of Nonconcentrating and Concentrating Solar Collectors. Argonne, IL: Argonne National Lab.; June; ANL-78-67.

Liu, B. Y. H.; Jordan, R. C. 1963. "A Rational Procedure for Predicting the Long-Term Average Performance of Flat-Plate Solar Energy Collectors." Solar Energy. Vol. 7: p. 53.

SECTION 4.0

ECONOMIC ANALYSIS

In order to rank the matches of collector, system, process, and location tested in the successive loops of PROSYS, it is necessary to estimate the initial and life-cycle costs of the solar IPH system. In the method adopted in this study, emphasis is placed upon the determination of initial capital costs of the system, since this dominates system life-cycle costs. Estimates of life-cycle costs of delivered energy can vary considerably due to the different sets of economic assumptions made by individual companies. Since such information was not readily available for specific plants in the IPHDB, a generalized form of analysis, described in this section, was developed. In this analysis an annual cost multiplier is chosen based on any of a large set of economic parameters and multiplied by a specific capacity cost in order to yield the levelized cost of delivered solar energy. The matches may then be selected and ranked on the basis of the levelized cost of delivered solar energy.

4.1 COST ESTIMATING

4.1.1 Methodology

Since the initial capital cost of solar process heat systems accounts for an overwhelming share of distributed yearly costs of providing energy (due to the required capital recovery), the initial capital costs of the systems included in this analysis must be identified accurately and consistently. However, due to the large numbers of systems evaluated in this analysis, a detailed estimate of the cost of each system configuration for a given load and location is difficult; instead, the method of factor estimating is used. As applied in the chemical industry, factor cost estimating is typically accurate to within 15%. However, considerable work is still required in the development of methods of cost estimating for solar systems.

Only current identifiable costs are used in this analysis. The end-use matching does not seek to identify or credit future cost reductions in solar equipment or systems. Costs used in COLDAT and in the equipment cost relations of SYSCOST (a subroutine of PROSYS) are in 1978 dollars and are typical of 1977 component costs.

The method applied is consistent with the methodology initially reported by Lang and Chilton and described by Holland et al. (1974). In short, fixed initial system capital costs may be expressed as follows:

$$C_{sys} = \phi_1 \phi_2 \phi_3 \sum C_{EQ}$$

where

C_{sys} = fixed initial system capital cost;

ϕ_1 = process type factor;

$\phi_2 = 1 + f_1 + f_2 + f_3 + f_4 + f_5$;

$\phi_3 = 1 + f_6 + f_7 + f_8$;

$\sum C_{eq}$ = sum of delivered, uninstalled, capital equipment costs for major equipment items.

As a result of experience and data collection in the chemical industry, values for the factors f_i have been proposed. These values are listed with their descriptions in Table 4-1. For fluid processing systems, the broad class into which we assume solar IPH falls, ϕ_1 equals 1.47.

At the Solar Energy Research Institute the Lang-Chilton method was applied in obtaining the initial cost estimates for a large-scale solar IPH test facility called SERAPH (Solar Energy Research and Applications in Process Heat). Early detailed estimates of the cost of this facility (which includes approximately 5,000 ft^2 of collector) were about $790,000. An adjusted cost estimate for the facility was calculated with the Lang-Chilton method and found to be $795,000, less than 1% above the initial factor estimate.

Major nonsolar equipment is listed for each generic system configuration modeled in PROSYS. In most cases, a capital cost equation for estimating costs of uninstalled components is assigned so that the equipment may be assigned a cost based on capacity. Where necessary, capacity is related to solar collector field area, fluid flow rate, or to the assumed heat rate. The values for Lang-Chilton f-factors within the ranges specified in Table 4-1, chosen to reflect the complexity and character of the various system configurations, are shown in Table 4-2. Systems are identified by numbers as defined in Table 3-1.

Note that the system cost model is applied only to the nonsolar portions of the IPH system. Since a large portion of system costs are associated with the installed collector field, costs of the collector field subsystem are calculated separately. To obtain an installed collector field cost, the required collector field area as defined in PROSYS output is multiplied by the installed cost per unit area. This per unit area cost is obtained from COLDAT and ECONDAT in the following manner:

(1) Collector equipment costs, $/SQM
    $/SQM = F.O.B. collector equipment cost per unit area;

(2) Installation labor costs, HR/SQM × L$
    HR/SQM = Person-hours required to install unit area of collector
    L$ = Local composite labor rate ($ per person-hour);

(3) Extra costs, (B$/SQM + A$/SQM)
    B$/SQM = Delivery and other costs per unit area
    A$/SQM = Cost of fittings and other material per unit area;

(4) Collector Subsystem Unit Area Cost, $C_{AC} = \sum$ (1) + (2) + (3).

The total installed collector subsystem cost is then $A_C \times C_{AC}$, where A_C is the required collector aperture area. The total system cost reported in ECONMAT output and used in the economic analysis as the total initial investment I is

$$I = C_{total} = A_C \times C_{AC} + C_{sys} \quad .$$

Table 4-1. LANG-CHILTON f-FACTORS FOR CAPITAL COST ESTIMATES

Factor and Range	Condition
f_1, process-piping factors	
0.07 to 0.10	Solids processing
0.10 to 0.30	Mixed solids/fluids processing
0.30 to 0.60	Fluid processing
f_2, instrumentation factors	
0.02 to 0.05	Little automatic control
0.05 to 0.10	Some automatic control
0.10 to 0.15	Complex automatic control
f_3, building factors	
0.05 to 0.20	Outdoor units
0.20 to 0.60	Mixed indoor and outdoor units
0.60 to 1.00	Indoor units
f_4, facilities factors	
0 to 0.05	Minor additions
0.05 to 0.25	Major additions
0.25 to 1.00	New site
f_5, outside lines factors	
0 to 0.05	Existing plant
0.05 to 0.15	Separated units
0.15 to 0.25	Scattered units
f_6, engineering and construction factors	
0.20 to 0.35	Straightforward plants
0.35 to 0.50	Complex plants
f_7, size factors	
0. to 0.05	Large plants
0.05 to 0.15	Small plants
0.15 to 0.35	Experimental plants
f_8, contingency factors	
0.10 to 0.20	Firm process
0.20 to 0.30	Process subject to change
0.30 to 0.50	Tentative process

$$\phi_1 = 1.47$$

$$\phi_2 = 1 + f_1 + f_2 + f_3 + f_4 + f_5$$

$$\phi_3 = 1 + f_6 + f_7 f_8$$

Table 4-2. SELECTED f-FACTORS

Factor	System Number[a] 1	2	3	4	5	6
f_1	0.30	0.30	0.30	0.30	0.35	0.35
f_2	0.05	0.09	0.05	0.09	0.09	0.09
f_3	0.20	0.20	0.20	0.20	0.20	0.20
f_4	0.05	0.05	0.05	0.05	0.10	0.10
f_5	0.10	0.10	0.10	0.10	0.10	0.10
f_6	0.20	0.20	0.20	0.20	0.20	0.20
f_7	0.10	0.10	0.10	0.10	0.10	0.10
f_8	0.20	0.20	0.20	0.20	0.20	0.20
ϕ_2	1.70	1.79	1.70	1.79	1.84	1.84
ϕ_3	1.50	1.50	1.50	1.50	1.50	1.50
$\phi_1\phi_2\phi_3$	3.75	3.95	3.75	3.95	4.06	4.06

[a]See Table 3-1.

4.1.2 Comparisons

Successive runs of the PROSYS-ECONMAT code have shown reasonable estimates of costs of solar IPH systems consistent with costs for current or proposed DOE IPH projects. In most cases, the relative amount of cost attributable to the collector subsystem is greater than that found in actual project data. A lack of information on direct hot air systems makes estimates of these systems difficult, however, and cost estimates from ECONMAT seem even more heavily weighted by collector costs than for equivalent liquid systems. The lower system costs from ECONMAT (as compared with actual data) probably result from insufficient design detail for non-collector subsystems and from the exclusion of data acquisition and energy storage subsystems in PROSYS-ECONMAT designs. Much work in the area of IPH cost analysis remains to be done, including:

- detailed review of costs of existing IPH projects to separate special items of cost and identify cost relationships,
- development of more accurate and sophisticated cost models for conceptual systems, and
- development of a capability to assess n^{th} unit component and system costs in order to study the effects of cost reduction on IPH system matchings in future years.

Figure 4-1 shows the relative contribution of installed subsystem costs to total installed system cost as determined from published and unpublished data of IPH field engineering experiments funded by DOE. The average contribution of collector field installed costs is 60%. Collector field contribution to total cost as determined by PROSYS-ECONMAT varies from approximately 60% to 90%.

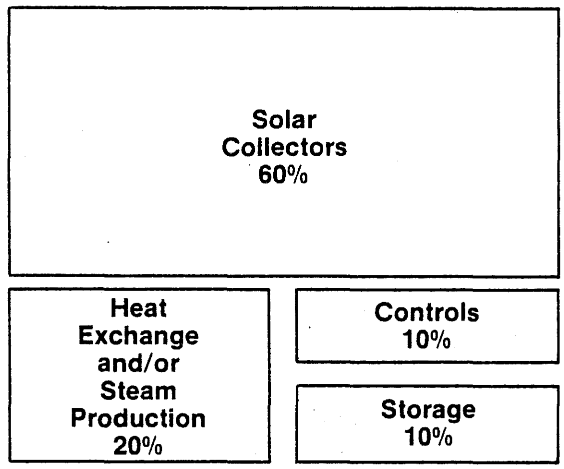


Figure 4-1. Relative Contribution of Various Installed Subsystem Costs to Total System Cost in Current IPH Field Engineering Experiments

4.2 ECONOMIC ANALYSIS

A number of evaluation techniques are available to a company considering capital investment in a given project. Return on invested capital is used as a measure of the relative, and sometimes the absolute, desirability of various capital investment schemes. Other considerations aside, the investment in a solar system must compete with a wide range of other investment options for a limited amount of capital. If energy supply systems are needed, the solar system probably will be compared to conventional process heaters. If no particular need for energy supply systems exists, then the solar system investment must be compared to investment in any number of other capital projects, such as plant expansion, production equipment, or business acquisition, or, in absolute terms, against the decision not to invest at all. Company management is responsible for optimal allocation of the stockholders' funds, with the long-term objective of maximizing returns on the stockholders' investments. It is important to realize that solar system investment will be considered in this light.

The most important techniques available for capital investment evaluation include: (1) payback period calculation, (2) annual discounted cash flow comparison, (3) net present value analysis, (4) calculation of discounted cash flow rate of return, and (5) determination of annual savings per investment dollar. According to the U.S. Department of Commerce (1977) the methods most often employed by large, energy-intensive industries are the simple payback period and the determination of discounted cash flow rate of return (ROR). Rates of return of the order of 15% to 30% are often quoted by company managers as necessary orders of merit; a payback period of from 3 to 5 years appears typical of industry preferences. The 3- to 5-year payback is a severe test for large, capital-intensive projects such as solar process heat systems. It essentially requires that accumulated net revenue (for example, net energy savings) over 3 to 5 years equal, at least, the initial capital investment in the solar system. Because the 15 or so years of service following this "payback period" are essentially neglected, the payback period method does not accurately reflect the total return on investment over the project lifetime.

The calculation of discounted cash flow rate of return, or its variants, is a more accurate method of comparing possible capital investments. A concise discussion of the calculation of the rate of return for solar process heat systems is offered in Dickinson and Freeman (1977) and is the basis for the net present value analysis presented in Appendix E. The method adopted and described in detail in this subsection is a variant of the basic discounted cash flow analysis and is known as a "required revenue approach." Given the internal rate of return desired and other specifics of a company's economic situation, one may calculate the essential "cost" of solar process heat over the lifetime of the system. By externalizing factors dealing with local economics, company rates of return, and alternative fuel costs, the essential cost-effectiveness of any solar system can be isolated from a mire of hidden assumptions. Once this levelized cost per unit of delivered energy is obtained, the cost of solar process heat may be directly compared to the levelized cost of conventional alternatives.

The required revenue methodology described in this section is based on work by Dickinson and Brown (1979) on a simplified approach to economic analysis for solar process heat systems. This approach seeks to clearly separate the issues of fuel price and fuel price escalation from the assessment of the cost of a solar energy system. While the principle of discounted cash flow is the same as that used in previous methods (see, for example: Dickinson and Freeman 1977; Lameiro and Brown 1978), the placement of variables and elements of the basic equations has been modified to clearly separate capital cost and performance from investment and tax factors and from fuel price and fuel price escalation. In the original versions of our study of IPH end-use matching, a net present value analysis was employed. This analysis, extremely useful in case studies and sensitivity studies, is described in Appendix E.

"Required revenue" is a term used in the utility industry for the total amount of money that must be generated through sales of power at a given rate over a given period of time in order to exactly cover the costs of building and operating the utility system. The costs include adequate return to investors, repayment of debt, and payment of taxes. In an analogous fashion, a "price" may be determined that must be charged implicitly for delivered solar heat over the lifetime of the solar process heat system. The revenue thus generated should cover the total costs of installing, maintaining, operating, and dismantling the solar process heat system and include an adequate return to corporate capital invested. Since the stream of yearly costs associated with the solar facility will be subject to the discounted future value, it is appropriate to levelize the stream of costs. Thus the yearly costs of the facility over a system lifetime of 20 years can be expressed as a series of 20 equal annual payments in current dollars that completely cover the costs of the system. This method is described by Doane et al. (1976) and in almost any standard engineering economic text [such as Grant and Ireson (1970)].

Figure 4-2 shows a typical stream of before-tax costs and savings, in actual current dollars (i.e., dollars in the year of payment), for a solar industrial process heat system.* Note that construction time is assumed to be one year (during year 0) and that the useful system operating lifetime is N years. The figure shows the initial capital cost of the system as a single large amount I paid at the end of year 0. This amount I includes the value of all expenditures during the construction period, including interest during construction and operation check-out and adjustment costs. It represents the future value at the end of year 0 of all expenditures of that year. The present value of future costs and savings (years 1 through N) may be determined by using the appropriate present worth factors to calculate the present values of the N cash amounts. These present values may be summed with I to yield the net present value of the total cash flow as of the end of year 0. If this is done, however, some weighted cost of capital must be defined and applied to all future expenses. This method does not allow explicit definition of the actual form of solar system financing (part debt, part equity). A more satisfactory cash flow representation is shown in Fig. 4-3, where actual annual payments to repay debt principal and equity capital and to pay debt interest and provide return on equity with tax considerations are shown for each of N years. The present value of this cash flow, excluding fuel savings, at the end of year 0 (i.e., the beginning of system operation) is then the sum of all the net annual costs multiplied by the appropriate present worth factor. Net present value at the end of year 0 is then converted to a series of N equal disbursements by multiplying by the capital recovery factor:

$$C_s = CRF(i,N)\ PV_s \quad , \tag{4-1}$$

where

C_s = levelized or annualized revenue required, before taxes, to cover solar system costs;

$CRF(i,N) = \dfrac{i(1+i)^N}{(1+i)^N - 1}$ = capital recovery factor, where i is the after-tax rate of return required over a period of N years;

PV_s = present value of solar system revenue requirements.

It is convenient to represent all of the terms in the present value analysis that are part of variable expenses (such as operation and replacement costs) as fractions of the initial total capital investment I. The expression for C_s then becomes an explicit function of I. Hence, a proportionality constant M which may be termed the "multiplier," as given by Dickinson and Brown (1979), is

*Investment in a solar IPH system is classified as a service-producing investment, rather than an income-producing investment, since actual income (as from external sales of a product) is not generated. However, when compared to alternative service-producing investments, the solar IPH system generates net savings, which may be considered in the same way as income.

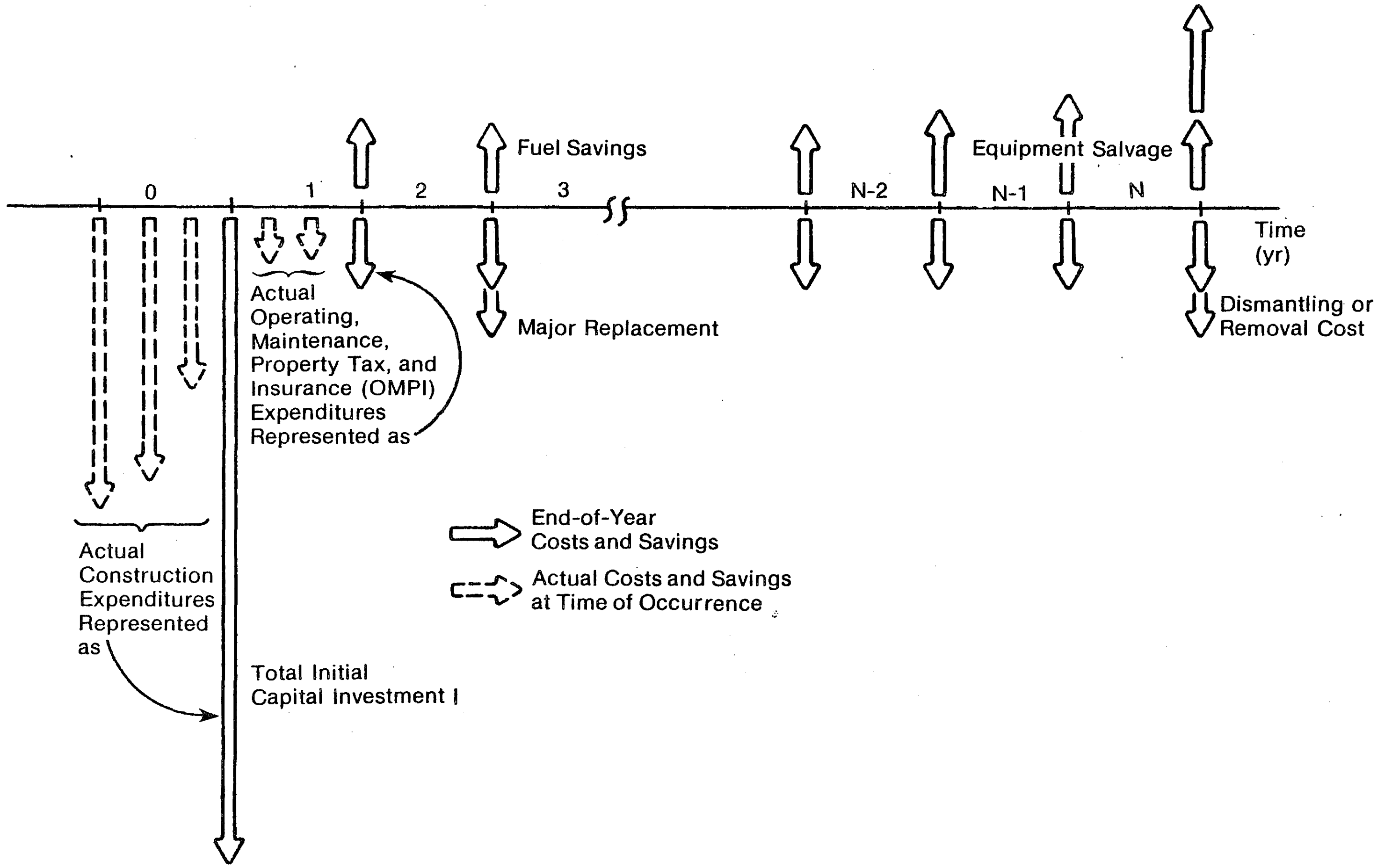


Figure 4-2. Typical Costs and Savings for a Solar IPH System over the System Lifetime of N Years (without Tax Considerations)

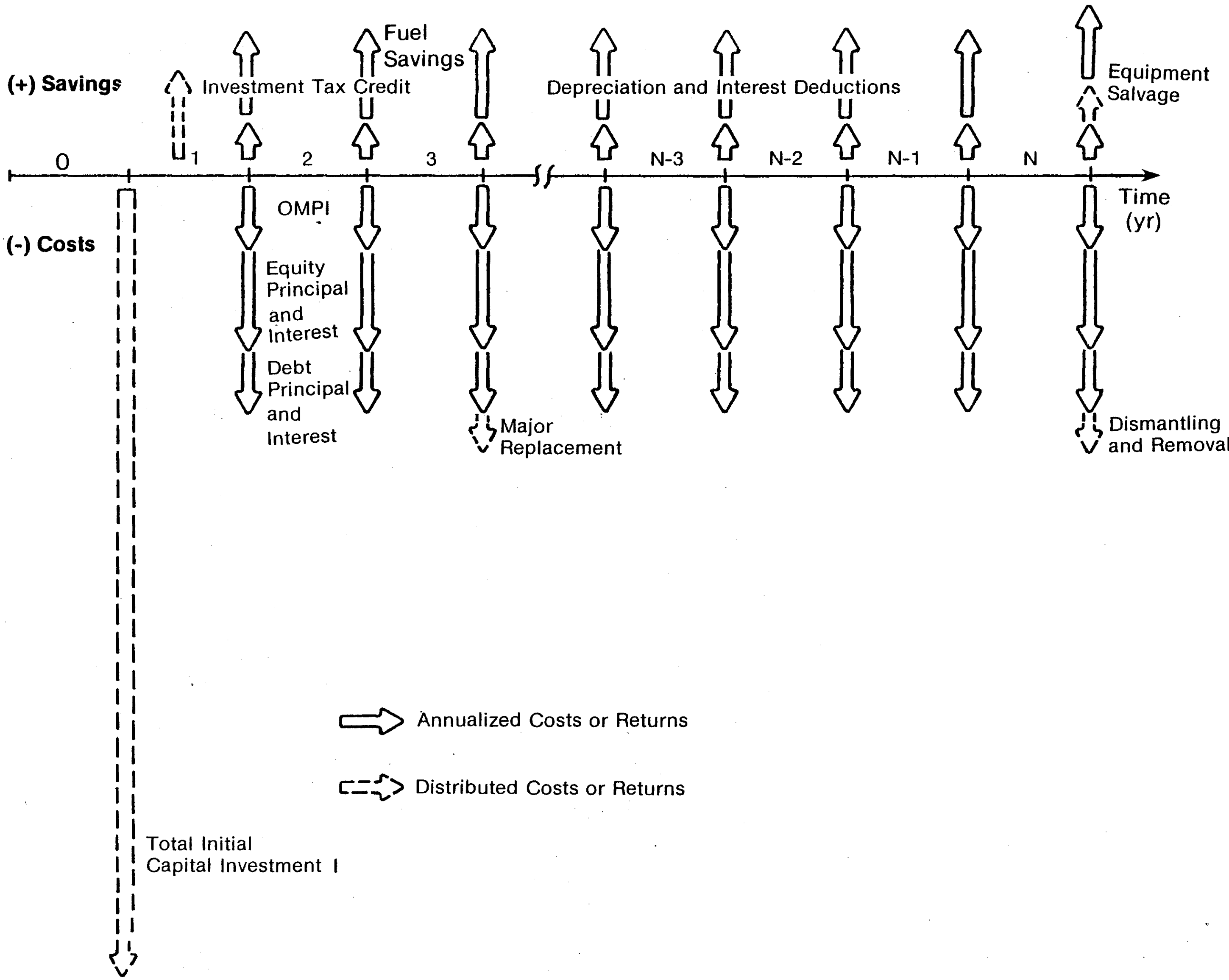


Figure 4-3. Distribution of Costs and Savings, Including Distributed Captial Repayment, for a Solar IPH System (with Tax Considerations)

Note: Lengths of arrows are not to scale.

$$M = \frac{C_s}{I} = OMPI + \frac{CRF(R,N)}{1 - \tau}\Bigg[(1 - f) + f(1 - \tau)\frac{CRF(r,LP)}{CRF(R,LP)} + \frac{f\tau}{1 + r}$$

$$\times \frac{CRF(r,LP) - r}{CRF(R'',LP)} - \frac{TC}{1 + R} - \tau\ DEP + \left(\frac{1 + g}{1 + R}\right)^{t_c}$$

$$\times\ m(t_c)\ (1 - TC - \tau\ DEP) - S\left(\frac{1 + g}{1 + R}\right)^N\Bigg] \quad . \qquad (4\text{-}2)$$

(See Section 4.4 for definitions of symbols.)

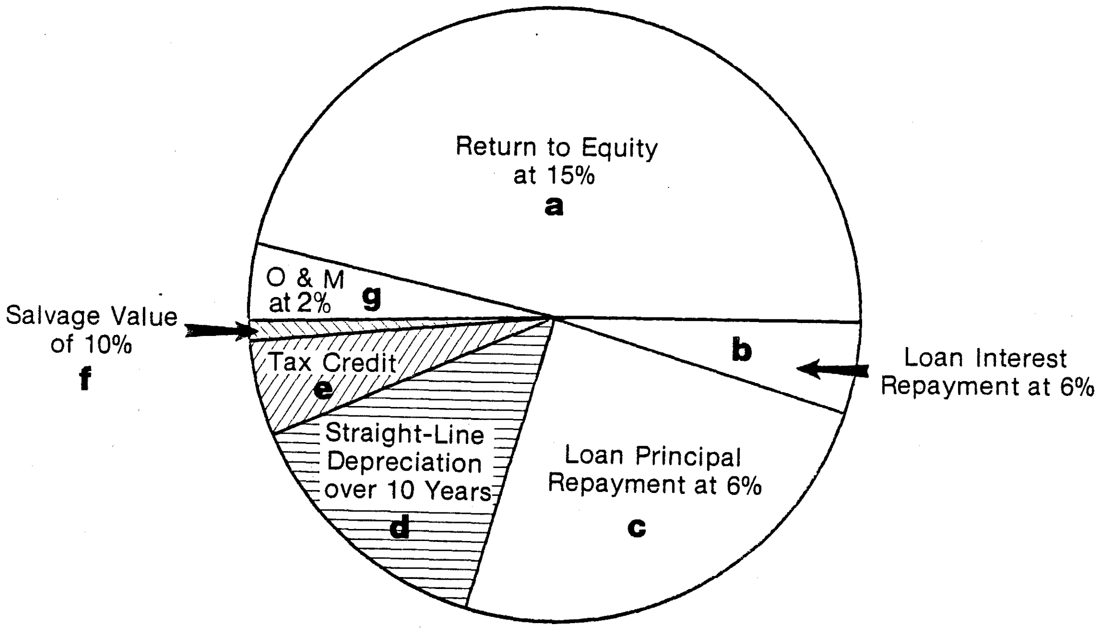
The expressions contained in this rather complicated equation can be related to the portions of annual revenue required to cover several items of cost. Figure 4-4 shows the distribution of these required returns for an annual payment corresponding to the case of 50/50 debt-to-equity financing at a discount rate of 15% and with an investment tax credit of 20%.

In many cases, a number of assumptions are made to simplify the expression for M. Since salvage value is uncertain and perhaps quite small due to dismantling and removal costs, the term is usually neglected. For example, a net salvage value of 10% of the original investment at the end of 20 years and at a discount rate of 15% yields a net reduction of only 0.002 in the multiplier, or a difference of less than 1%. If the solar system is financed out of general operating capital, then a simple weighted average cost of capital, k, may be used as the required after-tax rate of return and used to define a capital recovery factor for repayment of investment. The assumption that annual operating, maintenance, insurance, and local tax costs are a constant fraction of initial investment leads to further simplification of M. Finally, straight-line depreciation over the entire system lifetime of N years yields a depreciation factor DEP of 1/N. The resulting simplified multiplier is:

$$M = \frac{1}{1 - \tau}\left[(1 - \tau)B + CRF(k,N)(1 - TC) - \frac{\tau}{N}\right] , \qquad (4\text{-}3)$$

where B is the constant fraction of I attributable to variable operating, maintenance, insurance, and tax costs.

Equation 4-3 offers a convenient expression for M and is presented here as an example. Table 4-3 presents an array of values for M for various reasonable corporate investment scenarios. These M values are based on the more complete expression of Eq. 4-2 and are the values used in the end-use matching analysis. Selection of an M value appropriate for a particular industrial plant allows a correct comparison of solar and conventional process heat costs. Note that when M is used the cost of solar heat is to be compared to the before-tax cost of conventional process heat.



a $(1 + \tau)(1 - f)\ \mathrm{CRF}(R,N)$

b $\tau f\ \mathrm{CRF}(R,N) \left[\frac{\mathrm{CRF}(r,LP)}{\mathrm{CRF}(R,LP)} - \frac{\mathrm{CRF}(r,LP) - r}{(1 + r)\ \mathrm{CRF}(R'',LP)}\right]$

c $(1 + \tau)\ f\ \mathrm{CRF}(R,N) \frac{\mathrm{CRF}(r,LP)}{\mathrm{CRF}(R,LP)}$

d $\frac{\tau\ \mathrm{CRF}(R,N)}{DP\ \mathrm{CRF}(R,DP)}$

e $\frac{\tau\ \mathrm{CRF}(R,N)TC}{1 + R}$

f $\tau\ \mathrm{CRF}(R,N)\left(\frac{1 + g}{1 + R}\right)^{N} S$

g τ OMPI

Figure 4-4. Relative Distribution of Annual Required Revenue (Equivalent to Before-Tax Cost of Energy)

Table 4-3. TABLE OF MULTIPLIER (M) VALUES[a]

	Values of M									
	R = 0.10		R = 0.12		R = 0.15			R = 0.20		
f \ r =	0.06	0.09	0.06	0.09	0.06	0.09	0.12	0.06	0.09	0.12
0	0.130	0.130	0.152	0.152	0.187	0.187	0.187	0.254	0.254	0.254
0.3	0.098	0.104	0.110	0.115	0.129	0.135	0.141	0.168	0.173	0.179
0.5	0.077	0.086	0.082	0.091	0.091	0.010	0.110	0.111	0.119	0.130
0.7	0.056	0.069	0.054	0.067	0.052	0.064	0.079	0.053	0.065	0.079

[a]Fixed values: g = 0.06, OMPI = 0.02, N,LP = 20, τ = 0.50, $m(t_c)$ = 0, DP = 10, TC = 0.20, S = 0, and sum of the years-digits depreciation.

Use of the multiplier is facilitated by determining the capacity cost of a given solar system in an IPH application. The system capacity cost CAP is defined as the total initial capital cost of the solar IPH system per unit energy delivered per year; i.e.,

$$CAP = \frac{I}{Q_{del}} \; [\$/(MBtu/yr)] \qquad (4\text{-}4)$$

This quantity enables comparisons with conventional process heating equipment, which is normally sold based on heating capacity (e.g., MBtu/h).

The specific derivation of the multiplier expression in terms of levelized current dollars requires that the calculated solar process heat "price" be compared to the levelized cost of delivered heat from conventional fuels over the same lifetime N and at the same discount rate R. This is not equivalent to the actual price paid for coal, oil, or gas heat at the present time. Levelizing the expected costs of conventional fuels results in significantly higher costs. Table 2-7 presents levelized before-tax energy costs for conventional fuels in the six selected sites.

An alternative to comparison of levelized costs as described above is comparison of the levelized cost of solar process heat in real dollars with the current price of delivered, conventionally fueled heat during the first year of operation (N = 1). This method allows a simpler comparison using current fuel prices. The levelized price of solar process heat in current dollars (annual costs are the same in nominal terms over N years) may be transformed into a levelized price in real dollars (annual costs are the same in constant dollars over N years) with a simple multiplicative expression. A diagrammatic interpretation of the two levelizing schemes is shown in Fig. 4-5. Table 4-4 gives common values for the resultant proportionality factor ρ.

Table 4-4. TYPICAL VALUES FOR THE PROPORTIONALITY FACTOR ρ BETWEEN LEVELIZED COSTS IN NOMINAL AND REAL DOLLARS[a]

k	g	N	ρ
0.08	0.06	20	0.594
0.10	0.06	20	0.614
0.12	0.06	20	0.634
0.15	0.06	20	0.661
0.20	0.06	20	0.702
0.08	0.08	20	0.491
0.20	0.08	20	0.616
0.08	0.10	20	0.403
0.20	0.10	20	0.537
0.08	0.06	10	0.742
0.12	0.06	10	0.755
0.20	0.06	10	0.779

[a] $\dfrac{\text{Initial Annualized Cost in Zero-Year Dollars}}{\text{Levelized Cost in Current Dollars}}$

$$= \left\{ CRF(k,N) \left(\frac{1+g}{k-g} \right) \left[1 - \left(\frac{1+g}{1+k} \right)^N \right] \right\}^{-1} = \rho \, .$$

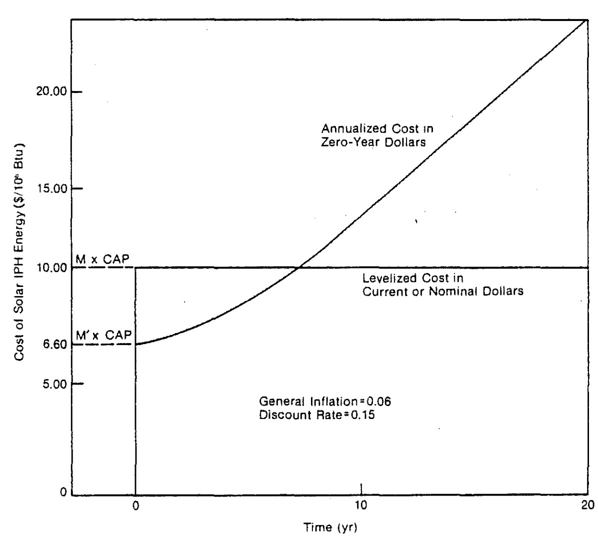


Figure 4-5. Levelized Costs of Solar IPH in Terms of Nominal and Real Dollar Values

4.3 FACTORS INFLUENCING INVESTMENT

While a value or price may be attached to solar process heat that accurately reflects the quantifiable aspects of the investment problem, a number of concerns often remain nonquantifiable for the plant manager and, particularly, the plant engineer. For example, uncertainty about the future cost of conventional fuels is certainly involved in the plant manager's perception of the value of solar energy, as is the nonquantifiable public relations value of solar energy. An important consideration for the plant engineer, whose responsibility is to maintain efficient production, is the relatively little accumulated experience in operating solar systems. The plant engineer must also consider, however, that a solar system provides the ability to avoid the risk of fuel shortages. In summary, the decision to make a solar system capital investment, particularly because it is such a new technology, depends on much more than is represented by the multiplier in Section 4.2.2. The factors upon which such decisions are based, including the assessment of value, are listed in Table 4-5. In this table, concerns of plant managers are distinguished from those of plant engineers (operation personnel). The first group is concerned mainly with profitable operation and adequate cash flows; the second group is concerned with efficient, smoothly operating production. The concerns of both parties can be grouped into two categories: (1) absolute constraints that must be satisfied in order to justify a solar investment, and (2) concerns that must be satisfied to some degree in order to make the solar investment compatible with normal opportunities for investment.

Table 4-5. FACTORS INFLUENCING INVESTMENT IN A SOLAR IPH SYSTEM

Management	Production
Constraints	
• Project must in some sense meet justification criteria in terms of adequate handling of stockholders capital; e.g., minimum adequate return	• System must meet minimum design and operating specifications
• Legal responsibilities, such as regulations and liability, must be minimized	• System must have a useful lifetime consistent with expected use of the plant
	• System must not interfere with production
	• System must have warranty
	• Adequate performance data and previous industry experience with this equipment or that of a similar type must be available
Concerns	
• Company energy consciousness	• Simplicity of operation
• Public perception of company's efforts in energy conservation	• Dependability
• Fuel costs and availability	• Previous experience with equipment and/or vendors
• Energy intensiveness of production, or cost of energy per unit production	• Fuel costs and availability
• Minimization of cost overrun potential (either construction or operating costs)	• Effect on product quality
	• Safety impacts
	• Noise level
	• Benefits in exposure to new technology
	• Limited number of vendors to reduce requirement for spare parts inventory
	• Availability of equipment, service, and spare parts

4.4 NOMENCLATURE*

C_s	annualized (or levelized) required revenue to purchase solar energy
CRF(R,N)	capital recovery factor = $\frac{R}{1 - (1+R)^{-N}}$
DEP	present value of depreciation charges as a fraction of initial investment
DP	depreciation period (equal to accounting life for tax purposes)
f	fraction of initial system investment financed by loan
g	assumed general inflation rate over life of system
g'	assumed inflation rate (including general inflation) of conventional fuel used in backup system; for a real escalation rate e, $1 + g' = (1 + g)(1 + e)$
I	initial system investment in dollars of construction year ($t = 0$)
LP	loan period (always to be taken as equal to or less than system life)
M	the M factor = C_s/I; annualized required revenue per investment dollar
$m(t_c)$	major component replacement cost in year $t = t_c$ as a fraction of initial investment; this cost is to be estimated in terms of dollars of year of construction rather than in current dollars
N	system life; also the period over which system costs are measured in a life-cycle costing calculation
OMPI	levelized annual cost for operation, maintenance, property tax, and insurance; expressed as a fraction of initial investment
R	after-tax, market rate of return on equity portion of solar investment
R'	after-tax real rate of return on equity = $\frac{1 + R}{1 + g} - 1$
R''	$\frac{1 + R}{1 + r} - 1$
r	market interest rate on loan
S	net salvage value of solar system in construction-year dollars, expressed as a fraction of the initial investment
t	year of system operation under consideration (system is constructed in year 0 and operation is begun on 1st day of year 1)
t_c	year in which a major component is replaced
TC	total investment tax credit rate = $TC_f + (1 - TC_f)TC_s$
TC_f	federal investment tax credit rate

*All costs are expressed in current dollars unless otherwise stated.

TC_s	state investment tax credit rate
τ	marginal composite income tax rate = $\tau_f + (1 - \tau_f)\tau_s$
τ_f	marginal federal income tax rate
τ_s	marginal state income tax rate

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SERI

SECTION 5.0

RESULTS

A substantial portion of the effort in FY78 was directed toward development of the end-use matching methodology. Thus, we consider the design of this methodology as implemented in the computer software PROSYS/ECONMAT to be the study's most important product. These tools provide an efficient procedure for a variety of analyses, but only preliminary evaluations were performed in the course of this task. Therefore, the analytical results presented in this chapter are not comprehensive, but they demonstrate the scope of analyses possible and provide a few preliminary appraisals of solar IPH.

Solar industrial process heat applications were investigated for six U.S. cities: Bismarck, N.D.; Brownsville, Tex.; Charleston, S.C.; Denver, Colo.; El Paso, Tex.; and Fresno, Calif. Analysis for each city included a performance comparison of several collector types, a ranking of all pertinent four-digit SIC industrial categories by annual energy capacity cost, and the calculation of levelized energy costs of two typical industries for several economic scenarios. Additional parametric sensitivity studies were conducted, including effects of changes in collector optical efficiency, collector cost, and collector array shading. Because a solar system often supplements a conventional energy system, the economic advantage of the solar system is fuel savings. Therefore, fuel price sensitivity is illustrated in examples of net present value analysis. The results of these analyses are presented in this section. Conclusions drawn from these results are discussed in Section 7.0.

5.1 COLLECTOR PERFORMANCE COMPARISON

In assessing the feasibility of solar IPH applications, one first calculates the amount of energy delivered by available solar collectors. A comparison of the performances of five collector types over a range of process temperatures is shown for the six cities in Figs. 5-1 through 5-6. Specified in this example is a direct hot water system, and the collector types include flat plate, compound parabolic concentrator, linear Fresnel lens, parabolic trough, and parabolic dish. The performance at a given temperature for a specific location is a function of the quantity and quality of local solar radiation and, of course, the collector energy losses.

5.2 RANKING OF SOLAR APPLICATIONS FOR INDUSTRIAL CATEGORIES

PROSYS and ECONMAT computer runs were made, using the information in the industrial process heat data base, for all identified four-digit SIC categories* in the six cities. The resultant ranking of solar industrial applications by annual energy capacity cost for each city is shown in Figs. 5-7 through 5-12. The capacity cost used in the ranking is for the best system/collector combination for each process and for a system sized to provide 50% of the annual energy specified in the IPHDB.

*Four-digit SIC categories are defined in Table 2-3.

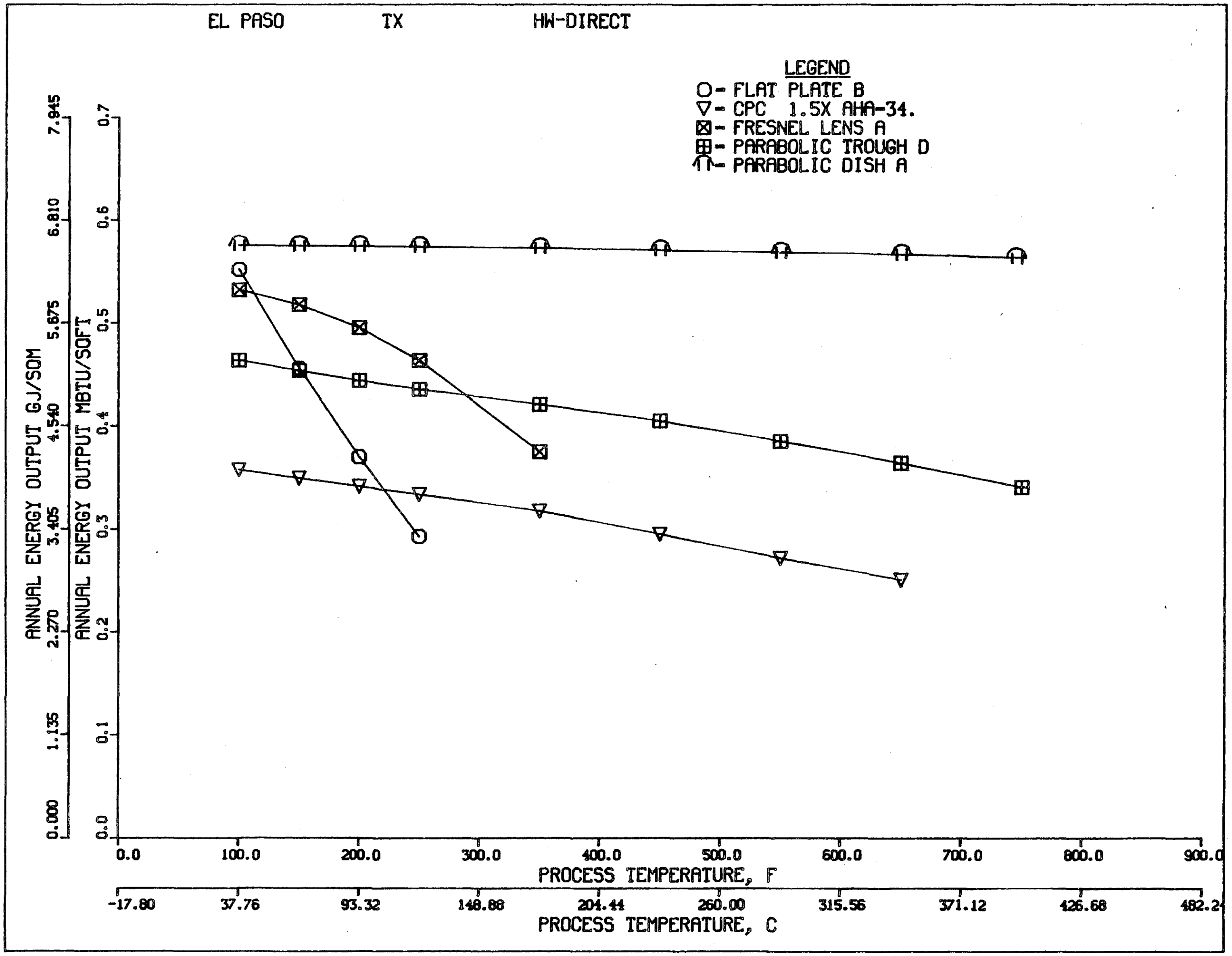

Figure 5-1. Annual Energy Output of Several Collector Types over a Range of Temperatures for El Paso, Tex.

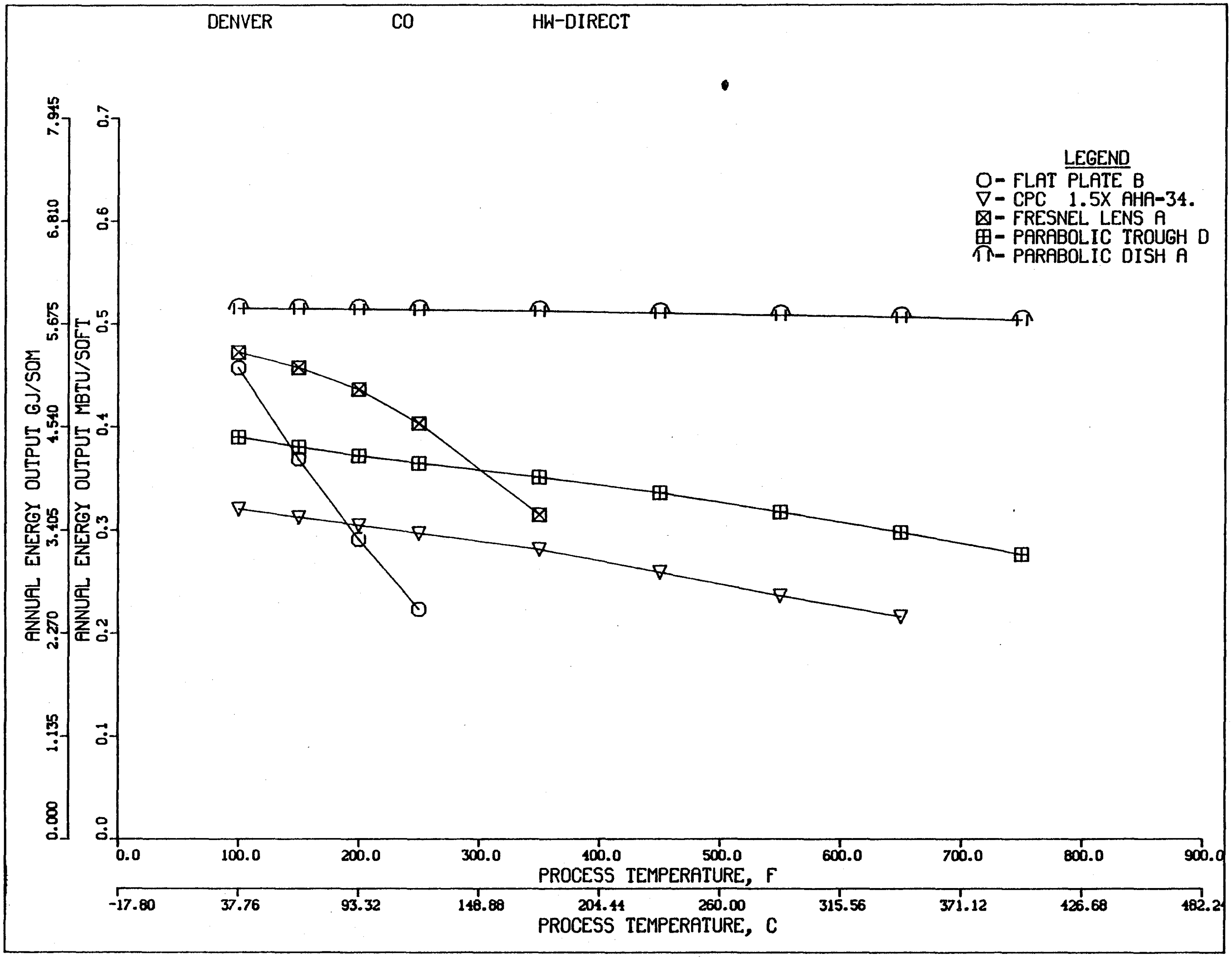

Figure 5-2. Annual Energy Output of Several Collector Types over a Range of Temperatures for Denver, Colo.

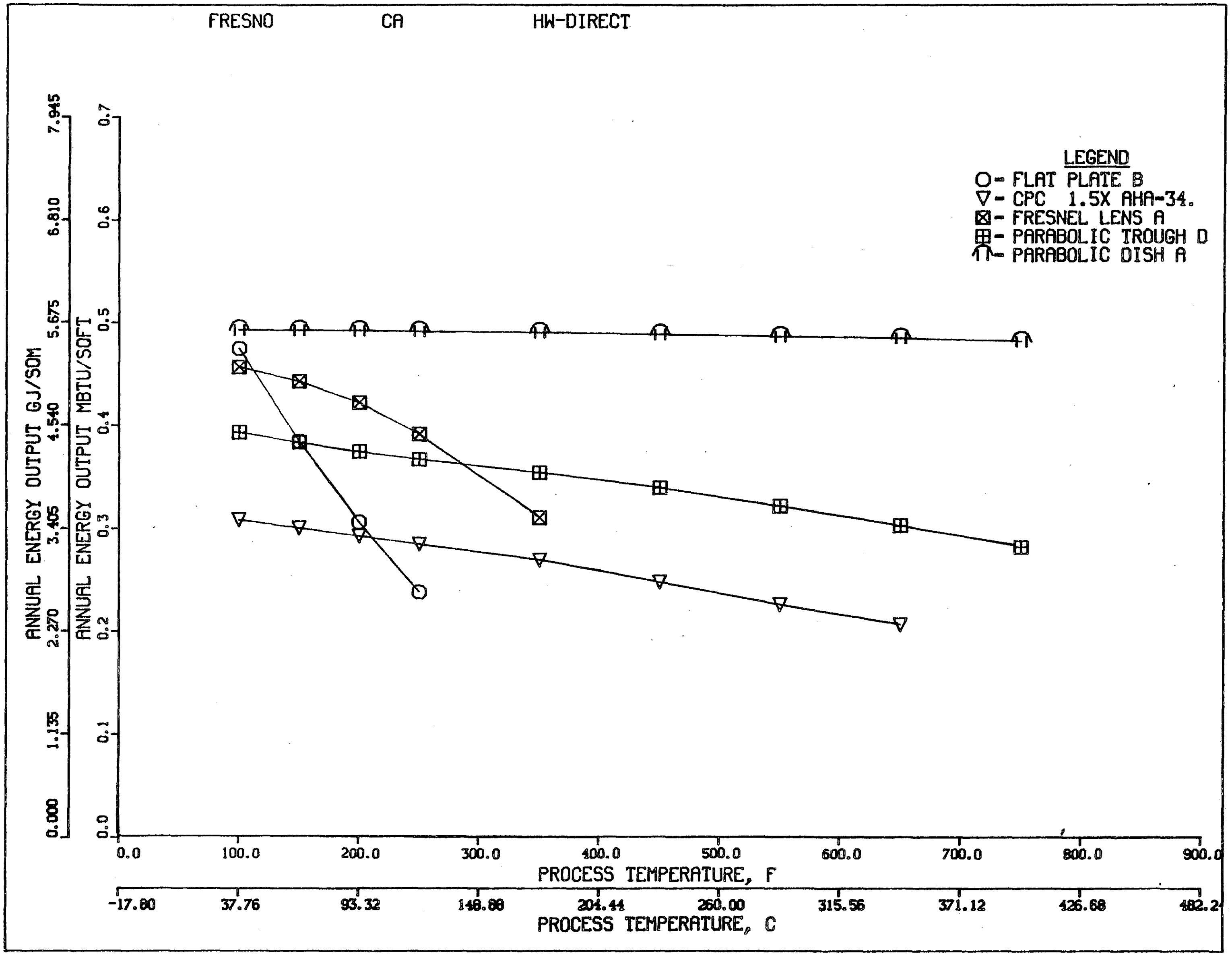

Figure 5-3. Annual Energy Output of Several Collector Types over a Range of Temperatures for Fresno, Calif.

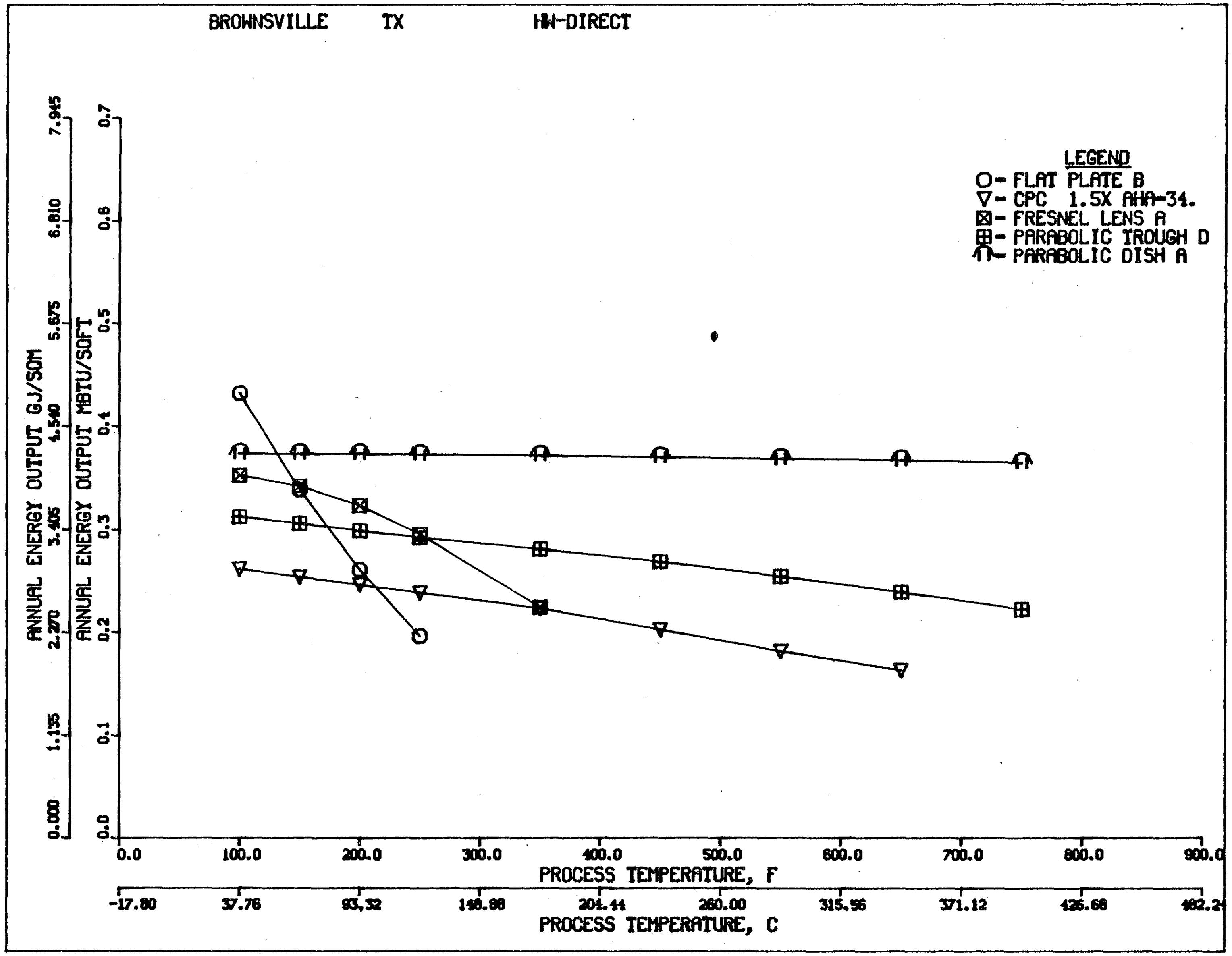

Figure 5-4. Annual Energy Output of Several Collector Types over a Range of Temperatures for Brownsville, Tex.

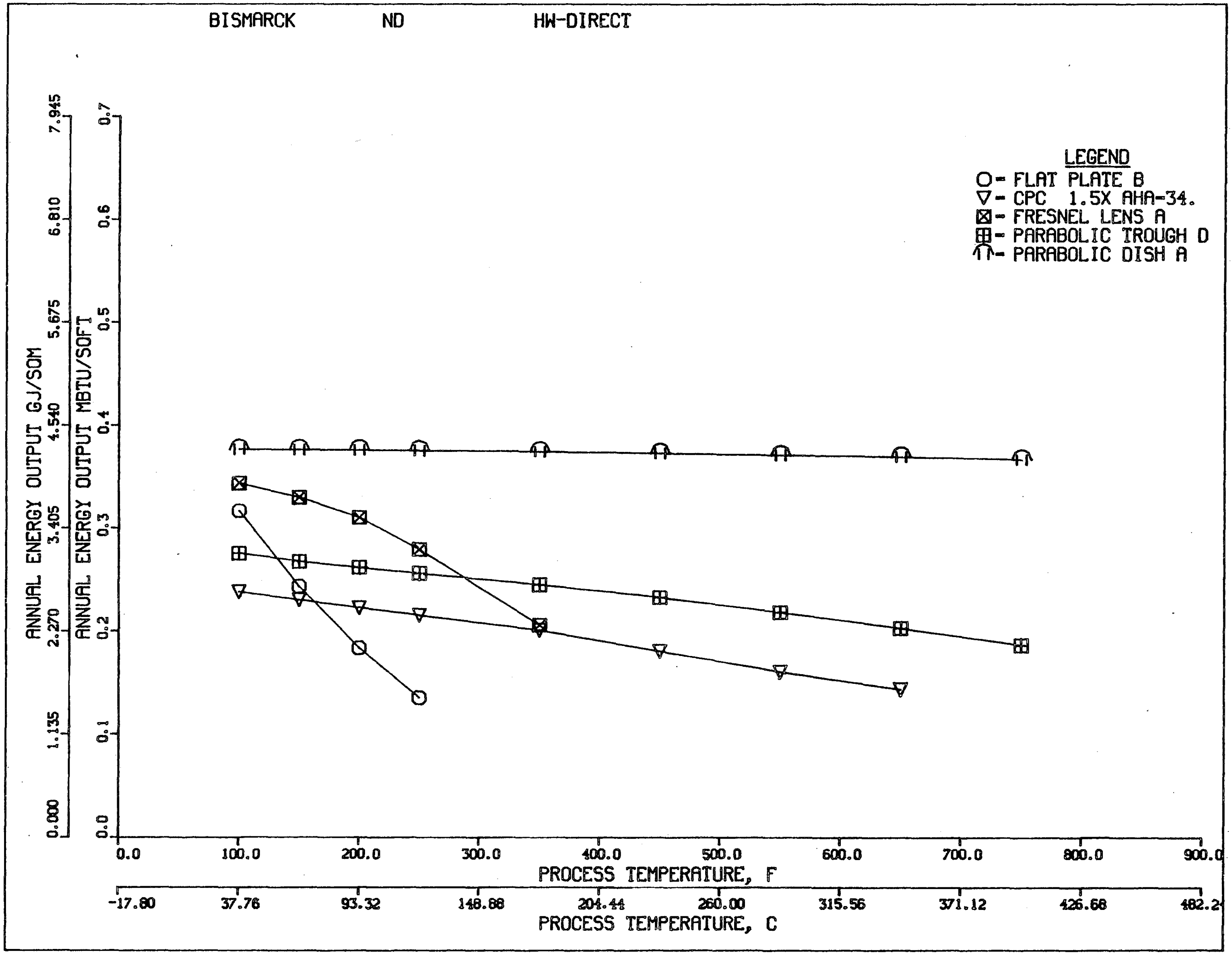

Figure 5-5. Annual Energy Output of Several Collector Types over a Range of Temperatures for Bismarck, N.D.

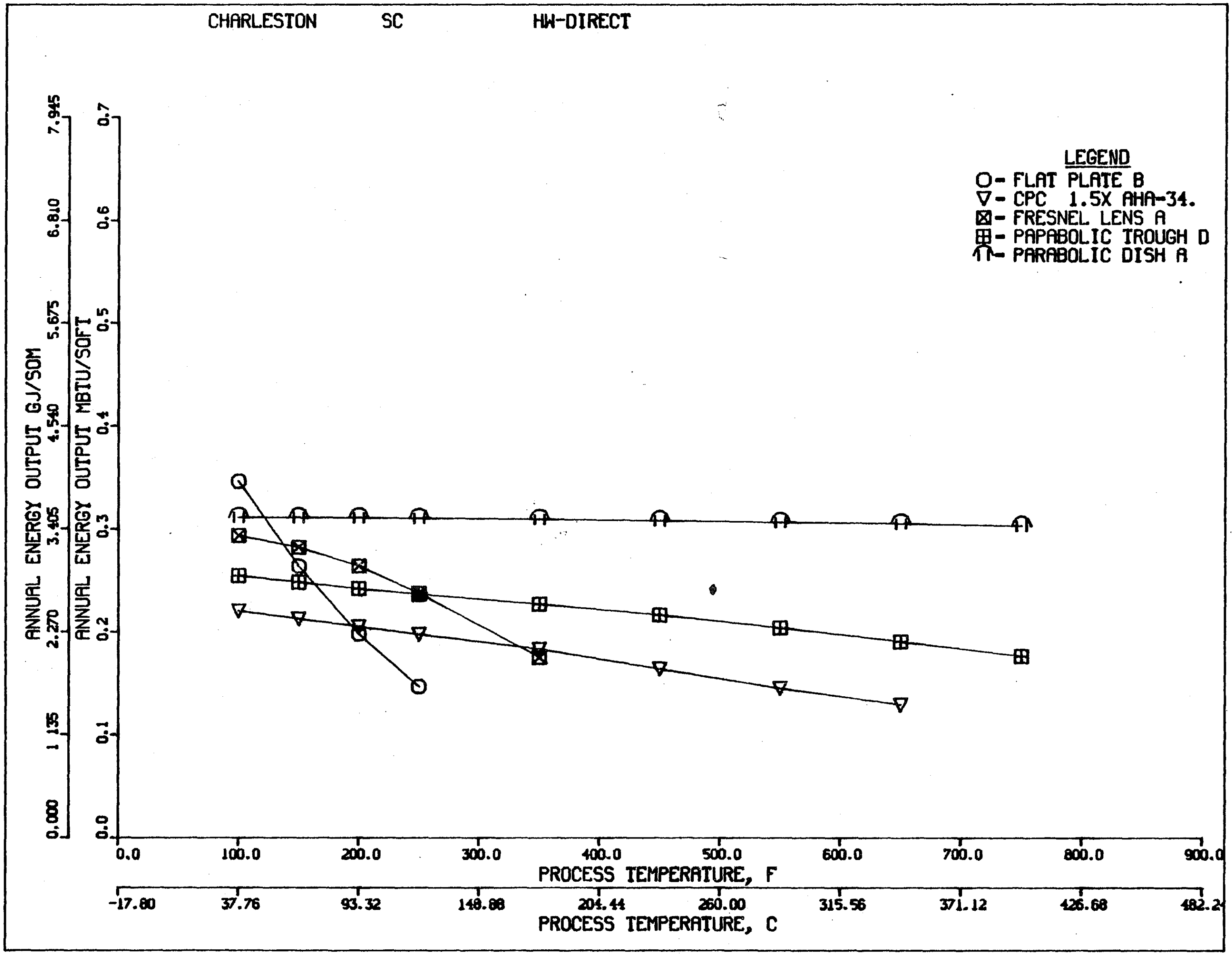

Figure 5-6. Annual Energy Output of Several Collector Types over a Range of Temperatures for Charleston, S.C.

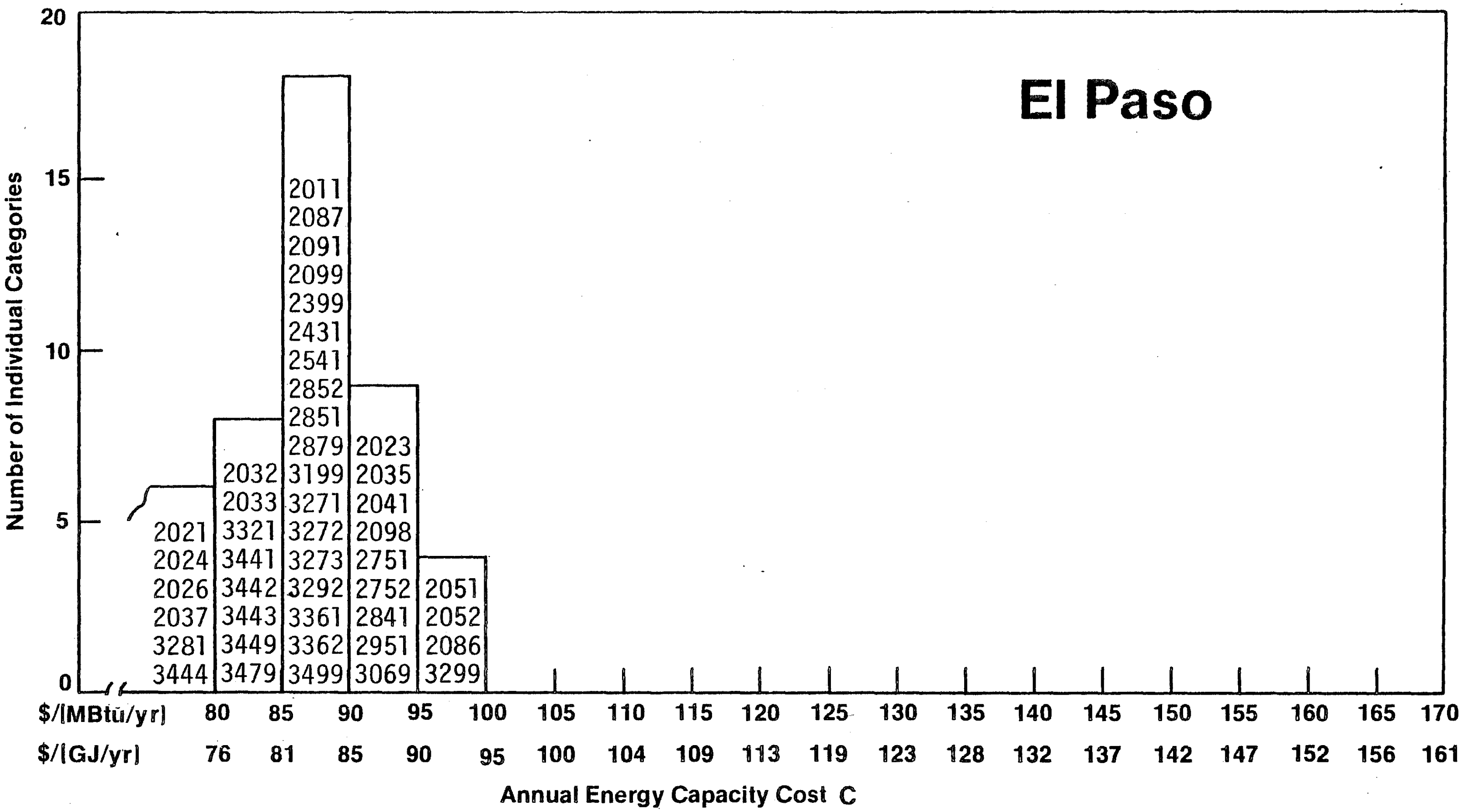

Figure 5-7. Ranking of Solar IPH Applications in El Paso, Tex., on the Basis of Energy Capacity Cost

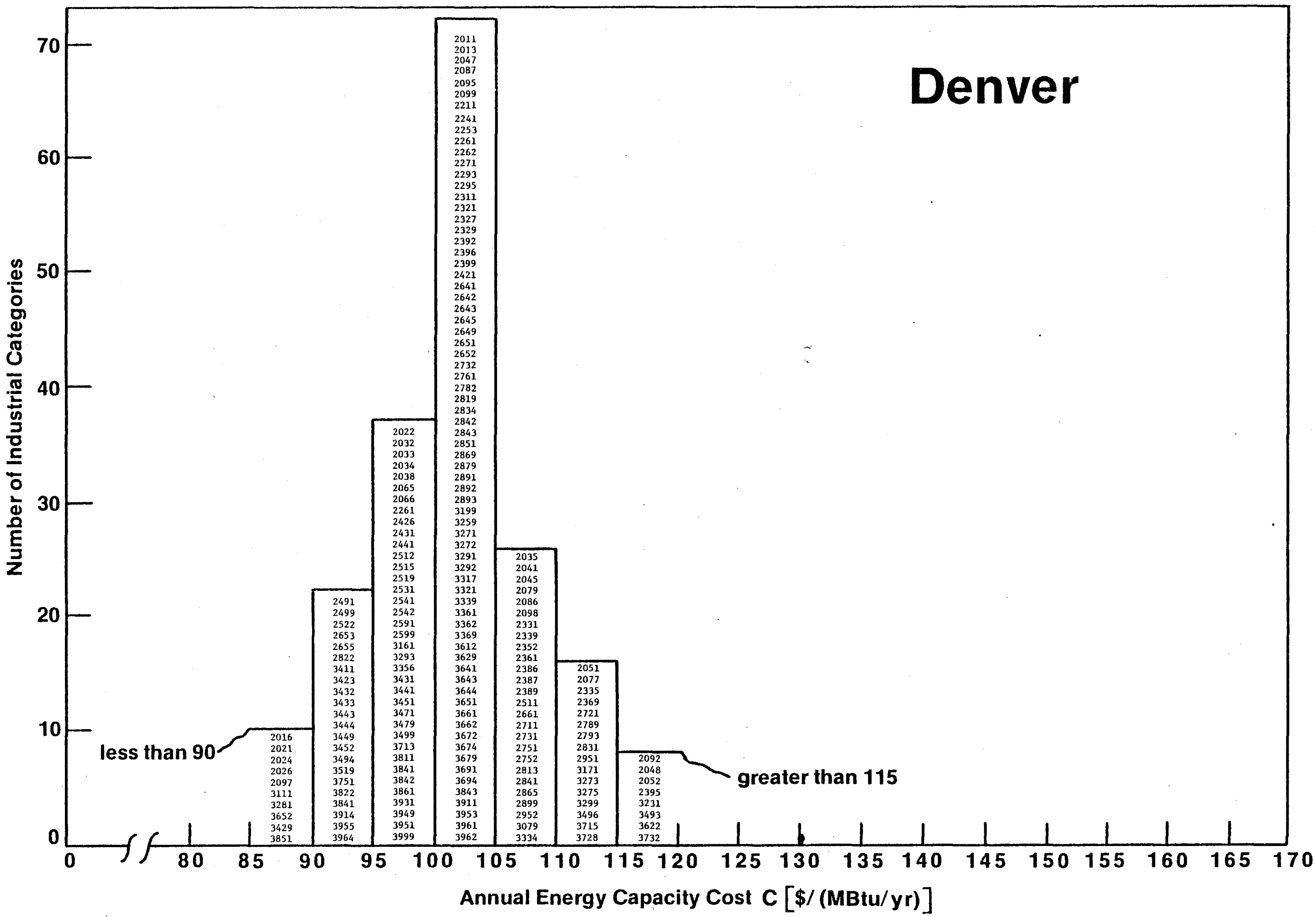

Figure 5-8. Ranking of Solar IPH Applications in Denver, Colo., on the Basis of Energy Capacity Cost

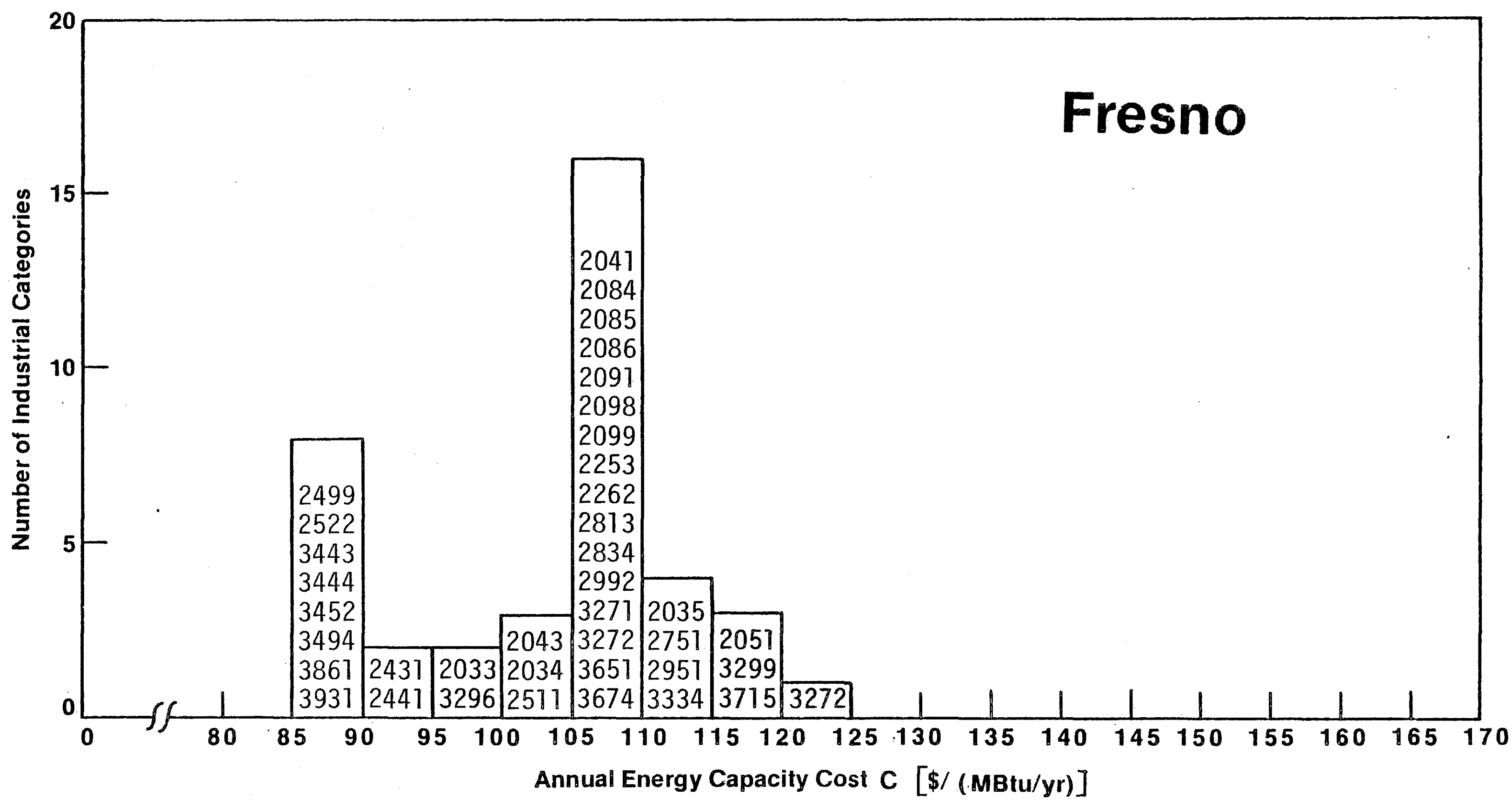

Figure 5-9. Ranking of Solar IPH Applications in Fresno, Calif., on the Basis of Energy Capacity Cost

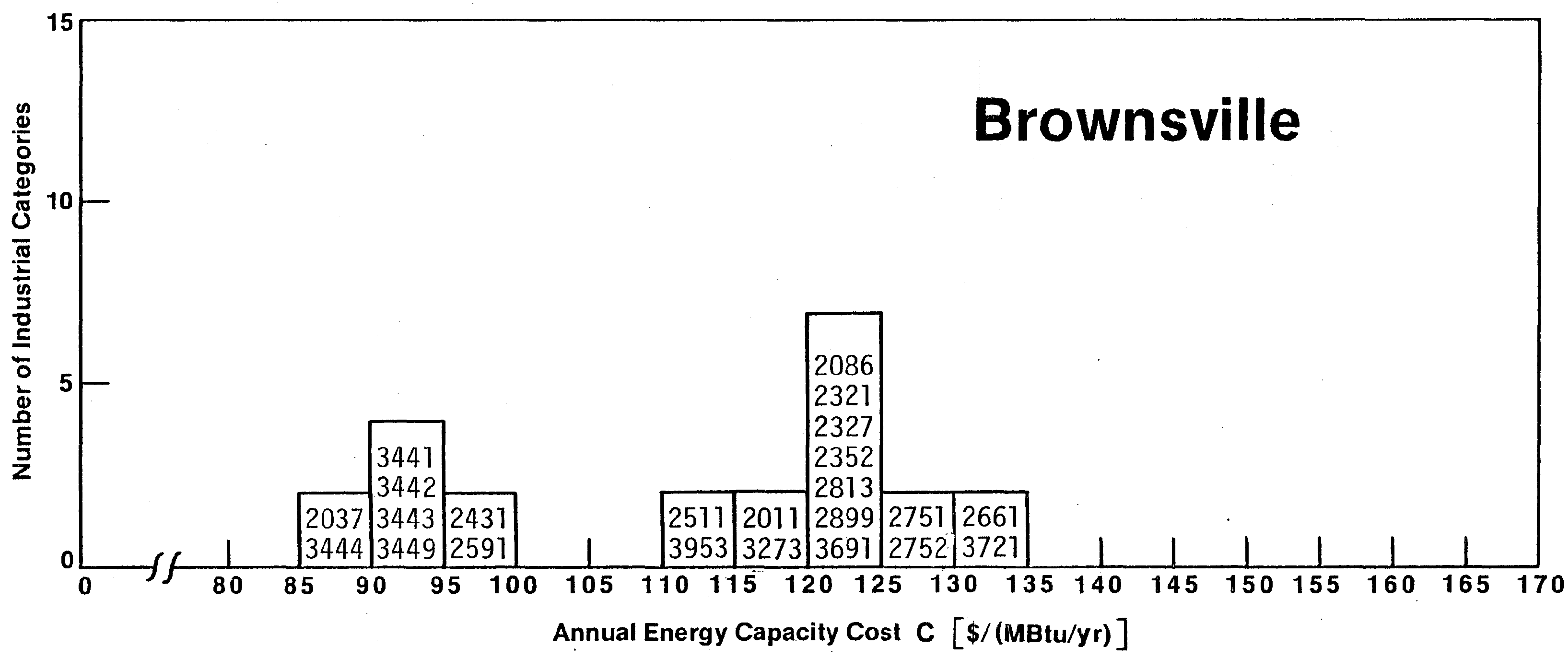

Figure 5-10. Ranking of Solar IPH Applications in Brownsville, Tex., on the Basis of Energy Capacity Cost

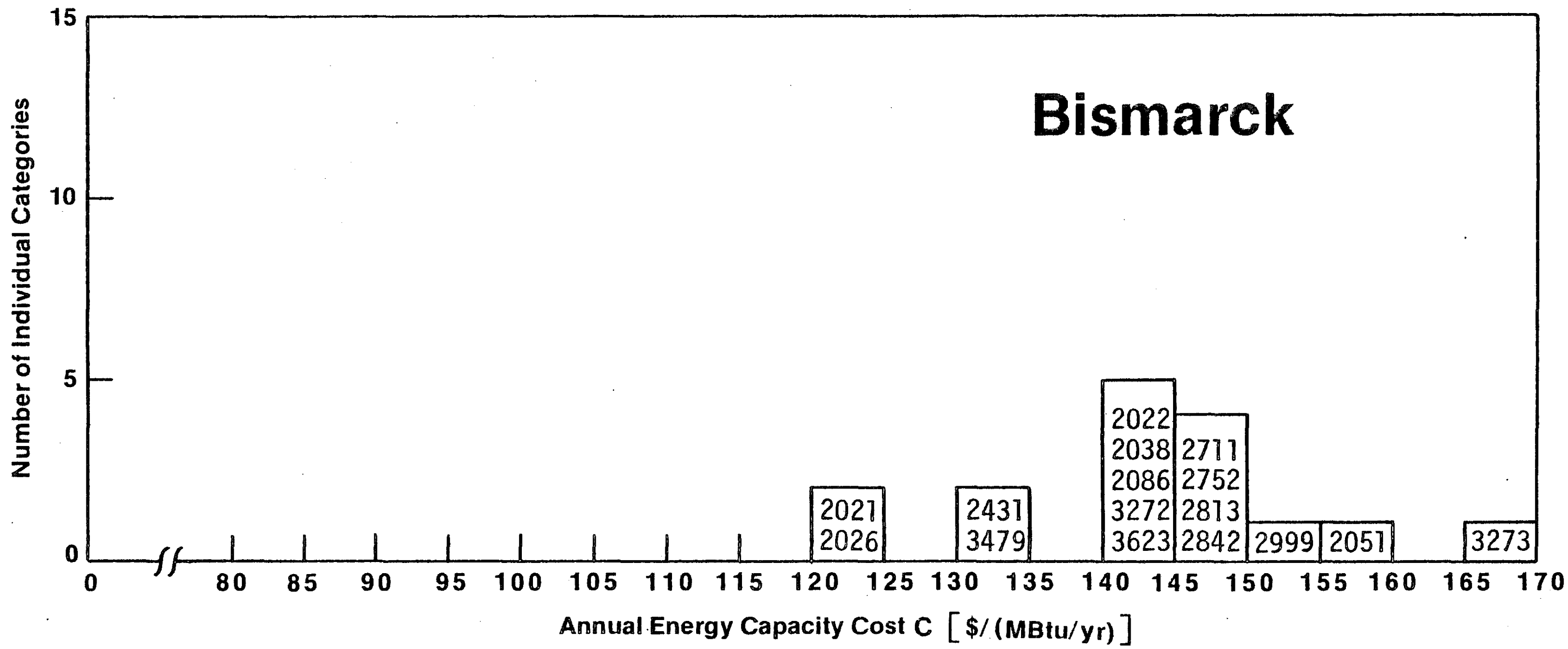

Figure 5-11. Ranking of Solar IPH Applications in Bismarck, N.D., on the Basis of Energy Capacity Cost

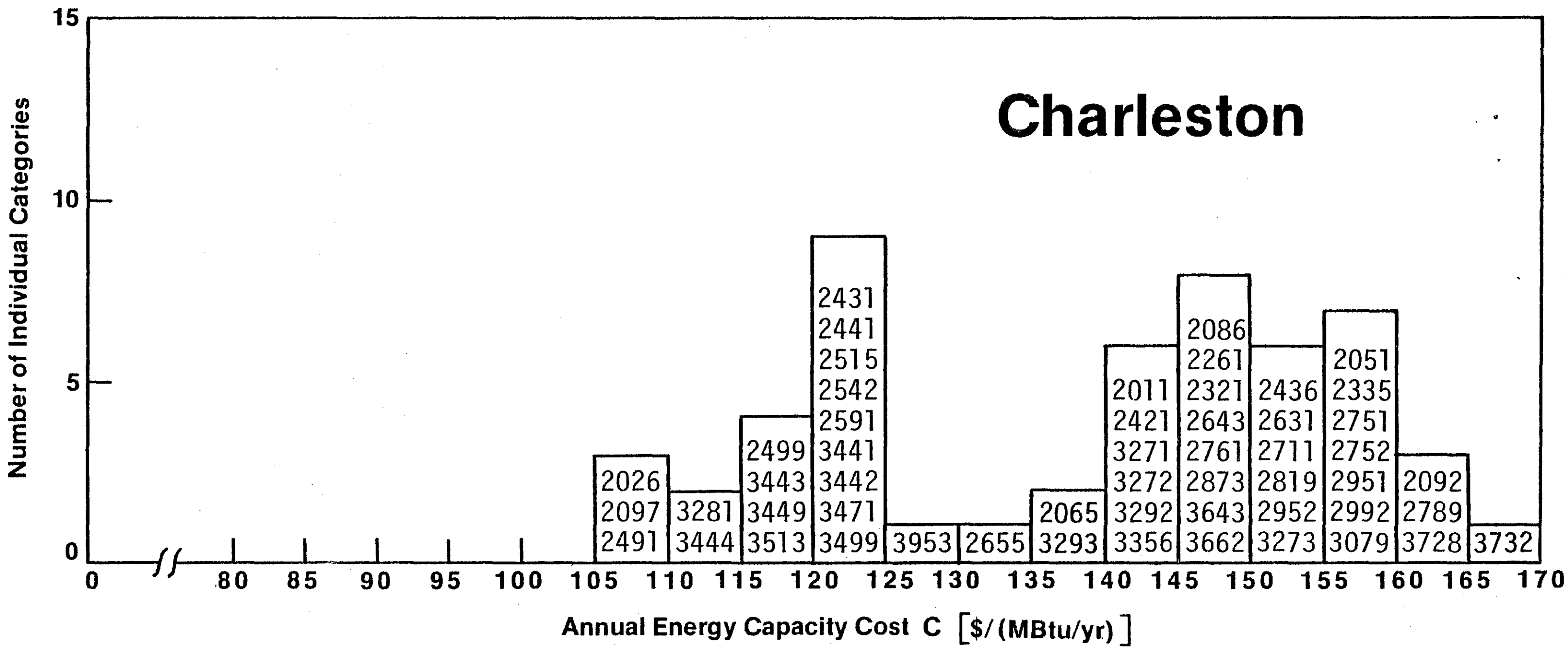

Figure 5-12. Ranking of Solar IPH Applications in Charleston, S.C., on the Basis of Energy Capacity Cost

The ranking of the SIC codes for "typical" industrial plants must be interpreted cautiously. For example, the fabricated metal processing industries (SIC 3440-3449) are shown among the higher ranking (lower cost) applications. The two processes in this industry most appropriate for solar energy are hot air enamel drying and hot water washing. Because the most economic system/collector is used, the capacity cost values shown are for a direct hot water system with a parabolic trough collector. Thus, the washing process is selected over the drying process. Direct hot air drying is eliminated because the collector has low efficiency and thus high cost at all but very low temperatures. An alternate indirect hot air system (liquid-to-air heat exchanger) for drying yields costs from $7 to $10/(MBtu/yr) more than the direct hot water system for washing. The costs for a specific SIC or an individual plant may vary considerably when subprocesses are considered.

Determination of solar IPH cost range or average is a more reliable interpretation of the ranking histograms. The average solar IPH annual energy capacity cost for each city is as follows:

	$/(MBtu/yr)
El Paso	87
Denver	103
Fresno	103
Brownsville	113
Charleston	139
Bismarck	143

5.3 LEVELIZED ENERGY COST

In addition to annual energy capacity cost, the levelized energy cost may be calculated, but it is dependent on economic factors which may vary from case to case. To calculate levelized energy cost, one computes the product of the capacity cost and a multiplier M, where M represents the effect of variable economic factors. The multiplier may be expressed in constant dollars (M) or base-year dollars (M'). The derivation and equations for M are given in Section 4.2. Table 5-1 shows several typical values of M and M' for corresponding values of pertinent economic parameters, and Table 5-2 shows the resultant levelized energy costs for two typical industrial categories in each city.

5.4 COLLECTOR SENSITIVITY STUDY

Because the solar collector is responsible for a significant portion of the total equipment cost, reduction of collector costs is an important goal. Alternatively, an effective cost reduction may be achieved by improving collector performance. Table 5-3 shows the effects of a 20% collector F.O.B. cost reduction and a 5% collector optical efficiency increase for several

Table 5-1. VALUES OF THE MULTIPLIER M FOR SEVERAL SETS OF ECONOMIC FACTORS[a]

Economic Factor	Base Value	Finance Variations			Tax Variations		OMPI Increase	Depreciation/Lifetime Variations	
Rate of return on equity R	0.12	0.15	--	--	--	--	--	--	--
Loan fraction f	0	--	0.25	0.50	--	--	--	--	--
Tax rate τ	0.50	--	--	--	0.40	--	--	--	--
Tax credit TC	0.20	--	--	--	--	0.40	--	--	--
Operation, maintenance, property tax, and insurance (OMPI)	0.02	--	--	--	--	--	0.05	--	--
Lifetime N (yr)	20	--	--	--	--	--	--	10	--
Loan period LP (yr)	20	--	--	--	--	--	--	10	--
Depreciation period DP	20	--	--	--	--	--	--	10	8
Interest rate on debt, r	0.09	--	--	--	--	--	--	--	--
M	0.168	0.206	0.137	0.107	0.154	0.114	0.198	0.187	0.148
M' (g = 0.06)	0.106	0.136	0.087	0.068	0.098	0.072	0.125	0.141	0.089

[a]M (constant dollars) is defined in Eq. 4-2 in Section 4.0. SOYD depreciation, no major replacement $[M(t_c) = 0]$, and no net salvage value are assumed. M' in base-year dollars is

$$M' = M \Big/ \left[\left(\frac{1+g}{R-g} \right) \left(1 - \frac{1+g}{1+R} \right)^N \right] \mathrm{CRF}(R,N) \quad .$$

Dashes indicate base value.

Table 5-2. LEVELIZED ENERGY COST FOR SEVERAL VALUES OF THE MULTIPLIERS M AND M'

	Capacity Cost [$/(MBtu/yr)]	Levelized Energy Cost ($/MBtu)					
		M=0.168	M'=0.106	M=0.206	M'=0.136	M=0.137	M'=0.087
Bismarck							
2086 Soft drinks	141.24	23.73	14.97	29.10	19.21	19.35	12.29
3272 Misc. Concrete	144.33	24.25	15.30	29.73	19.63	19.77	12.56
Brownsville							
2037 Frozen Fruit/Veg.	86.65	14.56	9.18	17.85	11.78	11.87	7.54
2431 Millwork	97.07	16.31	10.29	20.00	13.20	13.30	8.44
Charleston							
2011 Meat Packing	141.14	23.71	14.96	29.07	19.20	19.34	12.28
2421 Saw Mills	141.08	23.70	14.95	29.06	19.19	19.33	12.27
Denver							
2026 Fluid Milk	82.77	13.91	8.77	17.05	11.26	11.34	7.20
3449 Misc. Metalwork	94.20	15.83	9.99	19.41	12.81	12.91	8.20
El Paso							
2021 Creamery Butter	69.16	11.62	7.33	14.25	9.41	9.47	6.02
3444 Sheet Metal	79.85	13.41	8.46	16.45	10.86	10.94	6.95
Fresno							
2033 Canned Fruit/Veg.	99.85	16.77	10.58	20.57	13.58	13.68	8.69
2099 Misc. Foods	106.27	17.94	11.26	21.89	14.45	14.56	9.25

Table 5-2. LEVELIZED ENERGY COST FOR SEVERAL VALUES OF THE MULTIPLIERS M AND M' (Continued)

	Capacity Cost [$/(MBtu/yr)]	Levelized Energy Cost ($/MBtu)					
		M=0.107	M'=0.068	M=0.154	M'=0.098	M=0.114	M'=0.072
Bismarck							
2086 Soft drinks	141.24	15.11	9.60	21.75	13.84	16.10	10.17
3272 Misc. Concrete	144.33	15.44	9.81	22.22	14.14	16.45	10.39
Brownsville							
2037 Frozen Fruit/Veg.	86.65	9.27	5.89	13.44	8.49	9.88	6.24
2431 Millwork	97.07	10.39	6.60	14.95	9.51	11.07	6.99
Charleston							
2011 Meat Packing	141.14	15.10	9.59	21.74	13.83	16.09	10.16
2421 Saw Mills	141.08	15.10	9.59	21.73	13.83	16.08	10.16
Denver							
2026 Fluid Milk	82.77	8.86	5.63	12.75	8.11	9.44	5.96
3449 Misc. Metalwork	94.20	10.08	6.41	14.51	9.23	10.74	6.78
El Paso							
2021 Creamery Butter	69.16	7.40	4.70	10.65	6.78	7.88	4.98
3444 Sheet Metal	79.85	8.54	5.43	12.30	7.83	9.10	5.75
Fresno							
2033 Canned Fruit/Veg.	99.85	10.68	6.79	15.38	9.79	11.38	7.19
2099 Misc. Foods	106.27	11.37	7.23	16.37	10.41	12.11	7.65

Table 5-2. LEVELIZED ENERGY COST FOR SEVERAL VALUES OF THE MULTIPLIERS M AND M' (Concluded)

	Capacity Cost [$/(MBtu/yr)]	Levelized Energy Cost ($/MBtu)					
		M=0.198	M'=0.125	M=0.187	M'=0.141	M=0.148	M'=0.089
Bismarck							
2086 Soft drinks	141.24	27.97	17.66	26.41	19.91	20.90	12.57
3272 Misc. Concrete	144.33	28.58	18.04	26.99	20.35	21.36	12.85
Brownsville							
2037 Frozen Fruit/Veg.	86.65	17.16	10.83	16.20	12.22	12.82	7.71
2431 Millwork	97.07	19.22	12.13	18.15	13.69	14.37	8.64
Charleston							
2011 Meat Packing	141.14	27.95	15.88	26.39	19.90	20.89	12.56
2421 Saw Mills	141.08	27.93	17.64	26.38	19.89	20.88	12.56
Denver							
2026 Fluid Milk	82.77	16.39	10.35	15.48	11.67	12.25	7.37
3449 Misc. Metalwork	94.20	18.65	11.78	17.62	13.28	13.94	8.38
El Paso							
2021 Creamery Butter	69.16	13.69	8.65	12.93	9.75	10.24	6.16
3444 Sheet Metal	79.85	15.81	9.98	14.93	11.26	11.82	7.11
Fresno							
2033 Canned Fruit/Veg.	99.85	19.77	12.48	18.67	14.08	14.78	8.89
2099 Misc. Foods	106.27	21.04	13.28	19.87	14.98	15.73	9.46

Table 5-3. SENSITIVITY STUDY OF PARAMETERS AFFECTING CAPACITY COST FOR SEVERAL PROCESSES

	Capacity Cost C [$/(MBtu/yr)]			
	Nominal Case	Collector F.O.B. Cost Reduced 20%	Collector Optical Efficiency Increased 5%	10% Collector Array Shading Loss
2016 Poultry Dressing Temp. = 140 F Direct hot water Flat plate B	73.75	66.88	66.90	
2026 Fluid Milk Temp. = 170 F Direct hot water Flat plate B	82.77	74.89	77.92	
2491 Wood Preserving Temp = 200 F Direct hot water	Fresnel lens A 85.20	Parabolic trough D 75.50	Fresnel lens A 81.46	Flat plate A 90.80
2653 Cardboard Boxes Temp. = 300 F Direct hot water Parabolic trough D	90.54	77.89	86.42	100.21
3111 Leather Processing Temp. = 140 F Direct hot water Flat plate B	69.56	62.69	65.84	
3281 Cut Stone Products Temp. = 150 F Direct hot water Flat plate B	89.81	82.62	85.22	

industrial categories in Denver. The effect of the cost reduction depends on the size of the solar array area; as the array increases, the proportion of the total cost due to collector cost increases. The examples show a 20% collector cost reduction that decreases the total cost from 9% to 14%, depending on array size. Increased collector optical efficiency of 5% (with no consequent cost increase) results in an approximate 5% decrease in total cost. The effect of collector array shading on the cost of tracking concentrators is also illustrated in Table 5-3. For SIC 2653 (manufacture of cardboard boxes), a 10% collector shading loss results in an 11% cost increase.

At the 200 F process temperature required for wood preserving (SIC 2491), the energy cost is similar for the flat plate, Fresnel lens, and parabolic trough. Small changes in performance or cost may mean that an entirely different collector type is most cost-effective. As shown in the example, the Fresnel lens is optimum both for nominal and increased optical efficiency. Reducing all collector F.O.B. costs by 20%, however, allows the parabolic trough to compete. The assumed shading losses of the tracking concentrators make the less efficient flat-plate collectors the most cost-effective.

5.5 FUEL PRICE SENSITIVITY STUDY

Net present value analysis is an optional part of the computer economic evaluation and is useful in determining the benefit of fuel savings over the solar system lifetime. The net present value of the solar system depends primarily on the fuel price of the conventional energy system. This dependence is illustrated in Figs. 5-13 through 5-15, which show net present value of two solar systems over a range of fuel prices for a fluid milk process (SIC 2026) in El Paso, Denver, and Charleston. Local fuel prices are estimated for coal, natural gas, fuel oil, propane, and electricity. A 20-year solar system lifetime is assumed and systems are sized to deliver two levels of annual energy. Values of economic factors are the "base values" given in Table 5-1. For these conditions and the smaller solar system, the net present value for fluid milk processing becomes positive when the conventional fuel price is above $4.00/MBtu in El Paso, $4.75/MBtu in Denver, and $6.00/MBtu in Charleston. For the larger system, positive present values are obtained for fuel prices above $3.75/MBtu in El Paso, $4.25/MBtu in Denver, and $5.75/MBtu in Charleston. The losses or gains are proportional to system size; i.e., the larger the system, the larger the gains if the net present value is positive and the larger the losses if the net present value is negative.

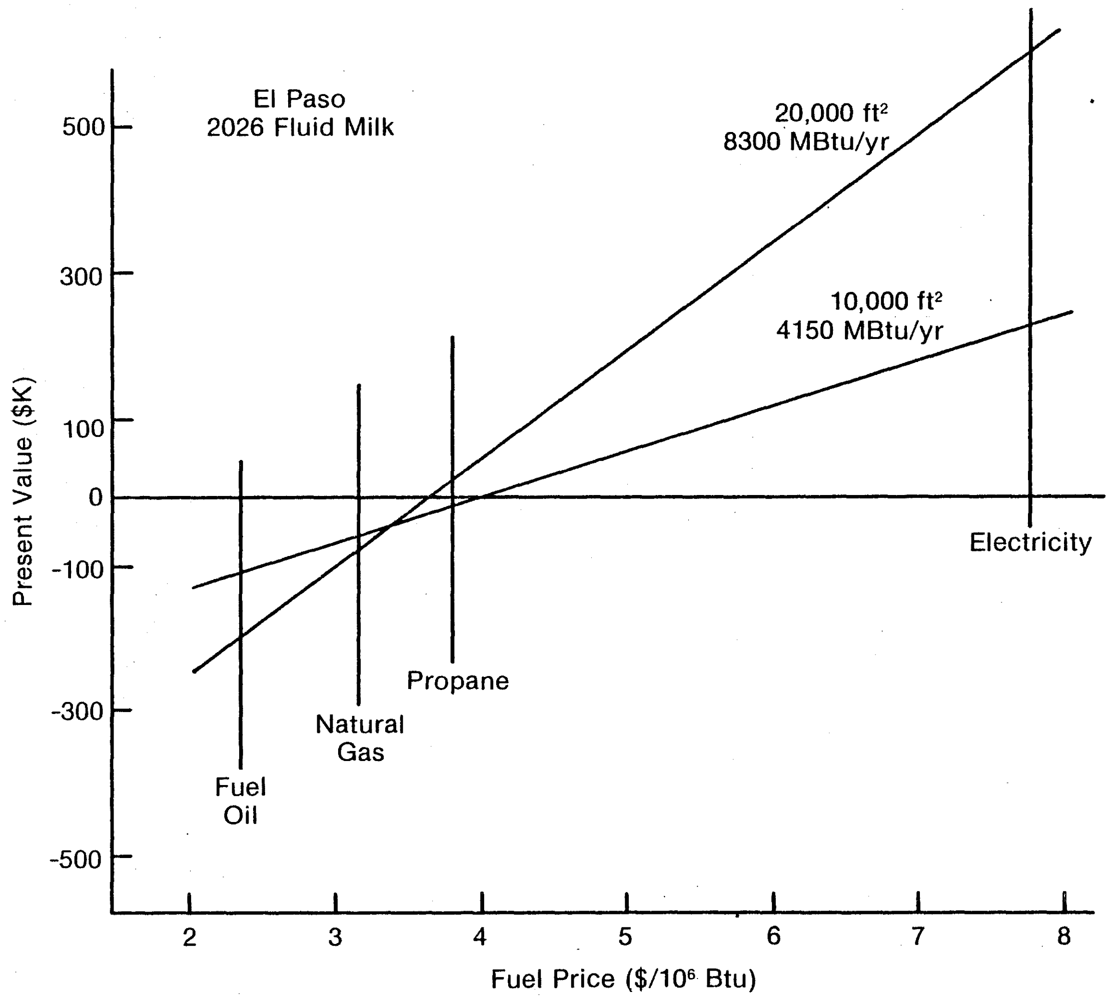

Figure 5-13. Net Present Value of Solar Energy Applied to Fluid Milk Processing in El Paso, Tex., for a Range of Fuel Prices

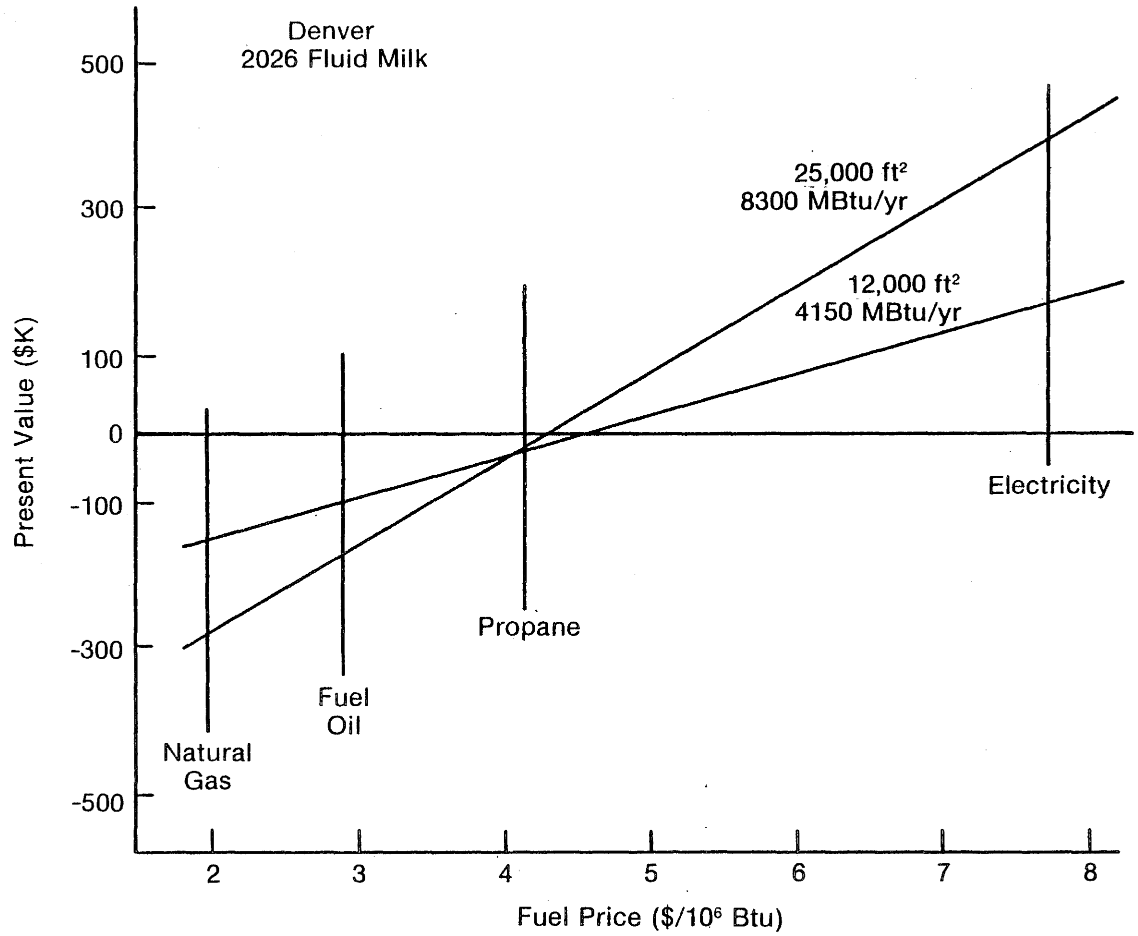

Figure 5-14. Net Present Value of Solar Energy Applied to Fluid Milk Processing in Denver, Colo., for a Range of Fuel Prices

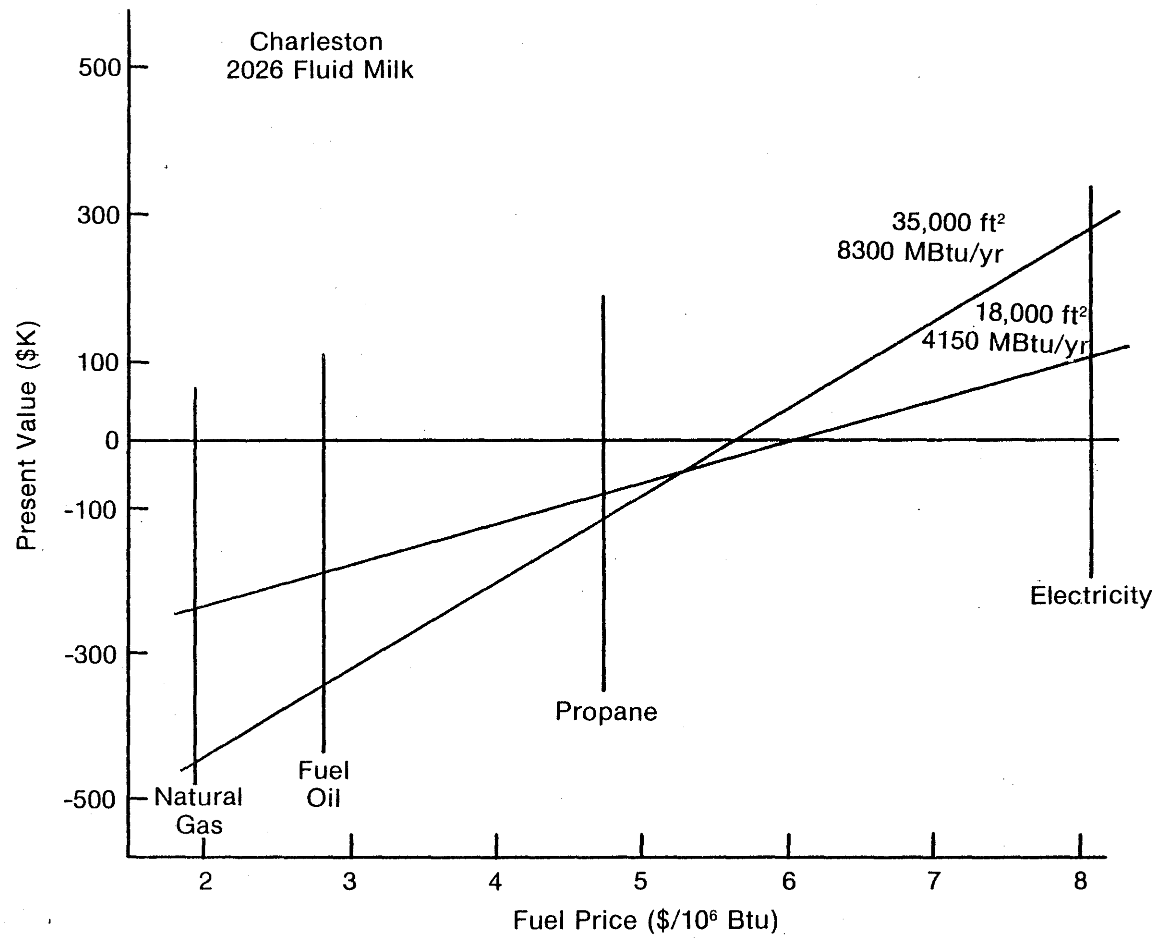

Figure 5-15. Net Present Value of Solar Energy Applied to Fluid Milk Processing in Charleston, S.C., for a Range of Fuel Prices

SERI

SECTION 6.0

CASE STUDIES

6.1 CASE STUDY SELECTION

Case studies provide a field check on the end-use matching methodology and indicate procedural improvements. In this study, a commercial laundry and two metal parts processing lines in a manufacturing plant were examined for energy conservation potential and solar heat applications.

These detailed case studies for two industrial/commercial processes were conducted to:

- identify conservation opportunities and energy-saving modifications of the processes;
- investigate the potential for solar energy use in these processes and compare it with conservation measures;
- compare field data with literature data used in the IPHDB;
- test the usefulness of the PROSYS program, identify problems in its application, and suggest future improvement; and
- identify conditions unique to the plant process and site that might be favorable or unfavorable to solar applications.

Processes for case studies were selected on the basis of:

- location in the Denver area to reduce travel cost;
- cooperativeness of the firm;
- large energy requirement in the low to intermediate temperature range, 65 to 175 C (150 to 350 F);
- widespread use of the process; and
- usefulness in testing IPHDB and the PROSYS program.

Initially, the purpose of the study was explained to key personnnel in several industries. Of nine organizations contacted, eight indicated interest. The selection of four organizations for follow-up meetings was based on their receptivity and their processes.

At the follow-up meeting, the SERI end-use matching project and the required data were described. The organization personnel discussed their processes, energy requirements, and interests in solar energy. Usually the process facility was toured. At one plant, it was immediately clear that insufficient area (unoccupied roof or land) was available for the installation of a significant solar collector field. In two of the four cases, mutual interest was sufficient to proceed with detailed case studies. Data were gathered at subsequent meetings using a form patterned after the IPHDB input data requirements.

Neither organization could supply all the desired data; therefore, calculations, conversations, and meetings determined the needed quantities. Additional process tours usually were necessary, and contacts with equipment vendors and building contractors provided important information.

6.2 PROCESS ANALYSIS

The first visit demonstrated that the load characteristics of each plant or process did not closely match those in the IPHDB for its SIC code. Repeated contacts yielded the process data necessary for analysis.

Process data for case study analyses must have two major characteristics:

- they must be amenable to the PROSYS program; and
- they must indicate temperatures, use rates, supply mediums, and purposes of the delivered energy.

Considerably more process detail is needed, however, for realistic energy-use and energy-need audits. The firms supplied the temperatures and the total heat and electricity requirements but did not supply the energy-use rate for individual processes or units within the plant.

For example, the laundry supplied the required temperatures for most units. Monthly utility bills (electricity, natural gas, and water) for a recent one-year period, washing formulas (the temperature and quantity of water required for each step of the washing cycle for various materials), and the total monthly weight of material washed were also provided. The laundry shared a recent consultant's study of energy use. A flow sheet was not included, but SERI obtained engineering drawings from the building contractor; however, these were 11 years old and numerous changes had been made. From the firm's engineering drawings and the operating data and schedule the SERI team constructed a quantitative energy-flow diagram.

The procedure evolved to search for energy conservation included the following steps:

- The total process energy-use rate was determined.
- The quantities of energy used were established as functions of the required supply temperature and the supply medium.
- A period long enough to show seasonal trends and average values was examined.
- The purpose of the heat and the importance of its means of supply were identified.
- Mass and energy balances were calculated to determine the end uses of the heat.
- Potential reduction of heat losses was examined. Specifically examined were:
  - energy use compared to actual needs,
  - losses from the process to surroundings, and
  - waste heat contained in streams leaving the process.

- The process operating schedule and the heating schedule were compared to identify opportunities to shut off heat.
- Heat requirements were identified that might be met by solar systems, as indicated by temperature requirements and the use schedule.

6.3 CONSERVATION POTENTIAL

The two most common types of conservation potential are:

- reduction of heat losses to the atmosphere and of waste heat in streams leaving the process; and
- reduction of energy necessary for the process by reducing process irreversibilities.

6.3.1 Commercial Laundry

The laundry studied is a relatively large and efficient energy user. Energy flows estimated from mass and heat balances are shown in Fig. 6-1. About 71% of the total heat input is lost as waste heat in streams leaving the process, and much of this is recoverable. About 24% is lost by heat transfer from the ironing machines, a loss that can be reduced. The remaining 5% loss is unaccounted for. The balances are summarized in Table 6-1 and described in more detail in Appendix G.

About 29% of the total energy input leaves as waste heat in the boiler stack gas, corresponding to a boiler efficiency of 66%. This efficiency could be raised to about 75% by two measures: (1) better control of the fuel-to-air ratio by using stack gas oxygen-content control, and (2) installation of a stack gas heat exchanger to preheat the combustion air or the boiler feed water. An increase in boiler efficiency from 66% to 75% would increase the steam output by 13% at the same fuel rate or reduce the fuel requirement by 12% at the same steam output.

An estimated 13% of the total energy input leaves in the gases from the natural-gas-fired driers. This waste heat appears to have attractive recovery potential, but it is especially unmanageable because the gas is laden with lint and is very humid, and its flow is intermittent. The boiler could provide hot stack gas to heat the driers, but boiler safety codes probably preclude this possibility.

Within the process, the biggest energy consumers are the ironing machines, which use 33% of the total energy input. About 6% is consumed in the evaporation of water, 3% leaves as sensible heat with the ironed material, and 24% appears to be lost by heat transfer to the surroundings. The machine surfaces are heated to about 150 C (300 F). Reduction of the heat loss from the iron ing machines has a large conservation potential.

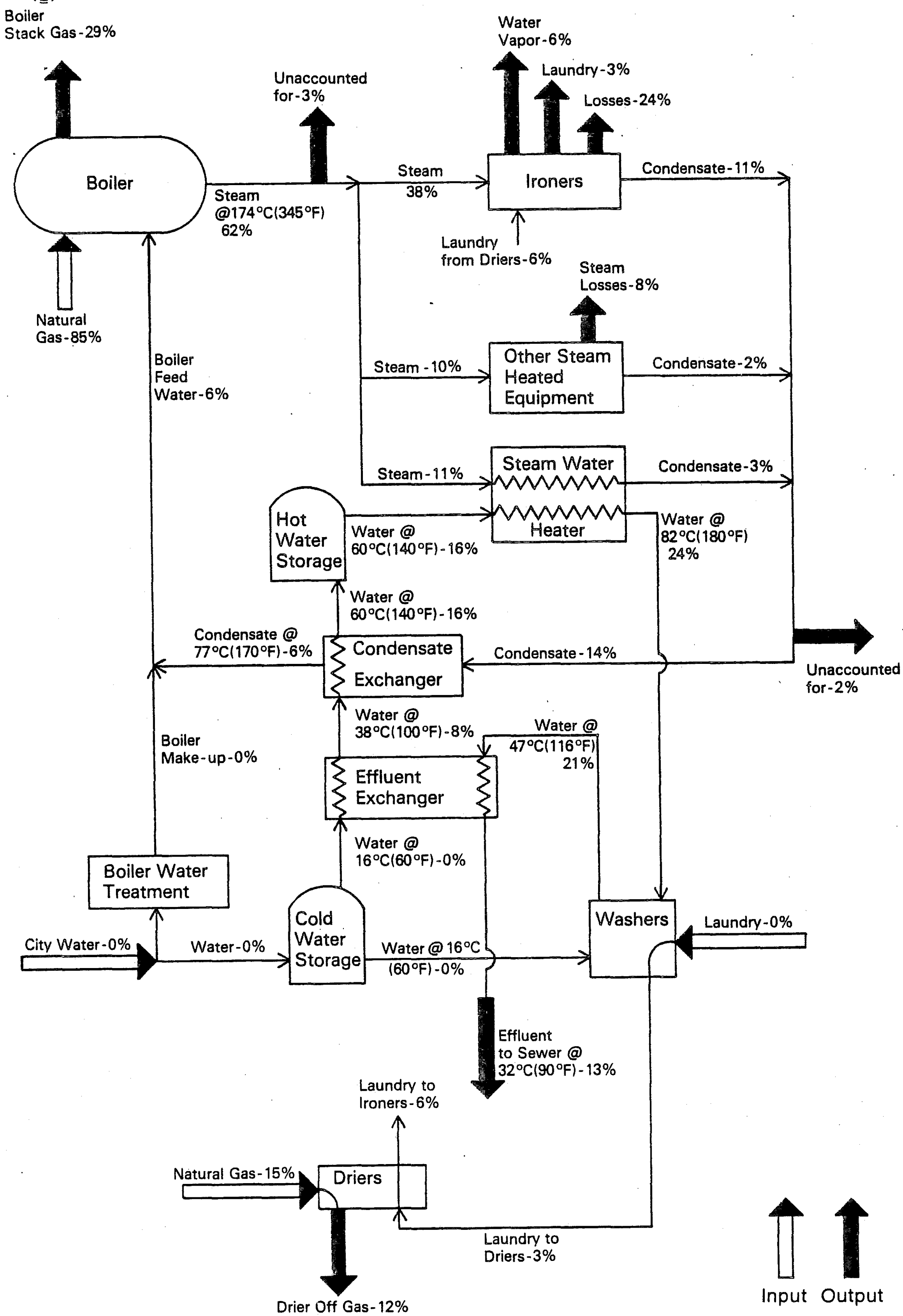

Figure 6-1. Schematic Diagram of Commercial Laundry

Percentages are percentage of total energy input of 174 GJ/day contained in a stream, relative to water at 16 C (60 F)

Table 6-1. WATER AND ENERGY INPUTS AND OUTPUTS FOR COMMERCIAL LAUNDRY

Stream	Water Rate (kg/day)	Energy Content[a] (GJ/day)	% of Total Energy Input
Inputs			
Natural gas to boiler	--	148	85
Natural gas to driers	--	26	15
City water	3.5×10^5	0	0
Totals	3.5×10^5	174	100
Outputs			
Waste water	3.3×10^5	23	13
Boiler stack gas	--	50	29
Drier off gas	0.1×10^5	21	12
Heat loss from ironers	--	42	24
Vapor from ironers	0.04×10^5	11	6
Material from ironers	--	5	3
Steam loss from equipment	0.02×10^5	13	8
Unaccounted for	0.04×10^5	9	5
Totals	3.5×10^5	174	100

*With respect to water at 16 C (60 F).

The engineering design required to reduce the ironer heat loss is beyond the scope of this study. A shield over the top of each ironing machine, however, could substantially decrease the loss by reducing convective heat transfer. Such a shield must be transparent for observation of the work, must be quickly removable for maintenance, and must allow sufficient air circulation to prevent saturation of the air above the working surface. A flat sheet of acrylic mounted a few inches above the ironer rollers, open on the sides and ends, and including hooks for hoist-lifting, is a possibility. Additional insulation on the bottom of the machines would also help. An added benefit of the reduction of heat loss from the ironers would be the decreased temperature of the surrounding working area. On the other hand, more space heat might be required for the building during the winter.

The laundry has a heat-recovery unit that reduces the effluent water temperature from about 47 C (116 F) to 32 C (90 F) by heat exchange with the cold water supply. About 13% of the total energy input leaves with the dirty water. (This value would be about 21% if there were no heat recovery.) This energy loss could probably be reduced to 7% with more effective heat exchange. The laundry may install an effluent water treatment and recycling process that probably would reduce the loss to 7% or less, as well as conserve water and laundry chemicals. The case study balances indicate that almost 95% of the water fed to the system leaves in the effluent to the sewer.

About 20% of the input energy evaporates water in the drying and ironing operations. It is difficult to reduce this energy requirement.

Waste-heat recovery, effluent water recycling, and ironer heat-loss reduction might reduce the total energy requirement of the process by about one third. Since the energy consumers with these conservation potentials are steam-heated, the boiler load might be reduced almost 40%. The conservation measures most easily implemented are the heat-loss shields and insulation for the ironing machines. Further engineering work on these possibilities is recommended.

The laundry operating schedule is one daytime shift per day. At the end of the operating shift, the boiler is shut off and all steam-heated equipment is allowed to cool. The boiler is started two hours prior to the beginning of the shift to bring it and the equipment up to temperature.

Mass and energy balances for this case study indicated 92% return of the condensate to the boiler. Independent studies have reported 50% to 60% condensate return (Pritchard 1977; Garrett-Callahan Co. 1977-78). Since none of these values are based on direct measurements of steam or condensate flows, the differences have not been resolved.

6.3.2 Manufacturing Process

Two process units in a manufacturing plant were investigated. One is an aluminum "bright-dip" process wherein aluminum parts are moved through a series of aqueous chemical and rinse water baths to produce a bright finish. A diagram of the bright dip line is shown in Fig. 6-2. The second is a "strip" operation in which improperly finished metal parts are dipped in aqueous chemical and water baths to remove the finish. The processes operate one shift per day, five days per week. The processes are heated by circulation of hot water (heated by interruptible natural gas at $1.29/GJ, or $1.36/MBtu, as of April 1978) via heat exchange and by electrical-resistance heaters (at $5.55/GJ, or $5.85/MBtu, as of July 1978). The process data supplied by the firm are summarized in Tables 6-2 and 6-3.

To maintain operating temperatures, heat is required to keep the metal parts warm as they move through the baths and to compensate for heat losses to the surroundings. When there is no parts throughput, heat is required only to offset heat losses. Data were insufficient to determine the heat necessary to heat the parts, but it is estimated to be less than 20% of the total heat load. Plant personnel have studied the temperature requirements of the processes and have found that the temperatures used by the plant are the minimum required for proper operation.

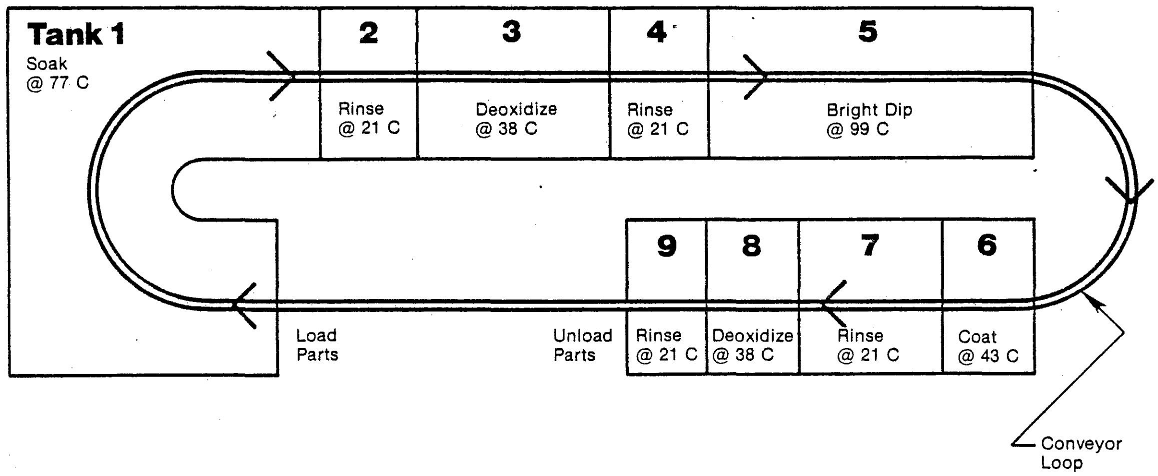

Figure 6-2. Schematic Top View of Bright-Dip Line

Table 6-2. OPERATING DATA FOR ALUMINUM BRIGHT-DIP PROCESS

Tank No.	Operation	Volume (m^3)	Operating Temperature (C)	Heat Input (MJ/h)	Heat Source
1	Soak	11.4	77	a	Process hot water
2	Rinse	1.3	21	b	--
3	Deoxidize	2.7	38	a	Process hot water
4	Rinse	1.3	21	b	--
5	Bright-dip	6.1	99	190	Electricity
6	Rinse	1.3	21	b	--
7	Deoxidize	2.7	38	a	Process hot water
8	Rinse	1.3	21	b	--
9	Coating	1.3	43	a	Process hot water

[a]Data not available.
[b]No heating.

Table 6-3. OPERATING DATA FOR METAL STRIPPING PROCESS

Tank No.	Volume (m^3)	Operating Temperature (C)	Heater Rating[a] (MJ/h)
1	3.0	82	71
2	1.5	82	52
3	1.0	27	23
4	0.2	21	22

[a]All tanks are heated electrically. The values given are heater ratings because actual heating rates were unavailable.

There are two major potentials for energy conservation in these heated-bath processes. The baths are generally maintained at operating temperature when the plant is closed. Energy use could be reduced by turning off the heat to the inactive baths. Heating would have to be resumed before process start-up to allow the operating temperature to be reached before the shift began. Appendix F demonstrates that less energy is required for a process if heating is shut off when the process is not operating. There may be process-related reasons for continued heating, however. For example, the stability of chemical baths might deteriorate if the temperature drops. In this process, the bright-dip bath tends to gel if it becomes too cold. The data are sufficient to make quantitative estimates of conservation for the electrically heated bright-dip tank. About seven hours would be required to heat the bright-dip bath and about 42% of the total energy requirement would be saved by turning off the heat to idle baths. These estimates are illustrated in Appendix F.

The second possible energy conservation measure involves reduction of heat losses from the baths. The baths are open to the atmosphere, so a major heat loss at elevated temperatures results from the evaporation of water. The evaporation rate and heat loss could be calculated from makeup water requirements, but these data were not available. The direct way to reduce heat losses is to reduce evaporation. This could be accomplished by covering the bath surface with plastic balls (similar to table tennis balls). The balls would allow parts to move through the bath without interference and could result in a heat loss reduction of 75% (Bonne et al. 1974). Estimates based on the evaporation rate indicate a 50% reduction in heat loss is achievable with evaporation suppression.

The total energy requirement would be reduced by these two conservation measures to $0.58 \times 0.5 = 0.29$ (29%) of the current value. For the bright-dip tank alone, possible energy savings are as high as $550 \times 0.71 = 390$ GJ/yr (373 MBtu/yr), and financial savings are about $2000/yr.

6.4 SOLAR END-USE MATCHING

End-use matching is accomplished by inputting process operating data to the PROSYS program. Since PROSYS automatically outputs results for fractions of the total process load, these results can be examined for the full process load and for reductions in the total load resulting from conservation measures. The economic parameters used in this study were the PROSYS default options unless otherwise indicated.

6.4.1 Commercial Laundry

All process heat for the laundry is supplied by natural gas. About 85% is supplied to the boiler, [interruptible, at $1.29/GJ ($1.36/MBtu) as of April 1978]. The remaining 15% is for drying and some space heating [noninterruptible, at $1.70/GJ ($1.79/MBtu) in April 1978].

The potential solar applications include:

- supplying the boiler load (85% of total) by a solar steam system;
- supplying the hot water load (8% of total) by a solar water system; and
- supplying the drier loads (15% of total) by a solar air system.

None of these applications give economically attractive results because of the low price of natural gas. Some of the results are summarized in Table 6-4.

Table 6-4. SOLAR HEATING APPLICATIONS FOR COMMERCIAL LAUNDRY

Application	Temperature [C (F)]	Load (GJ/day)	Medium	Investment for Most Cost-Effective System	Present Value of Project
Boiler load	174 (345)	100	Steam	$\$2.8 \times 10^6$ (parabolic trough D)	$-\$2.1 \times 10^6$
Hot water	82 (180)	14	Hot water exchange	$\$4.2 \times 10^5$ (parabolic trough C)	$-\$3.2 \times 10^5$
Gas-fired drier load	107 (225)	25	Hot air direct	$\$6.1 \times 10^5$ (flat plate A)	$-\$4.4 \times 10^5$

The laundry wanted especially to reduce the boiler load because a new boiler load brought on-line in May 1978 was 20% to 25% undersized for one-shift operation. The old boiler operated in parallel with the new one in order to handle the throughput in one shift. Laundry management hoped that by heating water with a solar system, the new boiler could handle the reduced load. The heat balances (Fig. 6-1) indicate, however, that water heating is only 10% of the boiler load. Even with solar energy applied to this task, two boilers are still needed and the investment in a solar water-heating system does not seem justified. About 30 GJ/day (28 MBtu/day) would have to be supplied by the solar system to insure the new boiler's adequacy. If the conservation measures discussed in Section 6.3.1 were shown to be cost-effective and were implemented, the new boiler could handle the reduced load without solar technology.

6.4.2 Metal Processing Lines

In the bright-dip line, the bright-dip tank is heated electrically while the other tanks are heated by process hot water (heated by exchange with hot water from the boiler plant, where natural gas is the fuel). Tanks in the strip room are heated electrically. The actual heating rate was available only for the bright-dip tank, so it is the only tank for which results are shown.

Results for a solar hot water system for heat exchange to the bright-dip tank are summarized in Table 6-5. The present value for the most cost-effective system (a parabolic trough) is negative; i.e., the application is not cost-effective. Results are presented for both 10- and 20-year lifetimes (10 years is the period the plant managers would use in economic calculations).

Table 6-5. PROSYS RESULTS FOR SOLAR HEATING OF BRIGHT-DIP TANK

	Fraction of Process Heat Provided by Solar Technology	
Process Parameter	100%	25% (with conservation)
Heat load (MJ/h)	190	48
Temperature	99 C (210 F)	99 C (210 F)
Medium	Electric	Electric
Cost	$5.55/GJ	$5.55/GJ
Investment for most cost-effective system	$56,570 (parabolic trough C)	$19,300
Present value of project[a]		
20-year life:	-$13,600	-$8,000
10-year life:	-$23,200	-$10,040

[a]Economic parameters are from Section 4.0.

The present value is a negative 14% of the initial investment for a twenty-year life, at full load; the application is almost cost-effective. By varying the cost of the alternate fuel, it was found that the present value of the project becomes zero at an initial fuel cost of $6.67/GJ ($7.04/MBtu) for a 20-year project life. Although this is higher than the fuel price paid by this manufacturer, higher rates are paid for electric heating in many locations. Thus, the displacement of electrical process heat by a solar system is almost economically feasible and may in fact be feasible in some locations.

The electricity price of $5.55/GJ (2¢/kWh) is a nominal value used by the manufacturer in economic analyses. The commodity rate is $3.61/GJ (1.3¢/kWh). With the demand charge included, the total rate is $8.29/GJ (2.9¢/kWh). At the latter price, the solar application would be economical with a 20-year life. The demand charge, however, is based on the peak 15-minute demand during the entire month. The manufacturing plant's peak demand occurs during daylight but a solar system must supply energy every operating day for a month in order to avoid that month's demand charge. Solar systems do not have such high reliability.

There is another incentive for the use of solar energy in this plant. Hot water from the boiler supplies space heat as well as process heat in the manufacturing building. During months when space heating is not required, hot water must be circulated from building to building only to supply heat to the bright-dip line. If this line were solar heated, circulation of hot water could be avoided, with attendant savings in pumping and fuel costs. These savings have not been estimated; however, since solar energy would displace heat from natural gas (as well as electricity) the application might be economical.

Solar heating of the metal-parts processing lines is sufficiently close to being cost-effective to merit further engineering study. Another potential solar application, a solar steam-driven gas compressor, was identified in this case study. Further development of the technology of this application is needed.

6.5 SUMMARY

Water and energy balances were calculated for the laundry from utility-use data and operating temperatures supplied by the firm. It was estimated that the energy input of 174 GJ/day could be reduced by one-third by a combination of boiler-stack gas heat exchange, recycling of effluent water, and reduction of heat loss from the ironing machines. No solar system was found to be cost-effective for the laundry when compared with natural gas prices of $1.29/GJ to $1.70/GJ.

An electrically heated tank in the metal parts bright-dip line requires 190 MJ/h. This heat input could be reduced by an estimated 70% by not heating the tank during the two shifts it is not in use and by evaporation suppression. Similar reductions in energy use could be achieved for the other heated tanks in the metal processing lines. The most cost-effective solar heating system for the metal parts processing is almost competitive with electrical heating costs of $5.55/GJ. Solar heating also would allow the hot water supply to the fabrication building to be shut off during warm months if the bright-dip line were solar heated. Further engineering studies of this application of solar energy are recommended.

Many processes similar to the metal processing lines are heated during idle shifts. These studies show that energy is always conserved if such lines are shut down when not in use, although some processes may require uninterrupted heating.

6.6 CONCLUSIONS

The case studies also provide a number of conclusions which relate both to the methodology applied and to the general principles governing solar industrial applications. For example, it is clear that process information more detailed than usually available in the literature should be collected in order to allow satisfactory analysis of solar applications. The process information required includes:

- Operating schedule: The energy use during the hours the collector is operating must be known.
- Heat transfer medium and operating mode: Can hot water or hot air be supplied directly to the process, or must heat exchange be used?
- The maximum and minimum process operating temperatures and the heat duty at the various temperatures: The use in the analysis of a maximum process temperature may be very pessimistic. On the other hand, the PROSYS assumption of collector operating temperature for exchange systems may be overly optimistic and must be reexamined.

To collect the same amount of heat for a given process temperature, a direct system is more advantageous than an exchange system because the collector must operate at a higher temperature (hence lower efficiency) in an exchange system. In some cases, however, exchange systems may recover some process waste heat and thus meet the process energy needs with less collected solar energy than necessary with a direct system. Therefore, an exchange system may be more economical in certain cases.

These studies suggest that preheating may be a particularly successful use of a solar system for process heat. Preheating is a particular form of low temperature processing; in general, low or intermediate temperature processes (<200 C) are attractive for solar application when cascaded thermal energy from other processes is not available.

The efficiency of solar application to preheating and the potential advantages of exchange systems indicate the need for a more detailed representation of process requirements in PROSYS. In addition, collector performance as governed by temperature levels should be more closely tuned to these detailed requirements. This tuning might be accomplished by refining the heat delivery system models in PROSYS. A process module general enough to handle many processes but sufficiently detailed to indicate exchange and preheat opportunities should be added to PROSYS.

Many applications, such as drying, use warm air in the 100 to 200 C (200 to 400 F) range. Collector absorbers for these temperatures with air as the working fluid should be given attention in component R&D programs.

Displacement of electrical energy was found to be the most economically favorable use of solar technology because of the high cost of electrical energy. Operations using electrical process heat at temperatures up to about 100 C (200 F) and electrical drives for air compressors, pumps, and other process equipment might be economical applications of solar energy. Economical applications of solar IPH will most likely be found for processes that use expensive energy sources or use energy very inefficiently, or for processes in which more energy can be displaced than must be supplied by solar energy. Future case studies should seek processes of these kinds.

6.7 REFERENCES

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SECTION 7.0

DISCUSSION AND RECOMMENDATIONS

7.1 DISCUSSION

As described in Section 5.0, the most significant results of this study are: (1) the development of analytic methods to identify and rank combinations of solar systems and industrial processes for solar industrial process heat applications, and (2) the development of the computer programs PROSYS and ECONMAT which implement the analysis. These software tools allow comparison of various collectors for diverse process requirements and provide a convenient means of selecting the solar equipment most suitable, in both performance and cost, for specific processes in given climates.

7.2 USE OF THE PROSYS/ECONMAT MODELS

The performance model PROSYS employs information on local climate, collector characteristics, and process requirements to calculate the long-term annual energy delivered for each location/process/solar-system configuration. Using calculated performance information, process energy use requirements, collector costs, and local economic factors, ECONMAT calculates the solar system capital cost and the annual energy capacity cost.

PROSYS is neither a dynamic simulation nor a means of detailed system design. The model includes certain assumptions and limitations. A constant collector operating temperature (with a variable flow rate) is assumed; therefore, the portion of the process load provided by the solar system varies. Because a full-scale conventional backup system is assumed, storage is not essential and is not included in the model. In addition, it is assumed that the process can absorb all energy delivered by the solar system. These assumptions are realistic since many industrial applications will use solar energy, at least initially, as a fuel-saving supplement to a conventional system.

Although the nondynamic nature of the model imposes some limitations, it has the advantages of speed and flexibility. The model provides an efficient preliminary appraisal of solar energy for industrial applications and a means of comparison of generic collector types. The model is also useful for a variety of sensitivity and parametric studies.

The computer software PROSYS/ECONMAT can be used for diverse analyses merely by varying information in the data bases. A ranking of solar IPH applications can be generated with an input IPH data base composed of information on many processes. Case studies, including detailed process breakdowns and potentials for preheat and process reconfiguration, can be performed when specific process data is known. Various parametric sensitivity studies are possible, including tests of the effects of changes in collector characteristics and studies of the impacts of changes in costs and economic factors. A comparison of collector types over a range of temperatures can be graphically illustrated. The software can also be used to determine solar system cost requirements for a given set of performance parameters and economic conditions.

7.3 END-USE MATCHING

The concept of end-use matching, i.e., selecting the most appropriate solar equipment for specific industrial process requirements, was developed and tested in this study. PROSYS and ECONMAT, though limited in some respects, were found to be adequate analytical tools for preliminary appraisal. The accuracy of the analysis, however, is directly dependent on the availability and validity of the input data, including meteorological conditions, collector characteristics, economic conditions, and, most importantly, process requirements and conversion efficiencies of competing fossil fuels.

The end-use matching analysis, using the data bases as currently configured, both reinforces and quantifies the intuitive supposition that the applications most amenable to solar energy are primarily those requiring low temperatures and using expensive fuels. Flat-plate collectors excel in performance and economics below 150 F, and parabolic troughs excel above 200 F. In the temperature region between 150 and 200 F, the optimum choice varies among flat-plate, linear Fresnel lens, and parabolic trough collectors, depending on meteorological conditions. The CPC/evacuated tube collector showed poor performance in this analysis, but recent evidence suggests that much better performance may be available from these collectors in the near future (Edgecombe et al. 1979). The system configuration consistently appearing most economical is the direct hot water system, which benefits from a lower required collector operating temperature and, therefore, performs more efficiently. In general, solar energy is currently not economically competitive with inexpensive fuels such as natural gas or fuel oil. Solar energy is, however, often competitive with more expensive fuels such as propane and electric power, and with all fuels when they are used inefficiently in a process.

7.4 ADEQUACY OF THE DATA BASES

Use of the IPHDB as currently configured, i.e., with average parameter values for "typical" industrial plants, can lead to misleading general conclusions. For instance, the IPHDB indicates that the majority of industries use natural gas. Though this may be true, there is no indication of the efficiency with which the natural gas is used or any estimate of what other more expensive fuel sources would be substituted in case natural gas were to become unavailable.

Moreover, the temperatures given in the IPHDB are normally the maximum required for the industrial plant. Breakdown of process structures and detailed temperature requirements at various process stages are not available. For each four-digit SIC code, one general process is assumed. Actually, each industry often involves numerous subprocesses with varying temperature requirements and sometimes different fuels for the manufacture of a product. The effect of this generalization is that often worst-case conditions are assumed for the solar analysis and the results are unrealistically pessimistic.

The inaccuracy of this analysis caused by generalization can be resolved in two ways. The first is to compile a set of specific plant data, including fuel source, fuel usage efficiency, and temperature requirements for as many processes as applicable in each plant. The data can be obtained through industrial contacts or from literature and gathered for industries in as many locations as available in METDAT: 26 SOLMET sites plus 222 ERSATZ sites. Data from several plants in the same industrial category should prove valuable in providing comparisons of process configurations and plant size. Although it is difficult to apply the results of a generalized study to specific plants, analysis of many individual cases may produce insights applicable to the entire industrial category.

The second approach to the problem of generalization is analysis of a set of generic processes. A number of characteristic processes occur in diverse industries. For example, pasteurization processes are common to fluid milk dairies, breweries, and juice concentrate processing plants. Pasteurizers are usually heated by steam to a temperature of 170 to 190 F with similar types of heat exchangers. Generic solar system designs could probably be generated for pasteurization processes. Generic systems might also be designed for various wash and cleanup processes (hot water) and many drying applications (hot air). Each of these processes can be characterized by a well-defined temperature range and one or more appropriate solar system configurations. With PROSYS/ECONMAT, parametric studies can be performed by varying location, energy requirement (and thus solar system size), and conventional fuel price. Thus, the conditions that allow solar energy to become economically competitive can be specified for each generic process. The industrial community could use this information as a guide to the viability of solar energy for specific process requirements.

7.5 ECONOMIC ANALYSIS

Generalizations affect the accuracy of the economic analysis of solar IPH systems as well as the performance comparisons. For example, although the installed capital cost of a complete solar IPH system of given annual energy capacity may be reasonably estimated from general site data, the actual value of such a system in producing energy depends heavily upon internal economic factors of a specific industrial plant as well as constraints such as capital and land availability. Specific plant values were not included in the IPHDB for factors such as the required rate of return. Typical values for these parameters were adopted early in the study to allow present value analysis of a given system/process match. This method of economic analysis, preserved in the version of ECONMAT described in Appendix E, is useful in performing sensitivity studies on size-related cost reductions, changes in the rate of return, and variations in financial incentives. Selection of a set of typical economic parameters, however, leads to inaccurate results in present value comparisons among industries due to the generalizations involved.

A solution to this problem of generalization has been implemented. Although the required-revenue approach to economic analysis may not be widely used by industry in project evaluation, it does satisfactorily separate generalizations from specific data in the economic analysis of solar IPH systems. After ECONMAT yields a capital energy capacity cost (the total solar system capital cost divided by the annual delivered energy), a multiplier may be selected (see Section 4.0) to derive the actual perceived energy cost of solar energy for a given industrial plant. The plant data collection described in Section 7.4 can be a source of information on economic parameters for determination of an appropriate multiplier, thus facilitating accurate calculation of the cost-effectiveness of a system/process match. More accurate rankings of industrial applications of solar energy will result.

7.6 RECOMMENDATIONS

Based on the results of end-use matching analyses and case studies, the following recommendations for future work in solar applications for industrial process heat are given:

- The IPHDB should be modified to include sufficient details on processes so that an end-use matching analysis does not impose unnecessarily restrictive requirements on the solar systems. Information that should be added includes temperature ranges for the individual processes within each SIC industry and the corresponding conversion efficiencies for the conventional sources. Significant constraints to system installation, such as land availability, should be identified.
- Since PROSYS is very useful in case study analyses, the capabilities of the model should be expanded. For example, specification of average collector operating temperatures would enable PROSYS to be applied to a wider range of process configurations. It may be possible to include some capability for storage analysis in PROSYS if reliable quasi-static storage algorithms can be generated.
- The required revenue approach to economic analysis places the burden for accuracy on the estimates of system capital and operating costs and on the knowledgeable assessment of key restraints to system installation. Little effort has been expended in cost engineering and cost analysis of IPH systems. Accurate models of initial solar system cost and operating and maintenance costs need to be created.
- The two case studies of this report provided useful data and insight into solar applications for industrial process heat. Additional case studies should concentrate on those industries that are most promising for solar applications. Concepts such as energy conservation, process reconfiguration to accommodate solar energy more readily, and the use of solar energy for preheat should be emphasized. Also, an effort should be made to define and analyze generic industrial processes.

7.7 REFERENCES

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APPENDIX A

INDUSTRIAL PROCESS HEAT DATA BASE

A.1 SI UNITS

SIC	Standard industrial classification code
PROC TMP	Process temperature (C)
HEATR	Heat rate (MW)
FLOWR	Maximum steam flow rate (kg/s)
SAE	Standard annual energy use (1.0E10 kJ/yr)
SYS	Possible systems in order of applicability:
1	Direct hot water
2	Indirect hot water
3	Direct hot air
4	Indirect hot air
5	Steam flash
6	Steam generator
B FUEL	Backup fuel
OP	Operation code
0	Continuous
1	Batch
SOP	Seasonal operation code
0	Continuous
1	Seasonal
ENERGY/UNIT	Energy required to produce one unit (kJ/unit)

SIC		PROC TMP	HEATR	FLOWR	SAF	SYS	B FUEL	GP	SOP	ENERGY/UNIT
2011	MEAT PACKING PLANT	176.7	2.137	.469	3.196	-2 1 6	NAT. GAS	0	0	
2013	SAUSAGES/PREPARED MEAT	176.7	1.079	.273	1.413	6 2 1	NAT. GAS	0	0	12657.60 /KG
2016	POULTRY DRESSING PLANT	60.0	3.869	.895	2.880	6 1 2	NAT. GAS	0	0	
2021	CREAMERY BUTTER	76.7	4.778	.804	3.576	6 1 2	NAT. GAS	1	0	
2022T	NAT. AND PROCESSED CHEESE	93.3	1.832	.262	2.405	6 3 2	NAT. GAS	1	0	722.54 /KG
2022A	CHEESE PRODUCTION	57.2	.001	.001	.002	6 0 0	NAT. GAS	1	0	
2022B	CHEESE PRODUCTION	39.4	.026	.008	.025	6 0 0	NAT. GAS	1	0	
2022C	CHEESE PRODUCTION	93.3	.959	.360	1.256	6 0 0	NAT. GAS	1	0	
2022D	CHEESE PRODUCTION	73.9	.023	.009	.030	6 0 0	NAT. GAS	1	0	
2022E	CHEESE PRODUCTION	68.3	.120	.046	.157	-2 6 0	NAT. GAS	1	0	
2022F	CHEESE PRODUCTION	37.8	.002	0.000	.003	-1 0 0	NAT. GAS	1	0	
2022G	CHEESE PRODUCTION	315.6	.276	0.000	.361	3 0 0	NAT. GAS	1	0	
2023T	CONDENSED/EVAP. MILK	204.4	4.162	1.507	5.453	3 6 0	NAT. GAS	1	0	
2023A	CONDENSED MILK PRODUCTION	71.1	1.246	.474	1.632	6 0 0	NAT. GAS	1	0	
2023B	CONDENSED MILK PRODUCTION	71.1	.245	.093	.321	6 0 0	NAT. GAS	1	0	
2023C	CONDENSED MILK PRODUCTION	121.1	.138	.051	.180	6 0 0	NAT. GAS	1	0	
2023D	CONDENSED MILK PRODUCTION	190.6	1.019	0.000	1.335	3 0 0	NAT. GAS	1	0	
2024	ICE CREAM/FROZEN DESERT	76.7	.706	.139	.530	6 2 1	NAT. GAS	1	0	
2026	FLUID MILK	76.7	1.164	.548	.875	6 2 1	NAT. GAS	1	0	25.32 /KG
2032	CANNED SPECIALTIES	121.1	5.525	2.495	8.272	6 3 0	NAT. GAS	1	0	263.70 /KG
2033	CANNED FRUIT/VEG.	121.1	2.931	.252	4.325	-2 6 1	NAT. GAS	1	0	
2034	DRIED FRUITS/VEG.	176.7	4.836	1.197	5.443	-2 4 6	NAT. GAS	0	0	
2035	PICKLED FRUITS/VEG.	148.9	1.263	.263	1.413	6 2 0	NAT. GAS	1	0	
2037	FROZEN FRUIT/VEG.	87.8	1.847	.624	2.742	-2 1 6	NAT. GAS	1	0	
2038	FROZEN SPECIALTIES	82.2	2.646	1.123	2.131	6 3 0	NAT. GAS	1	0	3586.32 /KG
2041	FLOUR/GRAINS	121.1	.762	.126	1.160	6 3 2	NAT. GAS	1	0	
2043	CEREALS	121.1	7.738	2.640	11.603	3 6 2	NAT. GAS	1	0	
2045	FLOUR/GRAIN MIXES	121.1	1.483	.592	1.111	6 3 0	NAT. GAS	0	0	226.78 /KG
2047	PET FOOD	121.1	2.711	1.265	2.029	3 6 0	NAT. GAS	1	0	1587.47 /KG
2048	ANIMAL FEED	273.9	2.087	.504	1.562	3 6 0	NAT. GAS	1	0	79.11 /KG
2051	BREAD/BAKED GOODS	232.2	.847	.097	.949	4 3 2	NAT. GAS	1	0	
2052	COOKIES/CRACKERS	232.2	3.582	.239	2.681	3 6 0	NAT. GAS	1	0	2847.96 /KG
2065	CANDY/CONFECTIONS	93.3	1.407	.178	1.540	6 4 3	NAT. GAS	1	0	
2066	CHOCOLATE PROD.	121.1	6.214	.406	4.652	3 4 6	NAT. GAS	1	0	
2077	ANIMAL FATS/OILS	176.7	2.028	.864	1.519	6 3 0	NAT. GAS	1	0	6117.84 /KG
2079	SHORTENINGS/OILS	176.7	37.224	10.420	17.510	6 3 0	NAT. GAS	1	0	290.07 /KG
2084	WINES	182.2	.616	.312	1.371	3 6 2	NAT. GAS	1	0	
2085	LIQUORS	182.2	6.565	3.360	14.767	6 5 2	NAT. GAS	1	0	
2086	SOFT DRINKS	76.7	.910	.179	1.022	-2 6 0	NAT. GAS	1	0	
2087	FLAVORINGS	121.1	2.374	0.000	1.777	3 4 0	NAT. GAS	1	0	
2091	CANNED SEAFOOD	176.7	1.114	.384	1.688	6 4 2	NAT. GAS	1	0	
2092	FISH/SEAFOOD	176.7	.513	.130	.579	6 2 0	OIL	1	0	
2095	COFFEE	148.9	3.259	.910	2.440	4 6 0	NAT. GAS	0	0	
2097	ICE	65.6	.073	0.000	.082	-2 1 0	NAT. GAS	0	0	
2098	MACARONI	148.9	.879	.210	.987	6 4 2	NAT. GAS	1	0	
2099	MISC. FOODS	148.9	1.287	.266	1.444	6 4 2	NAT. GAS	1	0	
2211	COTTON WEAVING	148.9	9.291	3.156	10.337	-1 3 6	NAT. GAS	0	0	
2241	SMALL WEAVE FABRIC	148.9	.938	.321	1.055	-1 3 6	NAT. GAS	0	0	
2253	KNIT OUTERWEAR	148.9	.979	.335	1.097	-1 3 6	NAT. GAS	0	0	
2261	FINISHING BROAD COTTON	135.0	15.857	5.438	17.826	-1 3 6	NAT. GAS	0	0	
2262	FINISHING BROAD FABRICS	148.9	3.517	1.201	3.934	-1 3 6	NAT. GAS	0	0	
2271	WOVEN CARPETS/RUGS	148.9	1.216	.417	1.371	-1 3 6	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	B FUEL	OP	SOP	ENERGY/UNIT
2293	UPHOLSTERY FILLINGS	148.9	4.103	2.378	4.451	1 3 6	NAT. GAS	0	0	
2295	COATED FABRICS	148.9	.538	.508	.949	1 3 6	NAT. GAS	0	0	
2311	MALE COATS	121.1	.497	.108	.548	1 3 6	NAT. GAS	0	0	
2321	MALE SHIRTS	121.1	.352	.078	.393	1 3 6	NAT. GAS	0	0	
2327	MALE PANTS	121.1	.528	.114	.580	1 3 6	NAT. GAS	0	0	
2329	MALE MISC. CLOTHES	121.1	.239	.053	.268	1 3 6	NAT. GAS	0	0	
2331	FEMALE TOPS	121.1	.132	.029	.149	1 3 6	NAT. GAS	0	0	
2335	FEMALE DRESSES	121.1	.092	.020	.103	1 3 6	NAT. GAS	0	0	
2339	FEMALE MISC. CLOTHES	121.1	.117	.026	.131	1 3 6	NAT. GAS	0	0	
2352	HATS/CAPS	121.1	.129	.025	.146	1 3 6	NAT. GAS	0	0	
2361	GIRLS OUTERWEAR	121.1	.131	.029	.147	1 3 6	NAT. GAS	0	0	
2369	GIRLS MISC. OUTERWEAR	121.1	.079	.018	.089	1 3 6	NAT. GAS	0	0	
2386	LEATHER/SHEEP CLOTHES	121.1	.171	.038	.192	1 3 6	NAT. GAS	0	0	
2387	BELTS	121.1	.108	.024	.121	1 3 6	NAT. GAS	0	0	
2389	MISC. ATTIRE	121.1	.133	.135	.148	1 3 6	NAT. GAS	0	0	
2392	HOUSE LINENS	121.1	.498	.166	.551	1 3 6	NAT. GAS	0	0	
2395	DECORATIVE ADORNING	121.1	.039	.012	.040	1 3 6	NAT. GAS	0	0	
2396	AUTO APPAREL	121.1	.290	.097	.327	1 3 6	NAT. GAS	0	0	
2399	MISC. FABRIC PROD.	121.1	.276	.092	.306	6 3 1	NAT. GAS	0	0	
2421	SAW MILLS	93.3	.703	.127	1.055	3 4 6	NAT. GAS	0	0	
2431	MILLWORK	93.3	.211	.036	.295	6 3 1	NAT. GAS	0	0	
2426	HARDWOOD/FLOOR MILLS	93.3	.246	.042	.348	1 3 6	NAT. GAS	0	0	
2431	MILLWORK	93.3	.211	.036	.295	1 3 6	NAT. GAS	0	0	
2436	PLYWOOD	176.7	7.152	1.265	10.548	3 6 0	NAT. GAS	0	0	
2441	WOOD BOXES	93.3	.234	.040	.338	1 3 6	NAT. GAS	0	0	
2491	WOOD PRESERVING	93.3	.193	.282	2.321	1 3 6	NAT. GAS	0	0	
2499	MISC. WOOD PROD.	93.3	.765	.130	1.055	1 3 6	NAT. GAS	0	0	
2511	WOOD FURNITURE	65.6	.117	.064	.179	3 4 6	NAT. GAS	0	0	
2512	WOOD FURN. W/UPHOLSTRY	60.0	.393	.157	.443	1 3 6	NAT. GAS	0	0	
2515	MATTRESSES	93.3	.296	.118	.331	1 3 6	NAT. GAS	0	0	
2519	MISC. FURN.	93.3	.193	.077	.222	1 3 6	NAT. GAS	0	0	
2521	WOOD OFFICE FURN.	93.3	.267	.107	.300	1 3 6	NAT. GAS	0	0	
2522	METAL OFFICE FURN.	93.3	2.169	.868	2.437	1 3 6	NAT. GAS	0	0	
2531	PUBLIC OFFICE FURN.	93.3	.683	.273	.770	1 3 6	NAT. GAS	0	0	
2541	WOOD PARTITIONS	93.3	.234	.094	.264	1 3 6	NAT. GAS	0	0	
2542	METAL PARTITIONS	93.3	.821	.329	.922	1 3 6	NAT. GAS	0	0	
2591	DRAPERY HARDWARE	93.3	.446	.178	.499	1 3 6	NAT. GAS	0	0	
2599	MISC. FURN.	93.3	.259	.104	.291	1 3 6	NAT. GAS	0	0	
2631	PAPERBOARD	182.2	169.998	56.372	253.152	6 1 0	NAT. GAS	0	0	
2641	COATED PAPER	162.8	4.103	.902	4.979	1 3 6	NAT. GAS	0	0	
2642	ENVELOPES	148.9	.592	.130	.728	3 1 6	NAT. GAS	0	0	
2643	BAGS	148.9	1.114	.242	1.371	3 1 6	NAT. GAS	0	0	
2645	DIE-CUT PAPER	148.9	.941	.204	1.160	3 1 6	NAT. GAS	0	0	
2649	CONVERTED PAPER	148.9	1.249	.272	1.529	3 1 6	NAT. GAS	0	0	
2651	FOLDING PAPER BOXES	148.9	1.076	.234	1.371	3 1 6	NAT. GAS	0	0	
2652	SET-UP PAPER BOXES	148.9	.296	.064	.363	3 1 6	NAT. GAS	0	0	
2653	CARDBOARD BOXES	148.9	.232	.504	2.848	3 1 6	NAT. GAS	0	0	
2655	FIBER CYLINDERS	148.9	.188	.407	2.321	3 1 6	NAT. GAS	0	0	
2661	BUILDING PAPER MILLS	187.8	35.172	9.576	42.614	3 1 6	NAT. GAS	0	0	
2711	NEWSPAPERS	148.9	.158	.026	.195	3 1 6	NAT. GAS	0	0	
2721	PERIODICALS	148.9	.069	.011	.085	3 1 6	NAT. GAS	0	0	
2731	BOOKS	148.9	.169	.027	.209	3 1 6	NAT. GAS	0	0	
2732	BOOK PRINTING	148.9	.469	.074	.565	3 1 6	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAF	SYS	B FUEL	OP	SOP	ENERGY/UNIT
2751	LETTER PRESS	148.9	.127	.021	.158	6 3 1	NAT. GAS	0	0	
2752	LITHOGRAPH	148.9	.160	.025	.193	6 3 1	NAT. GAS	0	0	
2761	MANIFOLD PRINTING	148.9	.352	.057	.435	3 1 6	NAT. GAS	0	0	
2782	BLANK BOOKS	148.9	.317	.051	.391	3 1 6	NAT. GAS	0	0	
2789	BOOK BINDING	148.9	.087	.014	.108	3 1 6	NAT. GAS	0	0	
2791	TYPESETTING	148.9	.046	.007	.057	3 1 6	NAT. GAS	0	0	
2793	PHOTOENGRAVING	148.9	.099	.016	.122	3 1 6	NAT. GAS	0	0	
2813	IND. GASES	148.9	8.793	2.609	9.008	6 2 3	NAT. GAS	0	0	
2819	IND. INORGANICS	148.9	121.343	36.061	126.576	6 2 3	NAT. GAS	0	0	
2821	PLASTICS	1176.7	64.462	21.420	73.836	6 2 3	NAT. GAS	0	0	
2822	SYNTHETIC RUBBER	93.3	88.809	29.988	103.476	6 2 3	NAT. GAS	0	0	
2831	BIOLOGICAL PROD.	148.9	.967	.287	.992	6 2 0	NAT. GAS	0	0	
2834	PHARMACEUTICALS	121.1	1.480	.641	2.215	6 2 0	NAT. GAS	0	0	
2841	SOAPS/DETERGENTS	260.0	3.224	1.087	3.745	1 6 3	NAT. GAS	0	0	
2842	SANITATION GOODS	162.8	.507	.150	.517	1 3 6	NAT. GAS	0	0	
2843	SURFACE AGENTS	148.9	6.187	.554	6.266	1 3 6	NAT. GAS	0	0	
2851	PAINTS	148.9	1.143	.339	1.171	1 3 6	NAT. GAS	0	0	
2865	CYCLIC ORGANICS	176.7	41.034	16.380	29.534	6 3 1	NAT. GAS	0	0	
2869	IND. ORGANICS	176.7	165.983	36.212	186.383	6 3 1	NAT. GAS	0	0	
2873	NITROGENEOUS FERTILIZER	204.4	9.965	4.273	14.767	6 3 1	NAT. GAS	1	0	
2874	PHOSPHATE FERTILIZER	371.1	40.155	36.616	126.576	3 6 0	NAT. GAS	1	0	
2879	PESTICIDES	148.9	3.224	.941	3.249	6 3 1	NAT. GAS	0	0	
2891	GLUES/SEALANTS	148.9	3.107	.924	3.185	3 1 6	NAT. GAS	0	0	
2892	EXPLOSIVES	148.9	26.877	5.819	30.167	6 3 1	NAT. GAS	0	0	
2893	INK	148.9	.950	.282	.973	3 1 6	NAT. GAS	0	0	
2899	MISC. CHEMICALS	148.9	2.843	.845	2.890	6 3 1	NAT. GAS	0	0	
2911	OIL REFINING	537.3	556.890	.483	1265.760	6 2 3	OIL	0	0	
2951	PAVING MATL.	260.0	3.224	.409	2.426	3 4 2	NAT. GAS	0	0	
2952	ASPHALT	260.0	2.052	.516	3.059	6 1 0	NAT. GAS	0	0	
2992	GREASES	148.9	.557	.143	.844	6 4 2	NAT. GAS	0	0	
2999	PETROLEUM/COAL PRODUCTS	162.8	12.984	2.520	14.767	6 3 2	NAT. GAS	0	0	
3069	MISC. RUBBER	260.0	3.810	.483	4.272	3 1 6	NAT. GAS	0	0	
3079	MISC. PLASTIC	218.3	.721	.913	.812	3 1 6	NAT. GAS	0	0	
3111	LEATHER PROCESSING	60.0	2.975	.356	3.344	3 1 6	NAT. GAS	0	0	
3161	LUGGAGE	93.3	.232	.028	.264	3 1 6	NAT. GAS	0	0	
3171	HANDBAGS	93.3	.120	.026	.162	3 1 6	NAT. GAS	0	0	
3199	MISC. LEATHER GOODS	93.3	.118	.026	.160	3 1 6	NAT. GAS	0	0	
3211	FLAT GLASS	1482.2	169.470	17.867	190.286	3 1 6	NAT. GAS	0	0	
3229	BLOWN GLASS	1426.7	6.624	.140	9.915	3 1 6	NAT. GAS	0	0	
3231	GLASS PROD.	646.9	.645	.138	.981	3 1 6	NAT. GAS	0	0	
3241	HYDRAULIC CEMENT	1482.2	162.084	34.184	242.604	3 1 6	NAT. GAS	0	0	
3251	BRICK/CLAY TILES	1204.4	14.069	2.972	21.096	3 6 0	NAT. GAS	0	0	
3253	CERAMIC TILES	1204.4	3.019	.639	4.536	3 1 6	NAT. GAS	0	0	
3259	MISC. CLAY	190.6	5.217	.902	6.213	3 1 6	NAT. GAS	0	0	
3269	POTTERY	1204.4	1.172	.125	.886	3 1 6	NAT. GAS	0	0	
3271	CONCRETE BLOCKS/BRICKS	204.4	.909	.193	1.403	3 1 6	NAT. GAS	0	0	
3272	MISC. CONCRETE	115.6	.645	.070	.499	3 1 6	NAT. GAS	0	0	
3273	READY MIXED CONCRETE	65.6	.001	.001	.007	3 1 6	OIL	1	0	
3274	LIME	1371.1	52.758	11.293	80.165	3 4 6	NAT. GAS	0	0	
3275	GYPSUM PROD.	167.2	31.743	3.348	35.652	3 1 6	NAT. GAS	0	0	
3281	CUT STONE PROD.	65.6	.100	.010	.074	3 1 6	NAT. GAS	0	0	
3291	ABRASIVES	190.6	2.509	.426	3.059	3 1 6	NAT. GAS	0	0	
3292	ASBESTOS	176.7	8.500	1.783	12.658	3 1 6	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLCLR	SAE	SYS	E FUEL	OF	SOF	ENERGY/UNIT
3293	GASKETS/SEALS	148.9	.616	.134	.549	3 1 6	OIL	0	0	
3295	GROUND MINERALS	1093.3	16.208	3.418	24.260	3 1 6	NAT. GAS	0	0	
3296	MINERAL WOOL	121.1	16.208	3.418	24.260	3 1 6	NAT. GAS	0	0	
3299	NON-METAL MINERALS	260.0	2.110	.222	1.582	3 1 6	NAT. GAS	0	0	
3317	STEEL PIPE/TUBE	145.9	6.741	.668	8.280	3 1 6	NAT. GAS	0	0	
3321	GRAY IRON	148.9	7.326	.941	8.997	3 1 6	NAT. GAS	0	0	
3333	ZINC REFINING	1315.6	264.816	20.714	257.348	3 1 6	NAT. GAS	0	0	
3334	ALUM. REFINING	215.6	43.965	10.471	100.206	3 1 6	NAT. GAS	0	0	
3339	MISC. METALS REFINING	148.9	12.515	1.607	15.400	3 1 6	NAT. GAS	0	0	
3341	ALLOYS	1287.8	5.774	.738	7.078	3 1 6	NAT. GAS	0	0	
3356	MISC. METAL FORMING	148.9	4.279	.184	6.888	3 1 6	NAT. GAS	0	0	
3361	ALUM. CASTING	148.9	1.867	.240	2.342	3 1 6	NAT. GAS	0	0	
3362	ALLOY CASTING	148.9	1.041	.134	1.276	3 1 6	NAT. GAS	0	0	
3369	MISC. CASTINGS	148.9	1.873	.240	2.299	3 1 6	NAT. GAS	0	0	
3411	METAL CANS	93.3	5.540	.227	6.540	3 1 6	NAT. GAS	0	0	
3423	HAND TOOLS	93.3	1.213	.050	1.435	3 1 6	NAT. GAS	0	0	
3429	MISC. HARDWARE	93.3	.404	.017	4.778	3 1 6	NAT. GAS	0	0	
3431	ENAMELED IRON PLUMBING	93.3	6.771	.276	7.953	3 1 6	NAT. GAS	0	0	
3432	BRASS PLUMBLING	93.3	.774	.043	1.245	3 1 6	NAT. GAS	0	0	
3433	FUEL HEATERS	93.3	1.621	.665	1.920	3 1 6	NAT. GAS	0	0	
3441	STRUCTURAL METAL	93.3	.580	.024	.686	3 1 6	NAT. GAS	0	0	
3442	METAL DOORS	93.3	.507	.021	.601	3 1 6	NAT. GAS	0	0	
3443	BOILER SHOPS	93.3	1.290	.053	1.529	3 1 6	NAT. GAS	0	0	
3444	SHEET METAL WORK	93.3	.069	.015	.439	3 1 6	NAT. GAS	0	0	
3449	MISC. METAL WORK	93.3	1.612	.066	1.899	3 1 6	NAT. GAS	0	0	
3451	SCREW MACHINES	93.3	.189	.008	.239	3 1 6	NAT. GAS	0	0	
3452	NUTS/BOLTS/SCREWS	93.3	1.888	.008	2.226	3 1 6	NAT. GAS	0	0	
3471	METAL PLATING	93.3	.539	.022	.643	3 1 6	NAT. GAS	0	0	
3479	MISC METAL SURFACE TREATMENT	93.3	.621	.016	.697	3 1 6	NAT. GAS	0	0	
3493	STEEL SPRINGS	454.4	3.605	.146	4.251	3 1 6	NAT. GAS	0	0	
3494	PIPE FITTINGS/VALVES	93.3	2.820	.113	3.280	3 1 6	NAT. GAS	0	0	
3496	WIRE PROD.	93.3	.050	.002	.059	3 1 6	NAT. GAS	0	0	
3499	MISC METAL PROD.	93.3	.352	.014	.415	3 1 6	NAT. GAS	0	0	
3519	INTERNAL COMB. ENGINES	93.3	6.712	1.319	8.238	3 1 6	NAT. GAS	0	0	
3522	FARM MACHINERY	1371.1	1.055	.254	1.582	3 6 0	NAT. GAS	0	0	
3524	GARDEN MACHINERY	1371.1	1.055	.254	1.582	3 1 6	NAT. GAS	0	0	
3531	CONSTRUCTION MACHINERY	1371.1	2.257	.541	3.375	3 1 6	NAT. GAS	0	0	
3533	OIL FIELD MACH.	1371.1	1.055	.254	1.582	3 1 6	NAT. GAS	0	0	
3541	METAL CUTTING TOOLS	1371.1	.786	.155	.965	3 1 6	NAT. GAS	0	0	
3542	METAL FORMING TOOLS	1371.1	.841	.166	1.033	3 1 6	NAT. GAS	0	0	
3544	TOOLS	1371.1	.106	.025	.158	3 1 6	NAT. GAS	0	0	
3545	MACHINE TOOL ACCESS	1371.1	.293	.068	.422	3 1 6	NAT. GAS	0	0	
3551	FOOD PROD. MACH.	1371.1	.293	.068	.422	3 1 6	NAT. GAS	0	0	
3559	SPECIAL MACHINERY	1371.1	.440	.101	.633	3 1 6	NAT. GAS	0	0	
3561	PUMPS	1371.1	.997	.237	1.477	3 1 6	NAT. GAS	0	0	
3566	GEARS	1371.1	.909	.220	1.371	3 1 6	NAT. GAS	0	0	
3568	POWER TRANS. EQUIP.	1371.1	.909	.220	1.371	3 1 6	NAT. GAS	0	0	
3573	COMPUTERS	1371.1	.651	.211	1.319	3 1 6	NAT. GAS	0	0	
3576	WEIGHING DEVICES	1371.1	.610	.120	.749	3 1 6	NAT. GAS	0	0	
3582	IND. LAUNDRY MACH.	1371.1	.821	16.178	1.008	3 1 6	NAT. GAS	0	0	
3585	REFRIG/HEATING EQUIP.	1371.1	2.257	.516	3.375	3 1 6	NAT. GAS	0	0	
3589	MISC. SERVICE MACH.	1371.1	.355	.040	.614	3 1 6	NAT. GAS	0	0	
3599	MISC. MACHINES	1371.1	.088	.017	.105	3 1 6	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	B FUEL	OP	SOP	ENERGY/UNIT
3612	TRANSFORMERS	176.7	3.708	.325	4.166	3 1 6	NAT. GAS	0	0	
3621	MOTORS/GENERATORS	925.7	3.459	.346	3.882	3 1 6	NAT. GAS	0	0	
3622	IND. CONTROLS	148.9	.539	.080	.150	3 1 6	NAT. GAS	0	0	
3623	WELDING APPARATUS	162.8	1.369	.203	1.730	3 1 6	NAT. GAS	0	0	
3629	ELECT. IND. APPARATUS	148.9	.718	.098	.833	3 1 6	NAT. GAS	0	0	
3641	ELECTRIC LAMPS	148.9	3.224	.475	4.050	3 1 6	NAT. GAS	0	0	
3643	MISC. ELECTIRCAL PARTS	148.9	.709	.105	.897	3 1 6	NAT. GAS	0	0	
3644	ELECT. INSUL/FITTINGS	148.9	2.541	.376	3.217	3 1 6	NAT. GAS	0	0	
3651	RADIO/TV	148.9	.994	.021	1.266	3 1 6	NAT. GAS	0	0	
3652	PHONO RECORDS/TAPE	148.9	.501	.074	6.339	3 1 6	NAT. GAS	0	0	
3661	TELEPHONE TELEGRAPH	148.9	5.628	.845	7.088	3 1 6	NAT. GAS	0	0	
3662	R/TV TRANSMIT	148.9	.718	.107	.918	3 1 6	NAT. GAS	0	0	
3672	CATHODE RAY TV TUBES	148.9	4.983	.735	6.234	3 1 6	NAT. GAS	0	0	
3674	SEMICONDUCTORS	148.9	1.580	.233	1.994	3 1 6	NAT. GAS	0	0	
3679	MISC. ELECT. COMP.	148.9	.821	.121	1.036	3 1 6	NAT. GAS	0	0	
3691	STORAGE BATTERIES	148.9	2.485	.389	3.059	3 1 6	NAT. GAS	0	0	
3694	ELECT. IC ENGINE	148.9	2.257	.334	2.859	3 1 6	NAT. GAS	0	0	
3711	MOTOR VEHICLES	1454.4	36.462	1.371	40.947	3 1 6	NAT. GAS	0	0	
3713	TRUCKS/BUS	93.3	.780	.053	1.048	3 1 6	NAT. GAS	0	0	
3714	MOTOR VEHICLE PARTS	1371.1	2.257	.169	3.375	3 1 6	NAT. GAS	0	0	
3715	TRUCK TRAILERS	315.6	.703	.053	1.055	3 1 6	NAT. GAS	0	0	
3721	AIRCRAFT	315.6	6.741	.503	10.021	3 1 6	NAT. GAS	0	0	
3728	AIRCRAFT PARTS	315.6	1.202	.090	1.793	3 1 6	NAT. GAS	0	0	
3731	SHIP BUILDING	1371.1	1.407	.106	2.110	3 1 6	NAT. GAS	0	0	
3732	BOATS	315.6	.117	.011	.211	3 1 6	NAT. GAS	0	0	
3751	MOTORCYCLES/BICYCLES	93.3	.856	.057	1.139	3 1 6	NAT. GAS	0	0	
3811	ENGINEERING INSTRUMENTS	93.3	.604	.172	.728	3 1 6	NAT. GAS	0	0	
3822	AUTOMATIC CONTROLS	93.3	1.612	.457	1.920	3 1 6	NAT. GAS	0	0	
3841	MEDICAL INSTRUMENTS	93.3	.413	.118	.498	3 1 6	NAT. GAS	0	0	
3842	MEDICAL SUPPLIES	93.3	.381	.108	.454	3 1 6	NAT. GAS	0	0	
3843	DENTAL EQUIP.	93.3	.132	.040	.169	3 1 6	NAT. GAS	0	0	
3851	OPHTHALMIC GOODS	76.7	.182	.051	.216	3 1 6	NAT. GAS	0	0	
3861	PHOTO EQUIP.	93.3	4.731	.290	5.316	3 1 6	NAT. GAS	0	0	
3911	JEWELRY	93.3	.093	.015	.118	3 1 6	NAT. GAS	0	0	
3914	SILVERWARE	93.3	1.105	.184	1.403	3 1 6	NAT. GAS	0	0	
3931	MUSICAL INSTRUMENTS	93.3	.495	.082	.628	3 1 6	NAT. GAS	0	0	
3949	SPORTING GOODS	93.3	.255	.042	.327	3 1 6	NAT. GAS	0	0	
3951	PENS/PENCILS	93.3	.242	.040	.308	3 1 6	NAT. GAS	0	0	
3953	MARKING DEVICES	93.3	.137	.023	.174	3 1 6	NAT. GAS	0	0	
3955	CARBON PAPER/INK RIBBONS	93.3	1.023	.170	1.297	3 1 6	NAT. GAS	0	0	
3961	COSTUME JEWELRY	93.3	.148	.025	.188	3 1 6	NAT. GAS	0	0	
3962	ARTIFICIAL PLANTS	93.3	.108	.018	.137	3 1 6	NAT. GAS	0	0	
3964	NEEDLES/PINS/HOOKS	93.3	.636	.106	.812	3 1 6	NAT. GAS	0	0	
3999	MISC.MANU.PRODUCTS	93.3	.169	.028	.214	3 1 6	NAT. GAS	0	0	

A.2 BRITISH UNITS

SIC	Standard industrial classification code
PROC TMP	Process temperature (F)
HEATR	Heat rate (Btu/h)
FLOWR	Maximum steam flow rate (10^3 lb/h)
SAE	Standard annual energy use (1.0E10 Btu/yr)
SYS	Possible systems in order of applicability:
1	Direct hot water
2	Indirect hot water
3	Direct hot air
4	Indirect hot air
5	Steam flash
6	Steam generator
B FUEL	Backup fuel
OP	Operation code:
0	Continuous
1	Batch
SOP	Seasonal operation code:
0	Continuous
1	Seasonal
ENERGY/UNIT	Energy required to produce one unit (Btu/Unit)

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	B FUEL	OP	SOP	ENERGY/UNIT
2011	MEAT PACKING PLANT	350.0	7.290	3.720	3.030	2 1 6	NAT. GAS	0	0	
2013	SAUSAGES/PREPARED MEAT	350.0	3.680	2.170	1.340	6 2 1	NAT. GAS	0	0	12000.00 /LB
2016	POULTRY DRESSING PLANT	140.0	13.200	7.100	2.730	6 1 2	NAT. GAS	0	0	
2021	CREAMERY BUTTER	170.0	16.300	6.379	3.390	6 1 2	NAT. GAS	1	0	
2022I	NAT. AND PROCESSED CHEESE	200.0	6.250	2.080	2.280	6 3 2	NAT. GAS	1	0	685.00 /LB
2022A	CHEESE PRODUCTION	135.0	.005	.005	.002	6 0 0	NAT. GAS	1	0	
2022B	CHEESE PRODUCTION	103.0	.067	.060	.024	6 0 0	NAT. GAS	1	0	
2022C	CHEESE PRODUCTION	200.0	3.273	2.654	1.191	6 0 0	NAT. GAS	1	0	
2022D	CHEESE PRODUCTION	165.0	.077	.068	.028	6 0 0	NAT. GAS	1	0	
2022E	CHEESE PRODUCTION	155.0	.410	.363	.149	2 6 0	NAT. GAS	1	0	
2022F	CHEESE PRODUCTION	100.0	.007	0.000	.003	1 0 0	NAT. GAS	1	0	
2022G	CHEESE PRODUCTION	600.0	.940	0.000	.342	3 0 0	NAT. GAS	1	0	
2023T	CONDENSED/EVAP. MILK	400.0	14.200	11.960	5.170	3 6 0	NAT. GAS	1	0	
2023A	CONDENSED MILK PRODUCTION	160.0	4.250	3.760	1.547	6 0 0	NAT. GAS	1	0	
2023B	CONDENSED MILK PRODUCTION	160.0	.835	.739	.304	6 0 0	NAT. GAS	1	0	
2023C	CONDENSED MILK PRODUCTION	250.0	.470	.403	.171	6 0 0	NAT. GAS	1	0	
2023D	CONDENSED MILK PRODUCTION	375.0	3.477	0.000	1.266	3 0 0	NAT. GAS	1	0	
2024	ICE CREAM/FROZEN DESERT	170.0	2.410	1.100	.502	6 2 1	NAT. GAS	1	0	
2026	FLUID MILK	170.0	3.970	4.350	.830	6 2 1	NAT. GAS	1	0	24.00 /LB
2032	CANNED SPECIALTIES	250.0	18.850	19.800	7.642	6 3 0	NAT. GAS	1	0	250.00 /LB
2033	CANNED FRUIT/VEG.	250.0	10.000	2.000	4.100	2 6 1	NAT. GAS	1	0	
2034	DRIED FRUITS/VEG.	350.0	16.500	9.500	5.160	2 4 6	NAT. GAS	0	0	
2035	PICKLED FRUITS/VEG.	300.0	4.310	2.090	1.340	6 2 0	NAT. GAS	1	0	
2037	FROZEN FRUIT/VEG.	190.0	6.300	4.952	2.600	2 1 6	NAT. GAS	1	0	
2038	FROZEN SPECIALTIES	180.0	9.710	8.910	2.020	6 3 0	NAT. GAS	1	0	3400.00 /LB
2041	FLOUR/GRAINS	250.0	2.600	1.000	1.100	6 3 2	NAT. GAS	1	0	
2043	CEREALS	250.0	26.400	20.950	11.000	3 6 2	NAT. GAS	1	0	
2045	FLOUR/GRAIN MIXES	250.0	5.060	4.700	1.053	6 3 0	NAT. GAS	0	0	215.00 /LB
2047	PET FOOD	250.0	5.250	10.040	1.924	3 6 0	NAT. GAS	1	0	1505.00 /LB
2048	ANIMAL FEED	525.0	7.120	4.000	1.481	3 6 0	NAT. GAS	1	0	75.00 /LB
2051	BREAD/BAKED GOODS	450.0	2.890	.772	.900	4 3 2	NAT. GAS	1	0	
2052	COOKIES/CRACKERS	450.0	12.220	1.900	2.542	3 6 0	NAT. GAS	1	0	2700.00 /LB
2065	CANDY/CONFECTIONS	200.0	4.600	1.410	1.460	6 4 3	NAT. GAS	1	0	
2066	CHOCOLATE PROD.	250.0	21.200	3.220	4.410	3 4 6	NAT. GAS	1	0	
2077	ANIMAL FATS/OILS	350.0	6.920	6.860	1.440	6 3 0	NAT. GAS	1	0	5800.00 /LB
2079	SHORTENINGS/OILS	350.0	127.000	82.700	16.600	6 3 0	NAT. GAS	1	0	275.00 /LB
2084	WINES	360.0	2.100	2.476	1.300	3 6 2	NAT. GAS	1	0	
2085	LIQUORS	360.0	22.400	26.670	14.000	6 5 2	NAT. GAS	1	0	
2086	SOFT DRINKS	170.0	3.106	1.420	.969	2 6 0	NAT. GAS	1	0	
2087	FLAVORINGS	250.0	8.100	0.000	1.685	3 4 0	NAT. GAS	1	0	
2091	CANNED SEAFOOD	350.0	3.600	3.047	1.600	6 4 2	NAT. GAS	1	0	
2092	FISH/SEAFOOD	350.0	1.750	1.030	.549	6 2 0	OIL	1	0	
2095	COFFEE	300.0	11.120	7.220	2.313	4 6 0	NAT. GAS	0	0	
2097	ICE	150.0	.250	0.000	.078	2 1 0	NAT. GAS	0	0	
2098	MACARONI	300.0	3.000	1.670	.936	6 4 2	NAT. GAS	1	0	
2099	MISC. FOODS	300.0	4.390	2.110	1.369	6 4 2	NAT. GAS	1	0	
2211	COTTON WEAVING	300.0	31.700	25.050	9.800	1 3 6	NAT. GAS	0	0	
2241	SMALL WEAVE FABRIC	300.0	3.200	2.550	1.000	1 3 6	NAT. GAS	0	0	
2253	KNIT OUTERWEAR	300.0	3.340	2.660	1.040	1 3 6	NAT. GAS	0	0	
2261	FINISHING BROAD COTTON	275.0	54.100	43.160	16.900	1 3 6	NAT. GAS	0	0	
2262	FINISHING BROAD FABRICS	300.0	12.000	9.530	3.730	1 3 6	NAT. GAS	0	0	
2271	WOVEN CARPETS/RUGS	300.0	4.150	3.310	1.300	1 3 6	NAT. GAS	0	0	
2293	UPHOLSTERY FILLINGS	300.0	14.000	18.870	4.220	1 3 6	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	P FUEL	OP	SOP	ENERGY/UNIT
2295	COATED FABRICS	300.0	2.660	4.030	.900	1 3 6	NAT. GAS	0	0	
2311	MALE COATS	250.0	1.660	.858	.520	1 3 6	NAT. GAS	0	0	
2321	MALE SHIRTS	250.0	1.200	.618	.373	1 3 6	NAT. GAS	0	0	
2327	MALE PANTS	250.0	1.800	.905	.550	1 3 6	NAT. GAS	0	0	
2329	MALE MISC. CLOTHES	250.0	.814	.421	.254	1 3 6	NAT. GAS	0	0	
2331	FEMALE TOPS	250.0	.450	.233	.141	1 3 6	NAT. GAS	0	0	
2335	FEMALE DRESSES	250.0	.314	.162	.096	1 3 6	NAT. GAS	0	0	
2339	FEMALE MISC. CLOTHES	250.0	.398	.206	.124	1 3 6	NAT. GAS	0	0	
2352	HATS/CAPS	250.0	.441	.228	.138	1 3 6	NAT. GAS	0	0	
2361	GIRLS OUTERWEAR	250.0	.446	.231	.139	1 3 6	NAT. GAS	0	0	
2369	GIRLS MISC. OUTERWEAR	250.0	.269	.139	.084	1 3 6	NAT. GAS	0	0	
2386	LEATHER/SHEEP CLOTHES	250.0	.584	.302	.182	1 3 6	NAT. GAS	0	0	
2387	BELTS	250.0	.368	.190	.115	1 3 6	NAT. GAS	0	0	
2389	MISC. ATTIRE	250.0	.453	1.075	.140	1 3 6	NAT. GAS	0	0	
2392	HOUSE LINENS	250.0	1.700	1.315	.522	1 3 6	NAT. GAS	0	0	
2395	DECORATIVE ADORNING	250.0	.134	.096	.038	1 3 6	NAT. GAS	0	0	
2396	AUTO APPAREL	250.0	.950	.769	.310	1 3 6	NAT. GAS	0	0	
2399	MISC. FABRIC PROD.	250.0	.940	.729	.290	6 3 1	NAT. GAS	0	0	
2421	SAW MILLS	200.0	2.400	1.004	1.000	3 4 6	NAT. GAS	0	0	
2431	MILLWORK	200.0	.720	.282	.280	6 3 1	NAT. GAS	0	0	
2426	HARDWOOD/FLOOR MILLS	200.0	.841	.331	.330	1 3 6	NAT. GAS	0	0	
2431	MILLWORK	200.0	.720	.282	.280	1 3 6	NAT. GAS	0	0	
2436	PLYWOOD	350.0	24.400	10.040	10.000	3 6 0	NAT. GAS	0	0	
2441	WOOD BOXES	200.0	.800	.314	.320	1 3 6	NAT. GAS	0	0	
2491	WOOD PRESERVING	200.0	.660	2.236	2.200	1 3 6	NAT. GAS	0	0	
2499	MISC. WOOD PROD.	200.0	2.610	1.030	1.000	1 3 6	NAT. GAS	0	0	
2511	WOOD FURNITURE	150.0	.400	.507	.170	3 4 6	NAT. GAS	0	0	
2512	WOOD FURN. W/UPHOLSTRY	140.0	1.340	1.244	.420	1 3 6	NAT. GAS	0	0	
2515	MATTRESSES	200.0	1.010	.936	.314	1 3 6	NAT. GAS	0	0	
2519	MISC. FURN.	200.0	.660	.613	.210	1 3 6	NAT. GAS	0	0	
2521	WOOD OFFICE FURN.	200.0	.910	.648	.284	1 3 6	NAT. GAS	0	0	
2522	METAL OFFICE FURN.	200.0	7.400	6.887	2.310	1 3 6	NAT. GAS	0	0	
2531	PUBLIC OFFICE FURN.	200.0	2.330	2.164	.730	1 3 6	NAT. GAS	0	0	
2541	WOOD PARTITIONS	200.0	.800	.745	.250	1 3 6	NAT. GAS	0	0	
2542	METAL PARTITIONS	200.0	2.800	2.608	.874	1 3 6	NAT. GAS	0	0	
2591	DRAPERY HARDWARE	200.0	1.520	1.410	.473	1 3 6	NAT. GAS	0	0	
2599	MISC. FURN.	200.0	.685	.824	.276	1 3 6	NAT. GAS	0	0	
2631	PAPERBOARD	360.0	580.000	447.400	240.000	6 1 0	NAT. GAS	0	0	
2641	COATED PAPER	325.0	14.000	7.156	4.720	1 3 6	NAT. GAS	0	0	
2642	ENVELOPES	300.0	2.020	1.030	.690	3 1 6	NAT. GAS	0	0	
2643	BAGS	300.0	3.800	1.923	1.300	3 1 6	NAT. GAS	0	0	
2645	PIE-CUT PAPER	300.0	3.210	1.623	1.100	3 1 6	NAT. GAS	0	0	
2649	CONVERTED PAPER	300.0	4.260	2.160	1.450	3 1 6	NAT. GAS	0	0	
2651	FOLDING PAPER BOXES	300.0	3.670	1.860	1.300	3 1 6	NAT. GAS	0	0	
2652	SET-UP PAPER BOXES	300.0	1.010	.510	.344	3 1 6	NAT. GAS	0	0	
2653	CARDBOARD BOXES	300.0	.790	3.996	2.760	3 1 6	NAT. GAS	0	0	
2655	FIBER CYLINDERS	300.0	.640	3.230	2.200	3 1 6	NAT. GAS	0	0	
2661	BUILDING PAPER MILLS	370.0	120.000	76.000	40.400	3 1 6	NAT. GAS	0	0	
2711	NEWSPAPERS	300.0	.540	.203	.185	3 1 6	NAT. GAS	0	0	
2721	PERIODICALS	300.0	.235	.087	.081	3 1 6	NAT. GAS	0	0	
2731	BOOKS	300.0	.575	.217	.198	3 1 6	NAT. GAS	0	0	
2732	BOOK PRINTING	300.0	1.600	.586	.536	3 1 6	NAT. GAS	0	0	
2751	LETTER PRESS	300.0	.435	.164	.150	6 3 1	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	B FUEL	OP	SOP	ENERGY/UNIT
2752	LITHOGRAPH	300.0	.546	.200	.183	6 3 1	NAT. GAS	0	0	
2761	MANIFOLD PRINTING	300.0	1.200	.452	.412	3 1 6	NAT. GAS	0	0	
2782	BLANK BOOKS	300.0	1.080	.407	.371	3 1 6	NAT. GAS	0	0	
2789	BOOK BINDING	300.0	.298	.112	.102	3 1 6	NAT. GAS	0	0	
2791	TYPESETTING	300.0	.158	.059	.054	3 1 6	NAT. GAS	0	0	
2793	PHOTOENGRAVING	300.0	.337	.127	.116	3 1 6	NAT. GAS	0	0	
2813	IND. GASES	300.0	30.000	20.710	8.540	6 2 3	NAT. GAS	0	0	
2819	IND. INORGANICS	300.0	414.000	286.200	120.000	6 2 3	NAT. GAS	0	0	
2821	PLASTICS	2150.0	220.000	170.000	70.000	6 2 3	NAT. GAS	0	0	
2822	SYNTHETIC RUBBER	200.0	303.000	238.000	98.100	6 2 3	NAT. GAS	0	0	
2831	BIOLOGICAL PROD.	300.0	3.300	2.281	.940	6 2 0	NAT. GAS	0	0	
2834	PHARMACEUTICALS	250.0	5.050	5.086	2.100	6 2 0	NAT. GAS	0	0	
2841	SOAPS/DETERGENTS	500.0	11.000	8.630	3.550	1 6 3	NAT. GAS	0	0	
2842	SANITATION GOODS	325.0	1.730	1.194	.490	1 3 6	NAT. GAS	0	0	
2843	SURFACE AGENTS	300.0	21.110	4.406	5.940	1 3 6	NAT. GAS	0	0	
2851	PAINTS	300.0	3.900	2.688	1.110	1 3 6	NAT. GAS	0	0	
2865	CYCLIC ORGANICS	350.0	140.000	130.000	28.000	6 3 1	NAT. GAS	0	0	
2869	IND. ORGANICS	350.0	566.300	287.400	176.700	6 3 1	NAT. GAS	0	0	
2873	NITROGENEOUS FERTILIZER	400.0	34.000	33.910	14.000	6 3 1	NAT. GAS	1	0	
2874	PHOSPHATE FERTILIZER	700.0	137.000	290.600	120.000	3 6 0	NAT. GAS	1	0	
2879	PESTICIDES	300.0	11.000	7.469	3.080	6 3 1	NAT. GAS	0	0	
2891	GLUES/SEALANTS	300.0	10.600	7.335	3.020	3 1 6	NAT. GAS	0	0	
2892	EXPLOSIVES	300.0	91.700	46.180	28.600	6 3 1	NAT. GAS	0	0	
2893	INK	300.0	3.240	2.236	.922	3 1 6	NAT. GAS	0	0	
2899	MISC. CHEMICALS	300.0	9.700	6.708	2.740	6 3 1	NAT. GAS	0	0	
2911	OIL REFINING	1000.0	1900.000	3.832	1200.000	6 2 3	OIL	0	0	
2951	PAVING MATL.	500.0	11.000	3.249	2.300	3 4 2	NAT. GAS	0	0	
2952	ASPHALT	500.0	7.000	4.096	2.900	6 1 0	NAT. GAS	0	0	
2992	GREASES	300.0	1.900	1.138	.800	6 4 2	NAT. GAS	0	0	
2999	PETROLEUM/COAL PRODUCTS	325.0	44.300	20.000	14.000	6 3 2	NAT. GAS	0	0	
3069	MISC. RUBBER	500.0	13.000	3.832	4.050	3 1 6	NAT. GAS	0	0	
3079	MISC. PLASTIC	425.0	2.460	7.247	.770	3 1 6	NAT. GAS	0	0	
3111	LEATHER PROCESSING	140.0	10.150	2.829	3.170	3 1 6	NAT. GAS	0	0	
3161	LUGGAGE	200.0	.790	.220	.250	3 1 6	NAT. GAS	0	0	
3171	HANDBAGS	200.0	.410	.206	.154	3 1 6	NAT. GAS	0	0	
3199	MISC. LEATHER GOODS	200.0	.404	.206	.152	3 1 6	NAT. GAS	0	0	
3211	FLAT GLASS	2700.0	578.200	141.800	180.400	3 1 6	NAT. GAS	0	0	
3229	BLOWN GLASS	2600.0	22.600	1.109	9.400	3 1 6	NAT. GAS	0	0	
3231	GLASS PROD.	1200.0	2.200	1.097	.930	3 1 6	NAT. GAS	0	0	
3241	HYDRAULIC CEMENT	2700.0	553.000	271.300	230.000	3 1 6	NAT. GAS	0	0	
3251	BRICK/CLAY TILES	2200.0	48.000	23.590	20.000	3 6 0	NAT. GAS	0	0	
3253	CERAMIC TILES	2200.0	10.300	5.071	4.300	3 1 6	NAT. GAS	0	0	
3259	MISC. CLAY	375.0	17.800	7.156	5.890	3 1 6	NAT. GAS	0	0	
3269	POTTERY	2200.0	4.000	.991	.840	3 1 6	NAT. GAS	0	0	
3271	CONCRETE BLOCKS/BRICKS	400.0	3.100	1.533	1.330	3 1 6	NAT. GAS	0	0	
3272	MISC. CONCRETE	240.0	2.200	.554	.473	3 1 6	NAT. GAS	0	0	
3273	READY MIXED CONCRETE	150.0	.003	.008	.007	3 1 6	OIL	1	0	
3274	LIME	2500.0	180.000	89.630	76.000	3 4 6	NAT. GAS	0	0	
3275	GYPSUM PROD.	333.0	108.300	26.570	33.800	3 1 6	NAT. GAS	0	0	
3281	CUT STONE PROD.	150.0	.340	.083	.070	3 1 6	NAT. GAS	0	0	
3291	ABRASIVES	375.0	8.560	3.399	2.900	3 1 6	NAT. GAS	0	0	
3292	ASBESTOS	350.0	29.000	14.150	12.000	3 1 6	NAT. GAS	0	0	
3293	GASKETS/SEALS	300.0	2.100	1.061	.900	3 1 6	OIL	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	B FUEL	OP	SOP	ENERGY/UNIT
3295	GROUND MINERALS	2000.0	55.300	27.130	23.000	3 1 6	NAT. GAS	0	0	
3296	MINERAL WOOL	250.0	55.300	27.130	23.000	3 1 6	NAT. GAS	0	0	
3299	NON-METAL MINERALS	500.0	7.200	1.765	1.500	3 1 6	NAT. GAS	0	0	
3317	STEEL PIPE/TUBE	300.0	23.000	6.887	7.650	3 1 6	NAT. GAS	0	0	
3321	GRAY IRON	300.0	25.000	7.469	8.530	3 1 6	NAT. GAS	0	0	
3333	ZINC REFINING	2400.0	903.500	164.400	261.900	3 1 6	NAT. GAS	0	0	
3334	ALUM. REFINING	420.0	150.000	83.100	95.000	3 1 6	NAT. GAS	0	0	
3339	MISC. METALS REFINING	300.0	42.700	12.750	14.600	3 1 6	NAT. GAS	0	0	
3341	ALLOYS	2350.0	19.700	5.859	6.710	3 1 6	NAT. GAS	0	0	
3356	MISC. METAL FORMING	300.0	14.600	1.456	6.530	3 1 6	NAT. GAS	0	0	
3361	ALUM. CASTING	300.0	6.370	1.901	2.220	3 1 6	NAT. GAS	0	0	
3362	ALLOY CASTING	300.0	3.550	1.060	1.210	3 1 6	NAT. GAS	0	0	
3369	MISC. CASTINGS	300.0	6.390	1.905	2.180	3 1 6	NAT. GAS	0	0	
3411	METAL CANS	200.0	18.900	1.798	6.200	3 1 6	NAT. GAS	0	0	
3423	HAND TOOLS	200.0	4.140	.394	1.360	3 1 6	NAT. GAS	0	0	
3425	MISC. HARDWARE	200.0	1.380	.132	4.530	3 1 6	NAT. GAS	0	0	
3431	ENAMELED IRON PLUMBING	200.0	23.100	2.187	7.540	3 1 6	NAT. GAS	0	0	
3432	BRASS PLUMBLING	200.0	2.640	.342	1.180	3 1 6	NAT. GAS	0	0	
3433	FUEL HEATERS	200.0	5.530	5.277	1.820	3 1 6	NAT. GAS	0	0	
3441	STRUCTURAL METAL	200.0	1.980	.188	.650	3 1 6	NAT. GAS	0	0	
3442	METAL DOORS	200.0	1.730	.165	.570	3 1 6	NAT. GAS	0	0	
3443	BOILER SHOPS	200.0	4.400	.419	1.450	3 1 6	NAT. GAS	0	0	
3444	SHEET METAL WORK	200.0	.236	.120	.416	3 1 6	NAT. GAS	0	0	
3449	MISC. METAL WORK	200.0	5.500	.537	1.800	3 1 6	NAT. GAS	0	0	
3451	SCREW MACHINES	200.0	.644	.066	.227	3 1 6	NAT. GAS	0	0	
3452	NUTS/BOLTS/SCREWS	200.0	6.440	.063	2.110	3 1 6	NAT. GAS	0	0	
3471	METAL PLATING	200.0	1.840	.176	.610	3 1 6	NAT. GAS	0	0	
3479	MISC METAL SURFACE TREATMENT	200.0	2.120	.128	.661	3 1 6	NAT. GAS	0	0	
3493	STEEL SPRINGS	850.0	12.300	1.162	4.030	3 1 6	NAT. GAS	0	0	
3494	PIPE FITTINGS/VALVES	200.0	9.620	.895	3.110	3 1 6	NAT. GAS	0	0	
3496	WIRE PROD.	200.0	.172	.016	.056	3 1 6	NAT. GAS	0	0	
3499	MISC METAL PROD.	200.0	1.200	.114	.393	3 1 6	NAT. GAS	0	0	
3519	INTERNAL COMB. ENGINES	200.0	22.900	10.470	7.810	3 1 6	NAT. GAS	0	0	
3522	FARM MACHINERY	2500.0	3.600	2.013	1.500	3 6 0	NAT. GAS	0	0	
3524	GARDEN MACHINERY	2500.0	3.600	2.013	1.500	3 1 6	NAT. GAS	0	0	
3531	CONSTRUCTION MACHINERY	2500.0	7.700	4.295	3.200	3 1 6	NAT. GAS	0	0	
3533	OIL FIELD MACH.	2500.0	3.600	2.013	1.500	3 1 6	NAT. GAS	0	0	
3541	METAL CUTTING TOOLS	2500.0	2.680	1.230	.915	3 1 6	NAT. GAS	0	0	
3542	METAL FORMING TOOLS	2500.0	2.870	1.315	.979	3 1 6	NAT. GAS	0	0	
3544	TOOLS	2500.0	.360	.201	.150	3 1 6	NAT. GAS	0	0	
3545	MACHINE TOOL ACCESS	2500.0	1.000	.537	.400	3 1 6	NAT. GAS	0	0	
3551	FOOD PROD. MACH.	2500.0	1.000	.537	.400	3 1 6	NAT. GAS	0	0	
3559	SPECIAL MACHINERY	2500.0	1.500	.805	.600	3 1 6	NAT. GAS	0	0	
3561	PUMPS	2500.0	3.400	1.879	1.400	3 1 6	NAT. GAS	0	0	
3566	GEARS	2500.0	3.100	1.745	1.300	3 1 6	NAT. GAS	0	0	
3568	POWER TRANS. EQUIP.	2500.0	3.100	1.745	1.300	3 1 6	NAT. GAS	0	0	
3573	COMPUTERS	2500.0	2.220	1.677	1.250	3 1 6	NAT. GAS	0	0	
3576	WEIGHING DEVICES	2500.0	2.080	.953	.710	3 1 6	NAT. GAS	0	0	
3582	IND. LAUNDRY MACH.	2500.0	2.800	128.400	.956	3 1 6	NAT. GAS	0	0	
3585	REFRIG/HEATING EQUIP.	2500.0	7.700	4.098	3.200	3 1 6	NAT. GAS	0	0	
3589	MISC. SERVICE MACH.	2500.0	1.210	.318	.582	3 1 6	NAT. GAS	0	0	
3599	MISC. MACHINES	2500.0	.300	.134	.100	3 1 6	NAT. GAS	0	0	
3612	TRANSFORMERS	350.0	12.650	2.578	3.950	3 1 6	NAT. GAS	0	0	

SIC		PROC TMP	HEATR	FLOWR	SAE	SYS	B FUEL	OP	SOP	ENERGY/UNIT
3621	MOTORS/GENERATORS	1700.0	11.800	2.745	3.680	3 1 6	NAT. GAS	0	0	
3622	IND. CONTROLS	300.0	1.840	.635	.142	3 1 6	NAT. GAS	0	0	
3623	WELDING APPARATUS	325.0	4.670	1.610	1.640	3 1 6	NAT. GAS	0	0	
3629	ELECT. IND. APPARATUS	300.0	2.450	.774	.790	3 1 6	NAT. GAS	0	0	
3641	ELECTRIC LAMPS	300.0	11.000	3.766	3.640	3 1 6	NAT. GAS	0	0	
3643	MISC. ELECTIRCAL PARTS	300.0	2.420	.832	.850	3 1 6	NAT. GAS	0	0	
3644	ELECT. INSUL/FITTINGS	300.0	8.670	2.988	3.050	3 1 6	NAT. GAS	0	0	
3651	RADIO/TV	300.0	3.391	.167	1.200	3 1 6	NAT. GAS	0	0	
3652	PHONO RECORDS/TAPE	300.0	1.710	.590	6.010	3 1 6	NAT. GAS	0	0	
3661	TELEPHONE TELEGRAPH	300.0	19.200	6.708	6.720	3 1 6	NAT. GAS	0	0	
3662	R/TV TRANSMIT	300.0	2.450	.850	.870	3 1 6	NAT. GAS	0	0	
3672	CATHODE RAY TV TUBES	300.0	17.000	5.814	5.910	3 1 6	NAT. GAS	0	0	
3674	SEMICONDUCTORS	300.0	5.390	1.852	1.890	3 1 6	NAT. GAS	0	0	
3679	MISC. ELECT. COMP.	300.0	2.800	.962	.982	3 1 6	NAT. GAS	0	0	
3691	STORAGE BATTERIES	300.0	8.460	3.090	2.900	3 1 6	NAT. GAS	0	0	
3694	ELECT. IC ENGINE	300.0	7.700	2.652	2.710	3 1 6	NAT. GAS	0	0	
3711	MOTOR VEHICLES	2650.0	124.400	10.880	38.820	3 1 6	NAT. GAS	0	0	
3713	TRUCKS/BUS	200.0	2.660	.418	.994	3 1 6	NAT. GAS	0	0	
3714	MOTOR VEHICLE PARTS	2500.0	7.700	1.345	3.200	3 1 6	NAT. GAS	0	0	
3715	TRUCK TRAILERS	600.0	2.400	.420	1.000	3 1 6	NAT. GAS	0	0	
3721	AIRCRAFT	600.0	23.000	3.993	9.500	3 1 6	NAT. GAS	0	0	
3728	AIRCRAFT PARTS	600.0	4.100	.715	1.700	3 1 6	NAT. GAS	0	0	
3731	SHIP BUILDING	2500.0	4.800	.841	2.000	3 1 6	NAT. GAS	0	0	
3732	BOATS	600.0	.400	.084	.200	3 1 6	NAT. GAS	0	0	
3751	MOTORCYCLES/BICYCLES	200.0	2.920	.452	1.080	3 1 6	NAT. GAS	0	0	
3811	ENGINEERING INSTRUMENTS	200.0	2.060	1.369	.690	3 1 6	NAT. GAS	0	0	
3822	AUTOMATIC CONTROLS	200.0	5.500	3.627	1.820	3 1 6	NAT. GAS	0	0	
3841	MEDICAL INSTRUMENTS	200.0	1.410	.939	.472	3 1 6	NAT. GAS	0	0	
3842	MEDICAL SUPPLIES	200.0	1.300	.854	.430	3 1 6	NAT. GAS	0	0	
3843	DENTAL EQUIP.	200.0	.480	.316	.160	3 1 6	NAT. GAS	0	0	
3851	OPHTHALMIC GOODS	170.0	.620	.408	.205	3 1 6	NAT. GAS	0	0	
3861	PHOTO EQUIP.	200.0	16.140	2.301	5.040	3 1 6	NAT. GAS	0	0	
3911	JEWELRY	200.0	.317	.123	.112	3 1 6	NAT. GAS	0	0	
3914	SILVERWARE	200.0	3.770	1.458	1.330	3 1 6	NAT. GAS	0	0	
3931	MUSICAL INSTRUMENTS	200.0	1.690	.653	.595	3 1 6	NAT. GAS	0	0	
3949	SPORTING GOODS	200.0	.870	.336	.310	3 1 6	NAT. GAS	0	0	
3951	PENS/PENCILS	200.0	.827	.319	.292	3 1 6	NAT. GAS	0	0	
3953	MARKING DEVICES	200.0	.466	.180	.165	3 1 6	NAT. GAS	0	0	
3955	CARBON PAPER/INK RIBBONS	200.0	3.490	1.351	1.230	3 1 6	NAT. GAS	0	0	
3961	COSTUME JEWELRY	200.0	.505	.195	.178	3 1 6	NAT. GAS	0	0	
3962	ARTIFICIAL PLANTS	200.0	.370	.143	.130	3 1 6	NAT. GAS	0	0	
3964	NEEDLES/PINS/HOOKS	200.0	2.170	.841	.770	3 1 6	NAT. GAS	0	0	
3999	MISC.MANU.PRODUCTS	200.0	.577	.222	.203	3 1 6	NAT. GAS	0	0	

APPENDIX B

SOLAR COLLECTOR EQUIPMENT DATA BASE

B.1 SI UNITS

A	Shading and blockage factor
XNUO	Optical efficiency
PHI-AHA	Tracking efficiency, where applicable; acceptance half angle for CPCs (degrees)
CR	Concentration ratio
DTILT	Difference in tilt from a polar axis mounting (degrees); if = 999, collector is horizontal
$/SQM	F.O.B. cost per m^2 of collector ($)
A$/SQM	Auxiliary equipment cost per m^2 of collector ($)
B$/SQM	Special additional costs per m^2 of collector ($)
HR/SQM	Required hours of installation labor per m^2 of collector (person-hours)
M-AREA	Standard area of one collector module (m^2)

Collector Type

0	Flat plate
1	Parabolic trough
2	Compound parabolic concentrator (CPC)
3	Parabolic dish

Annotation of Data Origin

TEST	Data derived from test data
MFG	Data derived from manufacturer information
DES	Data derived from design information
EDNR	Performance efficiency data not verified
CDBE	Cost data are best estimate

U	Heat loss coefficient as a function of collector operating temperature (W/m^2 C)

COLLECTOR PERFORMANCE AND COST DATA

	A	XNUO	PHI-AHA	CR	DTILT	$/SQM	A$/SQM	B$/SQM	HR/SQM	M-AREA	TYPE		NOTES	
FLAT PLATE A	0.0000	.77	1.00	1.0	0.00	161.40	16.14	0.00	2.69	2.23	0	TEST		CDBE
FLAT PLATE B	0.0000	.84	1.00	1.0	0.00	129.12	16.14	0.00	2.69	2.23	0	TEST		CDBE
FLAT PLATE C	0.0000	.78	1.00	1.0	0.00	161.40	26.90	0.00	2.15	1.67	0	MFG		CDBE
FLAT PLATE D	0.0000	.85	1.00	1.0	0.00	129.12	21.52	0.00	1.61	2.23	0	MFG		CDBE
FLAT PLATE E	0.0000	.63	1.00	1.0	0.00	129.12	5.68	0.00	2.15	1.86	0	TEST		
CPC 1.3X AHA=38.	0.0000	.54	38.00	1.3	0.00	269.00	0.00	0.00	2.15	3.25	2	MFG	EDNR	CDBE
CPC 1.5X AHA=34.	0.0000	.60	34.00	1.5	0.00	269.00	0.00	0.00	2.15	3.25	2	DES	EDNR	CDBE
FRESNEL LENS A	.0100	.68	.98	6.0	0.00	172.16	96.84	16.14	2.58	29.73	1	TEST		
FRESNEL LENS B	0.0000	.63	1.00	24.0	999.00	215.20	21.52	16.14	3.23	7.43	1	TEST		CDBE
PARABOLIC TROUGH A	.0650	.63	.98	36.7	999.00	155.48	0.00	22.06	4.30	44.59	1	MFG		
PARABOLIC TROUGH B	.1000	.72	.98	12.5	0.00	269.00	0.00	10.76	3.23	7.43	1	MFG		CDBE
PARABOLIC TROUGH C	.1000	.72	.98	25.0	999.00	236.72	0.00	10.76	3.23	14.86	1	MFG		
PARABOLIC TROUGH D	.1975	.66	.98	54.5	999.00	225.96	0.00	10.76	3.23	15.79	1	TEST		CDBE
PARABOLIC TROUGH E	.0560	.66	.98	26.1	999.00	204.44	64.86	16.14	3.23	32.52	1	TEST		
PARABOLIC TROUGH F	.1622	.60	.98	32.6	0.00	279.76	43.04	10.76	3.23	37.16	1	MFG	EDNR	CDBE
PARABOLIC TROUGH G	.1090	.68	.90	40.6	999.00	204.44	21.52	16.14	3.23	14.86	1	DES	EDNR	
LINE FOCUSING A	.2500	.63	.98	35.0	999.00	252.86	21.52	10.76	2.15	37.16	1	TEST		
LINE FOCUSING B	.2068	.47	.96	43.0	999.00	301.28	0.00	10.76	1.61	42.01	1	TEST		CDBE
LINE FOCUSING C	.2142	.39	.98	28.0	999.00	236.72	0.00	10.76	3.23	23.50	1	DES	EDNR	
PARABOLIC DISH A	0.0000	.77	1.00	2370.0	999.00	720.92	0.00	0.00	0.00	26.29	3	MFG	EDNR	

U -- HEAT LOSS COEFFICIENTS, W/SQM C

TEMPERATURE, DEGREE C	10.0	37.8	65.6	93.3	121.1	148.9	176.7	204.4	232.2	260.0	287.8	315.6	343.3	371.1	398.9	426.7	454.4	482.2
FLAT PLATE A	3.827	3.827	3.827	3.827														
FLAT PLATE B	4.622	4.622	4.622	4.622														
FLAT PLATE C	3.407	3.407	3.407	3.407														
FLAT PLATE D	6.814	6.814	6.814															
FLAT PLATE E	6.189	6.189	6.189	6.189	6.189													
CPC 1.3X AHA=38.	.454	.454	.454	.454	.511	.511	.568	.625	.738									
CPC 1.5X AHA=34.	.454	.454	.454	.454	.454	.511	.511	.568	.568	.568								
FRESNEL LENS A	.284	.284	.511	.852	1.192	1.533												
FRESNEL LENS B	.341	.341	.341	.341	.346	.369	.409	.454	.500	.562	.619	.681						
PARABOLIC TROUGH A	.534	.534	.534	.534	.534	.534	.534	.556	.579	.602	.625	.636						
PARABOLIC TROUGH B	.681	.681	.681	.681	.738	.852	.909											
PARABOLIC TROUGH C	.380	.380	.426	.437	.471	.494	.526	.568	.596	.636	.664	.681						
PARABOLIC TROUGH D	.273	.273	.273	.273	.273	.278	.295	.312	.329	.346	.369	.397						
PARABOLIC TROUGH E	.437	.437	.437	.437	.392	.386	.380	.386	.397	.426								
PARABOLIC TROUGH F	.852	.852	.852	.852	.852	.852	.852	.652										
PARABOLIC TROUGH G	.681	.681	.681	.681	.681	.681	.681	.681	.681									
LINE FOCUSING A	.244	.244	.244	.244	.256	.278	.312	.352	.397	.460	.517	.566						
LINE FOCUSING B	.165	.165	.165	.165	.187	.199	.221	.244	.261	.284	.312	.341						
LINE FOCUSING C	.114	.114	.114	.114	.114	.114	.170	.227	.284	.341	.397	.454						
PARABOLIC DISH A	.017	.017	.017	.023	.023	.028	.028	.034	.034	.040	.040	.045	.045	.051	.051	.057	.057	.057

B.2 BRITISH UNITS

A	Shading and blockage factor
XNUO	Optical efficiency
PHI-AHA	Tracking efficiency, where applicable; acceptance half angle for CPCs (degrees)
CR	Concentration ratio
DTILT	Difference in tilt from a polar axis mounting (degrees); if = 999, collector is horizontal
$/SQFT	F.O.B. cost per ft^2 of collector ($)
A$/SQFT	Auxiliary equipment cost per ft^2 of collector ($)
B$/SQFT	Special additional costs per ft^2 of collector ($)
HR/SQFT	Required hours of installation labor per ft^2 of collector (person-hours)
M-AREA	Standard area of one collector module (ft^2)

Collector Type

0	Flat plate
1	Parabolic trough
2	Compound parabolic concetrator (CPC)
3	Parabolic dish

Annotation of Data Origin

TEST	Data derived from test data
MFG	Data derived from manufacturer information
DES	Data derived from design information
EDNR	Performance efficiency data not verified
CDBE	Cost data are best estimate

U	Heat loss coefficient as a function of collector operating temperature (Btu/h ft^2 F)

SERI

COLLECTOR PERFORMANCE AND COST DATA

	A	XNUO	PHI-AHA	CR	DTILT	$/SQFT	A$/SQFT	B$/SQFT	HR/SQFT	M-AREA	TYPE		NOTES	
FLAT PLATE A	0.0000	.77	1.00	1.0	0.00	15.00	1.50	0.00	.25	24.00	0	TEST		CDBE
FLAT PLATE B	0.0000	.64	1.00	1.0	0.00	12.00	1.50	0.00	.25	24.00	0	TEST		CDBE
FLAT PLATE C	0.0000	.78	1.00	1.0	0.00	15.00	2.50	0.00	.20	18.00	0	MFG		CDBE
FLAT PLATE D	0.0000	.65	1.00	1.0	0.00	12.00	2.00	0.00	.15	24.00	0	MFG		CDBE
FLAT PLATE E	0.0000	.63	1.00	1.0	0.00	12.00	.90	0.00	.20	20.00	0	TEST		
CPC 1.3X AHA=38.	0.0000	.54	38.00	1.3	0.00	25.00	0.00	0.00	.20	35.00	2	MFG	EDNR	CDBE
CPC 1.5X AHA=34.	0.0000	.60	34.00	1.5	0.00	25.00	0.00	0.00	.20	35.00	2	DES	EDNR	CDBE
FRESNEL LENS A	.0100	.68	.98	6.0	0.00	16.00	9.00	1.50	.24	320.00	1	TEST		
FRESNEL LENS B	0.0000	.63	1.00	24.0	999.00	20.00	2.00	1.50	.30	80.00	1	TEST		CDBE
PARABOLIC TROUGH A	.0850	.63	.98	36.7	999.00	14.45	0.00	2.05	.40	480.00	1	MFG		
PARABOLIC TROUGH B	.1000	.72	.98	12.5	0.00	25.00	0.00	1.00	.30	60.00	1	MFG		CDBE
PARABOLIC TROUGH C	.1000	.72	.98	25.0	999.00	22.00	0.00	1.00	.30	160.00	1	MFG		
PARABOLIC TROUGH D	.1975	.66	.98	54.5	999.00	21.00	0.00	1.00	.30	170.00	1	TEST		CDBE
PARABOLIC TROUGH E	.0560	.66	.98	26.1	999.00	19.00	6.03	1.50	.30	350.00	1	TEST		
PARABOLIC TROUGH F	.1622	.60	.98	32.6	0.00	26.00	4.00	1.00	.30	400.00	1	MFG	EDNR	CDBE
PARABOLIC TROUGH G	.1050	.68	.90	40.6	999.00	19.00	2.00	1.50	.30	160.00	1	DES	EDNR	
LINE FOCUSING A	.2500	.63	.98	35.0	999.00	23.50	2.00	1.00	.20	400.00	1	TEST		
LINE FOCUSING B	.2068	.47	.98	43.0	999.00	28.00	0.00	1.00	.15	452.20	1	TEST		CDBE
LINE FOCUSING C	.2142	.39	.98	28.0	999.00	22.00	0.00	1.00	.30	253.00	1	DES	EDNR	
PARABOLIC DISH A	0.0000	.77	1.00	2370.0	999.00	67.00	0.00	0.00	0.00	283.00	3	MFG	EDNR	

U -- HEAT LOSS COEFFICIENTS, BTU/H SQFT F

TEMPERATURE, DEGREE F	50.	100.	150.	200.	250.	300.	350.	400.	450.	500.	550.	600.	650.	700.	750.	800.	850.	900.
FLAT PLATE A	.674	.674	.674	.674														
FLAT PLATE B	.814	.814	.814	.814														
FLAT PLATE C	.600	.600	.600	.600														
FLAT PLATE D	1.200	1.200	1.200															
FLAT PLATE E	1.090	1.090	1.090	1.090	1.090													
CPC 1.3X AHA=38.	.080	.080	.080	.080	.090	.090	.100	.110	.130									
CPC 1.5X AHA=34.	.080	.080	.080	.080	.080	.090	.050	.100	.100	.100								
FRESNEL LENS A	.050	.050	.090	.150	.210	.270												
FRESNEL LENS B	.060	.060	.060	.060	.061	.065	.072	.080	.088	.099	.109	.120						
PARABOLIC TROUGH A	.094	.094	.094	.094	.094	.094	.094	.098	.102	.106	.110	.112						
PARABOLIC TROUGH B	.120	.120	.120	.120	.130	.150	.160											
PARABOLIC TROUGH C	.067	.067	.075	.077	.083	.087	.093	.100	.105	.112	.117	.120						
PARABOLIC TROUGH D	.048	.048	.048	.048	.049	.049	.052	.055	.058	.061	.065	.070						
PARABOLIC TROUGH E	.077	.077	.077	.077	.069	.068	.067	.068	.070	.075								
PARABOLIC TROUGH F	.150	.150	.150	.150	.150	.150	.150	.150										
PARABOLIC TROUGH G	.120	.120	.120	.120	.120	.120	.120	.120	.120									
LINE FOCUSING A	.043	.043	.043	.043	.045	.049	.055	.062	.070	.081	.091	.100						
LINE FOCUSING B	.029	.029	.029	.029	.033	.035	.039	.043	.046	.050	.055	.060						
LINE FOCUSING C	.020	.020	.020	.020	.020	.020	.030	.040	.050	.060	.070	.080						
PARABOLIC DISH A	.003	.003	.003	.004	.004	.005	.005	.006	.006	.007	.007	.008	.008	.009	.009	.010	.010	.010

APPENDIX C

METEOROLOGICAL DATA BASE

HT	Long term average daily total insolation on a horizontal surface [kJ/m^2 (Btu/ft^2)]
KT	Long-term average cloudiness index
TA	Long-term average daytime ambient temperature [C (F)]
CLNO	Clearness number
DIR	Annual normal incident direct radiation

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ALBUQUERQUE NM												
LATITUDE, 35.05												
HT, KJ/SQM	11625.00	15235.00	20032.00	25392.00	28643.00	30605.00	28275.00	25973.00	22404.00	17501.00	12918.00	10536.00
HT, BTU/SQFT	1024.30	1342.40	1765.00	2237.30	2541.40	2696.60	2491.30	2288.50	1974.00	1542.00	1136.20	928.30
KT	.64	.66	.68	.72	.73	.74	.70	.70	.71	.70	.67	.63
TA, DEGREES C	2.94	6.28	10.06	15.33	20.78	26.17	28.22	27.00	23.11	16.72	8.78	4.11
TA, DEGREES F	37.30	43.30	50.10	59.60	69.40	79.10	82.80	80.60	73.60	62.10	47.80	39.40
CLNO	.95	.95	.95	.95	.99	.99	.95	.99	.99	.99	.95	.95
DIR/YR KJ/SQM 9376575.												
DIR/YR BTU/SQFT 826170.												
APALACHICOLA FL												
LATITUDE, 29.45												
HT, KJ/SQM	9667.00	12694.00	16650.00	21339.00	23681.00	22905.00	20423.00	19186.00	17391.00	15527.00	11807.00	9192.00
HT, BTU/SQFT	851.90	1118.50	1467.00	1880.20	2086.50	2018.20	1799.50	1690.50	1532.30	1368.10	1040.30	809.90
KT	.45	.45	.53	.58	.60	.56	.51	.51	.52	.56	.53	.46
TA, DEGREES C	14.06	15.00	17.17	20.83	24.67	27.67	28.39	28.39	27.00	22.89	17.61	14.72
TA, DEGREES F	57.30	59.00	62.90	69.50	76.40	81.80	83.10	83.10	80.60	73.20	63.70	58.50
CLNO	.76	.76	.76	.76	.81	.81	.81	.81	.81	.81	.76	.76
DIR/YR KJ/SQM 5628533.												
DIR/YR BTU/SQFT 495930.												
BISMARCK ND												
LATITUDE, 46.47												
HT, KJ/SQM	5276.00	8841.00	13332.00	16591.00	21011.00	23414.00	24727.00	21329.00	15440.00	10268.00	5751.00	4219.00
HT, BTU/SQFT	464.90	779.00	1174.70	1461.80	1851.30	2063.00	2178.70	1879.30	1360.40	904.70	506.70	371.70
KT	.48	.53	.55	.51	.54	.57	.62	.61	.57	.55	.46	.44
TA, DEGREES C	-10.89	-8.94	-1.28	8.11	14.78	19.94	24.50	23.06	16.44	9.78	-.33	-7.56
TA, DEGREES F	12.40	15.90	29.70	46.60	58.60	67.90	76.10	73.50	61.60	49.60	31.40	18.40
CLNO	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95
DIR/YR KJ/SQM 5878447.												
DIR/YR BTU/SQFT 517950.												
BOSTON MA												
LATITUDE, 42.22												
HT, KJ/SQM	5420.00	7987.00	11967.00	15050.00	19310.00	20262.00	19719.00	16853.00	14836.00	10277.00	5805.00	4760.00
HT, BTU/SQFT	477.60	703.70	1054.40	1326.10	1701.40	1785.30	1737.40	1484.90	1307.20	905.50	511.50	419.40
KT	.40	.42	.46	.45	.49	.49	.49	.47	.51	.49	.35	.35
TA, DEGREES C	-.33	-.33	4.39	9.72	15.78	16.00	23.61	23.22	19.33	14.11	8.11	1.61
TA, DEGREES F	31.40	31.40	39.90	49.50	60.40	60.80	74.50	73.80	66.80	57.40	46.60	34.90
CLNO	.91	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90
DIR/YR KJ/SQM 4287255.												
DIR/YR BTU/SQFT 377750.												
BROWNSVILLE TX												
LATITUDE, 25.55												
HT, KJ/SQM	10373.00	12827.00	16634.00	19540.00	21696.00	24475.00	25630.00	23140.00	19462.00	16434.00	12169.00	9783.00
HT, BTU/SQFT	914.00	1130.20	1465.60	1721.70	1911.60	2156.50	2256.30	2036.90	1714.80	1448.00	1072.20	862.00
KT	.44	.46	.51	.53	.55	.61	.65	.61	.57	.56	.50	.44
TA, DEGREES C	17.39	19.28	21.50	24.56	27.44	29.50	30.28	30.50	28.94	26.06	21.50	18.44
TA, DEGREES F	63.30	66.70	70.70	76.20	81.40	85.10	86.50	86.90	84.10	78.90	70.70	65.20
CLNO	.76	.76	.76	.76	.81	.81	.81	.81	.81	.81	.76	.76
DIR/YR KJ/SQM 5773278.												
DIR/YR BTU/SQFT 508680.												

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CAPE HATTERAS NC												
LATITUDE, 35.16												
HT, KJ/SQM	7769.00	10802.00	15056.00	20113.00	22236.00	23119.00	21968.00	19299.00	16651.00	12911.00	9934.00	7547.00
HT, BTU/SQFT	683.70	951.80	1330.30	1772.20	1959.20	2037.00	1935.60	1700.40	1467.10	1137.60	875.30	665.00
KT	.43	.47	.52	.57	.56	.56	.55	.52	.53	.52	.52	.46
TA, DEGREES C	9.94	9.72	12.61	16.39	21.06	25.11	26.67	26.56	24.83	19.94	15.06	10.72
TA, DEGREES F	49.90	49.50	54.70	61.50	69.90	77.20	80.00	79.80	76.70	67.90	59.10	51.30
CLNO	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
DIR/YR KJ/SQM	5497106.											
DIR/YR BTU/SQFT	484350.											
CARIBOU ME												
LATITUDE, 46.52												
HT, KJ/SQM	4822.00	8320.00	12845.00	16054.00	17832.00	19835.00	19647.00	16798.00	12468.00	7787.00	4192.00	3648.00
HT, BTU/SQFT	424.90	733.10	1131.80	1414.50	1571.20	1747.70	1731.10	1480.10	1098.60	686.10	369.40	321.40
KT	.44	.50	.53	.50	.46	.48	.49	.48	.46	.42	.34	.38
TA, DEGREES C	-11.39	-10.67	-4.22	2.94	11.00	16.44	19.56	18.33	13.44	7.06	-.39	-8.44
TA, DEGREES F	11.50	12.80	24.40	37.30	51.80	61.60	67.20	65.00	56.20	44.70	31.30	16.80
CLNO	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95
DIR/YR KJ/SQM	4260924.											
DIR/YR BTU/SQFT	375430.											
CHARLESTON SC												
LATITUDE, 32.54												
HT, KJ/SQM	6945.00	9902.00	13410.00	17152.00	21296.00	23810.00	24040.00	21335.00	16381.00	12387.00	7997.00	5945.00
HT, BTU/SQFT	611.90	872.50	1181.60	1511.30	1876.40	2097.90	2118.20	1879.80	1443.30	1091.40	704.60	523.80
KT	.36	.41	.44	.48	.54	.58	.60	.57	.51	.47	.39	.33
TA, DEGREES C	12.00	12.89	15.89	19.89	23.78	27.17	28.28	27.94	26.17	21.00	15.44	12.22
TA, DEGREES F	53.60	55.20	60.60	67.80	74.80	80.90	82.90	82.30	79.10	69.80	59.80	54.00
CLNO	.86	.86	.86	.86	.86	.86	.86	.86	.86	.86	.86	.86
DIR/YR KJ/SQM	4918511.											
DIR/YR BTU/SQFT	433370.											
COLUMBIA MO												
LATITUDE, 38.58												
HT, KJ/SQM	8449.00	11312.00	15104.00	19637.00	21533.00	21454.00	21347.00	19560.00	16042.00	13539.00	10603.00	8169.00
HT, BTU/SQFT	744.40	996.70	1330.80	1730.20	1897.30	1890.30	1880.90	1723.40	1413.50	1192.90	934.20	719.80
KT	.53	.54	.54	.57	.55	.52	.53	.54	.53	.59	.62	.56
TA, DEGREES C	.28	2.50	7.72	14.28	19.28	24.39	27.28	26.33	22.17	16.33	7.83	2.11
TA, DEGREES F	32.50	36.50	45.90	57.70	66.70	75.90	81.10	79.40	71.90	61.40	46.10	35.80
CLNO	.88	.88	.88	.88	.88	.88	.88	.88	.88	.88	.88	.88
DIR/YR KJ/SQM	5602315.											
DIR/YR BTU/SQFT	493620.											
DENVER CO												
LATITUDE, 39.50												
HT, KJ/SQM	10676.00	14152.00	18246.00	21729.00	24366.00	27382.00	26502.00	24785.00	20682.00	15491.00	10969.00	9127.00
HT, BTU/SQFT	940.70	1246.90	1607.80	1914.50	2146.90	2412.60	2335.10	2183.80	1822.30	1364.90	966.50	804.20
KT	.69	.69	.67	.63	.62	.66	.66	.68	.69	.69	.66	.65
TA, DEGREES C	-.83	1.67	5.00	11.22	19.06	23.28	27.06	25.44	20.89	14.61	4.56	-3.33
TA, DEGREES F	30.50	35.00	41.00	52.20	66.30	73.90	80.70	77.80	69.60	58.30	40.20	26.00
CLNO	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95
DIR/YR KJ/SQM	6388946.											
DIR/YR BTU/SQFT	739150.											

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
DODGE CITY KA												
LATITUDE, 37.46												
HT, KJ/SQM	9480.00	12723.00	16871.00	21506.00	23642.00	26652.00	26082.00	23434.00	18921.00	14684.00	10166.00	8360.00
HT, BTU/SQFT	835.30	1121.00	1486.50	1894.50	2100.70	2348.30	2298.10	2064.80	1667.10	1253.80	895.70	736.60
KT	.57	.58	.60	.62	.60	.65	.65	.64	.62	.62	.57	.55
TA, DEGREES C	1.00	3.72	8.06	14.28	19.28	25.11	28.78	28.00	23.17	16.50	8.06	2.67
TA, DEGREES F	33.80	38.70	46.50	57.70	66.70	77.20	83.80	82.40	73.70	61.70	46.50	36.80
CLNO	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90
DIR/YR KJ/SQM	7599478.											
DIR/YR BTU/SQFT	669590.											
EL PASO TX												
LATITUDE, 31.48												
HT, KJ/SQM	13390.00	16973.00	20556.00	26279.00	30690.00	31394.00	28591.00	26705.00	24360.00	18904.00	15502.00	12584.00
HT, BTU/SQFT	1179.80	1495.50	1811.20	2315.40	2651.20	2766.10	2554.40	2353.00	2146.40	1665.60	1365.90	1108.80
KT	.66	.68	.67	.73	.76	.77	.72	.71	.75	.71	.73	.67
TA, DEGREES C	8.39	11.72	14.83	19.61	24.28	29.00	29.39	28.56	25.83	20.56	13.33	9.17
TA, DEGREES F	47.10	53.10	58.70	67.70	75.70	84.20	84.90	83.40	78.50	69.00	56.00	48.50
CLNO	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90
DIR/YR KJ/SQM	9547611.											
DIR/YR BTU/SQFT	841240.											
ELY NV												
LATITUDE, 39.17												
HT, KJ/SQM	9425.00	13184.00	18383.00	22895.00	26086.00	28940.00	27922.00	25413.00	21840.00	16265.00	10704.00	8422.00
HT, BTU/SQFT	830.40	1161.60	1619.70	2017.30	2298.40	2549.90	2460.20	2239.10	1924.30	1433.10	943.10	742.10
KT	.61	.63	.67	.66	.66	.70	.69	.70	.73	.72	.64	.60
TA, DEGREES C	-2.61	.06	4.17	9.06	13.89	18.56	23.61	22.39	17.61	11.17	4.17	-.50
TA, DEGREES F	27.30	32.10	39.50	48.30	57.00	65.40	74.50	72.30	63.70	52.10	39.50	31.10
CLNO	.95	.95	.95	.95	1.04	1.04	1.04	1.04	1.04	1.04	.95	.95
DIR/YR KJ/SQM	8719101.											
DIR/YR BTU/SQFT	768240.											
FORT WORTH TX												
LATITUDE, 32.50												
HT, KJ/SQM	9623.00	12079.00	16081.00	18473.00	21568.00	24551.00	24677.00	22434.00	18385.00	14416.00	10949.00	9107.00
HT, BTU/SQFT	847.90	1064.30	1416.90	1627.70	1900.40	2166.70	2174.30	1976.70	1619.90	1270.20	964.70	802.40
KT	.49	.49	.53	.51	.55	.60	.61	.60	.57	.55	.53	.50
TA, DEGREES C	8.94	11.28	15.44	20.44	24.39	28.89	30.94	31.44	27.39	21.94	14.89	10.44
TA, DEGREES F	48.10	52.30	59.80	68.80	75.90	84.00	87.70	88.60	81.30	71.50	58.80	50.80
CLNO	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
DIR/YR KJ/SQM	6141526.											
DIR/YR BTU/SQFT	541130.											
FRESNO CA												
LATITUDE, 36.46												
HT, KJ/SQM	10000.00	11825.00	18511.00	22152.00	28024.00	29124.00	29623.00	25620.00	22049.00	15438.00	11452.00	6095.00
HT, BTU/SQFT	881.10	1041.90	1631.00	1951.80	2469.20	2566.10	2610.10	2257.40	1942.70	1360.20	1009.00	537.00
KT	.58	.53	.64	.63	.71	.71	.74	.70	.71	.64	.62	.39
TA, DEGREES C	8.50	12.17	15.06	18.67	23.06	27.06	30.83	29.39	25.89	20.39	14.06	9.39
TA, DEGREES F	47.30	53.90	59.10	65.60	73.50	80.70	87.50	84.90	78.60	68.70	57.30	48.90
CLNO	.87	.87	.87	.87	.96	.96	.96	.96	.96	.96	.87	.87
DIR/YR KJ/SQM	8061514.											
DIR/YR BTU/SQFT	710300.											

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
GREAT FALLS MT												
LATITUDE, 47.29												
HT, KJ/SQM	4919.00	8267.00	13760.00	17247.00	21106.00	24066.00	26736.00	22329.00	15629.00	10202.00	5610.00	4012.00
HT, BTU/SQFT	433.40	728.40	1212.40	1519.60	1859.60	2120.50	2355.70	1967.40	1377.10	898.90	494.30	353.50
KT	.46	.51	.58	.54	.55	.58	.67	.65	.59	.56	.47	.44
TA, DEGREES C	-3.67	-2.44	2.00	8.72	14.17	17.94	23.22	21.83	15.89	10.78	3.33	-1.61
TA, DEGREES F	25.40	27.60	35.60	47.70	57.50	64.30	73.80	71.30	60.60	51.40	38.00	29.10
CLNO	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95
DIR/YR KJ/SQM	5983657.											
DIR/YR BTU/SQFT	527220.											
LAKE CHARLES LA												
LATITUDE, 30.13												
HT, KJ/SQM	8219.00	11491.00	14846.00	17853.00	21225.00	23475.00	20302.00	18639.00	16754.00	14631.00	10446.00	7930.00
HT, BTU/SQFT	724.20	1012.50	1308.10	1573.00	1870.10	2068.40	1788.80	1642.30	1476.20	1289.10	920.40	698.70
KT	.39	.45	.48	.49	.54	.58	.51	.50	.51	.54	.47	.40
TA, DEGREES C	12.94	14.83	17.50	21.61	25.22	28.56	29.33	29.44	27.50	23.22	17.00	13.83
TA, DEGREES F	55.30	58.70	63.50	70.90	77.40	83.40	84.80	85.00	81.50	73.80	62.60	56.90
CLNO	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81
DIR/YR KJ/SQM	4786971.											
DIR/YR BTU/SQFT	421760.											
MADISON WI												
LATITUDE, 43.08												
HT, KJ/SQM	6003.00	9167.00	13138.00	15768.00	19517.00	22383.00	22316.00	19745.00	14877.00	10346.00	5770.00	4401.00
HT, BTU/SQFT	528.90	807.70	1157.60	1389.30	1719.60	1972.20	1966.30	1739.70	1310.80	911.60	508.40	387.80
KT	.46	.49	.51	.47	.50	.54	.56	.56	.52	.50	.40	.38
TA, DEGREES C	-5.67	-4.11	1.83	9.44	16.11	21.61	24.89	23.56	18.67	12.06	3.22	-3.67
TA, DEGREES F	21.80	24.60	35.30	49.00	61.00	70.90	76.80	74.40	65.60	53.70	37.80	25.40
CLNO	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90
DIR/YR KJ/SQM	4879015.											
DIR/YR BTU/SQFT	429890.											
MEDFORD OR												
LATITUDE, 42.23												
HT, KJ/SQM	4422.00	8433.00	12791.00	19353.00	22821.00	25897.00	27997.00	24046.00	18068.00	11321.00	5874.00	3711.00
HT, BTU/SQFT	389.60	743.00	1127.00	1705.20	2010.80	2281.80	2466.60	2118.90	1592.00	997.50	517.60	327.00
KT	.32	.44	.49	.56	.58	.63	.70	.67	.63	.54	.39	.30
TA, DEGREES C	4.11	7.44	10.44	13.50	17.28	20.78	24.94	24.67	20.89	14.83	8.39	4.72
TA, DEGREES F	39.40	45.40	50.80	56.30	63.10	69.40	76.90	76.40	69.60	58.70	47.10	40.50
CLNO	.85	.85	.85	.85	.95	.95	.95	.95	.95	.95	.85	.85
DIR/YR KJ/SQM	5681194.											
DIR/YR BTU/SQFT	500570.											
MIAMI FL												
LATITUDE, 25.47												
HT, KJ/SQM	12027.00	14942.00	18141.00	21473.00	21889.00	20190.00	21258.00	21616.00	17217.00	14915.00	12703.00	11562.00
HT, BTU/SQFT	1059.70	1316.50	1598.40	1892.00	1928.60	1778.90	1873.00	1904.60	1517.00	1314.20	1119.30	1018.70
KT	.51	.53	.55	.56	.56	.50	.54	.57	.50	.51	.52	.52
TA, DEGREES C	22.00	22.22	23.22	25.00	26.61	28.28	28.94	29.17	28.50	26.78	24.22	22.56
TA, DEGREES F	71.60	72.00	73.80	77.00	79.90	82.90	84.10	84.50	83.30	80.20	75.60	72.60
CLNO	.76	.76	.76	.76	.81	.81	.81	.81	.81	.81	.76	.76
DIR/YR KJ/SQM	5023607.											
DIR/YR BTU/SQFT	442630.											

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
NASHVILLE TN												
LATITUDE, 36.07												
HT, KJ/SQM	6491.00	9327.00	12849.00	17563.00	20808.00	22262.00	21281.00	19721.00	15717.00	12387.00	8021.00	5801.00
HT, BTU/SQFT	571.90	821.50	1132.10	1547.50	1833.40	1961.50	1875.10	1737.60	1384.80	1091.40	706.70	511.10
KT	.37	.41	.45	.50	.53	.54	.53	.54	.51	.51	.43	.36
TA, DEGREES C	5.89	7.28	11.61	17.22	21.89	26.72	28.44	27.72	24.78	18.56	11.28	6.83
TA, DEGREES F	42.60	45.10	52.90	63.00	71.40	80.10	83.20	81.90	76.60	65.40	52.30	44.30
CLNO	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
DIR/YR KJ/SQM 4721144.												
DIR/YR BTU/SQFT 415980.												
NEW YORK NY												
LATITUDE, 40.46												
HT, KJ/SQM	5702.00	8241.00	11765.00	15342.00	18384.00	20099.00	19773.00	17258.00	13741.00	10134.00	6003.00	4550.00
HT, BTU/SQFT	502.40	726.10	1036.60	1351.80	1619.80	1770.90	1742.20	1520.60	1210.70	892.90	528.90	400.90
KT	.39	.41	.44	.45	.47	.49	.49	.48	.47	.46	.38	.34
TA, DEGREES C	1.67	1.61	6.17	11.28	17.39	22.33	24.94	24.06	20.83	15.17	9.06	3.17
TA, DEGREES F	35.00	34.90	43.10	52.30	63.30	72.20	76.90	75.30	69.50	59.30	48.30	37.70
CLNO	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89	.89
DIR/YR KJ/SQM 3945296.												
DIR/YR BTU/SQFT 347620.												
NORTH OMAHA NE												
LATITUDE, 41.22												
HT, KJ/SQM	7179.00	10096.00	13996.00	17597.00	21297.00	24047.00	24046.00	21159.00	15540.00	12193.00	7530.00	5796.00
HT, BTU/SQFT	632.50	889.60	1233.20	1550.50	1876.50	2118.60	2118.70	1864.30	1369.20	1074.30	663.50	510.70
KT	.50	.51	.53	.52	.54	.58	.60	.59	.53	.56	.48	.45
TA, DEGREES C	-5.00	-2.78	2.78	10.00	17.22	22.22	25.00	22.78	18.89	12.22	3.89	-2.22
TA, DEGREES F	23.00	27.00	37.00	50.00	63.00	72.00	77.00	73.00	66.00	54.00	39.00	28.00
CLNO	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90	.90
DIR/YR KJ/SQM 5878447.												
DIR/YR BTU/SQFT 517950.												
PHOENIX AZ												
LATITUDE, 33.26												
HT, KJ/SQM	11491.00	15659.00	20629.00	26702.00	30280.00	31440.00	28267.00	25877.00	22938.00	18010.00	13142.00	10564.00
HT, BTU/SQFT	1012.50	1379.70	1817.60	2352.70	2668.00	2770.20	2490.60	2280.00	2021.10	1586.90	1157.90	930.80
KT	.60	.65	.69	.75	.76	.77	.70	.70	.72	.70	.65	.60
TA, DEGREES C	12.33	14.89	18.17	22.33	27.11	31.78	34.76	33.61	30.78	24.33	17.56	13.72
TA, DEGREES F	54.20	58.80	64.70	72.20	80.80	89.20	94.60	92.50	87.40	75.80	63.60	56.70
CLNO	.85	.85	.85	.85	.95	.95	.95	.95	.95	.95	.85	.85
DIR/YR KJ/SQM 9100443.												
DIR/YR BTU/SQFT 801840.												
SANTA MARIA CA												
LATITUDE, 34.54												
HT, KJ/SQM	9983.00	12941.00	18214.00	21755.00	24523.00	26956.00	27194.00	23946.00	19964.00	15669.00	11297.00	9161.00
HT, BTU/SQFT	879.60	1140.20	1604.80	1916.80	2160.70	2375.10	2396.10	2109.90	1759.00	1380.60	995.40	807.20
KT	.54	.56	.62	.61	.62	.66	.66	.65	.63	.62	.58	.54
TA, DEGREES C	12.28	12.94	14.22	15.28	16.22	17.50	18.50	18.72	18.83	17.83	16.00	13.39
TA, DEGREES F	54.10	55.30	57.60	59.50	61.20	63.50	65.30	65.70	65.90	64.10	60.80	56.10
CLNO	.85	.85	.85	.85	.95	.95	.95	.95	.95	.95	.85	.85
DIR/YR KJ/SQM 7219839.												
DIR/YR BTU/SQFT 636140.												

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
SEATTLE WA												
LATITUDE, 47.27												
HT, KJ/SQM	2978.00	5436.00	9892.00	14888.00	19455.00	204[illegible].00	22187.00	17968.00	12856.00	7268.00	3773.00	2324.00
HT, BTU/SQFT	262.40	479.00	871.60	1311.80	1714.20	1799.40	1954.50	1584.90	1132.70	640.40	332.40	204.60
KT	.28	.34	.42	.46	.51	.45	.56	.52	.48	.40	.32	.25
TA, DEGREES C	5.61	7.22	9.39	12.28	15.44	18.00	20.22	19.94	17.39	13.50	9.11	6.89
TA, DEGREES F	42.10	45.00	48.90	54.10	59.80	64.40	68.40	67.90	63.30	56.30	48.40	44.40
CLNO	.85	.85	.85	.85	.95	.95	.95	.95	.95	.95	.85	.85
DIR/YR KJ/SQM	3708546.											
DIR/YR BTU/SQFT	326760.											
WASHINGTON DC												
LATITUDE, 38.51												
HT, KJ/SQM	6495.00	9143.00	12774.00	16579.00	19758.00	21891.00	20617.00	18762.00	15220.00	11256.00	7383.00	5416.00
HT, BTU/SQFT	572.30	805.60	1125.50	1460.80	1740.90	1928.80	1616.60	1653.10	1341.00	991.80	650.50	477.20
KT	.41	.43	.46	.48	.50	.53	.51	.52	.50	.49	.43	.37
TA, DEGREES C	3.56	4.22	8.94	14.17	19.63	24.56	26.61	25.50	22.33	16.06	10.11	4.56
TA, DEGREES F	38.40	39.60	48.10	57.50	67.70	76.20	79.90	77.90	72.20	60.90	50.20	40.20
CLNO	.88	.88	.88	.86	.88	.88	.88	.88	.88	.88	.88	.88
DIR/YR KJ/SQM	4537056.											
DIR/YR BTU/SQFT	399760.											

APPENDIX D

PERFORMANCE METHODOLOGY DESCRIPTION*

D.1 INTRODUCTION

This appendix extends the utilizability method of Hottel and Whillier (1955) and Liu and Jordan (1963) for calculating the long-term average energy delivery of flat-plate collectors to concentrating solar collectors. To circumvent detailed derivation for the practical engineer, Sections D.2 through D.7 present the derivation while Sections D.8 through D.10 constitute a users' guide which may be understood independently. The solar radiation correlations which form the basis of the model are discussed by Collares-Pereira and Rabl (1978).

Recent investigations by Klein (to be published)** and by Beckman et al. (1977) have reconfirmed the usefulness and general validity of the Liu and Jordan approach, while pointing out corrections to the underlying meteorological correlations which are needed for improved accuracy. This approach automatically averages year-to-year weather fluctuations and is sufficiently simple to permit hand calculation. While an hour-by-hour simulation may be needed to predict the detailed performance of a particular installation, only average performance is of interest for general collector comparisons and for mass marketing calculations. For the latter purpose, the utilizability method is not only much simpler but also more reliable.

The method averages weather data over many locations and years. Although this smoothes out weather peculiarities of particular locations, this is not a drawback. For example, a manufacturer would prefer to sell a single collector that is a good compromise for many locations instead of offering a different collector optimized for each location.

This model predicts long-term average collector performance if the average receiver operating temperature (inlet, outlet, or mean fluid temperature) is known. If an operating temperature is not explicitly known, this method can

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*This appendix has been submitted as two articles for publication in Solar Energy: M. Collares-Pereira and A. Rabl, "Derivation of Method for Predicting Long-Term Average Energy Delivery of Solar Collectors; and M. Collares-Pereira and A. Rabl, "Simple Procedure for Predicting Long-Term Average Performance of Nonconcentrating and Concentrating Solar Collectors," Solar Energy, Vol. 23, p. 235 (1979).

**Klein's definition of utilizability is slightly different from ours, but his method is equivalent to ours. For the example of the flat-plate collector in Table VI of Collares-Pereira and Rabl (1978), Klein's method is in agreement to 1% if the same value is assumed for $\overline{H}_d/\overline{H}_h$.

be combined with the $\bar{\Phi}$ f-Chart method of Klein and Beckman (1978) which accounts for the penalties due to finite storage capacity. Although the $\bar{\Phi}$ f-Chart method was developed for flat-plate collectors, it may be extended to all collector types if the $\bar{\phi}\ \bar{H}_T$ product of Klein and Beckman (1978) is replaced by our $\phi\ \bar{H}_{coll}$ product (see Eqs. D.9-1 and D.10-5).

Experience in evaluating models of the Liu and Jordan type has shown that although the basic method is correct, specific formulas may be inaccurate because they are based on limited data. Therefore, Sections D.2 through D.7 present the derivation in detail in order to facilitate fine tuning of the model as more insolation data (beam and diffuse) become available.

Section D.2 of this appendix presents the factors r_h and r_d, correlation factors between the average instantaneous irradiance $\bar{I}$ and the average total daily irradiation $\bar{H}$. These are convoluted with the incidence angle cosines to yield a formula for the long-term average daily total insolation $\bar{H}_{coll}$ reaching the collector aperture during operating hours. The operating time from t_{c-} hours before noon to t_{c+} hours after noon is specified as input to account for collector shading.

Section D.3 shows that the radiation actually absorbed by the receiver can be approximated by the product of $\bar{H}_{coll}$ and the average optical efficiency $\bar{\eta}_o$. The average optical efficiency is obtained by averaging the instantaneous optical efficiencies η_o over an operating day.

Section D.4 describes the connection between instantaneous efficiency and long-term performance. The analysis is based upon the utilizability concept of Hottel, Whillier, Liu, and Jordan. The utilizability ϕ is the fraction of the daily average total incident solar radiation (D = day; t = time of day)

$$\bar{H}_{coll} = \frac{1}{N} \sum_{D=1}^{N} \int_{-t_c}^{t_c} I_{coll}(D,t)\ dt \qquad \text{(D.1-1)}$$

which is above the critical intensity level

$$I_x = \frac{q_{loss}}{\bar{\eta}_o A} \ , \qquad \text{(D.1-2)}$$

where q_{loss}/A is the heat loss per unit aperture area of the collector. The utilizability is defined as

$$\phi = \frac{\sum_{D=1}^{N} \int_{-t_c}^{t_c} \left[I_{coll}(D,t) - I_x(D,t)\right]_+ dt}{\sum_{D=1}^{N} \int_{-t_c}^{t_c} I_{coll}(D,t)\, dt} , \qquad (D.1\text{-}3)$$

where the plus sign under the bracket indicates that the summation and integration include only positive contributions. In terms of ϕ, the long-term average daily total energy delivered by the collector is

$$\bar{Q} = A\, \phi\, F\, \bar{\eta}_o\, \bar{H}_{coll} , \qquad (D.1\text{-}4)$$

where F is the factor in the Hottel, Whillier, Bliss equation (Duffie and Beckman 1974; Kreith and Kreider 1978) that accounts for heat removal efficiency. By a series of manipulations, the insolation values in Eq. D.1-3 can be replaced by location-independent, long-term average radiation correlations* (Collares-Pereira and Rabl 1978;** Liu and Jordan 1960).

Section D.5 approximates ϕ by simple analytical expressions that depend on only three variables.

Section D.6 addresses the choice of nominal collector cutoff time t_c.

Section D.7 presents a comparison of the model with the results of an hour-by-hour summation of radiation data. The average agreement is better than 3% for the available radiation data $\bar{H}_{coll}$ and 5% for heat delivery of thermal collectors.

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*This study is based on pyranometer plus pyrheliometer measurements that have recently been made available by the Aerospace Corporation. The data were taken at Albuquerque, N.M.; Fort Hood, Tex.; Livermore, Calif.; Maynard, Mass.; and Raleigh, N.C., with approximately two years at each station.

**Fluctuations in hourly insolation $I(f)/\bar{I}$ are expected to be larger than fluctuations in daily insolation $H(f)/\bar{H}$ since the reference period is shorter. Because of the dearth of data on hourly frequency distributions, we have used the fractional time distribution for daily insolation values, $H(f)/\bar{H}$. In so doing we smooth some of the fluctuations of solar radiation and hence underestimate the output of thermal collectors. Since the time we derived the least-square fits for our curves, the frequency distributions have been reinvestigated by S. A. Klein and J. A. Duffie (1978) and by M. Collares-Pereira and A. Rabl (forthcoming).

D.2 LONG-TERM AVERAGE INSOLATION $\bar{H}_{coll}$ AVAILABLE TO COLLECTOR

To simplify the presentation, assume that:

(1) the portion of the ground seen by the collector, if any, has the same average brightness as the sky, and

(2) the collector operates symmetrically around solar noon. The arguments can be carried through for more general operating conditions; one example being when the turn-on time t_{c-} and the turn-off time t_{c+} of a collector are different due to heat capacity effects or due to alignment away from the north-south direction. We consider a collector of geometric concentration C and allow for the possibility that C is low enough for a significant fraction of the diffuse irradiation I_d to be accepted. To a good approximation, I_d can be assumed to be isotropic; then the instantaneous irradiation available to the collector is

$$I_{coll} = \cos\theta_{coll}\, I_b + \frac{1}{C} I_d \quad , \tag{D.2-1}$$

where θ_{coll} is the solar incidence angle on the collector.

The long-term average daily total irradiation $\bar{H}_{coll}$ available to the collector during operating hours (i.e., from $t = -t_c$ to $t = +t_c$) is obtained by integrating over time of day t and averaging over a large number N of days:

$$\bar{H}_{coll} = \frac{1}{N} \sum_{D=1}^{N} \int_{-t_c}^{t_c} \left(\cos\theta_{coll}\, I_b(D,t) + \frac{1}{C} I_d(D,t)\right) dt \quad . \tag{D.2-2}$$

Because of the magnitude of year-to-year fluctuations in solar radiation, the result is representative of the true long-term average only if the summation includes data for many years, preferably more than ten. Typically, one is interested in the average corresponding to a particular month of the year; in that case the summation should include the days of the month in question, for all years for which data are available. (A month is a useful but rather arbitrary time interval, and long-term averages could be defined equally well for a day, a week, a season, or the entire year.)

Now, we replace the beam irradiance I_b by $(I_h - I_d)/\cos\theta$, where θ is the solar incidence angle on the horizontal. Interchanging the integral and summing in Eq. D.2-2, one obtains an expression

$$\bar{H}_{coll} = \int_{-t_c}^{t_c} \left[\frac{\cos\theta_{coll}}{\cos\theta} \frac{1}{N} \sum_{D=1}^{N} I_h(D,t) - \left(\frac{\cos\theta_{coll}}{\cos\theta} - \frac{1}{C}\right) \frac{1}{N} \sum_{D=1}^{N} I_d(D,t)\right] dt \quad , \tag{D.2-3}$$

which shows that only the long-term averages of the irradiances

$$\bar{I}_h(t) = \frac{1}{N} \sum_{D=1}^{N} I_h(D,t) \tag{D.2-4}$$

and

$$\bar{I}_d(t) = \frac{1}{N} \sum_{D=1}^{N} I_d(D,t) \tag{D.2-5}$$

are needed to predict $\bar{H}_{coll}$. It is convenient to replace irradiance I by daily total irradiation H by defining conversion factors

$$r_h(t) = \frac{\bar{I}_h(t)}{\bar{H}_h} = \frac{\sum_{D=1}^{N} I_h(D,t)}{\sum_{D=1}^{N} H_h(D)} \tag{D.2-6}$$

and

$$r_d(t) = \frac{\bar{I}_d(t)}{\bar{H}_d} = \frac{\sum_{D=1}^{N} I_d(D,t)}{\sum_{D=1}^{N} H_d(D)} \quad . \tag{D.2-7}$$

To an excellent approximation, r_d and r_h depend only on time of day t and sunset time t_s and can be represented* by the functions (Collares-Pereira and Rabl 1978; Liu and Jordan 1960):

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*These expressions for r_d and r_h were obtained by combining data before and after solar noon and thus neglect any systematic morning/afternoon differences which do occur in some locations; e.g., Colorado in summer. This has no effect on the prediction of radiation availability H_{coll}, and for thermal collectors it is one of the "smoothing assumptions" that lead to underprediction.

$$r_d(\omega,\omega_s) = \frac{\pi}{T}\,\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \tag{D.2-8}$$

and

$$r_h(\omega,\omega_s) = (a + b\cos\omega)\, r_d(\omega,\omega_s) \quad , \tag{D.2-9}$$

where

$$a = 0.409 + 0.5016\,\sin(\omega_s - 1.047),$$

$$b = 0.6609 - 0.4767\,\sin(\omega_s - 1.047),$$

$$T = \text{length of day} = 86{,}400 \text{ seconds},$$

and all times have been expressed as hour angles from noon in radians:

$$\omega = \frac{2\pi t}{T} \quad \text{and} \quad \omega_s = \frac{2\pi t_s}{T} \ . \tag{D.2-10}$$

In terms of r_d and r_h, the insolation available to the collector becomes

$$\bar{H}_{coll} = \bar{H}_h \int_{-t_c}^{t_c} \frac{\cos\theta_{coll}}{\cos\theta}\, r_h(t)\; dt$$

$$- \bar{H}\int_{-t_c}^{t_c} \left(\frac{\cos\theta_{coll}}{\cos\theta} - \frac{1}{C}\right) r_d(t)\; dt \ . \tag{D.2-11}$$

The time integrals are abbreviated by

$$R_d = \int_{-t_c}^{t_c} \left(\frac{\cos\theta_{coll}}{\cos\theta} - \frac{1}{C}\right) r_d(t)\; dt \tag{D.2-12}$$

and

$$R_h = \int_{-t_c}^{t_c} \frac{\cos\theta_{coll}}{\cos\theta}\, r_h(t)\; dt \tag{D.2-13}$$

in order to write the insolation available to the collector in the simple form

$$\bar{H}_{coll} = \left(R_h - R_d\,\frac{\bar{H}_d}{\bar{H}_h}\right)\bar{H}_h \ . \tag{D.2-14}$$

We have chosen to enter the diffuse irradiation by means of the ratio

$$\frac{\bar{H}_d}{\bar{H}_h} = \frac{\sum_{D=1}^{N} H_d(D)}{\sum_{D=1}^{N} H_h(D)} \qquad \text{(D.2-15)}$$

because analysis of insolation data has shown that this ratio can be correlated quite well with sunset hour angle ω_s and with long-term average clearness index (equal to the ratio of terrestrial over extraterrestrial irradiation)

$$\bar{K}_h = \frac{\bar{H}_h}{H_o} \qquad \text{(D.2-16)}$$

by the equation (Collares-Pereira and Rabl 1978)

$$\frac{\bar{H}_d}{\bar{H}_h} = 0.775 + 0.347(\omega_s - \frac{\pi}{2}) - \left[0.505 + 0.261\left(\omega_s - \frac{\pi}{2}\right)\right] \cos[2(\bar{K}_h - 0.9)] \quad , \qquad \text{(D.2-17)}$$

for $0.4 \lesssim \bar{K}_h \lesssim 0.75$.

The above discussion shows that Eq. D.2-14 for $\bar{H}_{coll}$ is completely equivalent to a summation of instantaneous insolation data for a particular location if r_d, r_h, and $\bar{H}_d/\bar{H}_h$ represent the correct long-term averages for that location. The validity of our radiation model is therefore guaranteed to the extent to which r_d, r_h, and $\bar{H}_d/\bar{H}_h$ can be approximated by the location-independent analytical expressions of Eqs. D.2-8, D.2-9, and D.2-17.

The quantities R_d and R_h depend on collector type, sunset time, and cutoff time; they are tabulated in Tables D-1 through D-5* for the principal collector types. The calculation of R_d and R_h is straightforward although in some cases a bit tedious. The simplest example is provided by the two-axis tracker because it satisfies $\cos \theta_{coll} = 1$ at all times.

*In Tables D-1 through D-5, d is equal to $\sin \omega_s - \omega_s \cos \omega_s$.

Table D-1. FUNCTIONS R_h AND R_d FOR FLAT-PLATE COLLECTOR WITH TILT β

$$R_h = \frac{1}{d}\left[\left(\frac{\cos(\lambda-\beta)}{\cos\lambda} + \frac{\rho}{2}(1-\cos\beta)\right)\left(a\sin\omega_c + \frac{b}{2}\left(\sin\omega_c\cos\omega_c + \omega_c\right)\right) - \left(\frac{\cos(\lambda-\beta)}{\cos\lambda}\cos\omega_s' + \frac{\rho}{2}(1-\cos\beta)\cos\omega_s\right)\left(a\omega_c + b\sin\omega_c\right)\right]$$

$$R_d = \frac{1}{d}\left[\left(\frac{\cos(\lambda-\beta)}{\cos\lambda} - \frac{1}{2}(1+\cos\beta)\right)\sin\omega_c - \left(\frac{\cos(\lambda-\beta)}{\cos\lambda}\cos\omega_s' - \frac{1}{2}(1+\cos\beta)\cos\omega_s\right)\omega_c\right]$$

Table D-2. FUNCTIONS R_h AND R_d FOR CONCENTRATORS WITH FIXED APERTURE (e.g., COMPOUND PARABOLIC CONCENTRATOR) WITH TILT β, LATITUDE λ

$$R_h = \frac{\cos(\lambda-\beta)}{d\cos\lambda}\left((a - b\cos\omega_s')\sin\omega_c - a\cos\omega_s'\,\omega_c + \frac{b}{2}\left(\sin\omega_c\cos\omega_c + \omega_c\right)\right)$$

$$R_d = \frac{1}{d}\left[\left(\frac{\cos(\lambda-\beta)}{\cos\lambda} - \frac{1}{C}\right)\sin\omega_c + \left(\frac{\cos\omega_s}{C} - \frac{\cos(\lambda-\beta)}{\cos\lambda}\cos\omega_s'\right)\omega_c\right]$$

Table D-3. FUNCTIONS R_h AND R_d FOR A COLLECTOR TRACKING ABOUT EAST-WEST AXIS

For high concentration $C \gtrsim 10$:

$$R_h = \frac{1}{d\cos\lambda}\int_0^{\omega_c} d\omega\,(a + b\cos\omega)\left(\cos^2\omega + \tan^2\delta\right)^{1/2}$$

$$R_d = \frac{1}{\cos\lambda}\int_0^{\omega_c} d\omega\,\left(\cos^2\omega + \tan^2\delta\right)^{1/2}$$

For low concentration $C \lesssim 10$:

$$R_d = \frac{1}{d\cos\lambda}\int_0^{\omega_c} d\omega\left(\left(\cos^2\omega + \tan^2\delta\right)^{1/2} - \frac{\cos\lambda}{C}\left(\cos\omega - \cos\omega_s\right)\right)$$

Table D-4. FUNCTIONS R_h AND R_d FOR A COLLECTOR TRACKING ABOUT NORTH-SOUTH AXIS

Tilt β of tracking axis = latitude λ (polar mount):

$$R_h = \frac{a\,\omega_c + b \sin \omega_c}{d \cos \lambda}$$

$$R_d = \begin{cases} \dfrac{\omega_c}{d \cos \lambda} & \text{for high concentration, } C \gtrsim 10. \\[2ex] \dfrac{\omega_c}{d \cos \lambda} - \dfrac{\sin \omega_c - \omega_c \cos \omega_s}{Cd} & \text{for low concentration, } C \lesssim 10 \end{cases}$$

Tilt β of tracking axis ≠ latitude λ:[a]

$$R_h = \frac{1}{d \cos \lambda} \int_0^{\omega_c} d\omega\,(a + b \cos \omega)\, g(\omega)$$

$$\text{with } g(\omega) = \left(\sin^2 \omega + \left[\cos(\lambda - \beta) \cos \omega + \tan \delta \sin(\lambda - \beta)\right]^2\right)^{1/2}$$

$$R_d = \begin{cases} \dfrac{1}{d \cos \lambda} \displaystyle\int_0^{\omega_c} d\omega\, g(\omega) & \text{for high concentration, } C \gtrsim 10 \\[2ex] \dfrac{1}{d \cos \lambda} \displaystyle\int_0^{\omega_c} d\omega\, g(\omega) - \dfrac{\sin \omega_c - \omega_c \cos \omega_s}{Cd} & \text{for low concentration, } C < 10 \end{cases}$$

[a]The integrals can be evaluated by Simpson's rule.

Table D-5. FUNCTIONS R_h AND R_d FOR A COLLECTOR WITH TWO-AXIS TRACKING

$$R_h = \frac{a\omega_c + b \sin \omega_c}{d \cos \lambda \cos \delta}$$

$$R_d = \begin{cases} \dfrac{\omega_c}{d \cos \lambda \cos \delta} & \text{for high concentration, } C \gtrsim 10 \\[2ex] \dfrac{\omega_c}{d \cos \lambda \cos \delta} - \dfrac{\sin \omega_c - \omega_c \cos \omega_s}{Cd} & \\[2ex] & \text{for low concentration, } C \lesssim 10 \end{cases}$$

The solar incidence angle on the horizontal is given by

$$\cos \theta = \cos \delta \cos \lambda (\cos \omega - \cos \omega_s) \quad , \qquad \text{(D.2-18)}$$

where δ is the solar declination and λ the latitude. When Eqs. D.2-9 and D.2-18 are inserted into the definition of R_h (Eq. D.2-13), the integration yields

$$R_{h,2axis} = \frac{a\omega_c + b \sin \omega_c}{(\sin \omega_s - \omega_s \cos \omega_s) \cos \delta \cos \lambda} \quad . \qquad \text{(D.2-19)}$$

R_d for the same collector is

$$R_{d,2\text{-axis}} = \frac{1}{(\sin \omega_s - \omega_s \cos \omega_s)} \left(\frac{\omega_c}{\cos \delta \cos \lambda} - \frac{\sin \omega_c - \omega_c \cos \omega_s}{C} \right) \quad .$$

(D.2-20)

Note that R_d for the case in which $C >> 1$ can be obtained from the corresponding equation for R_h by setting $a = 1$ and $b = 0$. For collectors that are sensitive to the exact value of the ground reflectance, Eqs. D.2-12 and D.2-13 must be appropriately modified. For the benefit of readers who wish to verify our calculation of R_h and R_d for other collector types, we list as an intermediate result the cosine ratio ($\cos \theta_{coll}$)/$\cos \theta$ in Table D-6.

D.3 LONG-TERM AVERAGE OPTICAL EFFICIENCY

Of the irradiance I_{coll} reaching the collector within its acceptance angle, only a fraction η_o is absorbed by the receiver; the rest is lost because of optical imperfections of the collector; for example, absorption in the reflector. (In the flat-plate literature, η_o has also been called the $\alpha\tau$ product.) For most collectors, the optical efficiency varies significantly with incidence angle and hence with time of day. For the purpose of calculating the long-term energy delivery one could measure the detailed functional dependence of η_o on incidence angle and then fold this functional dependence into an hour-by-hour simulation or into the integration underlying the functions R_d and R_h in Eqs. D.2-12 and D.2-13. Fortunately, such a tedious procedure can be avoided by working instead with the long-term average optical efficiency $\bar{\eta}_o$ (Tabor 1978*). Use of $\bar{\eta}_o$ is mathematically equivalent and greatly simplifies both collector testing and analysis. $\bar{\eta}_o$ is defined as the average of η_o over time of day t and over a large number N of days D, weighted by the irradiance $I_{coll}(D,t)$:

$$\bar{\eta}_o = \frac{\frac{1}{N} \sum_{D=1}^{N} \int_{-t_c}^{t_c} \eta_o(D,t)\, I_{coll}(D,t)\, dt}{\frac{1}{N} \sum_{D=1}^{N} \int_{-t_c}^{t_c} I_{coll}(D,t)\, dt} . \quad \text{(D.3-1)}$$

The denominator in this equation is the long-term average daily irradiation $\bar{H}_{coll}$ available to the collector, and the numerator is the long-term average irradiation $\bar{H}_{coll,abs}$ actually absorbed by the receiver:

$$\bar{H}_{coll,abs} = \bar{\eta}_o \bar{H}_{coll} . \quad \text{(D.3-2)}$$

Since the angular distribution of the beam component is nearly uniform when averaged over the year, it follows that $\bar{\eta}_o$ must be almost completely independent of clearness index. Furthermore, one does not need a large number of days to evaluate $\bar{\eta}_o$, provided the range of incidence angles corresponding to the days and hours in Eq. D.3-1 is representative of the year-round average.

*Tabor's use of an average filter factor F_f in his Eq. A2 is equivalent to our long-term average optical efficiency.

Table D-6. RATIO $(\cos \theta_{coll})/\cos \theta$ FOR DIFFERENT COLLECTOR TYPES AS A FUNCTION OF ω, ω_s, λ, β, and δ

Collector Type	$\frac{\cos \theta_{coll}}{\cos \theta}$
Flat plate (azimuth $\phi = 0$)	$\frac{\cos(\lambda - \beta)}{\cos \lambda} \frac{(\cos \omega - \cos \omega_s')}{(\cos \omega - \cos \omega_s)}$
Flat plate (azimuth $\phi \neq 0$)	$\frac{\cos \beta_o \left[\cos(\omega - \phi_o) - \cos(\omega_s' - \phi_o)\right]}{\cos \lambda (\cos \omega - \cos \omega_s)}$ $\left(\text{with } \sin \beta_o = \cos \beta \sin \lambda - \sin \beta \cos \lambda \cos \phi\right.$ $\left.\text{and } \tan \phi_o = \frac{\sin \beta \sin \phi}{\cos \beta \cos \lambda + \sin \beta \sin \lambda \cos \phi}\right)$
CPC (azimuth $\phi = 0$)	$\frac{\cos(\lambda - \beta)}{\cos \lambda} \frac{(\cos \omega - \cos \omega_s')}{(\cos \omega - \cos \omega_s)}$
One-axis tracking, E-W oriented	$\frac{(\cos^2 \omega + \tan^2 \delta)^{1/2}}{\cos \lambda (\cos \omega - \cos \omega_s)}$
One-axis tracking, N-S	$\frac{\left\{\sin^2 \omega + \left(\cos(\lambda - \beta) \cos \omega + \tan \delta \sin(\lambda - \beta)\right)^2\right\}^{1/2}}{\cos \lambda (\cos \omega - \cos \omega_s)}$
Two-axis tracker	$\frac{1}{\cos \delta \cos \lambda (\cos \omega - \cos \omega_s)}$

For most collectors sufficiently accurate results can be obtained by measuring the average day-long performance during a single clear day. For thermal collectors one should measure the heat output q_{out} (in watts) at zero heat loss (i.e., when receiver surface temperature T_r equals ambient temperature T_a) and integrate over time of day to get $\bar{\eta}_o$ as

$$\bar{\eta}_o = \frac{\int_{-t_{c-}}^{t_{c+}} [q_{out}(t)/A]dt}{\int_{-t_{c-}}^{t_{c+}} I_{coll}(t)\,dt} , \qquad (D.3-3)$$

measured on a clear day, with the receiver at ambient temperature. The turn-on and turn-off times t_{c-} and t_{c+} should be typical of actual collector operation, and the demand for testing on a clear day is added to insure uniform distribution of beam insolation.

If the condition $T_r = T_a$ cannot be satisfied, one must correct Eq. D.3-3 by adding the daily total heat loss calculated from the known U-value

$$\bar{\eta}_o = \frac{\int_{-t_c}^{t_{c+}} \left(\frac{q_{out}(t)}{A} + U[T_r(t) - T_a(t)] \right) dt}{\int_{-t_{c-}}^{t_{c+}} I(t)\,dt} \qquad (D.3-4)$$

if the receiver temperature $T_r(t)$ has been monitored, and

$$\bar{\eta}_o = \frac{\int_{-t_c}^{t_{c+}} \left(\frac{q_{out}(t)}{AF'} + U[T_f(t) - T_a(t)] \right) dt}{\int_{-t_{c-}}^{t_{c+}} I(t)\,dt} \qquad (D.3-5)$$

if the average fluid temperature $T_f(t)$ has been monitored.

A comment should be added regarding the relation between η_o and partial loss of diffuse and circumsolar radiation (Grether et al. 1974). To a certain extent, whether such losses are included in the insolation model or in the optical efficiency is a matter of bookkeeping. We have found it most convenient to define the optical efficiency of collectors with low concentration ($C \lesssim 10$) with respect to the radiation I_{coll} within the acceptance angle (i.e., beam plus 1/C diffuse). For collectors with high concentration (acceptance half angles smaller than 2.8°) we assume that the efficiency is specified in terms of the beam radiation measured with a pyrheliometer of 2.8° acceptance half angle, as is standard practice. Thus the measured η_o automatically includes the loss of circumsolar radiation, but only for the time and location of the collector test. The problem of extrapolating to areas with different behavior of circumsolar radiation requires further analysis.

D.4 ENERGY DELIVERY OF THERMAL COLLECTORS

The Hottel-Whillier-Bliss equation (Duffie and Beckman 1974; Liu and Jordan 1960) for the instantaneous collector efficiency

$$\eta = F[\eta_o - U(T_{coll} - T_a)/I_{coll}] \tag{D.4-1}$$

serves as a starting point, with the notation

- U = collector loss coefficient or U-value (W/m^2 C) relative to aperture area A,
- η_o = optical efficiency
- I_{coll} = irradiance (W/m^2) on collector aperture within acceptance angle of collector,
- T_{coll} = collector temperature, specified either as receiver surface temperature T_r, average fluid temperature $T_f = (T_{in} + T_{out})/2$, inlet fluid temperature T_{in}, or outlet fluid temperature T_{out},
- F = heat extraction or removal efficiency factor which accounts for temperature base chosen for T_{coll}.

The long-term average heat $\bar{Q}$ delivered by the collector is obtained by integrating the instantaneous collector output per aperture area A

$$\frac{q_{out}}{A} = F[\eta_o I_{coll} - U(T_{coll} - T_a)] \tag{D.4-2}$$

over time of day t and averaging over a large number N of days D

$$\frac{\bar{Q}}{A} = \frac{1}{N} \sum_{D=1}^{N} \int_{-t_c}^{t_c} F[\eta_o(D,t)\ I_{coll}(D,t) - U(T_{coll} - T_a)]_+ \, dt \ . \tag{D.4-3}$$

The plus sign under the bracket indicates that only positive values of the integrand are to be included. The functional dependence of η_o on D and t accounts for incidence angle modifiers. The collector turn-on and turn-off times are indicated as $\pm t_c$ from solar noon. Asymmetric operating times can easily be accommodated by writing t_{c-} and t_{c+} instead of $\pm t_c$. Shading between adjacent collector modules is accounted for by choosing appropriate values for collector cutoff time t_c.

Since we want to derive a model based on horizontal insolation data, we relate I_{coll} to the hemispherical and diffuse irradiances I_h and I_d on a horizontal surface. The precise connection of I_{coll} with I_h and I_d depends on collector type--in particular, on the ability of the collector to collect diffuse radiation from sky or ground. For simplicity we specify a collector of high concentration, but it will be clear that the argument is general and holds for any collector type. The irradiance available to a collector of high concentration is

$$I_{coll} = \frac{\cos \theta_{coll}}{\cos \theta} (I_h - I_d) \quad , \tag{D.4-4}$$

where θ_{coll} and θ are the solar incidence angles on collector aperture and on horizontal surface, respectively.

As shown in Section D.3, the optical efficiency η_o inside the integral can be replaced by the long-term average optical efficiency $\bar{\eta}_o$ outside the integral. Since an average collector temperature $\bar{T}_{coll}$ is assumed, and since the fluctuations in ambient temperature T_a are relatively small, we can also replace the heat loss term by its long-term average

$$\frac{\bar{q}_{loss}}{A} = U(\bar{T}_{coll} - T_a) \quad . \tag{D.4-5}$$

Taking into account these points, we can rewrite Eq. D.4 in the form

$$\frac{\bar{Q}}{A} = \frac{F\bar{\eta}_o}{N} \sum_{D=1}^{N} \int_{-t_c}^{t_c} \left(\frac{\cos \theta_{coll}}{\cos \theta} [I_h(D,t) - I_d(D,t)] - \frac{\bar{q}_{loss}}{A\,\bar{\eta}_o} \right)_+ dt \quad . \tag{D.4-6}$$

The summation over days can be carried out in any order; in particular, one can order the days according to their level of hemispherical insolation I_h. We do this by interchanging $\sum_D$ and $\int dt$ and then replacing

$$\frac{1}{N} \sum_{D=1}^{N} \cdots \left[I_h(D,t) - I_d(D,t)\right]$$

by the integral over fractional time distribution

$$\int_0^1 \cdots \left[I_h(f,t) - I_d(f,t)\right] df \quad .$$

f is the fraction of time that the hemispherical irradiance values $I_h(D,t)$ are below the value $I_h(f,t)$. A typical fractional time distribution of hemispherical irradiance is shown in Fig. D-1 [Fig. 12 of Liu and Jordan (1960)] and tabulated in Table D-7 [Table 3 of Liu and Jordan (1960)]; we used this table as the basis for our computations. In terms of fractional time distribution we can rewrite Eq. D.4-6 as

$$\frac{\bar{Q}}{AF\bar{\eta}_o} = \int_{-t_c}^{t_c} dt \int_0^1 \left(\frac{\cos \Theta_{coll}}{\cos \theta} \left[I_h(f,t,)-I_d(f,t) \right] - \frac{\bar{q}_{loss}}{A\bar{\eta}_o} \right)_+ df \quad . \quad (D.4-7)$$

We interchanged $\sum_D$ and $\int dt$ to allow for the possibility that the fractional time distribution may vary with time of day t; in this case the f integration would have to be done first, as shown in Eq. D.4-7. However, Liu and Jordan (1963) found that the differences between fractional time distributions for different times of day were small enough to be negligible as far as the calculation of $\bar{Q}$ is concerned. Following Liu and Jordan we shall henceforth assume the distribution of irradiance $I_h(f,t)$ to be given by the fractional time distribution of daily total hemispherical irradiation $H_h(f)$.* This assumption can be expressed by the equation

$$\frac{I_h(f,t)}{\bar{I}_h(t)} = \frac{H_h(f)}{\bar{H}_h} \quad , \quad (D.4-8)$$

where I_h and H_h have been normalized by their long-term averages. In terms of the correlation function $r_h(t)$ of Eq. (D.2-6) between irradiance and irradiation, $I_h(f,t)$ is therefore given by

$$I_h(f,t) = r_h(t)\, H_h(f) \quad . \quad (D.4-9)$$

The values of I_d and I_h are not correlated one-to-one, but only in the sense of long-term averages. When transforming the sum over days to an integral over fractional time distribution we have implicitly neglected relative fluctuations beween I_d and I_h. The resulting error should not be too serious because the hemispherical component dominates. In any case, it must produce a conservative estimate of $\bar{Q}$, just like all the other approximations that smooth fluctuations in operating conditions. Hence we assume the equivalent of Eq. D.4-8 for the diffuse component

*The curves of Liu and Jordan (see Fig. D-1) have been reconfirmed except for some discrepancy which is due to the fact that Liu and Jordan, lacking the power of modern computers, had to assume a single value of extraterrestrial insolation for the entire month and thereby obtained some unrealistically large values of K_h. In view of the other uncertainties and approximations we decided not to redo the analysis of the curves at the present time.

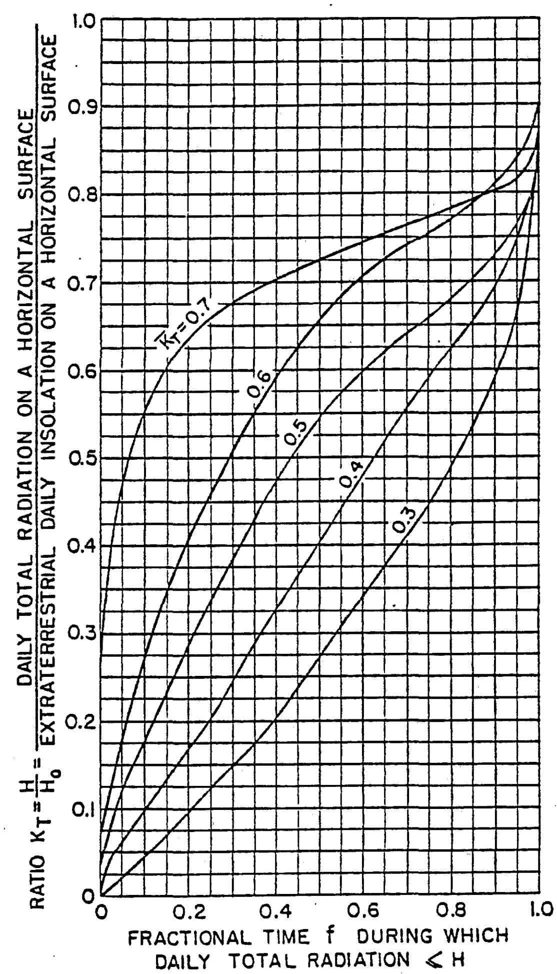

Figure D-1. Fractional Time Distribution Curves of Liu and Jordan (1960, 1963)

Note difference in notation: we use the symbols K_h instead of K_T, and H_h instead of H

Table D-7. FRACTIONAL TIME DISTRIBUTION K_h AS FUNCTION OF f and $\bar{K}_h$ [a]

	Value of f for $\bar{K}_h$ =				
K_h	0.3	0.4	0.5	0.6	0.7
0.04	0.073	0.015	0.001	0.000	0.000
0.08	0.162	0.070	0.023	0.008	0.000
0.12	0.245	0.129	0.045	0.021	0.007
0.16	0.299	0.190	0.082	0.039	0.007
0.20	0.395	0.249	0.121	0.053	0.007
0.24	0.496	0.298	0.160	0.076	0.007
0.28	0.513	0.346	0.194	0.101	0.013
0.32	0.579	0.379	0.234	0.126	0.013
0.36	0.628	0.438	0.277	0.152	0.027
0.40	0.687	0.493	0.323	0.191	0.034
0.44	0.748	0.545	0.358	0.235	0.047
0.48	0.793	0.601	0.400	0.269	0.054
0.52	0.824	0.654	0.460	0.310	0.081
0.56	0.861	0.719	0.509	0.360	0.128
0.60	0.904	0.760	0.614	0.410	0.161
0.64	0.936	0.827	0.703	0.467	0.228
0.68	0.953	0.888	0.792	0.538	0.295
0.72	0.967	0.931	0.873	0.648	0.517
0.76	0.979	0.967	0.945	0.758	0.678
0.80	0.986	0.981	0.980	0.884	0.859
0.84	0.993	0.997	0.993	0.945	0.940
0.88	0.995	0.999	1.000	0.985	0.980
0.92	0.998	0.999		0.996	1.000
0.96	0.998	1.000		0.999	
1.00	1.000			1.000	

[a]From Liu and Jordan 1960, 1963. Note change in notation from K_T to K_h.

$$\frac{I_d(f,t)}{\bar{I}_d(t)} = \frac{H_d(f)}{\bar{H}_d} \quad \text{(D.4-10)}$$

or, in terms of the conversion factor $r_d(t)$ of Eq. D.2-7,

$$I_d(f,t) = r_d(t)\ H_d(f) \quad . \quad \text{(D.4-11)}$$

For the relation between $H_d(f)$ and $H_h(f)$, we refer to the correlation

$$\frac{H_d(f)}{H_h(f)} = d(K_h) = 1.188 - 2.272\ K_h + 9.473\ K_h^2 - 21.856\ K_h^3 + 14.648\ K_h^4 \quad , \quad \text{(D.4-12)}$$

with clearness index

$$K_h = K_h(f) = \frac{H_h(f)}{H_o} \quad , \quad \text{(D.4-13)}$$

which was recommended in Collares-Pereira and Rabl (1978). The seasonal variation in the relation between H_d and H_h that was found by Collares-Pereira and Rabl has almost no effect on the calculation of $\bar{Q}$, and thus the year-round average correlation D.4-12 is acceptable for the present purpose. In terms of the function $d(K_h)$, $I_d(f,t)$ can be written as

$$I_d(f,t) = r_d(t)\ d(K_h)\ H_h(f) \quad . \quad \text{(D.4-14)}$$

Inserting Eqs. D.4-9 and D.4-14 into Eq. D.4-7, a new expression for $\bar{Q}$ is obtained:

$$\frac{\bar{Q}}{AF\bar{\eta}_o} = \int_{-t_c}^{t_c} dt \int_0^1 df \left(\frac{\cos\theta_{coll}}{\cos\theta} \{r_h(t) - r_d(t)\ d[K_h(f)]\} H_h(f) - \frac{\bar{q}_{loss}}{A\bar{\eta}_o} \right)_+ \quad \text{(D.4-15)}$$

which shows the advantage of having transformed everything to fractional time distribution. Since the integrand increases monotonically with f, the subscript + to the expression can be dropped if a lower limit f_x is indicated for the f integration; f_x is that value of f for which the integrand vanishes.

If the heat loss were zero, the lower limit f_x would also vanish, and the right side of Eq. D.4-15 would integrate to

$$\left(R_h - R_d \frac{\bar{H}_d}{\bar{H}_h}\right) \bar{H}_h \quad ,$$

which is just $\bar{H}_{coll}$ of Eq. D.2-14 with the rotation factors R_h and R_d. (Note that the f integrations yield

$$\int_0^1 H_h(f)\, df = \bar{H}_h$$

and (D.4-16)

$$\int_0^1 d(K_h)\, H_h(f)\, df = \bar{H}_d$$

in that case.)

At this point we recall the relation D.1-4 between utilizability function ϕ and energy delivery $\bar{Q}$:

$$\frac{\bar{Q}}{AF\bar{\eta}_o} = \phi\, \bar{H}_{coll} \quad . \qquad \text{(D.4-17)}$$

Comparison between Eqs. D.4-15 and D.4-17 shows that ϕ can be calculated from the formula

$$\phi = \int_{-t_c}^{t_c} dt \int_{f_x(t)}^{1} df \left(\frac{\cos\theta_{coll}}{\cos\theta} \left[r_h(t) - r_c(t)\, d(K_h) \right] H_h(f) - \frac{\bar{q}_{loss}}{A\bar{\eta}_o} \right) \Big/ H_{coll} \quad .$$

(D.4-18)

Our definition of ϕ includes the cutoff time t_c explicitly and therefore differs, both in concept and in numerical value, from the ϕ curves defined by other investigators.

D.5 SIMPLIFICATION OF UTILIZABILITY

In the last section we have approximated the exact expression (Eq. D.1-3) for the utilizability (which needs actual insolation data as input) with Eq. D.4-18, which is based instead on long-term average correlations. The latter equation is simpler and more universal, but it is still too complicated to be practical because it depends on a large number of variables (e.g., collector type, tracking mode, latitude, declination, and cutoff time, in addition to clearness index and heat loss). If the lower limit f_x of the fractional time integration were independent of time of day t, the order of integration could be interchanged. Then the integration over t would be straightforward and result in the simple expression

$$\tilde{\phi} = \int_{f_x}^{1} \left(\left[R_h - R_d\, d(K_n)\right] H_h(f) - \frac{2t_c\, \bar{q}_{loss}}{A\bar{\eta}_o} \right) \Big/ \bar{H}_{coll}\, df \quad , \tag{D.5-1}$$

with the functions R_d and R_h as defined in Eqs. D.2-12 and D.2-13. With the tilde we indicate that this expression is not the correct ϕ. The formula for $\tilde{\phi}$ can be simplified further by defining a ratio

$$R = \frac{R_h}{R_d} \quad , \tag{D.5-2}$$

and a critical energy ratio

$$X = \frac{2t_c\, \bar{q}_{loss}}{A\bar{\eta}_o\, \bar{H}_{coll}} \tag{D.5-3}$$

of daily total heat loss over daily total absorbed insolation. Inserting Eq. D.2-14 for $\bar{H}_{coll}$ into the first term of Eq. D.5-1 and dividing by R_h we obtain

$$\tilde{\phi} = \int_{f_x}^{1} \left[\left(\frac{1 - R\, d(K_h)}{1 - R\, \bar{H}_d/H_h} \right) \frac{H_h(f)}{\bar{H}_h} - X \right] df \quad . \tag{D.5-4}$$

We recall that

$$d(K_h) = \frac{H_d(f)}{H_h(f)}$$

is a function of K_h which in turn depends only on f and $\bar{K}_h$; in other words,

$$d(K_h) = d\left[K_h(f,\bar{K}_h)\right] \quad .$$

Therefore, $\tilde{\phi}$ depends on only three variables: R, $\bar{K}_h$, and X. This observation provided the crucial clue to developing simple correlations for ϕ. From an exhaustive numerical analysis we found that ϕ and $\tilde{\phi}$ differ by less than 10% for all reasonable operating conditions:

$$0.9 \lesssim \frac{\tilde{\phi}}{\phi} \leq 1; \tag{D.5-5}$$

the discrepancy increases with X and vanishes for small heat losses. Only when the heat loss is so large as to imply utilizability values below about

0.4 does the discrepancy become excessive; in fact, under these circumstances, ϕ curves may differ markedly even though their R parameter is the same. We do not believe this to be a serious limitation of our approach because it is unlikely that a collector with $\phi \lesssim 0.4$ could be economical.

Having learned that ϕ can be approximated by a function of R, $\bar{K}_h$, and X, we discarded $\tilde{\phi}$ and developed analytic expressions directly by comparison with the correct expression (Eq. D.4-18) for ϕ. The coefficients of these expressions were determined by least-square fits to ϕ values computed for a wide range of conditions:

Collector type (flat plate, CPC, east-west axis, polar axis, two-axis),
Each month of the year,
Latitude (0^o, 10^o, 20^o, 30^o, 50^o),
Tilt (= latitude $\pm 0^o$, $\pm 15^o$) ,
Cutoff time t_c (3 h, 4 h, 5 h, 6 h),
Critical energy ratio X (0, 0.1, 0.2, . . ., 1.2),
Clearness index $\bar{K}_h$ (0.3, 0.4, 0.5, 0.6, 0.7).

Inequality (Eq. D.5-5) implies that such a procedure will approximate the correct ϕ with a maximum error of less than about 5%. For flat plates and for nontracking collectors of low concentration (e.g., CPC), the R parameter ranges from about -0.1 to 0.8, and the fitting procedures yielded

$$\phi = \exp\left[-X + (0.337 - 1.76\ \bar{K}_h + 0.55\ R)X^2\right] \qquad \text{(D.5-6a)}$$

$$\text{for } 0.3 \lesssim \bar{K}_h \lesssim 0.5 \text{ and } 0 \lesssim \times\ 1.2 \quad ;$$

and

$$\phi = 1 - X + (0.50 - 0.67\ \bar{K}_h + 0.25\ R)X^2 \qquad \text{(D.5-6b)}$$

$$\text{for } 0.5 \lesssim \bar{K}_h \lesssim 0.75 \text{ and } 0 \lesssim X \lesssim 1.2 \quad .$$

The standard deviation between these fits and ϕ of Eq. D.4-18 is approximately 0.01 for $1 \gtrsim \phi \gtrsim 0.7$ and 0.02 for $0.7 \gtrsim \phi \gtrsim 0.4$. For the flat plate by itself a slightly closer fit could be derived, but we do not consider the improvement significant in view of all the approximations involved in this approach; hence, we lumped flat plates and nontracking concentrators together.

For tracking concentrators of high concentration ($C \gtrsim 10$) the R parameter lies in the range of 0.95 to 1.06. The corresponding variation of ϕ with R turns out not to be sufficiently strong and systematic to justify keeping R as a parameter for this case. We derived separate fits for east-west axis tracking, polar axis tracking, and two-axis tracking but found insignificant gain in accuracy over a single fit for all collectors of high concentration:

$$\phi = 1 - (0.049 + 1.44\ \bar{K}_h)\ X + 0.341\ \bar{K}_h\ X^2 \qquad \text{(D.5-6c)}$$

$$\text{for } 0.3 \lesssim \bar{K}_h 0.75 \lesssim \text{ and } 0 \leq X \lesssim 1.2 \quad .$$

For exceptionally clear climates, i.e., $\bar{K}_h \gtrsim 0.75$, a single straight line fit

$$\phi = 1 - X \text{ for } \bar{K} \gtrsim 0.75 \qquad \text{(D.5-6d)}$$

is recommended for all collector types.

Since the radiation correlations used in this paper treat the diffuse and the hemispherical radiation as independent components and since these correlations were optimized for accuracy during the central hours of the day, relatively large errors may occur for the beam component near sunrise and sunset. For extremely cloudy days, they may result in the prediction of periods of negative beam insolation. As a consequence of such manifestly unphysical contributions, Eq. D.2-14 for $\bar{H}_{coll}$ may underpredict the radiation availability, while Eq. D.4-18 for ϕ has a built-in cutoff $f_x(t)$ which compensates for this error by yielding ϕ values slightly larger than 1.0 at X = 0. We did indeed find ϕ (X = 0) = 1.03 for $\bar{K}_h$ = 0.3, and ϕ (X = 0) = 1.01 for $\bar{K}_h$ = 0.4. For $\bar{K}_h \gtrsim 0.5$, this effect amounted only to a small fraction of a percent. This apparent inconsistency illustrates our comment about the difference between the validity of the basic method and the inaccuracy of specific correlations that are derived from limited data. We could correct for this effect by multiplying $\bar{H}_{coll}$ of Eq. D.2-14 by ϕ (X = 0) as calculated from Eq. D.4-18, but we decided to neglect this effect because of the poor statistics of the data base currently available for $\bar{K}_h \lesssim 0.4$.

D.6 CUTOFF TIME t_c

The model has been constructed for explicit input of cutoff time t_c in order to permit greater flexibility and applicability in situations with any shading configuration. The cutoff time is limited by optical constraints and may be further reduced by thermal considerations for thermal collectors.

The highest possible value of the cutoff hour angle ω_c is the sunset hour angle ω_s for a completely unshaded collector. For fixed collectors ω_c also has to be less than ω'_s, defined by

$$\cos \omega'_s = -\tan \delta \tan(\lambda - \beta) \quad , \qquad \text{(D.6-1)}$$

except in the unlikely case of a collector that can operate on diffuse radiation alone. In collector arrays some shading between adjacent rows will usually occur close to sunrise and sunset, and ω_c has to be calculated from the trigonometry of the collector array. This is straightforward for an array with continuous collector rows, for example, with long horizontal parabolic troughs. For arrays with rows of separate collector units (e.g., parabolic dishes) the analysis of shading is more complicated. In either case a good, albeit slightly optimistic, approximation is obtained by setting t_c equal to the time at which half of the collector aperture is shaded.

For nontracking concentrators of the CPC type, the optical cutoff time depends on the acceptance half angle θ_c of the collector. If a trough-like CPC with east-west axis is mounted at tilt β = latitude λ, ω_c is given by

$$\cos \omega_c = \frac{\tan |\delta|}{\tan \theta_c} \quad . \tag{D.6-2}$$

For CPCs with concentration $C \gtrsim 2$, the tilt generally differs from the latitude, with tilt adjustments during the year, and ω_c is given by

$$\cos \omega_c = \frac{\tan \delta}{\tan (\lambda - \beta + \theta_c \delta/|\delta|)} \quad . \tag{D.6-3}$$

Note that for a CPC with tilt adjustments, it should always be verified that the sun at noon is within the acceptance angle.

For most thermal collectors the cutoff time will be smaller than $t_{c,max}$ because for times t close to $t_{c,\,max}$ the insolation may not suffice to overcome the heat losses. $t_{c,th}$ is defined as the time at which the heat loss equals the solar irradiance on a clear day. To find a procedure for calculation of the daily heat delivery $\bar{Q}$, even if $t_{c,th}$ is not known explicitly, we plot in Fig. D-2 the typical variation of $\bar{Q}$ with t_c. The solid line shows $\bar{Q}_{exact}$ as obtained by means of the expression (Eq. D.4-18) for ϕ_{exact}. During times $t_{c,th} < t < t_{c,max}$ the insolation is below the critical level even on clear days, and the lower limit $f_x(t)$ of the fractional time integration in Eq. D.4-18 is equal to 1. Hence, time intervals beyond $t_{c,th}$ contribute nothing to $\bar{Q}_{exact}$, and the graph of $\bar{Q}_{exact}$ versus t_c is flat for $t_c > t_{c,th}$. Of course, for $t_c < t_{c,th}$, periods of useful energy collection are missed and $\bar{Q}_{exact}(t_c)$ is smaller than $\bar{Q}_{exact}(t_{c,th})$.

The dotted line in Fig. D-2 shows $\tilde{Q}$, the energy delivery calculated by means of the incorrect utilizability $\tilde{\phi}$ of Eq. D.5-1. $\tilde{Q}$ increases with t_c up to a maximum near $t_c = t_{c,th}$ and then decreases. The decrease at large t_c occurs because $\tilde{\phi}$ averages the utilizability over the entire day and contains no mechanism for excluding periods near the end of the day when the insolation is below the critical level. Inequality (Eq.D.5-5) implies that values for $\tilde{Q}(t_c)$ and $\bar{Q}_{exact}(t_c)$ differ by less than 10% for any reasonable circumstances and that $\tilde{Q}$ is less than $\bar{Q}_{exact}$.

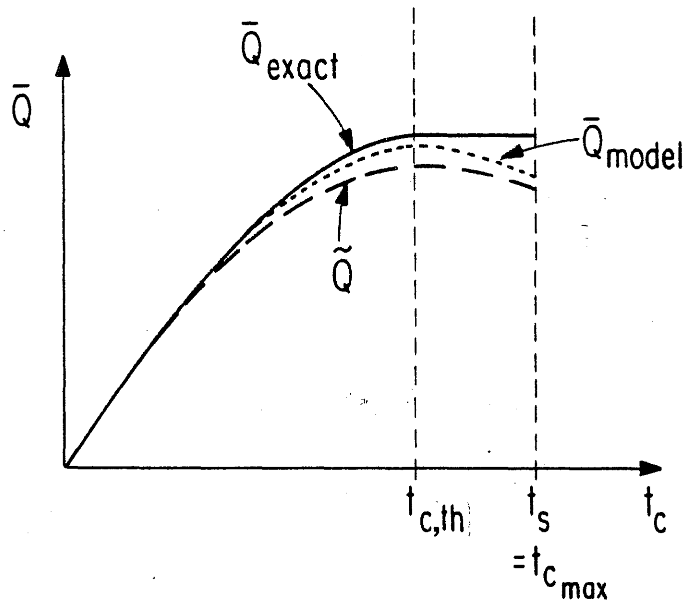

Figure D-2. Typical Variation of Heat Delivery $\bar{Q}$ with Cutoff Time t_c for Different Methods of Calculation

The utilizability of our model, ϕ_{model}, given by Eq. D.5-6, is based on the functional form of $\tilde{\phi}$ but fitted to the exact expression ϕ_{exact} of Eq. D.6-17. Therefore, the energy delivery $\bar{Q}_{model}(t_c)$ predicted by our model also has a maximum near $t_c = t_{c,th}$, and it is closer to $\bar{Q}_{exact}$ than $\tilde{Q}$, as shown by the dashed line in Fig. D-2. In order to select the best value of t_c, i.e., the one most likely to yield the closest approximation to $\bar{Q}_{exact}$, we note that a smaller t_c implies a larger ϕ and this, in turn, implies better agreement between ϕ_{model} and ϕ_{exact}. Therefore, t_c should be chosen to be as small as possible without causing any loss of usable insolation. This is the case for $t_c \simeq t_{c,th}$. The thermal cutoff time $t_{c,th}$ could be calculated explicitly from the radiation correlations underlying the present model; however, we are primarily interested in $\bar{Q}$, not in t_c, and the precise value of t_c does not matter since $\bar{Q}_{model}(t_c)$ has a broad maximum. Therefore, we recommend the following convenient iteration procedure for determining the best value of t_c:

- Start with $t_c = t_{c,1} = t_{c,max}$ = maximum permitted by optics, as discussed above; for example, $t_{c,1} = t_s$ for flat-plate or tracking collectors if there is no shading. For the CPC, $t_{c,1}$ is given by Eqs. D.6-2 or D.6-3.
- Calculate corresponding output $\bar{Q}_1$.
- Decrease t_c by Δt_c to get new $t_{c2} = t_{c1} - \Delta t_c$. ($\Delta t_c$ = 0.5 h will give sufficient accuracy in most cases.)
- Calculate output $\bar{Q}_2$ for $t_{c,2}$ and repeat procedure until maximal $\bar{Q}$ is found.

The smaller the heat loss, the closer the optimal t_c will be to $t_{c,max}$. This is illustrated by the sample calculations in Tables D-3 and D-4 of Collares-Pereira and Rabl (1978).

D.7 ACCURACY OF MODEL

Long-term performance models cannot be validated by comparison with short-term data. The variability of the weather from year to year is so large that prediction and data for a particular period (e.g., April 1980) may differ by over 50%. However, such short-term discrepancies are irrelevant provided the long-term average (e.g., average over all Aprils, 1980 to 2000) is predicted correctly. "Long term," in this context, means many years, preferably more than 10.

Comparison with measured long-term collector performance is desirable but impossible at the present time. First of all, no such data are available for a sufficiently long period. Secondly, the measured collector output would introduce all the uncertainties due to poorly known collector properties; what, for example, is the long-term average effect of dirt on the optical efficiency of the collector?

It is therefore more to the point to compare the model with insolation data. We have used the data base described by Collares-Pereira and Rabl (1978) because it provides measurements of hemispherical and beam radiation. With only five stations and only 1 to 4 years at each, this is certainly not a representative long-term data base as demanded above, but it was the best we were able to obtain.

From these data we calculated $\bar{H}_h$ for each month and used this value as input for our model. The model prediction $\bar{Q}_{model}$ for various collector types was then compared with the result $\bar{Q}_{data}$ obtained by summing the appropriate hourly contributions read from the weather tapes. Table D-8 lists the most important results of this evaluation, expressed as deviation

$$\varepsilon = \frac{\bar{Q}_{model} - \bar{Q}_{data}}{\bar{Q}_{data}} \quad . \tag{D.7-1}$$

Apart from tracking mode and concentration, only one collector parameter is relevant for this comparison: the ratio $\bar{q}_{loss}/(\bar{\eta}_o A)$ of long-term average heat loss (in W/m^2) and optical efficiency, for which we have chosen 0, 150, and 300 W/m^2 as typical values spanning all cases of interest. For zero heat loss, $\bar{Q}$ equals $\bar{H}_{coll}$, the radiation available to the collector; for this case the comparison between model and data is shown in more detail in Fig. D-4(a) and D-4(b) of Collares-Pereira and Rabl (1978), including the test for absence of seasonal bias.

Table D-8 indicates that $\bar{\bar{H}}_{coll}$ is predicted correctly within a few percent. For thermal collectors, the magnitude of the errors increases somewhat with heat loss to an average of about -5% at the large heat loss of $\bar{q}_{loss}/(\bar{\eta}_o A)$ = 300 W/m^2. We note a general trend toward negative errors for thermal collectors, especially at high heat loss. The fact that our model is conservative and tends to underpredict is to be expected because of the smoothing assumptions made in Section D.8. The statistics in Table D-8 are not equally significant for each location; Livermore and Raleigh, for example, had less than a year's worth of reliable data.

Table D-8. COMPARISON BETWEEN MODEL AND DATA: DEVIATION $\varepsilon = (\bar{Q}_{model} - \bar{Q}_{data})/\bar{Q}_{data}$ in PERCENT AVERAGED FOR EACH LOCATION

Location \ $\bar{q}_{loss}/A\bar{\eta}_o$ (W/m^2)	Flat Plate			Two-Axis Tracker (high concentration)		
	0	150	300	0	150	300
Albuquerque	-1.2	-1.7	-2.8	0.5	-3.4	-8.0
Fort Hood	-2.5	-5.2	-9.3	-1.1	-3.1	-4.1
Livermore	-0.9	-1.1	-1.1	-3.1	-5.9	-8.6
Maynard	1.2	-4.0	-7.3	2.6	0.7	0.8
Raleigh	-1.6	-2.9	-5.2	0.3	-0.1	0.4
Average error all locations	-1.4	-2.9	-5.0	0.5	-2.4	-4.7
Standard deviation	2.4	3.9	6.5	9.2	11.8	15.3

As a measure of the scatter of predicted values about the mean, we include, as the last line in Table D-3, the standard deviation (rms error), also in percent. The standard deviation increases with heat loss and with concentration ratio and is in the range of 5% to 15%.

There are different sources of error for different collector types. A flat plate, for example, is relatively insensitive to the ratio of diffuse over hemispherical radiation, but it will often be operated at high heat loss where the inherent errors of the utilizability curve dominate. For concentrating collectors, on the other hand, the prediction of $\bar{H}_{coll}$ is less certain, but the heat losses will usually be lower. The low heat loss coefficient of collectors that are suitable for high temperature operation also implies that the average operating temperature need not be known exactly. The need for methods of the f-Chart type that account for effects of finite storage is greatest for flat-plate collectors. Flat plates and CPCs are susceptible to nonuniformities in the angular distribution of diffuse sky radiation (although the resulting error appears to be only a few percent), whereas collectors of high concentration see essentially only the beam component and, therefore, their performance predictions are unaffected by anisotropy of the diffuse radiation. Thus, it seems that long-term performance predictions can be equally reliable for most collector types. From the available evidence we conclude that our model is reliable, but we recommend further validation and, if necessary, recalibration when a much larger insolation data base (pyranometer plus pyrheliometer) becomes available.

Further refinements may also be needed to account for spectral effects in photovoltaic converters. For collectors with wavelength cutoff, the radiation correlations should be recalibrated with respect to the relevant portion of the solar spectrum, another task for which data are insufficient at the present time.

D.8 SPECIFICATION OF INSTANTANEOUS EFFICIENCY

The instantaneous collector efficiency (Tabor 1978; Hill and Streed 1976; Simon 1976) serves as basis of the performance calculation and must be specified in a clear and unambiguous manner. In this section the most important characteristics are briefly reviewed.

D.8.1 Specification of Insolation

Traditionally the efficiency of flat-plate collectors has been defined with respect to hemispherical (also called global or total) irradiance I_h, and the efficiency of collectors with high concentration has been defined with respect to beam (also called direct) irradiance I_b; this is the basic assumption of this appendix. For the intermediate case of concentrators with low concentration, no clear consensus has yet emerged. Within the framework of this appendix, it is most convenient to base the efficiency of such collectors on radiation within the acceptance angle. If the efficiency data are not presented in this form, correction factors must be applied. Fortunately the conversion from one insolation base to another is straightforward and involves only a multiplicative factor. To find this factor, we add subscripts to the efficiency. If q_{out} is the collector output (in watts) relative to net collector aperture area A, then the efficiency with respect to hemispherical irradiance I_h (pyranometer) is

$$\eta_h = \frac{q_{out}}{A\ I_h} \quad , \tag{D.8-1}$$

while the efficiency with respect to beam irradiance I_b (pyrheliometer) is

$$\eta_b = \frac{q_{out}}{A\ I_b} \quad . \tag{D.8-2}$$

The conversion from one to the other is therefore

$$\eta_b = \eta_h \frac{I_h}{I_b} = \eta_h \left(1 + \frac{I_d}{I_b}\right) \quad , \tag{D.8-3}$$

where $I_d = I_h - I_b$ is the diffuse component. Since efficiency measurements should always be done under clear sky, the ratio I_d/I_b of diffuse over beam is about 0.1 to 0.15. This means that the efficiency curve of a collector is at least 10% higher when stated in terms of beam radiation rather than in terms of hemispherical radiation.

For collectors with low concentration $1 < C \lesssim 10$ (e.g., CPC and V-trough), the efficiency relative to the irradiance

$$I_c = I_b + \frac{1}{C}\, I_d \tag{D.8-4}$$

within the acceptance angle is

$$\eta_c = \frac{q_{out}}{A\ I_c} \quad . \tag{D.8-5}$$

The conversion factor from η_h to η_c is given by

$$\eta_c = \eta_h \frac{I_b + I_d}{I_h + I_d/C} \quad ; \tag{D.8-6}$$

and the conversion from η_c to η_b is

$$\eta_c = \eta_b \frac{1}{1 + I_d/CI_b} \quad . \tag{D.8-7}$$

D.8.2 Reference Temperature

Several collector temperatures can serve as references for stating efficiency; the most useful are:

T_r = average collector receiver surface temperature,
T_{in} = fluid inlet temperature,
T_{out} = fluid outlet temperature, and
$T_f = (T_{in} + T_{out})/2$ = average fluid temperature.

To a very good approximation, only the difference between the collector temperature and the ambient temperature T_a matters. The heat loss coefficient or U value (in W/m^2 C) is defined relative to collector aperture area A as

$$U = \frac{q_\ell}{A(T_r - T_a)} \quad , \tag{D.8-8}$$

where q_ℓ is the heat loss (in watts). Strictly speaking, U is not constant but its dependence on temperature, wind, and other environmental factors is fairly weak, and a good approximation is obtained by using an average U value corresponding to the anticipated operating temperature. For a better approximation, we recommend Tabor's parameterization (Tabor 1978)

$$q_\ell = AU_o \left(T_r - T_a\right)^p \quad , \tag{D.8-9}$$

where p is a collector-dependent coefficient, typically in the range of 1.1 to 1.3 for nonevacuated collectors and somewhat larger for evacuated collectors.

In terms of U, the instantaneous collector efficiency reads

$$\eta = \eta_o - U\left(T_r - T_a\right)/I \tag{D.8-10}$$

if the average receiver surface temperature T_r is given. η_o is the optical efficiency or efficiency at zero heat loss; it has also been called $\tau\alpha$ product in the flat-plate literature.

Usually it is more practical to measure the fluid temperature than the receiver surface temperature. In terms of the average fluid temperature T_f the efficiency is

$$\eta = F'[\eta_o - U(T_f - T_a)/I] \quad , \qquad (D.8\text{-}11)$$

where F' is the heat extraction factor [called collector efficiency factor by Duffie and Beckman (1978) and Kreith and Kreider (1978)] given by the ratio of the thermal conductance U_{fa} from fluid to ambient temperature over the thermal conductance from receiver surface to ambient temperature:

$$F' = \frac{U_{fa}}{U} \quad . \qquad (D.8\text{-}12)$$

(In Eq. D.8-12 both U values must refer to aperture area.) If the fluid inlet temperature T_{in} is specified, the efficiency is

$$\eta = F_R [\eta_o - U(T_{in} - T_a)/I] \quad , \qquad (D.8\text{-}13)$$

with the heat removal factor (Grether et al. 1974)

$$F_R = \frac{\dot{m}c_p}{UA}\left[1 - \exp\left(-\frac{UAF'}{\dot{m}c_p}\right)\right] \quad . \qquad (D.8\text{-}14)$$

The mass flow rate through the collector (kg/s) is $\dot{m}$, and C_p is the fluid heat capacitance (J/kg C) at constant pressure. Finally, the dependence of efficiency on fluid outlet temperature T_{out} is given by a modification (deWinter 1976) of Eq. D.8-13:

$$\eta = \frac{F_R}{1 - F_R UA/\dot{m}c_p} [\eta_o - U(T_{out} - T_a)/I] \quad . \qquad (D.8\text{-}15)$$

Any of the four expressions for efficiency, Eqs. D.8-10, D.8-11, D.8-13, or D.8-15, can be used as starting points for the calculation of long-term average performance.

D.9 INSOLATION $\bar{H}_{coll}$ REACHING COLLECTOR APERTURE WITHIN ITS ACCEPTANCE ANGLE

The long-term average daily total irradiation incident on the collector within its acceptance angle is obtained from the daily hemispherical insolation $\bar{H}_h$ on a horizontal surface by means of the formula

$$\bar{H}_{coll} = R_h\bar{H}_h - R_d\bar{H}_d \quad . \qquad (D.9\text{-}1)$$

For the energy actually absorbed per aperture area A of the collector, $\bar{H}_{coll}$ is multiplied by the average optical efficiency $\bar{\eta}_o$:

$$(\bar{Q}_{abs}/A) = \bar{\eta}_o \bar{H}_{coll} \quad . \tag{D.9-2}$$

The functions R_h and R_d are given in Tables D-1 to D-5, and $\bar{H}_d/\bar{H}_h$ is the long-term average ratio of diffuse over hemispherical irradiation on a horizontal surface. This ratio is correlated (Collares-Pereira and Rabl 1978) with the clearness index $\bar{K}_h$ and sunset hour angle ω_s by

$$\frac{\bar{H}_d}{\bar{H}_h} = 0.775 + 0.347\left(\omega_s - \frac{\pi}{2}\right) - \left[0.505 + 0.261\left(\omega_s - \frac{\pi}{2}\right)\right]\cos\left[2(\bar{K}_h - 0.9)\right] \quad . \tag{D.9-3}$$

For nonconcentrating collectors, the ω_s dependence may be neglected by setting $\omega_s = \frac{2}{\pi}$ in this equation; this curve is shown by the solid line in Fig. D-3 (the dotted lines show Eq. D.9-2 at $\omega_s = \frac{2}{\pi} - 0.2$ and $\omega_s = \frac{2}{\pi} + 0.2$). The clearness index $\bar{K}_h$ is the long-term average ratio of daily total hemispherical insolation on a horizontal surface over H_o = extraterrestrial insolation = insolation that would have reached the same surface in the absence of any atmosphere:

$$\bar{K}_h = \bar{H}_h/\bar{H}_o \quad . \tag{D.9-4}$$

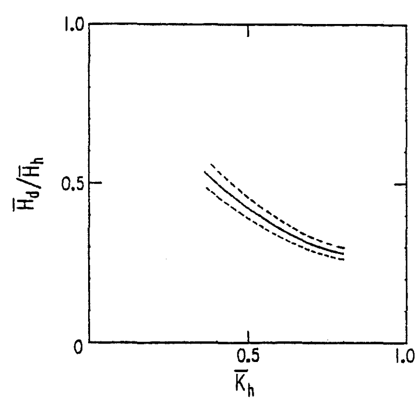

Figure D-3. $\bar{H}_d/\bar{H}_h$ vs. $\bar{K}_h$ (Eq. D.2-3).
The solid line corresponds to $\omega_s = \omega/2$ and the dashed lines correspond to $\omega_s = \frac{\pi}{2} - 0.2$ (bottom) and $\omega_s = \frac{\pi}{2} + 0.2$ (top)

R_h and R_d depend on collector type, collector orientation, latitude, and collector turn-on and turn-off times. We evaluated these functions for the following collector types, all with zero azimuth:

- Table D-1 -- nonconcentrating collector with fixed aperture; e.g., flat-plate collector with tilt β, latitude λ;
- Table D-2 -- concentrators with fixed aperture; e.g., compound parabolic concentrator (CPC) with tilt β, latitude λ;
- Table D-3 -- one-axis tracker of concentration C, tracking about east-west horizontal axis;
- Table D-4 -- one-axis tracker of concentration C, tracking about north-south axis of tilt:
  - tilt β = latitude λ (polar mount),
  - tilt $\beta \neq$ latitude λ; and
- Table D-5 -- two-axis tracker of concentration C.

Provided internal shading effects are included in the long-term average optical efficiency $\bar{\eta}_o$, Table D-2 applies also to high concentration systems with fixed reflectors and tracking receivers, such as the hemispherical reflector (Duffie and Beckman 1974; Kreith and Kreider 1978) and the segmented cylindrical reflector developed by General Atomic.

Tables D-3 and D-4 hold for both reflective (mirror) and refractive (lens) concentrators if the aperture moves as a single unit; included is almost any reasonable solar concentrator with trough or dish reflector or with Fresnel lens. This is in contrast to Fresnel reflector systems; e.g., the power tower (Duffie and Beckman 1974; Kreith and Kreider 1978), whose aperture consists of reflector segments that follow the sun individually. For this latter case, use of Tables D-3 through D-5 is not quite correct. If more accurate formulas are needed for Fresnel reflectors, they can be derived by the method described in Sections D.2 through D.7. For linear Fresnel reflectors with east-west axes, linear interpolation between the results obtained from Tables D-2 and D-3 should be adequate.

The remainder of this section describes in detail the terms that appear in the equations in Tables D-1 through D-5. We find it convenient to express all times t in dimensionless form as hour angle ω from solar noon:

$$\omega = \frac{2\pi t}{T}, \text{ with } T = \text{length of day} = 24 \text{ h} \quad . \qquad \text{(D.9-5)}$$

Note that throughout this appendix all angles are in radians, except for a few cases where degrees are indicated. The sunset hour angle

$$\omega_s = \frac{2\pi t_s}{T} \quad ,$$

corresponding to sunset hour t_s, is given by

$$\cos \omega_s = -\tan \lambda \tan \delta \quad , \tag{D.9-6}$$

where λ = geographic latitude and δ = solar declination. The quantities a, b, and d in the tables are functions of ω_s:

$$a = 0.409 + 0.5016 \sin(\omega_s - 1.047), \tag{D.9-7a}$$

$$b = 0.6609 - 0.4767 \sin(\omega_s - 1.047), \tag{D.9-7b}$$

and

$$d = \sin \omega_s - \omega_s \cos \omega_s \quad . \tag{D.9-7c}$$

(Note that 1.047 radians = 60°.) In the equations for a flat plate and a CPC, there is also the quantity ω'_s, given by

$$\cos \omega'_s = -\tan(\lambda - \beta) \tan \delta \quad . \tag{D.9-8}$$

The reflectance ρ of the ground in front of a flat-plate collector is also needed for Table D-1. Recommended values (Duffie and Beckman 1974; Kreith and Kreider 1978) are $\rho = 0.7$ with snow and $\rho = 0.2$ without snow (in the absence of better information).

One further variable remains to be explained, the collector cutoff time t_c, or, equivalently, the cutoff angle

$$\omega_c = \frac{2\pi t_c}{T} \quad . \tag{D.9-9}$$

If the collector is placed due south, i.e., with zero azimuth, and if its time constant is short, it will operate symmetrically around solar noon, being turned on at

$$\text{turn-on time } t_{c-} = -t_c \tag{D.9-10a}$$

and turned off at

$$\text{turn-off time } t_{c+} = t_c \quad . \tag{D.9-10b}$$

This has been assumed for all collectors with zero azimuth.

The model has been written for explicit input of cutoff time t_c in order to permit greater flexibility and applicability in situtations with any shading configuration. The cutoff time is limited by optical constraints and may be further reduced by thermal considerations for thermal collectors. The procedure of finding t_c for thermal collectors is described in Section D.10.

The highest possible value of ω_c is the sunset hour angle ω_s for a completely unshaded collector. For fixed collectors ω_c also has to be less than ω'_s of Eq. D.9-8, except in the unlikely case of a collector that can operate on diffuse radiation alone. In collector arrays some shading between adjacent rows will usually occur close to sunrise and sunset, and ω_c has to be calculated from the trigonometry of the collector array. This is straightforward for an array with continuous collector rows, for example, with long horizontal parabolic troughs. For arrays with rows of separate collector units, such as parabolic dishes, the analysis of shading is more complicated. In either case a good, albeit slightly optimistic, approximation is obtained by setting t_c equal to the time at which half of the collector aperture is shaded.

For nontracking concentrators of the CPC type (Rabl 1976; Winston 1974) the optical cutoff time depends on the acceptance half-angle θ_c of the collector. If a trough-like CPC with east-west axis is mounted at tilt β = latitude λ, ω_c is given by

$$\cos \omega_c = \frac{\tan |\delta|}{\tan \theta_c} \quad . \tag{D.9-11}$$

For CPCs with concentration $C \gtrsim 2$, the tilt will generally differ from the latitude, with tilt adjustments during the year, and ω_c is given by

$$\cos \omega_c = \frac{\tan \delta}{\tan(\lambda - \beta + \theta_c \delta/|\delta|)} \quad . \tag{D.9-12}$$

Note that for a CPC with tilt adjustments it should always be verified that the sun at noon is within the acceptance angle.

D.10 HEAT LOSS, UTILIZABILITY, AND CUTOFF TIME

If all days and hours were identical, $\bar{Q}$ could be obtained by simply subtracting the total daily heat loss

$$\bar{Q}_{loss}/A = 2\, t_c\, U(\bar{T}_{coll} - \bar{T}_{amb}) \tag{D.10-1a}$$

from the absorbed solar energy $\bar{\eta}_o\, \bar{H}_{coll}$. $\bar{T}_{coll}$ is the operating temperature of the collector (absorber surface or fluid temperature, depending on choice of temperature base in Section D.8). Since the heat loss from transport lines between collector and storage or point of use occurs at the same time as the loss from the collector, i.e., only when the circulating pump is turned on, the equation for $\bar{Q}_{loss}$ should include the loss from the transport lines, q_{line} (which depends, of course, on the installation):

$$\bar{Q}_{loss} = 2t_c[AU(\bar{T}_{coll} - \bar{T}_{amb}) + q_{line}] \quad . \tag{D.10-1b}$$

Due to the variability of the weather, the true energy gain can be significantly higher. This feature can be illustrated by the following two artificial climates. Climate 1 has identical days, all uniformly overcast, while Climate 2 has clear days half of the time and no sunshine for the rest; both climates have the same long-term average insolation $\bar{H}$. If the heat loss of a collector equals the peak insolation of Climate 1, no useful energy can be collected. In Climate 2, however, the same collector can collect some useful energy on the clear days.

It is convenient to calculate this effect once and for all for any concentrator type and any climate and to summarize the result in terms of the utilizability function ϕ. ϕ depends on the critical intensity ratio

$$X = \frac{(\bar{Q}_{loss}/A)}{\bar{\eta}_o \bar{H}_{coll}} \tag{D.10-2}$$

and is defined in such a way that the long-term average collected energy $\bar{Q}$ per aperture area A is

$$\bar{Q}/A = F \phi \bar{\eta}_o \bar{H}_{coll} , \tag{D.10-3}$$

where F is the heat extraction or heat removal efficiency factor. F depends on the type of operating temperature that has been specified and is given by

$$F = \begin{cases} 1 & \text{for average receiver surface temperature } T_r, \\ F' & \text{of Eq. D.1-13 for average fluid temperature } T_f, \\ F_R & \text{of Eq. D.1-15 for fluid inlet temperature } T_{in}, \\ F_R/[1 - F_R UA/\dot{m}C_p] & \text{of Eq. D.1-16} \\ & \text{for fluid outlet temperature } T_{out}. \end{cases}$$

The calculation up to and including ϕ is the same regardless of which temperature base (T_{in}, T_{out}, T_f, or T_r) is used to specify the instantaneous efficiency. Only at the last step is the temperature base accounted for by inserting the appropriate factor F in Eq. D.10-2 for $\bar{Q}$.

In principle, ϕ is a complicated function of many variables, but fortunately the dependence on most of these variables is rather weak. From a large number of numerical simulations it has been shown that ϕ can be approximated within a few percent by a function of only three variables: the clearness index $\bar{K}_h$, the ratio

$$R = \frac{R_d}{R_h} , \tag{D.10-5}$$

and the critical intensity ratio X of Eq. D.10-2.

For nontracking collectors, ϕ is given by the parametric expressions

$$\phi = \exp\left[- X + (0.337 - 1.76\ \bar{K}_h + 0.55\ R)X^2\right] \quad \text{for } 0.3 \lesssim \bar{K}_h \lesssim 0.5 \text{ and } 0 \lesssim X \lesssim 1.2 \tag{D.10-6a}$$

and

$$\phi = 1 - X + \left(0.50 - 0.67\ \bar{K}_h + 0.25\ R\right)X^2 \quad \text{for } 0.5 \lesssim \bar{K}_h \lesssim 0.75 \text{ and } 0 \lesssim X \lesssim 1.2\ . \tag{D.10-6b}$$

For tracking collectors of high concentration ($C \gtrsim 10$), the R dependence can be neglected and the fit

$$\phi = 1 - \left(0.049 + 1.44\ \bar{K}_h\right)X + 0.341\ \bar{K}_h\ X^2 \tag{D.10-6c}$$

can be used for all values of $\bar{K}_h \lesssim 0.75$ and for $0 \lesssim X \lesssim 1.2$. For exceptionally clear climates, i.e., with $\bar{K} \gtrsim 0.75$, the simple expression

$$\phi = 1 - X \quad \text{for } \bar{K}_h \gtrsim 0.75 \tag{D.10-6d}$$

should be used for all collector types.

The fits were derived with emphasis on accuracy at reasonably large values of ϕ because collectors with low utilizability will not collect enough energy to be economical. The above expressions for ϕ are reliable whenever ϕ is larger than approximately 0.4. At smaller values of ϕ, the above fits are not recommended (nor is a collector likely to be practical if its heat loss is so large as to imply $\phi \lesssim 0.4$). Since the above fits may increase with X at very large X, they must not be used outside the specified range of X values.

The values of R will range from about −0.1 to 0.8 for nontracking collectors and from 0.95 to 1.05 for collectors with high concentration. For tracking collectors with significant acceptance of diffuse radiation (i.e., $C \lesssim 10$), R may fall between 0.8 and 1.0. For such a configuration, we recommend linear interpolation in R between the R = 0.8 value of Eqs. D.10-6a or 6b and Eq. D.10-6c, with the assumption that the latter equation corresponds to R = 1.0. (This is not very accurate because the variation of ϕ with R in this range is not uniform for all $\bar{K}_h$. Tracking thermal collectors of very low concentration, however, appear to have little practical interest.)

D.11 NOMENCLATURE

We use the symbols I for irradiance (or instantaneous insolation in W/m^2) and H for irradiation (or daily total insolation in J/m^2), together with subscripts b for beam (also called direct), d for diffuse, and h for hemispherical (also called global or total). To minimize use of subscripts, we refer all insolation values to horizontal surface except for $\bar{H}_{coll}$ and I_{coll}. Bars indicate long-term average. Note that beam is defined with respect to the 2.8° acceptance half angle of the pyrheliometer and not with respect to the solar disc; thus "it" includes the circumsolar component (Grether et al. 1974).

A	net aperture area of collector
C	geometric (or area) concentration
F	factor to account for heat extraction or removal efficiency
H_o	extraterrestrial irradiation on horizontal surface (daily total)
$\bar{H}_{coll}$	irradiation incident on collector aperture (daily total)
$\bar{H}_d$	diffuse irradiation on horizontal aperture (daily total)
$\bar{H}_h$	hemispherical irradiation on horizontal surface (daily total)
I_o	solar constant = 1353 W/m^2
I_b	beam irradiance on horizontal surface (measured by pryheliometer)
I_{coll}	irradiance on collector aperture within acceptance angle
I_d	diffuse irradiance on horizontal surface
I_h	hemispherical irradiance on horizontal surface (measured by pyranometer)
$\bar{K}_h$	$\bar{H}_h/H_o$ = long-term average clearness index (called $\bar{K}_T$ in some references)
q_{out}	instantaneous collector output (W)
q_{loss}	$AU(T_{coll} - T_{amb})$ = instantaneous collector heat loss (W)
$\bar{Q}$	long-term average energy delivered by collector (J)
$\bar{Q}_{loss}$	long-term average heat loss of collector (J)
R_d, R_h	functions to convert horizontal irradiation to irradiation on collector aperture

R	R_d/R_h
t	time of day from solar noon (p.m. is positive)
t_c	collector cutoff time (if $-t_{c-} = t_{c+}$)
t_{c-}	collector turn-on time (hours before noon)
t_{c+}	collector turn-off time (hours after noon)
t_s	sunset time
T	length of day = 24 hours = 86,400 seconds
T_a	ambient temperature
T_f	$(T_{in} + T_{out})/2$ = average fluid temperature
T_{in}	inlet fluid temperature
T_{out}	outlet fluid temperature
T_r	average receiver surface temperature
U	U value (W/m^2 C)
β	collector tilt from horizontal surface (positive towards equator)
δ	solar declination
λ	geographic latitude
η_o	optical efficiency (also called $\alpha\tau$ product in the flat-plate literature) = fraction of insolation absorbed by absorber = efficiency if receiver at ambient temperature, i.e., no heat loss
$\bar{\eta}_o$	long-term average optical efficiency
θ	incidence angle of sun on horizontal surface
θ_c	acceptance half angle of compound parabolic concentrator (CPC)
θ_{coll}	incidence angle of sun on collector aperture
ϕ	collector azimuth from due south, relative to horizontal plane (west is positive, east is negative)
ϕ	utilizability
ω	$2\pi t/T$ = hour angle
ω_s	$2\pi t_s/T = \arccos(-\tan\lambda \tan\delta)$ = sunset hour angle
ω_s'	$2\pi t_s'/T = \arccos[-\tan\delta \tan(\lambda - \beta)]$

D.12 REFERENCES

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APPENDIX E

ECONOMIC ANALYSIS AND SELECTION PROGRAM (ECONMAT)

E.1 ECONOMIC ANALYSIS

The required revenue methodology presented in Section 4.0 permits separation of the life-cycle cost analysis of a solar system from assumptions regarding fuel costs and fuel cost escalation. Solar systems in a given location can thus be modeled and evaluated under any chosen set of economic parameters; and this set of conditions can be changed without affecting the performance and capital cost output of PROSYS/ECONMAT. In order to perform sensitivity studies and applications rankings under a baseline economic scenario, however, an economic analysis was devised for the program ECONMAT. This economic analysis was used early in the end-use matching program, for it fully accounts for system, location, and baseline economic parameters in order to calculate solar energy costs and hence provide applications rankings. In the present form of ECONMAT, the economic analysis is overridden and the only output is energy capacity cost, which is used to compare capital cost-effectiveness of systems. The chosen multiplier can then be applied to the capacity cost in order to yield a solar energy cost that can be compared to a chosen fuel price. By not overriding the economic analysis, a net present value of the solar system (assuming no storage, full-capacity backup system, and fuel savings only) is calculated. This net present value can be used as a measure of economic viability under baseline or user-defined economic assumptions. Net present value also facilitates sensitivity studies, as described in Section 5.0.

Although industrial management utilizes a variety of criteria in evaluating alternative investment proposals (such as the payback period, judgmental analysis, or some forms of risk analysis under uncertainty), the most standard means of consistent and realistic analysis of capital-intensive investments is the evaluation of internal rate of return or net present value. The form of this analysis can be outlined and nominal values for certain parameters can be assigned. (The nominal values selected may be later changed without affecting the form of analysis.) The analysis described in this appendix is based on the assumptions made by Dickinson and Freeman of Lawrence Livermore Laboratories (1977). The equations in the Dickinson analysis have been modified to calculate the net present value of the solar system rather than an equivalent rate of return.

The output of the performance analysis for a given process, site, system, and collector contains (or references) the following information:

- expected annual energy per unit collector area delivered to the load at the required temperature: Q_{del};
- installed collector equipment cost per unit area: C_{AC};

- installed cost of the balance of the system as a function of collector field area: C_{sys}; and
- costs of alternative fuels at the site based on net deliverable energy to the customer: P_f.

Several other important parameters might also be included in the economic analysis, such as operation, maintenance, property tax, and insurance (OMPI) costs; local land costs; and tax rates. In the present case, Q_{del}, C_{AC}, C_{sys}, P_f are of primary importance. Average values are assumed for other parameters.

No storage is provided in the solar IPH systems considered in this analysis. Therefore, each solar system requires a full-capacity backup system (e.g., a conventional fossil- or electrically fueled system) for which fixed and variable costs will be incurred. As a result, the solar system makes an impact on the operating costs of the industry only insofar as it saves on the outlays for fuel not burned. The solar system is a fuel saver, and its return to the company is in the form of fuel bill savings. This form of analysis is a severe test of solar economic feasibility.

We assume that the industrialist is faced with two alternative investment strategies. On the one hand, he may elect to continue to pay annual operating charges for a conventional process heat system, so that the stream of annual outlays (after taxes) is as shown in Fig. E-1. Alternatively, the industrialist may elect to add a solar IPH system (of any given size), which will reduce annual outlays for fuel (but not for other annual costs such as maintenance or debt service on the conventional system) and correspondingly add outlays for solar system investment debt service, operation, maintenance, or other costs. The cash flow for this alternative is shown in Fig. E-2. The decision to install a solar system will be sound on a life-cycle cost basis if the net present value of this alternative is at least as great as the net present value of the first alternative (no solar system). A cash flow shown in Fig. E-3 represents the net benefit of Alternative II (the net cash flow of Alternative II minus the net cash flow of Alternative I) in each year of operation. In this way, the operating, maintenance, and debt service charges for the conventional process heat system cancel. The resultant after-tax cash flow for Alternative II shows savings due to fuel-bill reduction and additional depreciation and costs due to the additional outlays for operation and maintenance and for an investment at the beginning of year 1. Note that we assume one year for construction. The investment outlay I is made at the beginning of year 0. Interest during construction (at 9%) brings the effective net investment, after taxes, at the beginning of year 1 to

$$I' = 1.09\ I - TC \times I - 0.9\tau\ I \quad . \qquad \text{(E-1)}$$

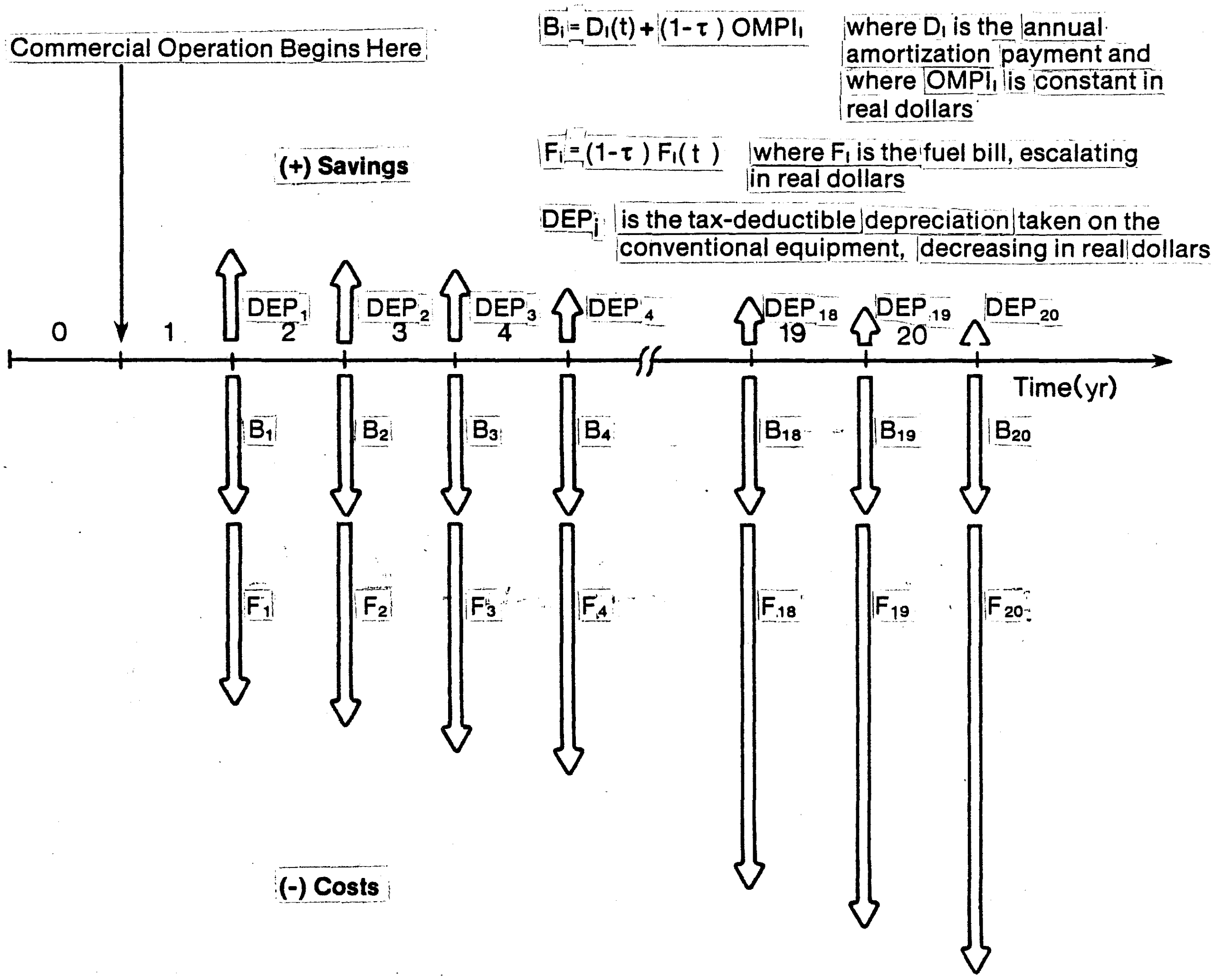
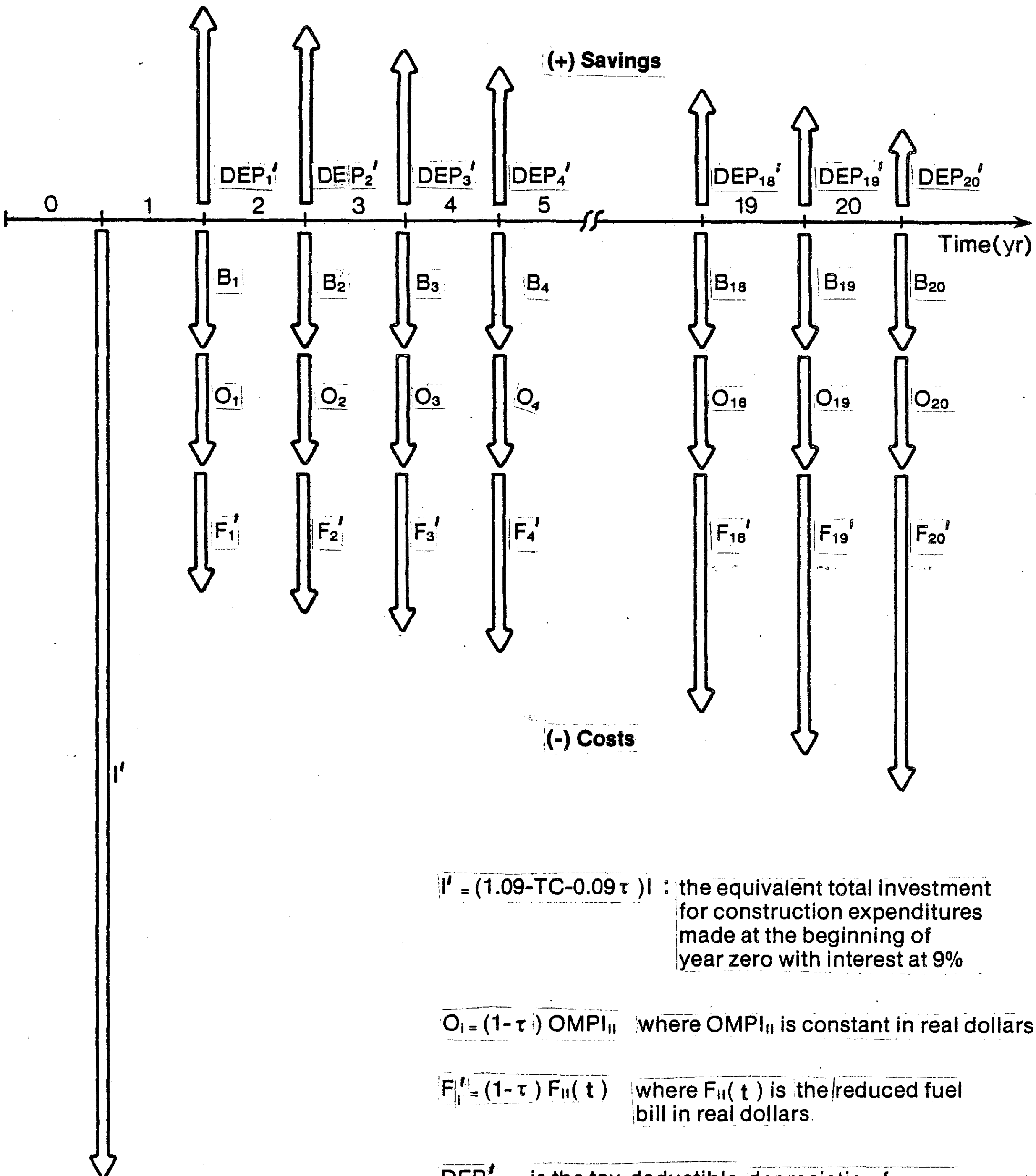


Figure E-1. Year-End, After-Tax Cash Flow for a Fossil-Fueled Conventional IPH System: Alternative I

Note: Lengths of arrows are not to scale.



$I' = (1.09\text{-}TC\text{-}0.09\tau)I$: the equivalent total investment for construction expenditures made at the beginning of year zero with interest at 9%

$O_i = (1-\tau)\,OMPI_{II}$ where $OMPI_{II}$ is constant in real dollars

$F_i' = (1-\tau)\,F_{II}(t)$ where $F_{II}(t)$ is the reduced fuel bill in real dollars

DEP_i' is the tax-deductible depreciation for the hybrid system

Figure E-2. Year-End, After-Tax Cash Flow for a Solar-Supplemented Hybrid IPH System: Alternative II

Note: Lengths of arrows are not to scale.

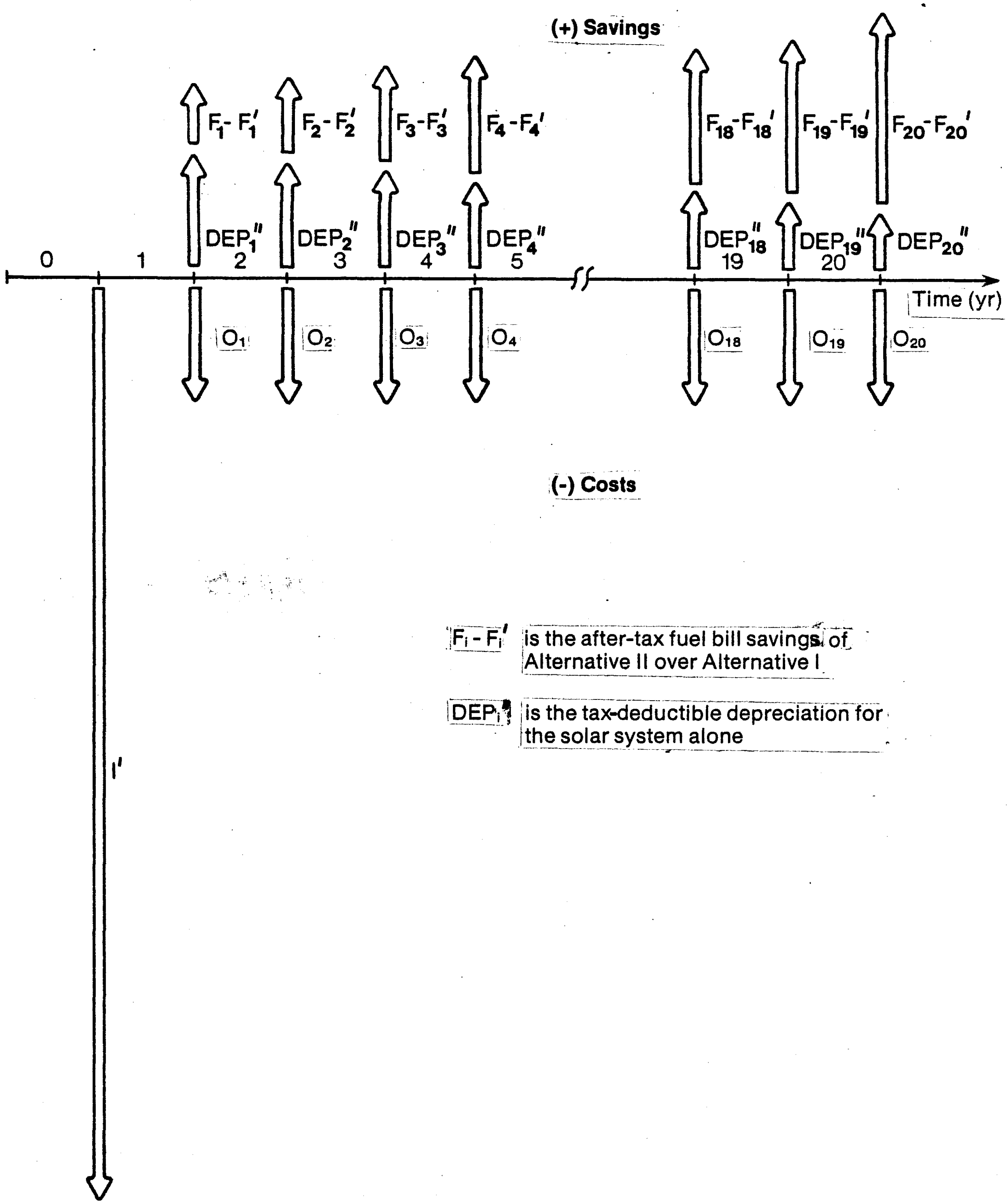


Figure E-3. Year-End, After-Tax Cash Flow Showing the Net Benefit of Alternative II over Alternative I

Note: Lengths of arrows are not to scale.

All cash flows are represented in constant dollars. No salvage value for either system is assumed.

The investment in a solar IPH system (Alternative II) will be sound if the present value of the benefit stream is greater than zero. The cash flow represented in Fig. E-3 can be collapsed into a single present value using standard compound interest formulas under the following assumptions:

- General inflation occurs at an annual rate of g.
- A real escalation in the cost of conventional fossil fuel occurs at an annual rate of e.
- Straight-line depreciation over lifetime N is used.
- Operation, maintenance, property tax, and insurance (OMPI) costs for the solar system will be a constant real fraction B of initial investment.
- Industry will require a real after-tax rate of return R on investment.

The present value PV of the stream can be calculated as

$$PV = (1 - \tau)Q_{del}P_fA_c \sum_{j=1}^{N} \left(\frac{1 + e}{1 + R}\right)^j + \tau \frac{I}{N} \sum_{j=1}^{N} \left(\frac{1 - g}{1 + R}\right)^j$$

$$- (1 - \tau)BI \sum_{D=1}^{N} \left(\frac{1}{1 + R}\right)^j - I' \quad . \qquad \text{(E-2)}$$

Each summation in Eq. E-2 may be replaced by an equivalent closed-form expression, such that

$$PV = (1 - \tau)Q_{del}P_fA_c\left(\frac{1 + e}{R - e}\right)\left[1 - \left(\frac{1 + e}{1 + R}\right)^N\right] + \tau \frac{I}{N} \left(\frac{1 - g}{1 + g}\right)\left[1 - \left(\frac{1 - g}{1 + R}\right)^N\right]$$

$$- (1 - \tau)BI \frac{1}{R}\left[1 - \left(\frac{1}{1 + R}\right)^N\right] - I' \quad . \qquad \text{(E-3)}$$

Simplifying and consolidating terms and substituting Eq. E-1 gives

$$PV = I\left((TC + 0.09\tau - 1.09) + (\tau - 1)BE_1 + \frac{\tau}{N} E_0\right) + (1 - \tau)Q_{del}P_fA_cE_2 \quad , \qquad \text{(E-4)}$$

where

$$I = C_{AC}A_c + C_{sys}(A_c) \quad ,$$

A_c = collector area (m^2 or ft^2) ,

$$E_0 = \left(\frac{1-g}{R+g}\right)\left[1-\left(\frac{1-g}{1+R}\right)^N\right] ,$$

$$E_1 = \frac{(1-g)^N - 1}{R(1+R)^N} ,$$

$$E_2 = \left(\frac{1+e}{R-e}\right)\left[1-\left(\frac{1+e}{1+R}\right)^N\right] .$$

The solar IPH system investment can be evaluated with respect to the fraction of the annual average energy requirement supplied by solar energy. Fractional displacements from 10% to 100% in 10% increments are evaluated. The required collector area used in the present value formula is

$$A_c = \frac{\text{annual process heat load}}{Q_{del}} . \qquad \text{(E-5)}$$

Whether a break-even solar collector field exists will depend on the nature of the change in unit system costs as the required collector field size varies.

Present value analysis allows a few interesting observations to be made about the effects of system size on economic viability. For example, if system costs are subject to economies of scale, applications may be found in which the system is uneconomical at small capacities but economical beyond a certain threshold capacity. The following example illustrates this effect.

Consider the present value function, Eq. E-4, with the following nominal parameter values:

τ = composite tax rate = 0.50,

e = real fuel escalation rate = 0.05,

R = required after-tax market rate of return = 0.15,

N = lifetime = 20 yr,

B = OMPI annual fraction of I = 0.02,

g = inflation rate = 0.05,

TC = tax credit = 0.20.

Equation E-3 then becomes

$$PV = 6.48\ Q_{del}A_c(P_f) - 0.065\ I - 0.80\ I + 0.12\ I$$

$$= 6.48\ Q_{del}A_c(P_f) - 0.745\ I . \qquad \text{(E-6)}$$

If solar system costs were constant with respect to collector field size--for example, $\$350/m^2$--then I is equal to 350 A_c and

$$PV = 102.64\ A_c - 260.75\ A_c \quad ,$$

where

$$Q_{del} = 5.28\ GJ/m^2 \quad ,$$
$$(P_f) = 3.00\ \$/GJ \quad .$$

Obviously, this expression is always negative and reaches zero only for an effective fuel cost, such that

$$PV = 0 = 6.48\ Q_{del}A_c(P_f) - 0.745\ I$$

and hence

$$P_f = \frac{0.745\ I}{6.48\ Q_{del}A_c} = \frac{(0.745)(350)}{(6.48)(5.28)} = 7.62\ \$/GJ \quad ,$$

where solar system costs are a constant $\$350/m^2$.

Consider, however, a reduction in solar system costs per unit area with increase in size. If costs decrease uniformly according to the equation

$$\frac{I_s}{A_c} = 500 - 50 \log A_c \tag{E-7}$$

(shown graphically in Fig. E-4), then Eq. E-6 becomes

$$PV = 6.48\ Q_{del}A_c(P_f) - (0.745)[500\ A_c - 50\ A_c \log A_c]$$

$$= [6.48\ Q_{del}(P_f) - 372.50 + 37.25 \log A_c]A_c \quad . \tag{E-8}$$

From a plot of this function for $Q_{del} = 5.28\ GJ/m^2$ and $(P_f) = \$8.00/GJ$ (see Fig. E-5), one obtains

$$PV = A_c[37.25 \log A_c - 98.78] \quad . \tag{E-9}$$

Hence, the break-even or threshold size for such a system is approximately 450 m^2.

System costs may not decrease as radically or as continuously as suggested by the functional relationship shown in Fig. E-5. However, this example illustrates the usefulness of present value analysis in studying the effects of

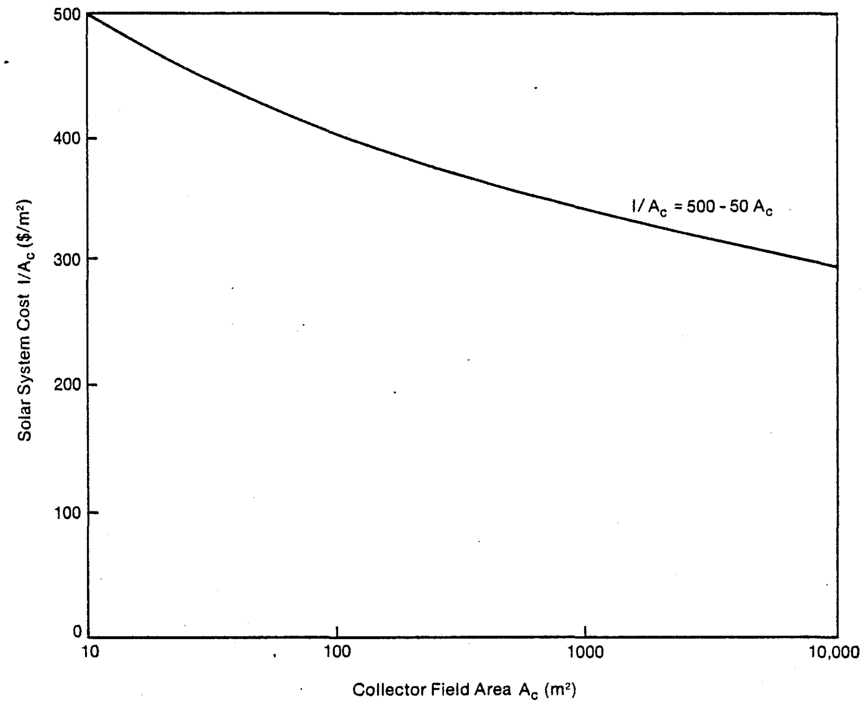


Figure E-4. Possible Scenario for Economies of Scale in Solar IPH System Cost

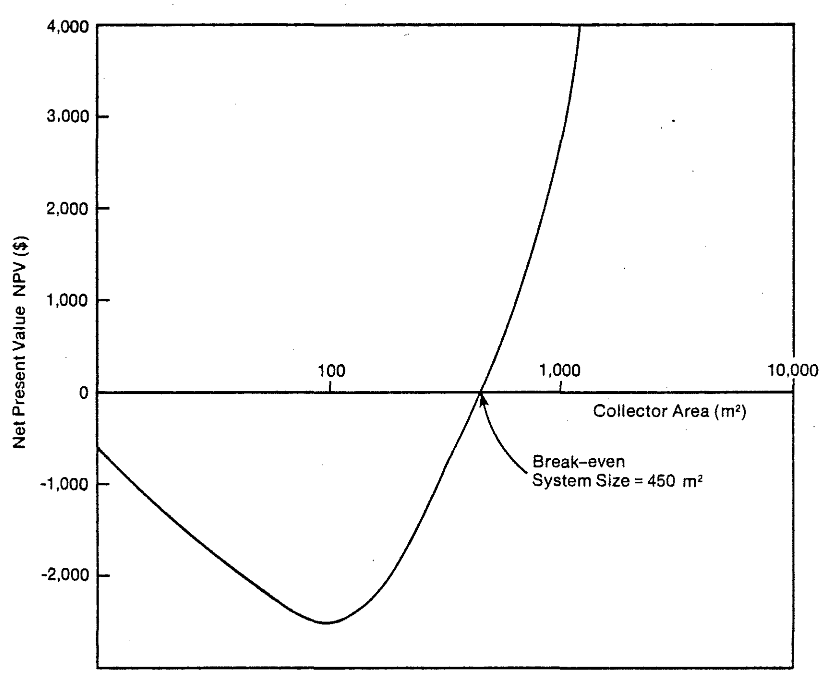


Figure E-5. Effect of Collector Field Area (System Size) on Net Present Value

system economies of scale. In the same manner, present value analysis and the use of ECONMAT allow many useful studies to be made of solar IPH economics with full interaction among costs, economic factors, and fuel price scenarios.

E.2 COMPUTER PROGRAM DESCRIPTION (ECONMAT)

The ECONMAT computer program provides the economic analysis used in conjunction with the performance model PROSYS. Local fuel costs and labor rates are obtained from the data base ECONDAT and collector costs are obtained from COLDAT. Performance results from the PROSYS execution are communicated to ECONMAT through the performance data base PERFDAT. The annual process load and the annual deliverable energy per unit area of collector are obtained from PERFDAT for each process/system/collector combination. Costs and net present values are computed for each combination for increments of annual deliverable energy.

E.2.1 Program Logic

The basic logic structure of ECONMAT is shown in Fig. E-6. Economic parameters are initialized to preset values unless modified by user inputs. These parameters and default values are discussed in Table E-1. Costs per unit area for all collectors specified in COLDAT are read and stored. Fuel prices and labor rates for a selected site are accessed from ECONDAT.

A series of three nested loops is entered. The outermost loop is the process loop, the middle loop is the system/collector loop, and the innermost loop is the incremental energy output loop. Information read from PERFDAT for each process includes process identification, required temperature, heat rate, steam flow rate, and estimated standard annual energy use. The deliverable annual energy per unit area for each system/collector entry is accessed from PERFDAT, and the incremental energy output loop is entered. The collector areas required to meet varying energy output levels are calculated. In addition, the resultant collector cost, system cost, total cost, net present value, and cost per unit of heat energy are calculated for each energy level.

Results are printed in the economic report.

E.2.2 Input

Normally ECONMAT is used with PROSYS to analyze all industrial processes at a selected site. In this mode all required information is contained on PERFDAT, ECONDAT, and COLDAT or is preset within the program, and no user input is required. However, the user may want to redefine certain economic parameters in special circumstances, such as case studies or sensitivity analyses. The new

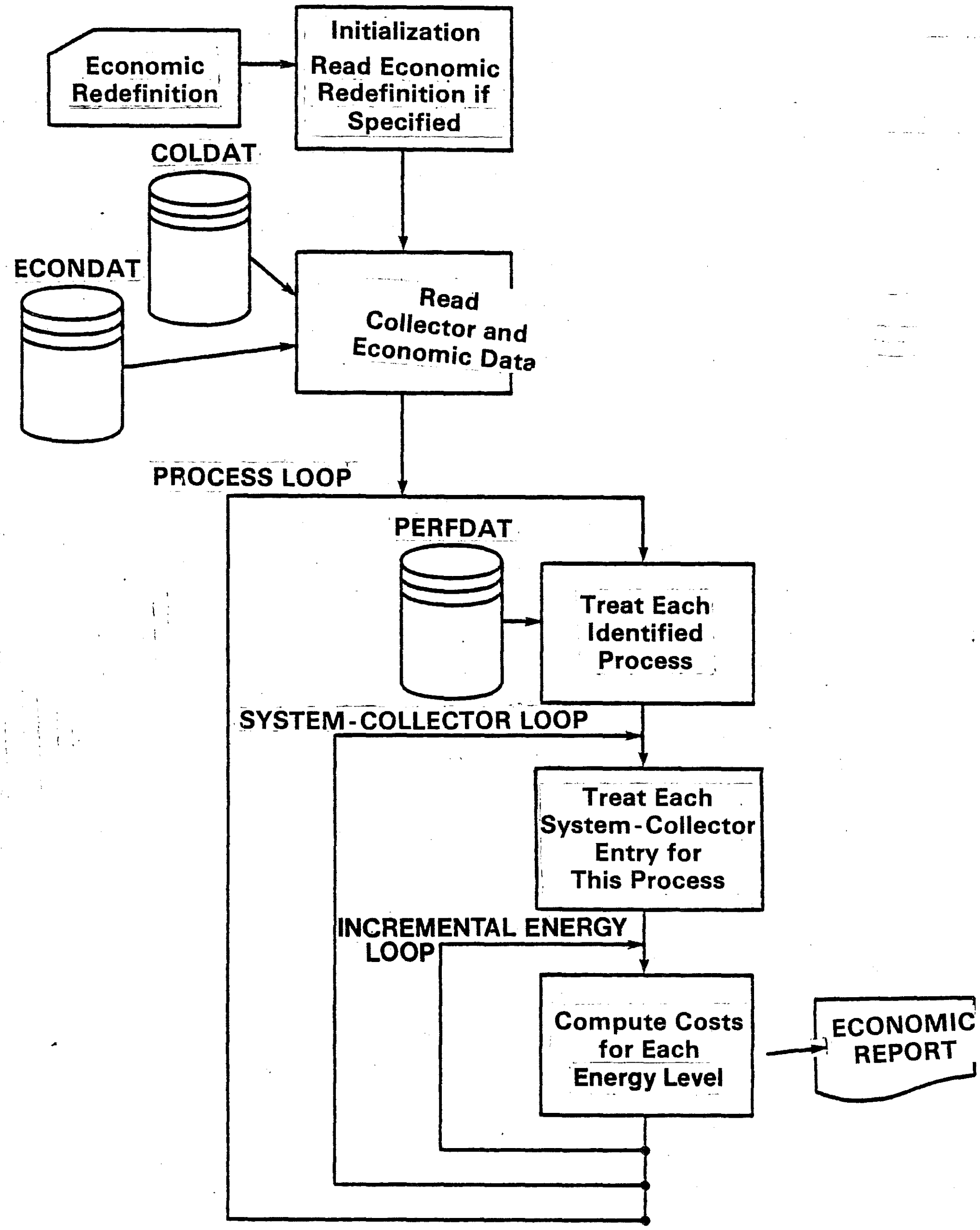


Figure E-6. ECONMAT Logic Flow Diagram

Table E-1. ECONOMIC PARAMETERS

Label	Description/Comments
ROR	Internal rate of return: 0.05
GIR	General inflation rate: 0.06
FERG	Fuel escalation rate, natural gas: 0.05
FERE	Fuel escalation rate, electricity: 0.05
FERO	Fuel escalation rate, oil: 0.05
FERC	Fuel escalation rate, coal: 0.05
TAXR	Tax rate: 0.50
TAXCR	Tax credit: 0.10
OMPI	Operation, maintenance, property tax, and insurance cost; fraction of total cost: 0.02
CONI	Interest rate during construction: 0.09
NYR	System lifetime in years: 20
NFUEL	Fuel type:
1	Natural gas
2	Electric
3	Oil
4	Coal
	(Normally given in PERFDAT as defined in the process data base IPHDB)
FPRICE	Fuel price ($/MBtu) (Normally given in ECONDAT)
SHDLSS	Fraction of deliverable energy lost because of collector shading in large array configurations; applied to tracking concentrators only; assumed to be zero unless otherwise specified

values are read through the name list ECONDEF, and any of the parameters shown in Table E-1 may be specified. If they are not redefined, the nominal default values shown in parentheses will be retained. A sample input is shown in Fig. E-7.

```
$ECODEF
NFUEL = 2,
FPRICE = 6.00,
$END
```

Figure E-7. Sample Economic Redefinition Input for ECONMAT

E.2.3 Output

The ECONMAT output is a printed economic report. The values of all economic parameters are listed. The backup fuel and its respective cost are identified for each process. The delivered energy, required collector area, collector cost, system cost, total cost, cost per unit area, cost per unit heat energy, capital cost of energy capacity, and net present value for each energy level are then printed for each system/collector combination. A sample output is shown in Fig. E-8. The ECONMAT output quickly shows which system/collector combinations are most cost-effective for a specific process.

E.2.4 Additional Uses

In addition to its application in end-use matching analysis, ECONMAT is a valuable tool in case studies and sensitivity analyses. Detailed information regarding fuel cost, system lifetime, tax rate, etc., can be specified for individual case studies, yielding an accurate economic picture. Additional runs can be made to compare results due to changes in fuel cost or to estimate the impact of a fuel change.

The performance sensitivity analysis outlined in Section 3.4 can be extended to include cost factors by running ECONMAT in conjunction with the specified PROSYS runs. For example, in addition to the performance efficiency of a number of collectors over a range of temperatures, cost per unit energy can be compared. A sample plot of cost in $/GJ (or $/MBtu) versus temperature for a number of collectors is shown in Fig. E-9.

ECONMAT analysis can also be useful in determining cost goals. A number of ECONMAT runs can be made using the same PROSYS-generated PERFDAT file as input

DENVER CO

LEATHER PROCESSING BACKUP FUEL IS NAT GAS AT 1.73 $/GJ (1.83 $/MBTU)

		ANNUAL DELIVERED ENERGY INCREMENTS									
	Q DEL MBTU	3170.0	6340.0	9510.0	12680.0	15850.0	19020.0	22190.0	25360.0	28530.0	31700.0
	Q DEL GJ	3343.7	6687.4	10031.1	13374.9	16718.6	20062.3	23406.0	26749.7	30093.4	33437.2
	COL. SQM	1355.8	2711.6	4067.4	5423.2	6779.0	8134.8	9490.6	10846.4	12202.2	13558.0
3111	COL. SQFT	14593.8	29187.5	43781.3	58375.1	72968.8	87562.6	102156.4	116750.1	131343.9	145937.7
LEATHER PROCESSING	COL. COST	269308.	538615.	807923.	1077230.	1346538.	1615845.	1885153.	2154461.	2423768.	2693076.
HA-DIRECT	SYS. COST	38706.	76303.	113718.	151039.	188300.	225518.	262703.	299862.	337001.	374122.
FLAT PLATE E	TOT. COST	308013.	614918.	921641.	1228270.	1534838.	1841363.	2147856.	2454323.	2760769.	3067197.
	COST/SQM	227.18	226.77	226.59	226.48	226.41	226.36	226.31	226.28	226.25	226.23
	COST/SQFT	21.11	21.07	21.05	21.04	21.03	21.03	21.03	21.02	21.02	21.02
	C$/GJ/YR	92.12	91.95	91.88	91.83	91.80	91.78	91.77	91.75	91.74	91.73
	C$/MBTU/YR	97.17	96.99	96.91	96.87	96.84	96.81	96.79	96.78	96.77	96.76
	COL. SQM	766.5	1533.0	2299.5	3066.1	3832.6	4599.1	5365.6	6132.1	6898.6	7665.1
3111	COL. SQFT	8250.7	16501.4	24752.1	33002.8	41253.5	49504.2	57754.9	66005.6	74256.3	82507.0
LEATHER PROCESSING	COL. COST	166495.	332990.	499485.	665980.	832475.	998970.	1165464.	1331959.	1498454.	1664949.
HW-DIRECT	SYS. COST	120772.	170797.	209183.	241544.	270054.	295830.	319533.	341595.	362316.	381915.
FLAT PLATE B	TOT. COST	287267.	503787.	708668.	907524.	1102529.	1294799.	1484997.	1673554.	1860770.	2046864.
	COST/SQM	374.77	328.62	308.18	295.99	287.67	281.53	276.76	272.92	269.73	267.04
	COST/SQFT	34.82	30.53	28.63	27.50	26.73	26.16	25.71	25.35	25.06	24.81
	C$/GJ/YR	85.91	75.33	70.65	67.85	65.95	64.54	63.45	62.56	61.83	61.22
	C$/MBTU/YR	90.62	79.46	74.52	71.57	69.56	68.08	66.92	65.99	65.22	64.57
	COL. SQM	826.4	1652.9	2479.3	3305.7	4132.2	4958.6	5785.1	6611.5	7437.9	8264.4
3111	COL. SQFT	8895.7	17791.4	26687.1	35582.8	44478.5	53374.2	62269.9	71165.6	80061.3	88957.0
LEATHER PROCESSING	COL. COST	272167.	544335.	816502.	1088670.	1360837.	1633005.	1905172.	2177340.	2449507.	2721675.
STEAM-GEN	SYS. COST	78518.	93506.	108493.	123481.	138468.	153456.	168443.	183431.	198418.	213406.
PARABOLIC TROUGH D	TOT. COST	350686.	637841.	924996.	1212151.	1499306.	1786461.	2073616.	2360770.	2647925.	2935080.
	COST/SQM	424.33	385.90	373.09	366.68	362.84	360.27	358.44	357.07	356.00	355.15
	COST/SQFT	39.42	35.85	34.66	34.07	33.71	33.47	33.30	33.17	33.07	32.99
	C$/GJ/YR	104.88	95.38	92.21	90.63	89.68	89.05	88.59	88.25	87.99	87.78
	C$/MBTU/YR	110.63	100.61	97.27	95.60	94.59	93.93	93.45	93.09	92.81	92.59

Figure E-8. Sample ECONMAT Output

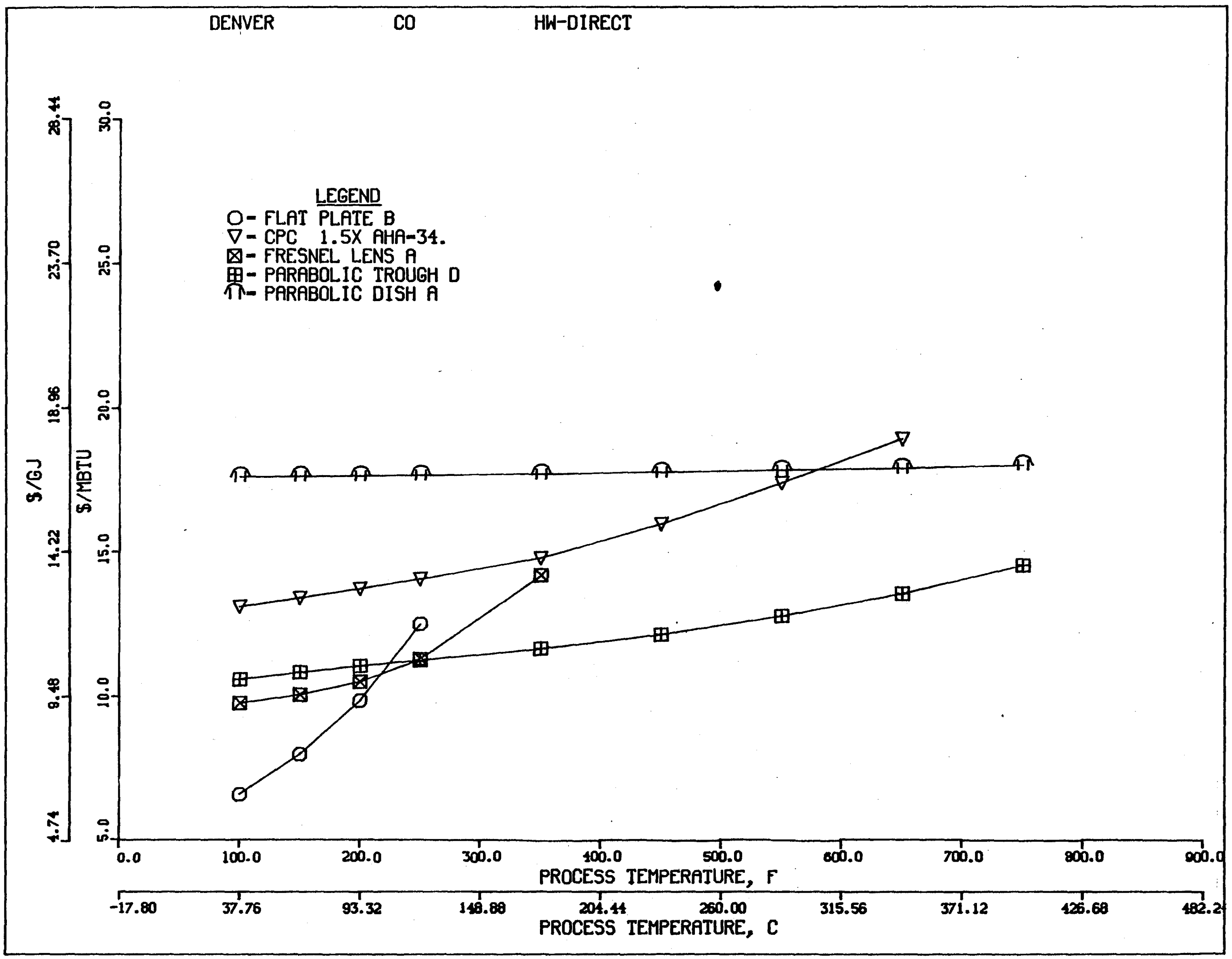


Figure E-9. $/GJ vs. Temperature for a Hot Water Heat Exchange System in Denver, Colo.

but varying the collector cost data in COLDAT for each run. This approach shows the collector costs required to produce the desired economic results.

The sensitivity of economic parameters can be investigated easily with ECONMAT. All other input files remain unchanged while the parameter of interest is changed in ECONDEF for multiple ECONMAT runs.

E.2.5 Restrictions

ECONMAT is not intended to provide an economic analysis that can stand alone; it can be used only in conjunction with PROSYS. The analysis is based on the assumption that no storage is available, and thus a full capacity backup system is required. The only solar system benefit under these conditions is fuel bill savings, due to the displacement of conventional fuel by solar energy. There is no capacity displacement credit.

The standard annual energy use or load for each process in the IPHDB is the average annual load for a typical plant. As there is no storage, the solar energy system can provide only that portion of the load occurring during the hours of sunlight. Therefore, in some cases the results for the higher energy increments (the maximum being the estimated standard annual energy use) are not realistic if a plant's operation schedule is longer than the period of daylight. In fact, the solar energy system without storage could never meet 100% of the load. Incremental energy levels were analyzed to show cost options at a number of increasing levels of energy supply, the largest of which approaches the industrial load demand of an average plant. The most valid interpretation of the ECONMAT results is in terms of cost for the amount of energy delivered by a location/process/system/collector combination at any chosen energy supply level.

PROSYS performance predictions used by ECONMAT are based on calculations for a single collector module and do not account for the effect of shading in large collector array configurations. Such shading can result in a 10% or more reduction in energy output of tracking concentrators (Collares-Pereira and Rabl 1978). Future expansions of PROSYS will include this factor. In the interim, to ensure an accurate economic measure, shading losses in large arrays may be taken into account through the ECONDEF user input parameter SHDLSS. A value may be assigned to SHDLSS that represents the fractional energy loss of tracking concentrators due to shading. If not specified, the shading loss is assumed to be zero.

E.3 REFERENCES

Dickinson, W. C.; Freeman, H. J. 1977. An Economic Methodology for Solar-Assisted Industrial Process Heat Systems: The Effect of Government Incentive. Livermore, CA: Lawrence Livermore Labs.; June 6; UCRL-52254.

APPENDIX F

ANALYSIS OF HEATING POLICY DURING NONOPERATING PERIODS

The case studies reveal an interesting problem in energy conservation: Is it more conservative of energy to heat or not to heat process units when the process is not operating? (The two options are referred to herein as "continued heating" and "interrupted heating.") In this appendix this problem is analyzed and it is shown that it is always more energy-conservative not to heat during nonoperating periods.

F.1 A BASIC ARGUMENT FOR INTERRUPTED HEATING

Basically the argument is this:

(1) When the process unit temperature is maintained during nonoperating periods, heat must be added to a process unit to make up for heat losses from the unit to the surroundings.

(2) The heat loss rate to the surroundings is related to the temperature difference between the unit and the surroundings. As a first approximation, it is directly proportional to this temperature difference. Thus, if heating is stopped and the unit is allowed to cool, the heat loss rate decreases as the temperature decreases.

(3) The total amount of heat that must be added to bring the unit back to the operating temperature after a complete shutdown equals the amount of heat lost during the shutdown and reheating periods. The amount of heat lost is the integral of the heat loss rate with respect to time. The heat loss rate in the interrupted heating case is always equal to or less than that in the continued heating case because the temperature is always the same as or lower than the temperature in the continued heating case. Therefore, the integral (the total energy to be added) is always less if heating is stopped during the nonoperating period.

There may be valid process reasons for keeping the unit at the operating temperature during down times, such as instabilities of chemical solutions or thermal stresses on the equipment. However, energy conservation is not a valid reason because less energy is required when the heat is shut off.

F.2 QUANTITATIVE ANALYSIS

The rate of heat loss from a process unit to the surroundings is given by

$$q = UA(T - T_S) \quad , \qquad \text{(F-1)}$$

where q is the rate of heat loss, UA is the overall conductance for heat transfer between the unit and the surroundings, T is the temperature of the unit, and T_s is the temperature of the surroundings. The conductance UA is assumed constant, but it may actually depend on temperature. Consideration of temperature-dependent mechanisms that affect UA--radiation, natural convection, and evaporation--results in increasing values of UA with increasing temperature. Thus, UA is expected to be lower at lower temperatures, thereby causing the rate of heat loss to be even less than that estimated by assuming UA constant at operating conditions. The temperature of the unit, T, is assumed to be uniform, but it may not be. The temperature at any point in the interrupted heating case, however, will always be equal to or less than the temperature in the continued heating case; thus the argument is quantitatively valid.

At the operating temperature T_o, the rate of heat loss q_o is

$$q_o = UA(T_o - T_s) \tag{F-2}$$

and the overall conductance is

$$UA = \frac{q_o}{(T_o - T_s)} \quad . \tag{F-3}$$

Thus UA may be determined from the temperatures of the unit and surroundings and from the heating rate required to keep the temperature constant at T_o during the operating period.

The rate of temperature change of the unit is given by

$$M_T \frac{dT}{dt} = q_H - q \quad , \tag{F-4}$$

where M_T is the thermal mass of the unit (the mass times the heat capacity, including latent heat effects), t is time, and q_H is the reheating rate (the capacity of the heater which must exceed the steady-state heating rate). The thermal mass can be calculated from the mass and heat properties of the unit.

When there is no heating, q_H equals 0. Substituting q from Eq. F-4 into Eq. F-1 and rearranging and integrating gives

$$\int_{T_o}^{T} \frac{dT}{(T - T_s)} = -\int_{t_1}^{t} \frac{UA}{M_T}\, dt \quad ,$$

where t_1 is the time at which process operation ends and the heat is shut off, t is a later time, and T is the temperature of the unit at time t. The integrated result is

$$\ln[(T - T_s)/(T_o - T_s)] = -\frac{UA}{M_T}(t - t_1) \quad . \tag{F-5}$$

Since UA and M_T can be determined, the temperature T after any time interval $(t - t_1)$ can be calculated. Solving for T with Eq. F-5 gives

$$T = T_s + \left(T_o - T_s\right) \exp\left(- \frac{UA}{M_T} \left(t - t_1\right)\right) \quad . \tag{F-6}$$

The rate of heat loss is found by substituting T from Eq. F-6 into Eq. F-1, which gives

$$q = UA\left(T_o - T_s\right) \exp\left(- \frac{UA}{M_T} \left(t - t_1\right)\right) \quad . \tag{F-7}$$

The total energy loss while the heat is off is

$$Q_{loss} = \int_{t_1}^{t_2} q\ dt = \int_{t_1}^{t_2} UA\left(T_o - T_s\right) \exp\left(- \frac{UA}{M_T} \left(t - t_1\right)\right) dt \quad ,$$

where t_2 is the time at which heating is resumed. Integration gives

$$Q_{loss} = M_T\left(T_o - T_s\right)\left[1 - \exp\left(- \frac{UA}{M_T} \left(t_2 - t_1\right)\right)\right] \quad .$$

Q_{loss} is also given by

$$Q_{loss} = M_T\left(T_o - T_2\right) \quad , \tag{F-8}$$

where T_2 is the temperature at the time heating is started again. Equating the two expressions for Q_{loss} and solving for T_2 yields

$$T_2 = T_o - \left(T_o - T_s\right)\left[1 - \exp\left(- \frac{UA}{M_T} \left(t_2 - t_1\right)\right)\right] \quad . \tag{F-9}$$

Equation F-4, for the reheating period when $q_H \neq 0$, integrates to

$$\left(T - T_s\right) - \frac{q_H}{UA}\left[1 - \exp\left(- \frac{UA}{M_T} \left(t - t_2\right)\right) - \left(T_2 - T_s\right) \exp\left(- \frac{UA}{M_T} \left(t - t_2\right)\right)\right] = 0 \quad .$$

At the time the operating temperature is reached, t equals t_o and T equals T_o. Solving for T_2 gives

$$T_2 = T_o \exp\left(-\frac{UA}{M_T}(t_2 - t_o)\right) + \left(T_s + \frac{q_H}{UA}\right)\left[1 - \exp\left(-\frac{UA}{M_T}(t_2 - t_o)\right)\right] . \quad \text{(F-10)}$$

Equating Eqs. F-9 and F-10 and solving for $(t_o - t_2)$ yields

$$(t_o - t_2) = -\frac{M_T}{UA} \ln\left\{1 + \frac{UA(T_o - T_s)}{q_H}\left[\exp\left(-\frac{UA}{M_T}(t_o - t_1)\right)^{-1}\right]\right\} . \quad \text{(F-11)}$$

When the terms on the right-hand side of Eq. F-11 are known, the time required to reheat the unit, $(t_o - t_2)$, can be calculated. With this value, T_2 can be calculated from Eq. F-9 and the heat lost during the off period can be calculated from Eq. F-8.

The amount of heat added during the reheat period, Q_H, in the interrupted heating case is

$$Q_H = q_H(t_o - t_2) . \quad \text{(F-12)}$$

The energy added if heating is continued rather than interrupted is

$$Q_{CH} = q_o(t_o - t_1) . \quad \text{(F-13)}$$

The energy saved by shutting off the heat is

$$Q_{CH} - Q_H = q_o(t_o - t_1) - q_H(t_o - t_2) . \quad \text{(F-14)}$$

The heat saved as a fraction of the total heat requirement of continuous heating is

$$F = \frac{q_o(t_o - t_1) - q_H(t_o - t_2)}{q_o(t_o - t_1 + t_p)} = \frac{(t_o - t_1)}{(t_o - t_1 + t_p)} - \frac{q_H(t_o - t_2)}{q_o(t_o - t_1 + t_p)} , \quad \text{(F-15)}$$

where t_p is the length of time the process operates continuously.

Equations F-11 and F-15 can be used to determine the energy-saving potential for equipment operated part-time, as illustrated in Section F.3.

F.3 APPLICATION OF ANALYSIS TO BRIGHT-DIP TANK

The data available for the bright-dip tank are:

- volume = 6.1 m^3;
- average heating rate = 0.19 MJ/h;

- operating temperature = 99 C (210 F) and temperature of surroundings = 21 C (70 F) (assumed);
- unknown heating capacity of the electric heaters assumed to be twice that of the average heating rate, or 0.38 MJ/h; and
- operating schedule of one shift per day (9 h), 5 days per week.

From this information the energy savings resulting from shutting off the heating when the process is not operating can be estimated.

Consider first one working day. The process operates for 9 h and is off for 15 h. If the end of the operating period is $t_1 = 0$, then the time when the process starts operating again is $t_o = 15$ h, and t_p is 9 h.

The thermal mass of the water in the tank is

$$M_T = 6.1\ m^3 \times 10^3\ kg/m^3 \times 4.183\ kJ/kg\ C = 25.5\ MJ/C \quad .$$

The tank actually contains an acid solution, but the properties of water are assumed. The mass of the tank walls is neglected. The rate of heat loss is

$$q_o = 0.19\ GJ/h \quad .$$

The assumed heating capacity is

$$q_H = 0.38\ GJ/h \quad .$$

The conductance between the tank and the surroundings at the operating conditions can be calculated from Eq. F-3:

$$UA = \frac{q_o}{(T_o - T_s)} = \frac{0.19\ GJ/h}{(99 - 21)C} = 2.4\ MJ/h\ C \quad .$$

These values are substituted into Eq. F-11 to give

$$\left(t_o - t_2\right) = - \frac{25.5\ MJ/C}{2.4\ MJ/h\ C} \ln\left\{1 + \frac{2.4(99 - 21)}{380} \times \left[\exp\left(- \frac{2.4}{25.5} \times 15\right) - 1\right]\right\} = 4.9\ h \quad .$$

Hence, we find $t_2 = 15 - 4.9 = 10.1$ h; i.e., heating must be started at full capacity 10.1 h after shutdown to bring the tank back to the operating temperature by the time the process is to resume operation. From Eq. F-9, the temperature to which the tank cools is

$$T_2 = 99 - (99 - 21)\left[1 - \exp\left(- \frac{2.4}{25.5}(10.1 - 1)\right)\right] = 51\ C \quad .$$

The energy saved as a fraction of the total energy input in a 24-hour period is

$$F = \frac{15}{24} - \frac{0.38}{0.19}\left(\frac{4.9}{24}\right) = 0.22, \text{ or } 22\% \quad .$$

The weekend situation may be examined in the same way. For this case (again with $t_1 = 0$), t_o equals 63 h and t_p is 0. The other values are the same as they were for one working day.

From Eq. F-11 we find

$$t_o - t_2 = -\frac{25.5}{2.4} \ln\left\{1 + \frac{2.4(78)}{380}\left[\exp\left(-\frac{2.4}{25.5} \times 63\right) - 1\right]\right\} = 7.1 \text{ h} \quad .$$

This gives $t_2 = 63 - 7.1 = 55.9$ h.

The fractional energy saved over the weekend is

$$F = 1 - \frac{0.38}{0.19}\left(\frac{7.1}{63}\right) = 0.77, \text{ or } 77\% \quad .$$

Consider now a full 168-hour week. From 8 a.m. Monday until 8 a.m. Friday, there are four 24-hour periods (96 hours) during which the energy saving is 22%. There is a 9-hour period from 8 a.m. Friday to 5 p.m. Friday in which the process operates and there is no saving. Then there is a 63-hour period from 5 p.m. Friday until 8 a.m. Monday during which the saving is 77%. Thus, for the entire week, the saving is

$$\frac{96}{168} \times 0.22 + \frac{9}{168} \times 0.00 + \frac{63}{168} \times 0.77 = 0.42, \text{ or } 42\% \quad .$$

APPENDIX G

WATER AND ENERGY BALANCES FOR COMMERCIAL LAUNDRY

The data, assumptions, and methods of determining water and energy balances for the commercial laundry case study are discussed and the results tabulated in this appendix.

G.1 THE DATA

The basic data for the laundry, obtained from the laundry management, engineering drawings, and the Public Service Company of Colorado, are the following:

(1) Monthly water use rates for May 1977 through April 1978.

(2) Monthly natural gas use rates for May 1977 through April 1978 for (a) the boiler and (b) a noninterruptible supply. The noninterruptible supply was primarily for the gas-fired driers but included an undetermined amount for space heat. There was no clear-cut seasonal trend in this gas usage, so it was assumed that all of this natural gas was used in the driers.

(3) Monthly electricity use rates and demand rates. No electricity was used for process heat, so this information was not used in the process heat study.

(4) Monthly weight of laundry processed, May 1977 through April 1978.

(5) Washing formulas, i.e., the number of steps in a wash cycle and the temperature and amount of water in each step for each of the several types of laundry.

(6) The temperatures at normal operating conditions of several streams as follows:

   (a) average temperature of the city water supplied: 16 C (60 F);

   (b) boiler-produced saturated steam: 174 C (345 F) at 858 kPa (125 psia);

   (c) condensate in condensate exchanger: 77 C (170 F);

   (d) cold water leaving condensate exchanger: 60 C (140 F);

   (e) effluent leaving effluent exchanger: 32 C (90 F);

   (f) effluent into effluent exchanger: about 49 C (120 F);

   (g) water leaving steam water heater: 52 C (180 F); and

   (h) maximum temperature of gas for gas-fired driers: 107 C (225 F).

(7) Water content of laundry entering driers: about 50% of total weight; and water content of laundry leaving driers, going to ironers: about 30% of total weight.

(8) Operating schedule. The laundry operated 5.5 days per week, one 8-hour shift per day, all year (280 working days per year). The boiler operated 10 h per day; it was turned on 2 h prior to startup to bring the steam and the equipment to operating temperature.

(9) Steam rates for the various equipment as obtained from the engineering drawings. For units added subsequently, the steam rates for equivalent equipment in the drawings were used. The rates were 25,000 kg/day (55,000 lb/day) for all the ironers and 6,000 kg/day (14,000 lb/day) for all the other equipment using steam. Several pieces of equipment (not including the ironers) used open steam; i.e., the steam escaped from the system.

(10) Condensates return: estimated to be 50% to 60% of the steam rate in reports to the laundry (Pritchard 1977; Garrett-Callahan Co. 1977-78).

(11) Heating value of the natural gas at the flow rate conditions of 31 MJ/m^3 (840 Btu/ft^3), as obtained from the utility company.

G.2 ASSUMPTIONS AND APPROXIMATIONS

No particular seasonal trends in utility use were found, so utility data were converted to a working-day basis by dividing the annual total by 280 working days per year.

A weighted average temperature for a wash formula was found by multiplying the temperature by the weight of water for each step, summing these products, and dividing the total by the total weight of water per cycle. An overall average wash-water temperature was estimated from the approximate distribution of the various types of laundry. The overall average used was the 47 C (116 F) thus estimated, rather than the 49 C (120 F) estimated in the data given in (6f) of Section 6.1.

The rate of steam generation used in the calculations was back-calculated from the estimated steam requirements of the equipment and for heating water. This value agreed satisfactorily with that estimated from the fact that the new 300-hp boiler (1 boiler hp = 34.5 lb/h steam at 212 F, or 31.6 lb/h steam at 345 F) was found to be 20% to 25% undersized. This value corresponds to a boiler efficiency of 66%. The boiler efficiency was not independently checked and may be higher. If the efficiency were higher, the energy lost in the boiler stack gas would be lower and the respective percentage of the total energy input would be lower.

In order to obtain mass-and-energy-balance closure with a higher boiler efficiency, the loss of steam and energy would have to be greater and more boiler makeup water would have to be added. The other values calculated in the water and energy balances would not change significantly. It is estimated that if the boiler efficiency were actually 75%, the condensate-return rate would be 80% instead of 92% and the makeup water rate would be 7700 kg/day (17,000 lb/day) instead of the calculated value of 3100 kg/day (7,000 lb/day). The steam losses unaccounted for would be about 8% of the steam rate instead of 3% and the energy losses unaccounted for would be 10% instead of 5% of the total energy input.

G.3 METHODS AND RESULTS

A schematic flow sheet of the process, based on the data and assumptions described above, was constructed from the engineering drawings (see Fig. 6-1). Calculations of water and energy balances were made iteratively.

A water-mass balance was estimated from the available data. Energy balances were calculated for the effluent exchanger, the condensate exchanger, and the steam water heater. The reported 50% to 60% condensate return flow did not give closure of the condensate-exchanger energy balance. The condensate-return flow rate was estimated from the condensate-exchanger energy balance. The boiler makeup water requirement was determined from the condensate-return flow rate.

Unknown flow rates and temperatures were calculated and the water and energy balances were repeated until mass balance closure was obtained as closely as possible. At this point, about 3% of the steam and about 5% of the energy were unaccounted for, probably due to inaccuracies in the data and miscellaneous steam leaks and heat losses from the equipment, storage tanks, and pipes.

The results of the water and energy balances are summarized in Table G-1.

Table G-1. MASS AND ENERGY BALANCE RESULTS FOR COMMERCIAL LAUNDRY

Stream[a]	Water Flow Rate (10^5 kg/day)	Water Flow Rate (10^5 lb/day)	Temperature (C)	Temperature (F)	Energy[b] (GJ/day)	Energy Transferred (GJ/day)	Source of Values
1. City water	3.5	7.7	16	60	0	Input	Utility bills
2. Boiler makeup water	0.03	0.07	16	60	0	--	Water balance
3. Cold water to storage	3.4	7.6	16	60	0	--	Streams 1 & 2
4. Cold water to heating	1.6	3.6	16	60	0	--	Water and energy balances
5. Cold water to washers	1.8	4.0	16	60	0		Streams 3 & 4
						+15	Stream 4 and effluent-exchanger balance
6. Cold water leaving effluent exchanger	1.6	3.6	38	100	15		Condensate-exchanger balance
						+15	
7. Cold water leaving condensate exchanger	1.6	3.6	60	140	30		Stream 6 and condensate-exchanger balance
8. Water to steam heater	1.6	3.6	60	140	30		Stream 7
						+15	Stream heater balance
9. Water leaving steam heater	1.6	3.6	82	180	45		Stream 8 and known outlet temperature
10. Total water to washers	3.4	7.6	47	116	45	--	Streams 5 & 9

[a]Streams are shown on Fig. 6-1.
[b]Energy values are with respect to water at 16 C (60 F). One GJ = 0.948 MBtu.

Table G-1. MASS AND ENERGY BALANCE RESULTS FOR COMMERCIAL LAUNDRY (Continued)

Stream[a]	Water Flow Rate (10^5 kg/day)	Water Flow Rate (10^5 lb/day)	Temperature (C)	Temperature (F)	Energy[b] (GJ/day)	Energy Transferred (GJ/day)	Source of Values
11. Water leaving washers	3.3	7.3	47	116	42	--	Stream 10 less Stream 13
						-15	Effluent-exchanger balance
12. Effluent to sewer	3.3	7.3	32	90	23	Output	Stream 11 and temperature data
13. Wet laundry leaving washers	0.14	0.3	47	116	4	--	Wet laundry = 50% water; temperature from wash formulas
14. Laundry leaving driers	0.05	0.1	93	200	6	--	30% moisture, temperature estimated
15. Drier off gas	0.09	0.2	93	200	21	Output	Streams 13 and 14 and energy balances
16. Steam from boiler	0.4	0.88	174	345	101	--	Equipment data and steam heater balance
17. Steam to ironers	0.25	0.55	174	345	68		Equipment data
						loss, -42	Energy balances
18. Condensate from ironers	0.25	0.55	174	345	17		Stream 17
19. Evaporation from ironers	0.05	0.1	150	300	10	Output	Stream 14
20. Steam to other equipment	0.06	0.14	174	345	17	--	Equipment data
21. Steam loss from other equipment	0.02	0.04	174	345	14	Output	Energy balance

[a]Streams are shown in Fig. 6-1.
[b]Energy values are with respect to water at 16 C (60 F). One GJ = 0.948 MBtu.

Table G-1. MASS AND ENERGY BALANCE RESULTS FOR COMMERCIAL LAUNDRY (Concluded)

Stream[a]	Water Flow Rate (10^5 kg/day)	Water Flow Rate (10^5 lb/day)	Temperature (C)	Temperature (F)	Energy[b] (GJ/day)	Energy Transferred (GJ/day)	Source of Values
22. Condensate from other equipment	0.04	0.10	174	345	3	--	Streams 20 and 21
23. Steam to water heater	0.07	0.16	174	345	20		Streams 8 and 9
						-15	Water and energy balance
24. Condensate from water heater	0.07	0.16	174	345	5		Energy balance
25. Total condensate to condensate exchanger	0.37	0.81	174	345	24		Energy balance
						-15	Water and energy balance
26. Condensate from condensate exchanger	0.37	0.81	77	170	9		Energy balance
27. Condensate make-up water to boiler	0.40	0.88	71	160	10	--	Water balance
28. Natural gas to boiler	--	--	--	--	148	Input	Utility bills
						-98	Boiler energy balance
29. Boiler stack gas	--	--	--	--	50	Output	Energy balance
30. Natural gas to gas-fired driers	--	--	--	--	26	Input	Utility bills
31. Unaccounted-for steam	0.01	0.03	--	--	3	Loss	Water and energy balances
32. Unaccounted-for energy	--	--	--	--	9	Loss	Energy balance

[a]Streams are shown in Fig. 6-1.
[b]Energy values are with respect to water at 16 C (60 F). One GJ = 0.948 MBtu.

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16. Abstract (Limit: 200 words) Increasing attention is being given to the characteristics of energy end-use demand sectors in the U.S. economy. With respect to effective national energy policy, the efficiency with which these demands are met by available energy supplies must be considered. Solar thermal technology is uniquely capable of providing energy at selected temperature levels, thus minimizing waste of energy and maximizing Second Law thermodynamic efficiency. Because of the large energy demand of industry (37% of U.S. demand) and the wide spectrum of temperatures at which heat is required, the industrial sector appears to be very suitable for the matching of solar thermal technology with industrial process heat (IPH) requirements. A methodology for "end-use matching" has been devised, complete with required data bases and an evaluation program PROSYS/ECONMAT. Six cities in the United States were selected for an analysis of solar applications to IPH. Typical process heat requirements for 70% of the industrial plants in each city were identified and evaluated in conjunction with meteorological and economic data for each site to determine lowest-cost solar systems for each application. The flexibility and scope of PROSYS/ECONMAT is shown in a variety of sensitivity studies that expand the results of the six-city analysis. Case studies of two industrial plants were performed to evaluate the end-use matching procedure; these results are reported.

17. Document Analysis

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