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ANALYSIS OF THE ECONOMIC POTENTIAL OF SOLAR THERMAL ENERGY TO PROVIDE INDUSTRIAL PROCESS HEAT

Final Report. Volume I

February 7, 1977

Work Performed Under Contract No. EY-76-C-02-2829

InterTechnology Corporation
Warrenton, Virginia

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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Final Report

Volume I

InterTechnology Corporation
100 Main Street
Warrenton, Virginia 22186

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Prepared for the united States
Energy Research and Development Administration
Division of Solar Energy

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ANALYSIS OF THE ECONOMIC POTENTIAL OF SOLAR THERMAL ENERGY TO PROVIDE INDUSTRIAL PROCESS HEAT

ABSTRACT

This quantitative assessment of the potential of solar thermal energy systems to provide industrial process heat indicates that solar has a maximum potential to provide 0.6 quadrillion Btu (0.6 quadrillion kJ) per year in 1985, and 7.3 quadrillion Btu (7.7 quadrillion kJ) per year in 2000 in economic competition with the projected costs of conventional fossil fuels -- for applications having a maximum required temperature of 550°F (288°C).

Solar process heat at temperatures up to 550°F (288°C) provided by a tracking parabolic trough collector might be cost effective now in competition with oil heat in the region of the country with the highest insolation. By 1985, solar process heat should be cost competitive with: (1) oil in all locations for producing steam for indirect heat and in some locations for direct heat, and (2) gas in some situations. By 2000, solar process heat should be able to compete with the fuel cost of oil and gas anywhere in any application below 550°F (288°C).

The process heat data base assembled as the result of this survey includes specific process applications from 78 4-digit SIC groups. These applications account for the consumption of 9.81 quadrillion Btu (10.4 quadrillion kJ) in 1974, about 59 percent of the 16.6 quadrillion Btu estimated to have been used for all process heat in 1974. About 7-1/2 percent of industrial process heat is used below 212°F (100°C), and 28 percent below 550°F (288°C).

As the result of a comparison of the performance and cost characteristics of a wide variety of flat-plate and concentrating collectors, polar-axis mounted, single-axis tracking concentrating collectors gave a performance superior to that of all other collectors evaluated. The parabolic trough collector looked especially good at temperatures above about 250°F (121°C), and provided a significant amount of energy even at 550°F (288°C). Below about 175°F (79°C), the best performing flat-plate collector -- a single-glazed collector with a black chrome selective surface -- might be competitive with the parabolic trough. At 125°F (52°C), the shallow solar pond appeared to be the best collector in the regions of the country with the highest insolation. Performance calculations were carried out for a baseline solar system providing hot water in representative cities in six geographical regions within the U.S. which were defined on the basis of a constant performance of the solar process heat system.

Specific industries which should have significant potential for solar process heat for a variety of reasons include food, textiles, chemicals and primary metals. Lumber and wood products, and paper and allied products also appear to have significant potential. However, good potential applications for solar process heat can be found across the board throughout industry.

Finally, an assessment of nontechnical issues which may influence the use of solar process heat in industry showed that the most important issues are the establishment of solar rights, standardization and certification for solar components and systems, and resolution of certain labor-related issues.

ACKNOWLEDGEMENTS

Many individuals made many significant contributions to the work performed in this project.

Due to the nature of the project, the efforts of many different people with specialized knowledge of solar thermal systems and various industries were required to make this project successful. These individuals deserve personal recognition, and they include the following at InterTechnology Corporation: Mrs. P. P. Brooks, D. R. Eaton, C. H. Harmer, Dr. J. F. Henry, P. Kando, Dr. S. Kumar, Dr. H. S. Liers, D. F. Ludwig, Dr. W. S. McEver, G. Sandridge, Dr. K. R. K. Sarma, Dr. W. B. Scholten, J. E. Taylor and C. W. Vail.

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Finally, a warm expression of thanks is due also to W. R. Cherry and W. W. Auer of the Energy Research and Development Administration for their support, interest, and patience during the course of this work.

Malcolm D. Fraser
Project Manager

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I. INTRODUCTION AND SUMMARY

A. Description of Project

1. Industrial Process Heat -- Overview

It is widely recognized that among the various sectors of the economy, the largest energy user is the industrial sector. In 1968 it accounted for about 41 percent of the total national energy use. It accounts for about 40 percent at the present time, compared with about 20 percent in the residential sector, 15 percent in the commercial sector, and 25 percent in the transportation sector.

In the industrial sector, energy is used for a number of purposes, including the nonenergy use as a feedstock for chemical manufacture. In 1968 the total industrial use of energy was 25.0×10^{15} Btu for all purposes, including 2.2×10^{15} Btu used as feedstock.[1] The breakdown of the total industrial use of energy is as follows:

Process steam	40.6%
Electric drive	19.2%
Electrolytic processes	2.8%
Direct process heat	27.8%
Feedstock for chemicals	8.8%
Other	0.8%

Process steam and direct process heat together accounted for 68.4 percent of the total industrial use of energy. It is thus clear that the greater portion of the energy used in the industrial sector is used in the form of thermal energy rather than in the form of power, and this is an important fact to consider in estimating the potential use of solar thermal energy in industry.

[1] Stanford Research Institute, "Patterns of Energy Consumption in the United States; Office of Science and Technology, Executive Office of the President, Washington, D. C. (January 1972).

Basic data on the quantities and types of fuels purchased by industry for heat and power are available from the *Census of Manufactures* published by the Bureau of the Census, with breakdowns not only by fuel type, but also by user classifications, including the two-digit Standard Industrial Classification (SIC) industry groups, plus three-digit subgroups and four-digit SIC individual industries. The data come from a sampling of about 65,000 manufacturing establishments, and the 65,000 represent collectively more than two-thirds of the total manufacturing employment. Thus, the data provide valuable basic information not only on the current state of fuel and energy use by industry, but also on the long-term trends; not only for industry as a whole, but also by industrial use, broken down by states and by Standard Metropolitan Statistical Areas (SMSA).

The census data show that six of the twenty two-digit industry groups* are so extremely energy intensive that in 1971 they accounted for 80 percent of all purchased energy used in manufacturing. And the least energy-intensive of these groups, food and kindred products, is about 2.6 times as energy intensive as the next industry group, transportation equipment. These six energy-intensive industries have been studied extensively with respect to total energy usage and energy used per unit of product .

Numerous surveys of industrial energy consumption have been done, particularly recently in view of the increased awareness of and concern for dwindling supplies of conventional fossil fuels. However, these previous surveys have tended to concentrate on simply the gross amounts of fuels used with perhaps some discussion of the prospects for energy conservation in given industries. In addition, because the primary concern has been energy conservation, generally only the most energy-intensive industries have been surveyed, and these most energy-intensive industries tend to be the ones which use process heat at very high temperatures -- precisely the ones with little immediate potential for solar process heat.

---

*Primary metal industries; chemical industries; petroleum and coal products industries; stone, clay, and glass industries; paper and allied products industries; and food and kindred products industries.

However, the needs and levels of process heat in industry as a whole are so extremely numerous and varied that detailed analyses are needed for many other industries besides the energy-intensive six. It must suffice here to say that essentially every chemical change and almost every physical change effected on materials in process in industry involves some kind of process heat application. Many of them are not within the realm of possibility as targets for solar thermal energy applications. But while the available information from government and other sources is very extensive with respect to all the various fuel types used by all the various industries, little information has been available with regard to specific process heat requirements as a function of the temperature range at which it is used.

On the other hand, the potential for solar thermal energy systems to provide industrial process heat is strongly influenced by a number of variables, including the temperature required, the form of the heat used, the amount of heat required in a specific application, geographical distribution of the industry, and competing conventional fossil fuels. It is clear that a different type of survey with more detail is required for the purpose of assessing the potential of solar process heat, and this is the type of survey developed as part of this project.

2. Survey of the Potential Applications of Solar Process Heat

To assess properly the potential use of solar thermal energy for process heat in industry, a great deal of information and data is required, both on the use of process heat in industry, and on the performance and cost characteristics of solar thermal energy systems. Information is also required on costs of conventional fossil fuels with which solar energy will be competing. Finally, nontechnical issues which may affect implementation of solar energy on a widespread scale should be identified now so that they can possibly be resolved before they begin to hinder the installation of solar process heat systems which otherwise would be technically feasible.

One of the major tasks in the project was to identify and summarize the important characteristics, including performance and cost, of various solar thermal energy systems pertinent to their use as providers of industrial process heat. Major technical problems remaining to be solved before these systems can come into general use were also identified. To compare the performance of various types of solar systems, the performance calculations were done for an assumed base-line configuration for an industrial process heat system delivering a constant load of hot water. This assumed configuration was used to calculate the performance of solar process heat systems in different climatic regions for different values of the important operating variables such as temperature and percent annual load carried by solar.

To examine the influence of climatic region upon system performance and to define constant-performance solar regions, calculations were done with this base-line system to determine its low-temperature performance in 90 locations throughout the country. Quantities calculated included collector area required and useful collector output in Btu per square foot per year. These results were used to define regions in the country for which the performance of industrial solar systems is approximately constant. Further performance calculations and comparisons of various types of solar systems were done for a representative city within each constant-performance region.

The various types of solar thermal energy systems which were analyzed in this study include shallow solar ponds, a wide variety of flat-plate collectors -- different coatings (flat black, black chrome), single and double glazings, with and without a reflector -- the Northrup and Winston concentrating collectors, tracking parabolic trough, Owens-Illinois evacuated tubular collector, and paraboloid (solar furnace). Simulation models were developed for these collector systems, and performance calculations were done for different values of important operating parameters. Estimated costs and state-of-the-art reviews for these systems were compiled, also.

To analyze the economics of solar thermal energy applied to industrial process heat, a procedure was developed which was used to calculate the cost of solar energy for the different systems as a function of temperature and solar region. First, collector area for the prototype system was calculated as a function of temperature and percent annual load for each representative city. Then the life-cycle cost of the heat was calculated for each temperature and city as a function of percent annual load using the best current estimates for capital and maintenance costs.

Finally, the marginal cost of solar process heat was calculated for each city as a function of temperature and percent annual load. This marginal cost was compared to present and estimated future costs for conventional fuels to indicate when, where, and under what conditions of system type, temperature, and percent annual load, solar process heat will be cost effective for industrial use.

Another task -- and possibly the most important task -- was to develop an industrial process heat data base with the required amount of detail. Unlike other surveys of industrial energy consumption, which have tended to concentrate on simply the gross amounts of fuel used, the present survey includes the temperature ranges, forms of heat, and amounts of heat used in specific applications in specific processes. This amount of detail is necessary because all of these variables strongly influence the potential for solar thermal energy systems to provide industrial process heat. In particular, the temperature determines the type of system which may be used and its performance, and the cost of process heat. Specific applications in specific processes must be studied to develop conceptualized designs of solar process heat systems, and to determine the potential markets for such systems.

Finally, the survey was performed from the point of view of process requirements rather than the point of view of current methods of using heat. Thus, the temperature of major interest for a particular application was the required temperature of the process material rather than the temperature at which the heat is currently provided. Currently much heat of high thermodynamic availability is wasted because it is used for a low-temperature application which could readily be satisfied with lower-temperature heat. Fuels with the capability of a flame temperature of 2000+ °F are burned with the ultimate objective of making hot water, for example. A solar process heat system should be designed to satisfy the needs of a process and not merely to substitute for the current method of providing heat.

The survey was organized to develop a broad-based coverage of industry and yet to obtain detailed information on specific processes. The data base is organized on the basis of 4-digit Standard Industrial Classification (SIC) groups as defined by the Federal government for the purposes of data collection and analysis. By organizing the survey around 4-digit SIC groups, advantage was taken of data bases and previous studies organized in this fashion. Because this classification system is familiar to many people, easy access to the data developed in this survey is facilitated. However, the process heat data are developed and presented in terms of processes and specific applications within processes rather than in terms of the process heat used by groups per se.

Rather obviously, not all of the 4-digit SIC groups could be included specifically in the survey, there being over 450 in mining and manufacturing categories. Groups were selected for specific study which consumed over 5×10^9 kWh of fuels, excluding electricity, according to the *1972 Census of Mining and Manufactures*. This sample was further refined to include some groups in the sample to obtain a broad-based coverage of industry even though they did not meet the fuels consumption requirement for an individual group, and some of the groups were ultimately excluded from the final sample because it was not possible to obtain data on them. The final data sample included applications from 78 SIC groups, and these applications consume 9.8×10^{15} Btu per year -- about 59 percent of the estimated total amount of process heat used by indus

The present survey is of course concerned only with heat used in production processes in industry; it is not concerned with total energy consumption, use of electricity, or fuels for power. In addition, the survey is concerned with process heat from the point of view of the process rather than the point of view of the amount of primary fuels used.

The information and data gathered in this survey are organized in the form of a basic typical flow sheet indicating individual operations with typical operating conditions such as temperture, source of heat, and amount of heat used per unit of product. In addition, both current production and estimated future production data are being accumulated to be used to estimate the total amount of heat used and the potential market for solar thermal energy systems for a particular application. Finally, because geographical location influences the performance of solar thermal energy systems and consequently their impact for a particular application, production data are broken down into production by States for analysis with respect to solar climatic region.

The process heat data contained in the data base developed in the survey were analyzed to identify process heat applications and production processes in which solar thermal energy can be expected to have an impact. This impact has been assessed in terms of the potential use of solar energy. The variables considered in this assessment for a particular process included climatic region, geographical distribution of production and therefore process heat requirements, competing fuels, and time frame of reference. The particular points of time included in this analysis were 1976, 1985, and 2000.

Another part of this project was to conceptualize industrial process heat systems involving solar thermal energy. System concepts developed in this work are shown in process diagrams, including the method by which solar thermal energy systems are integrated with the conventional fuel systems used for back up. Because the same type of process heat operation is common to many processes -- indirect heating of a process liquid of some type, for example -- this work was organized by process operation rather than by process or industry. In this fashion, generalized process heat systems which may have numerous applications in many different processes and industries were conceived and defined. Solar process heat systems may then be thought of as a plant utility, and standardized system designs developed, leading to reduced costs. Designed as a plant utility system rather than as an integral part of an industrial process, solar process heat systems should have a longer expected useful lifetime, again leading to reduced costs.

A final task in the project was concerned with a preliminary identification and assessment of pertinent nontechnical issues associated with the widespread implementation of solar thermal energy systems for providing process heat. Critical issues are identified which may impede or even prevent such implementation on a national scale. Such nontechnical issues include financial issues, legal problems, and institutional factors.

B. Summary

1. Characterization of Solar Thermal Energy Systems

In the part of the project concerned with characterizing solar thermal energy systems, we have investigated on a systematic basis the relative capabilities of the various types of solar collectors which are available to produce process heat. In carrying out this work, we have performed state-of-the-art reviews, selected a baseline solar system which was mathematically modelled and programmed for computer usage, determined geographical regions of constant solar performance with representative cities for each region, and carried out performance calculations for a variety of flat-plate and concentrating collectors.

State-of-the-art reviews were written for a variety of solar collector types. These include flat-plate collectors, tubular collectors, solar ponds and concentrating collectors. In the case of flat-plate collectors, a further breakdown into liquid and air collectors was made, and the liquid collectors were further broken down into collectors with and without selective surfaces. The use of flat-plate collectors with mirror reflectors was also investigated.

Concentrating collectors were divided into tracking Fresnel, compound parabolic, and tracking parabolic trough. Solar furnaces are included in the reviews even though their potential for supplying significant quantities of cost-effective process heat is severely limited.

General discussions of storage and control systems are also included in the state-of-the-art reviews.

In the state-of-the-art reviews, a basic description of each collector is given. Measured data on collector efficiencies are presented whenever possible; however, in some cases theoretical figures had to be derived. Cost data are included to as great an extent as possible.

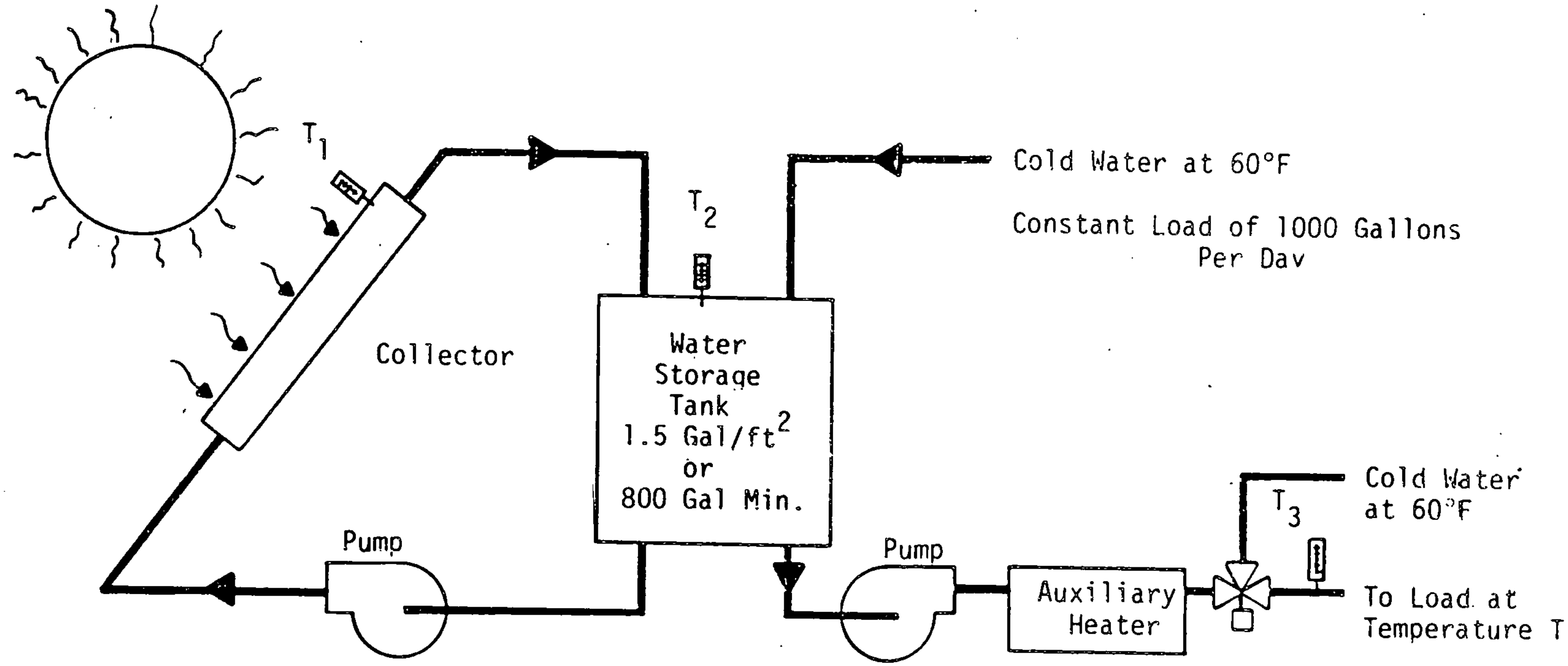
In general, it was found that a great deal of information was available on flat-plate collectors, basically due to the fact that these collectors are used in heating, cooling and hot water systems for residential and commercial use. On the other hand, very little reliable information is available for concentrating systems. In most of these cases, thermal performance models had to be developed to understand their expected efficiency across the wide range of temperatures over which they may be expected to operate. It was clear, as a result of our work, that a great deal more work needs to be done on the concentrating collectors in terms of calculation of thermal performance and systems conceptual design. This is especially true in view of the fact that the performance of the polar-axis mounted, single-axis tracking, concentrating Fresnel and parabolic trough collectors showed superior performances in our calculations.

To make performance comparisons of various solar collectors, it was necessary to devise a simple baseline system which could be mathematically modelled and programmed for computer usage. A diagram of this baseline system is shown in Figure I-1. Basically, this system consists of a collector array with the collectors tilted to the latitude angle, a storage tank, a delivery system which allows heated water to be delivered at a temperature T to a fixed load of 1,000 gallons per day. This load is assumed to be continuous and uniformly distributed over the day. The basic collector efficiency equation and cost parameters were put into the computer program, and information such as the fraction of the load carried by solar energy (solar fraction) versus collector area and the marginal cost of solar energy versus solar fraction over a range of temperatures was outputted. Examples of these outputs for a single-glazed flat-plate collector with a black chrome selective surface are shown in Figures I-2 and I-3.

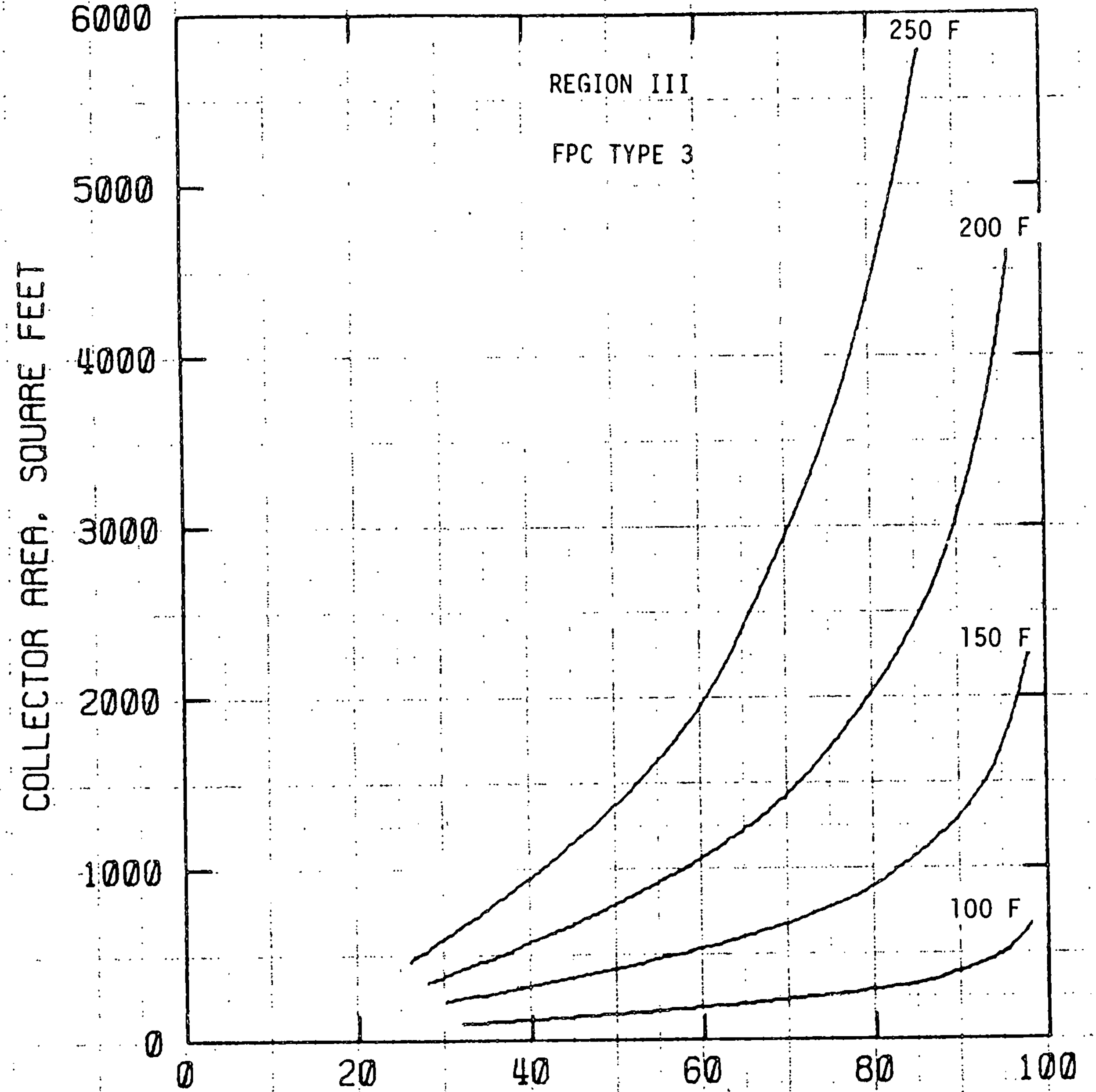
A section is included in the report on how these curves may be used in the design and analysis of solar systems for process heat. The basic advantage of using the marginal cost of solar energy in the analysis is that the cost of conventional

InterTechnology Corporation
Box 340
Warrenton, Virginia 22186, U.S.A.

FIGURE I-1
BASELINE SOLAR SYSTEM

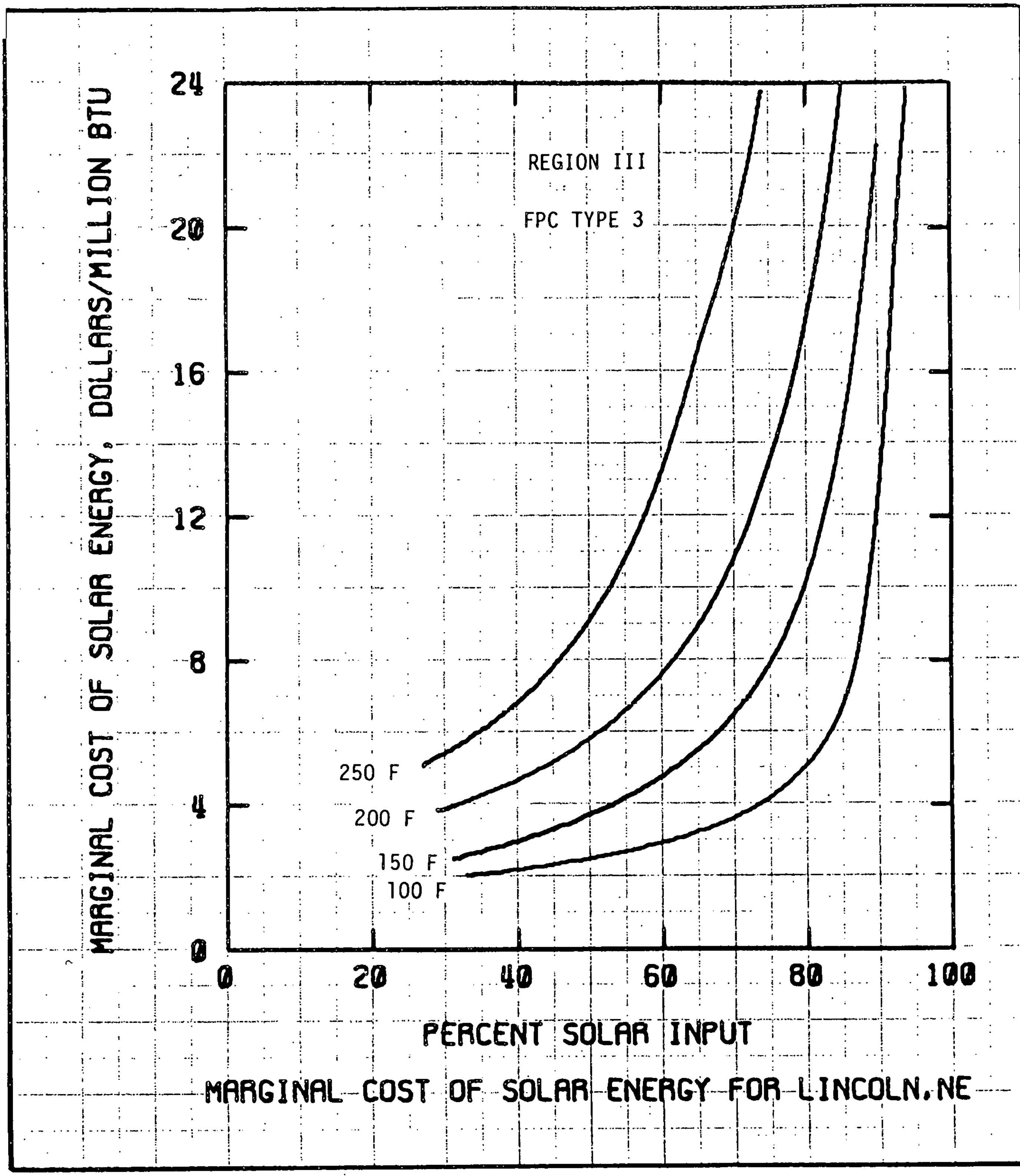


Schematic of System Assumed for Analysis



COLLECTOR AREA VS. PERCENT SOLAR INPUT
FOR LINCOLN, NE

FIGURE I-2



REGION III
FPC TYPE 3
250 F
200 F
150 F
100 F
MARGINAL COST OF SOLAR ENERGY, DOLLARS/MILLION BTU
0
4
8
12
16
20
24
0
20
40
60
80
100
PERCENT SOLAR INPUT
MARGINAL COST OF SOLAR ENERGY FOR LINCOLN, NE

FIGURE I-3

energy both now and in the future doesn't enter into the collector performance calculations. The decision as to the present and future cost of energy is made by the individual owner, and it is on the basis of his perceptions that the economic optimum collector square footage may be selected.

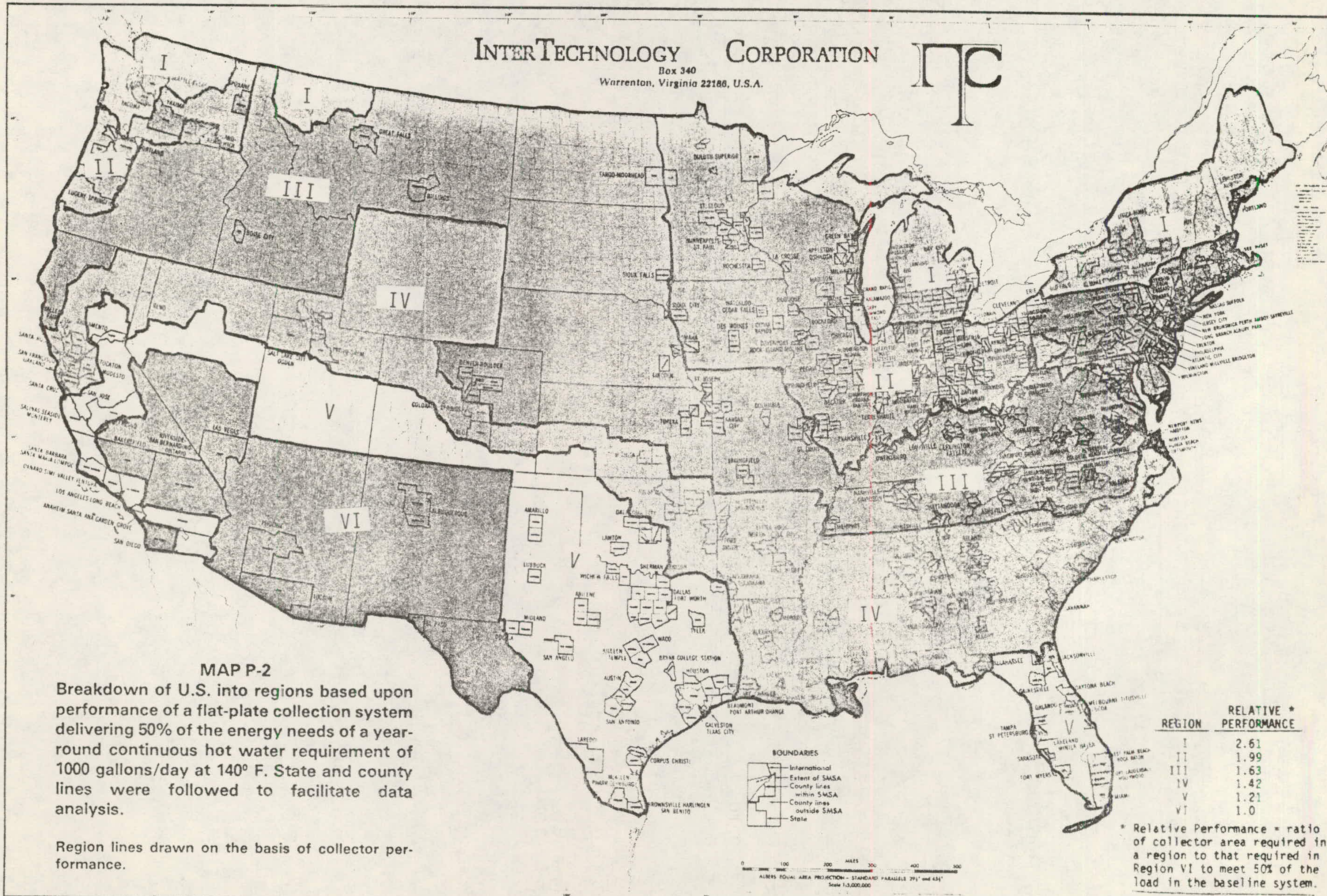
InterTechnology Corporation has available insolation data from some 90 cities scattered around the United States. However, to carry out calculations for all of the collectors for each of these cities would have been an impossible and undesirable task. Therefore, we have broken down the country into six geographical regions of relatively constant solar performance. This breakdown into regions was done first on the basis of constant insolation and then on the basis of performance calculations for a flat-plate collector providing 140°F (60°C) water in the baseline system for each of 90 cities. Region lines were adjusted to conform to state and county lines so that process heat data could more easily be analyzed later. The constant-performance region map is shown as Map P-2.

On the basis of the calculations for 90 cities, a representative city was selected for each region, and the six representative cities are given in Table I-1. Further calculations were carried out for each of the representative cities.

TABLE I-1

REPRESENTATIVE CITIES FOR CONSTANT-PERFORMANCE SOLAR REGIONS

Region	City
I	Schenectady, New York
II	Madison, Wisconsin
III	Lincoln, Nebraska
IV	Stillwater, Oklahoma
V	Fort Worth, Texas
VI	El Paso, Texas



MAP P-2

Breakdown of U.S. into regions based upon performance of a flat-plate collection system delivering 50% of the energy needs of a year-round continuous hot water requirement of 1000 gallons/day at 140° F. State and county lines were followed to facilitate data analysis.

Region lines drawn on the basis of collector performance.

REGION	RELATIVE * PERFORMANCE
I	2.61
II	1.99
III	1.63
IV	1.42
V	1.21
VI	1.0

* Relative Performance = ratio of collector area required in a region to that required in Region VI to meet 50% of the load in the baseline system.

REGION I II III IV V VI

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The basic parameters which were investigated with the performance calculations were collector type, region, delivery temperature, collector area required for various solar fractions and systems cost. Calculations were carried out for ten different collectors. These are as follows:

1. Liquid, flat-plate, black paint, double glazed
2. Liquid, flat-plate, selective surface (ε = 0.4), double glazed
3. Liquid, flat-plate, selective surface (ε = 0.1), single glazed
4. Liquid, flat-plate, selective surface (ε = 0.1), double glazed
5. Air, flat-plate, selective surface (ε = 0.1), single glazed
6. Tubular, Owens-Illinois
7. Shallow solar pond
8. Linear Fresnel, Northrup
9. Compound parabolic, Winston type
10. Tracking parabolic trough

Calculations for the tubular, linear Fresnel lens and compound parabolic type collectors were carried out only for Region III. Calculations for the other collectors were carried out for all six regions.

A variety of delivery temperatures was included in the calculations. For the flat-plate collectors, these ranged from 100°F (38°C) to 250°F (121°C). The solar pond calculations were carried out for temperatures less than 175°F (79°C). Temperatures from 125°F (52°C) to 600°F (316°C) were included in the calculations for concentrating collectors.

Each calculation was carried out in such a way that a curve of collector area versus percent solar input could be plotted over a range of percents from about 30-90%. An example of such a plot is shown in Figure I-2 for a single-glazed collector with a black chrome selective surface. This calculation was done for

Region III at delivery temperatures of 100, 150, 200 and 250°F (38, 66, 93, and 121°C). On the basis of this calculation and an assumed solar system cost, a marginal cost curve was generated according to:

$$\text{Marginal Cost} = \frac{C_2}{L_{20}} \frac{\partial A}{\partial f_s} \qquad \text{(I-1)}$$

where

solar system lifetime cost = $C_1 + C_2A$

A = collector area

L_{20} = total energy provided over 20-year system lifetime

f_s = fraction of total load supplied by solar energy.

In order to calculate the marginal cost curve, it was necessary to input the variable life-cycle cost factor C_2 into the computer and to differentiate the collector area curve with respect to the solar fraction, f_s. The cost factors were obtained from data obtained in the state-of-the-art reviews. (Owing to the fitting procedure used to generate the collector area versus solar fraction curves, the marginal cost curves show small spikes at some points.) It is shown in Section II.J of the report that at the minimum life-cycle cost, the marginal cost of solar energy is equal to the average cost paid for conventional energy over the system lifetime. Thus, if the average cost of conventional energy can be estimated, the marginal cost curve can be entered, and the optimal solar fraction and hence collector area can be determined. If the term C_2 for a given design is different from the one used to generate the marginal cost curve, a new marginal cost curve can be generated simply by changing the scale of the given curve by the ratio of the new cost to the one used in our analysis.

The marginal cost curves were used in the later analysis of process heat data to obtain an estimate of the potential of solar energy for process heat.

From the results calculated for each collector, the useful energy collected per square foot of collector per year can be determined for various solar fractions. Such results are tabulated below for a single-glazed flat-plate collector with a black-chrome selective surface and for a polar- axis mounted, single-axis tracking concentrating parabolic trough collector. Each collector is supplying 50% of the load, and the results are given for both 150 (66°C) and 200°F (93°C) delivery temperatures.

TABLE I-2

ANNUAL THOUSANDS OF BTU/FT^2 DELIVERED BY FLAT-PLATE AND CONCENTRATING COLLECTORS OPERATING AT 150 AND 200°F

Region	Flat-plate, kBtu/ft^2/Yr		Concentrating, kBtu/ft^2/Yr	
	150°F	200°F	150°F	200°F
I	205	157	273	265
II	273	218	390	366
III	329	268	454	432
IV	374	312	487	471
V	407	353	542	530
VI	496	451	706	692

These data give an idea of the relative technical performance which may be expected for these two collectors operating at the indicated temperatures. One is cautioned from drawing conclusions as to the most economical system from these data. Even though the concentrating collector yields about 30%

more energy at the 150°F (66°C) temperature, the flat-plate collector system is expected to cost significantly less and may yield energy at a lower cost. At 200°F (93°C), the concentrating collector yields about 50% more energy and, assuming the cost is not 50% more than the flat-plate system, appears to be the best collector to use.

It is emphasized that the approach we have taken in our analyses is very broad and touches only the major variables. It is not intended that the information we have given here be used in the actual design of systems. We believe that the information we have presented will help a prospective user to select the right collector for his application and to determine approximately the collector area and the energy supplied by the solar system.

2. Economics of Energy Sources

One of the important elements of information needed in an assessment of the potential of solar process heat is the cost of conventional fossil fuels with which solar energy will be competing. The cost of a conventional fossil fuel varies with fuel type, of course, and also varies with geographical location within the United States. The most up-to-date source of fuel costs which shows these details appears to be the compilation prepared periodically by the Federal Power Commission (FPC). Fuel costs obtained by the FPC are of course fuel costs paid by utilities. However, because an up-to-date compilation of fuel costs paid by industry similar to the FPC's compilation for utilities does not appear to exist, the FPC costs were assumed to be representative of industrial fuel costs.

To reduce the amount of detail required in the analysis of fuel costs, average fuel costs have been calculated for the constant-performance solar regions from the FPC data on fuel costs by state. These costs were calculated by averaging the quantity-weighted costs for each fuel type for the states within each solar region.

As noted above, it would be difficult to compile current costs of conventional fuels as a function of industry, fuel type, and geographical location in a precise manner. It would be even more difficult to estimate what these costs might be in the future. Future costs of conventional fossil fuels are subject to a variety of influences, such as inflation, governmental policy, technical recovery factors, costs of environmental protection, labor contracts, and the international situation, to name but a few. It is beyond the scope of this study to analyze the major influences upon future costs of fossil fuels, and to develop independent estimates of these costs. Instead, various potential sources of estimates of future fuel costs were investigated, such as the literature, governmental agencies, and knowledgeable people in a position to make such estimates. Little information was found; few estimates are published.

For the purposes of this study, the most probable future fuel costs are estimated from 1976 fuel costs by applying an annual percent increase comprised of two parts. One of these is the annual increase due to inflation, and the other is a composite of social, political, economic and technical factors. The rate of inflation used in the calculations in this study is 7 percent. The other part of the annual percent increase in the cost of fuel is more difficult to quantify. However, some estimates have been derived from discussions with energy economists and fuel managers of utilities.

The projected future costs used in this study of the three major fuels for the years 1985 and 2000 are:

$$\text{Cost of coal in 1985} = (\text{1976 unit cost})\ (1 + 0.07 + 0.03)^{9} \qquad \text{(I-2a)}$$

$$\text{Cost of coal in 2000} = (\text{1985 unit cost})\ (1 + 0.07 + 0.05)^{15} \qquad \text{(I-2b)}$$

$$\text{Cost of oil in 1985} = (\text{1976 unit cost})\ (1 + 0.07 + 0.055)^{9} \quad \text{(I-3a)}$$

$$\text{Cost of oil in 2000} = (\text{1985 unit cost})\ (1 + 0.07 + 0.08)^{15} \quad \text{(I-3b)}$$

$$\text{Cost of gas in 1985} = (\text{1976 unit cost})\ (1 + 0.07 + 0.13)^{9} \quad \text{(I-4a)}$$

$$\text{Cost of gas in 2000} = (\text{1985 unit cost})\ (1 + 0.07 + 0.08)^{15} \quad \text{(I-4b)}$$

These expressions were used to calculate projected future costs for the three fuels for 1985 and 2000 for the solar regions, and to illustrate these projections, estimated future costs are shown in Table I-3.

3. Method of Analyzing and Comparing Economics of Solar and Competing Fossil Fuels

One of the significant objectives of this project is to estimate the potential for solar thermal energy to provide industrial process heat practically and economically, as well as technically. In the final analysis, the potential for solar process heat must be determined by means of an economic analysis to compare the economics of solar thermal energy with those of competing fossil fuels. One basic assumption in the analysis presented here is that the total cost of solar thermal energy--both capital and operating costs--must compete against the fuel cost of delivered thermal energy provided by conventional fossil fuels. Thus, it is assumed that at the present time, a process heat system fired with a conventional fossil fuel and having 100-percent capacity to provide the required process heat, is necessary as a backup system. What the economic analysis presented in this study hopes to achieve is to suggest potentially economic applications of solar process heat.

To compare the investment in a solar process heat system--a capital cost--against future savings in fossil fuel bills--an operating expense--life-cycle costing methods must be used. The method developed and used in the present analysis is based upon calculating "present equivalent" life-cycle costs for both the solar system and the expected savings in fossil fuel costs.

TABLE I-3

FUEL COSTS (AS DELIVERED) AS FUNCTION OF SOLAR REGION

Estimated Actual Cost in $ Per Million Btu

Regional Average Costs

Solar Region	Coal 1976	Coal 1985	Coal 2000	Oil 1976	Oil 1985	Oil 2000	Natural Gas 1976	Natural Gas 1985	Natural Gas 2000
I	1.01	2.38	13.03	1.97	5.69	46.30	1.46	7.53	61.30
II	0.86	2.03	11.11	1.92	5.54	45.08	1.00	5.16	41.99
III	0.82	1.93	10.56	1.82	5.25	42.72	0.64	3.30	26.85
IV	0.83	1.96	10.73	1.91	5.51	44.84	0.90	4.64	37.76
V	0.70	1.65	9.03	2.08	6.00	48.82	1.06	5.47	44.51
VI	0.23	0.54	2.97	2.37	6.84	55.67	0.84	4.33	35.27
National Average	0.84	1.98	10.84	1.99	5.74	46.71	0.97	5.00	40.69

The essence of a life-cycle cost analysis is to calculate the total costs involved in operating a system over its expected lifetime, and to compare such total costs for alternative systems to determine the better investment. In calculating the total costs over the system lifetime, future sums of money are discounted appropriately to recognize the time factor in the value of money. Several different types of life-cycle costs can be computed, the two most common being: the total cost of operating the system in terms of present dollars--the "present equivalent" life-cycle cost--or the uniform annual equivalent cost. The life-cycle cost method adopted here is the present equivalent life-cycle cost, expressed in terms of the average present equivalent life-cycle cost per million Btu provided by the system over its lifetime, which is defined and used here as the total present equivalent life-cycle cost divided by the total amount of energy provided over the system lifetime. In addition, the analyses presented here will be in terms of 1976 dollars, even when investments in 1985 or 2000 are analyzed.

The present equivalent life-cycle cost (PE LCC) per million Btu delivered by a solar process heat system is defined here as follows:

$$\text{PE LCC per } 10^6 \text{ Btu Delivered by Solar} = \frac{\text{Investment and Discounted Future (Main. + Op. Costs)}}{\text{Total Energy Delivered Over 20 Years}} \qquad \text{(I-5)}$$

The return on an investment in solar process heat is in the form of reduced future fossil fuel bills. This analysis assumes that a conventional fossil fuel system which has a 100-percent capacity must be installed along with the solar so that no savings are obtained on the capital investment involved in the conventional fuel-using system. The PE LCC for these fuel savings is calculated as follows:

$$\text{PE LCC per } 10^6 \text{ Btu Provided by Conventional Fuel} = \frac{\sum_{n=1}^{20} \frac{C(1+r_n)^n}{(1+i)^n}}{20} \quad \text{or} \quad \frac{C\left[\sum_{n=1}^{9}\left(\frac{1+r_1}{1+i}\right)^n + \left(\frac{1+r_1}{1+i}\right)^9 \sum_{n=1}^{11}\left(\frac{1+r_2}{1+i}\right)^n\right]}{20}$$

for PE LCC in 1976

where C = the cost of fuel per 10^6 Btu (in 1976 dollars for an analysis in 1976 dollars); for comparison with solar, this cost must be the cost of heat delivered to the process, not merely the fuel cost.

r_n = annual rate of increase in C, including inflation

i = discount rate or desired rate of return, also assumed to include compensation for inflation

n = summation index.

The result of this calculation is the PE LCC per million Btu averaged over a period of 20 years. For comparison with solar, the PE LCC for the fuel cost must be adjusted to calculate the cost of heat delivered to the process. For heat delivered to the process directly, the PE LCC must be divided by the ratio of net heating value to gross heating value--0.96 for coal, 0.95 for oil, and 0.90 for natural gas, for example--because the latent heat in the water vapor evolved cannot be utilized. For heat delivered to the process indirectly by means of steam, the fuel cost PE LCC must be divided by an average boiler efficiency for heat content of steam produced relative to the gross heating value of the fuel--0.85, for example. If the solar system is designed <u>at a certain point in time</u> to provide energy at a (marginal) PE LCC equal to the PE LCC of delivered heat from a competing fuel calculated at a certain discount rate, then the solar system investment provides a rate of return equal to that discount rate.

The discount rate or rate of return which is selected to apply to a given investment decision is an important variable. If the potential investment is one which entails a significant amount of risk or which is likely to have a fairly short useful lifetime, the rate of return is set at a high value. On the other hand, if an investment has a low risk and the facility appears to have a long expected useful lifetime, a lower rate of return might be acceptable.

Because solar process heat would essentially be a utility, a solar process heat system should have a long expected useful lifetime and not become obsolete in a short time. It might then be possible for industry to accept a lower rate of return for an investment in a solar process heat system as long as it is designed as a utility and not as an integral part of a new process which is likely to become obsolete soon. With this idea in mind, the analysis in this study of the potential of solar process heat has been made with the assumption of a 15 percent rate of return.

PE LCC's per 10^6 Btu have been calculated for the three fuels for three possible times of investment--1976, 1985 and 2000. Because all of the comparisons between solar and fossil fuels, whether made for 1976 or ensuing years, will be made in present dollars, these costs have been calculated in terms of 1976 dollars. These PE LCC's are shown in Table I-4 as a function of solar region, along with the future costs of the fuels in 1985 and 2000. The future fuel costs in Table I-4 were calculated from the current costs by applying the total estimated escalation rates and then discounting with the rate of inflation to express these costs in 1976 dollars.

4. Total Use of Process Heat in Industry

The energy consumption data of a specific industry are usually recorded (or reported) as fuels consumed. These fuel usage figures generally include fuels for all kinds of uses such as power, space heat, process requirements and in some cases even energy sold. The survey in this project is concerned with the amount of energy used as process heat in mining and manufacturing industries. To develop an estimate of the total amount of process heat used in industry, the basic data on fuel consumption were analyzed by 2-digit SIC groups to evaluate this particular component of the fuel usage.

Fuel consumption data of the various industries were obtained essentially from two sources: (1) *Energy Facts* published by the Bureau of Mines and (2) *Fuels and Electrical Energy Consumed* from the Census of Manufactures. However, the data from these two sources do not correspond, caused mainly by differences in the methods of data collection. The data from the Bureau of Mines are believed to be more complete than the Census of Manufactures data. The latter therefore were scaled up to match the former so that the total consumption of each f by industries as a whole agreed between the two sources.

TABLE I-4

FUEL COSTS (AS DELIVERED) AS FUNCTION

OF SOLAR REGION, FUEL TYPE, AND TIME

(In 1976 Dollars)

COAL

Solar Region	1976 Cost $\$/10^6$ Btu	1976 PE LCC @ DR* 15%	1985 Cost $\$/10^6$ Btu	1985 PE LCC @ DR* 15%	2000 Cost $\$/10^6$ Btu	2000 PE LCC @ DR* 15%
I	1.01	0.68	1.30	1.00	2.58	1.98
II	0.86	0.58	1.10	0.84	2.18	1.67
III	0.82	0.56	1.05	0.80	2.08	1.59
IV	0.83	0.56	1.06	0.81	2.10	1.61
V	0.70	0.47	0.90	0.69	1.79	1.37
VI	0.23	0.16	0.29	0.22	0.58	0.44
National Average	0.84	0.57	1.08	0.83	2.14	1.64

OIL

Solar Region	1976 Cost $\$/10^6$ Btu	1976 PE LCC @ DR* 15%	1985 Cost $\$/10^6$ Btu	1985 PE LCC @ DR* 15%	2000 Cost $\$/10^6$ Btu	2000 PE LCC @ DR* 15%
I	1.97	1.68	3.09	3.09	9.11	9.11
II	1.92	1.64	3.01	3.01	8.88	8.88
III	1.82	1.56	2.86	2.86	8.43	8.43
IV	1.91	1.63	3.00	3.00	8.85	8.85
V	2.08	1.78	3.27	3.27	9.64	9.64
VI	2.37	2.03	3.72	3.72	10.97	10.97
National Average	1.99	1.70	3.12	3.12	9.20	9.20

NATURAL GAS

Solar Region	1976 Cost $\$/10^6$ Btu	1976 PE LCC @ DR* 15%	1985 Cost $\$/10^6$ Btu	1985 PE LCC @ DR* 15%	2000 Cost $\$/10^6$ Btu	2000 PE LCC @ DR* 15%
I	1.46	2.00	4.10	4.10	12.09	12.09
II	1.00	1.37	2.81	2.81	8.29	8.29
III	0.64	0.87	1.80	1.80	5.31	5.31
IV	0.90	1.23	2.53	2.53	7.46	7.46
V	1.06	1.45	2.97	2.97	8.76	8.76
VI	0.84	1.15	2.36	2.36	6.96	6.96
National Average	0.97	1.33	2.72	2.72	8.02	8.02

* Present Equivalent Life-Cycle Cost at Discount Rate.

From this analysis, it was determined that industry--manufacturing and mining--used 15.2 quadrillion Btu (16.0 quadrillion kJ) for process heat (delivered to the process, not in terms of primary fuels combusted) in 1971.

However, the process heat data base developed in this survey generally contains more recent data, from 1974 or 1975, depending on the latest available production data. The total amount of process heat in 1971 was extrapolated up to the time frame of the data base to determine the proportion of industrial process heat represented by the data base. Analysis of the growth of the total use of process heat shows that it is increasing at about the rate of 3.0 percent per year. If 1974 is taken as the base year for the data base (1975 was a recession year which saw the normal growth in production and energy use interrupted), then the total amount of process heat, to be compared to the data base, is 16.6 quadrillion Btu (17.5 quadrillion kJ).

To estimate the total potential use of solar process heat in mining and manufacturing in the future, estimates had to be developed for total future industrial process heat requirements. The growth in the total use of process heat was estimated by forecasting the expected or estimated growth in production for each 2-digit SIC group in mining and manufactures. In developing estimates of the growth in the use of process heat in the future, trends in technology and the use of process heat per unit product were taken into consideration, depending upon the nature of the industry and current information regarding such trends. It is estimated that industry will require 23.0 quadrillion Btu (24.3 quadrillion kJ) for process heat in 1985 and 36.6 quadrillion Btu (38.6 quadrillion kJ) in 2000.

5. Industrial Fossil Fuel Consumption Patterns

The economic viability of solar thermal systems is in large part controlled by the cost of available competing fuels. Data were obtained on the costs for coal, oil and natural gas throughout the country. To make this information useful, it is necessary to look at which fuels are actually used in specific industries and geographical areas. To this end, fuel consumption figures were examined to identify which parameters most affected the fuel mix distribution. The primary source for this data was the *1972 Census of Manufactures*. The fuel consumption figures were adjusted in accordance with the assumptions used to quantify the total industrial use of heat energy and specifically process heat.

The first step in this systematic analysis of fuel mix data was to determine which parameters influence fuel mix significantly enough to fall within the scope of this project, and to estimate the probable fuel mix to be used by industry in the future. However, the time dependence of the national fuel mix distribution appears to be low. Only three sets of national fuel consumption estimates were available; these were reports from the Federal Energy Administration, the Federal Power Commission and the Bureau of Mines. There was as much scatter between the current estimates as there were differences between 1976 data and projections for 2000.

With respect to regional variations in fuel availability, census data confirm that fuel mixes for contiguous states tend to be very similar. The same data show that industries are more likely to reflect their region's fuel distribution than that of their national two-digit SIC classification. This indicates that regional variations in fuel mix are the primary factors reflecting fuel usage in individual industrial operations. Consequently, regional fuel mix and fuel cost data were used in estimating the potential impact of solar energy on all industrial operations in a given region.

A tabulation of the fuel mixes for the constant-performance solar regions appears in Table I-5. Nationally, gas accounts for 73.7 percent of industrial fuel requirements. Within the solar regions, however, this number varies from half to essentially all of the respective fuel requirements. The same variation is evident in the percentage of oil used. This represents a more important case because solar will generally be most cost effective when replacing oil, the highest price fossil fuel. These fuel mix data are a quantitative measure of the amount of competition that solar will face from each competing fossil fuel in each solar region.

6. Procedure for Quantitative Assessment of Potential for Solar Process Heat

One of the significant objectives of this project is to make a quantitative estimate of the potential for solar thermal energy to provide industrial process heat practically and economically. This estimation must consider the variables of process application (temperature and type of heat), geographic location (amount of heat required for the process based upon regional production, performance and cost of solar systems), and cost and availability of competing fuels. The six so-called constant-performance solar regions have been used as the basic variable of geographical location. The year for which the assessment is made is also an important factor.

Data concerning process applications are contained within the process heat data base. Data concerning the performance and cost of solar thermal energy systems were obtained in the analysis of the different solar systems which might be used to provide industrial process heat. The analysis of the costs of and expected demand for fossil fuels by solar region provided the needed information on the fuels with which solar energy is competing. This information was combined to make a quantitative assessment of the potential of solar process heat.

TABLE I-5

ESTIMATED FUEL MIX FOR THE INDUSTRIAL SECTOR

Constant-Performance Solar Region	Percent of Thermal Needs Supplied by		
	Coal	Oil	Gas
United States	14.5	11.8	73.7
I	22.2	23.4	54.4
II	21.5	18.1	60.4
III	30.9	10.0	59.1
IV	6.1	7.8	86.1
V	1.2	3.3	95.5
VI	0.0	9.4	90.6

The performance and costs for the various types of solar thermal energy systems for the different solar regions were analyzed and compared to determine the most cost-effective system or systems which should be used for this quantitative assessment of solar's potential to provide process heat. It turned out that for the costs assumed for all of the systems, the tracking parabolic trough collector appears generally to deliver the cheapest thermal energy for all temperatures and solar regions. This type of collector system was adopted as the standard solar system for all applications for the purposes of this assessment.

The optimum design of a solar system for a particular application, in terms of percent annual load to be supplied by solar, depends upon the marginal cost. At the optimum percent annual load supplied by solar, the marginal cost of solar energy is equal to the PE LCC of the competing fuel, and the investment in the solar system will provide the rate of return which is used to discount the future fuel costs to calculate the PE LCC.

The calculated PE LCC's for the three fuels for direct and indirect heat for the six solar regions were used in conjunction with the calculated marginal cost curves for the tracking parabolic trough collector to determine the optimum percent annual load supplied by solar for each combination of variables, at each of nine temperatures ranging from 150°F (66°C) to 550°F (288°C) in 50°F (27°C) increments. This analysis was done for each time frame of interest. The values obtained for the optimum percent annual load supplied by solar for these combinations of conditions are shown in Tables I-6, I-7 and I-8.

This analysis shows that solar process heat is potentially economic right now in Solar Region VI in competition with oil. By 1985, solar should be able to compete with oil in almost all situations except for direct heat, where the combustion gases are applied to the process, in Regions I, II and III. Also by 1985, solar should be able to compete with gas in a number of situations. By the year 2000, solar should be able to compete with oil and gas anywhere. The tables do show, however, that solar probably cannot compete against the fuel cost of coal anywhere up to and including the year 2000.

For each application, the amount of heat which can be supplied by solar in competition with each fuel is the total heat requirement for a solar region times the fraction of the heat supplied by the fuel times the optimum fraction annual load which can be supplied by solar. This latter quantity depends upon the assumed temperature, solar region, type of fuel, and type of heat application. The total amount of heat which can be supplied by solar in a particular solar region is simply the sum of the solar heats in competition with oil and gas (solar heat in competition with coal is always zero). The total heat which can be supplied nationally by solar for the given application is simply the sum of the quantities for the six solar regions.

This analysis was done for each application for each time frame of interest --1976, 1985 and 2000. The table for each application shows the potential for solar process heat as a function of solar region, competing fuel, and time frame. The total potential for solar process heat was obtained by summing the individual application tables to develop the potential for the data base, and then scaling up the potential to cover the total use of process heat by industry.

7. Summary of Data Base

As a result of the survey, a great deal of information and data has been collected and assembled on the use of process heat in industry. Included in this data base are applications from 78 SIC groups, and these applications account for the consumption of 9.81×10^{15} Btu (10.4×10^{15} kJ) in 1974. The total amount of process heat estimated to have been used in 1974 is 16.6×10^{15} Btu (17.5×10^{15} kJ). Thus, the data base covers approximately 59.1 percent of the total use of process heat in industry.

TABLE I - 6

OPTIMUM PERCENT ANNUAL LOAD

AS FUNCTION OF FUEL TYPE AND SOLAR REGION - 1976

Assumed Solar System: Tracking Parabolic Trough Collector

Solar Region		Fuel Type[1]	PE LCC[2] @ 15% $/10^6 Btu	Desired Temperature, °F 150	200	250	300	350	400	450	500	550
I	Direct Heat	C	0.71	-	-	-	-	-	-	-	-	-
		O	1.77	-	-	-	-	-	-	-	-	-
		G	2.22	-	-	-	-	-	-	-	-	-
	Indirect Heat	C	0.80	-	-	-	-	-	-	-	-	-
		O	1.98	-	-	-	-	-	-	-	-	-
		G	2.35	-	-	-	-	-	-	-	-	-
II	Direct Heat	C	0.60	-	-	-	-	-	-	-	-	-
		O	1.73	-	-	-	-	-	-	-	-	-
		G	1.52	-	-	-	-	-	-	-	-	-
	Indirect Heat	C	0.68	-	-	-	-	-	-	-	-	-
		O	1.93	-	-	-	-	-	-	-	-	-
		G	1.61	-	-	-	-	-	-	-	-	-
III	Direct Heat	C	0.58	-	-	-	-	-	-	-	-	-
		O	1.64	-	-	-	-	-	-	-	-	-
		G	0.97	-	-	-	-	-	-	-	-	-
	Indirect Heat	C	0.66	-	-	-	-	-	-	-	-	-
		O	1.84	-	-	-	-	-	-	-	-	-
		G	1.02	-	-	-	-	-	-	-	-	-

[1]C = Coal
O = Oil
G = Gas

[2]PE LCC = Present Equivalent Life-Cycle Cost in 1976 Dollars
- = Solar System is not competitive

TABLE I-6 (CONT'D)

OPTIMUM PERCENT ANNUAL LOAD

AS FUNCTION OF FUEL TYPE AND SOLAR REGION - 1976

Assumed Solar System: Tracking Parabolic Trough Collector

Solar Region		Fuel Type[1]	PE LCC[2] @ 15% \$/10⁶ Btu	Desired Temperature, °F 150	200	250	300	350	400	450	500	550
IV		C	0.58	-	-	-	-	-	-	-	-	-
	Direct	O	1.72	-	-	-	-	-	-	-	-	-
	Heat	G	1.37	-	-	-	-	-	-	-	-	-
		C	0.66	-	-	-	-	-	-	-	-	-
	Indirect	O	1.92	-	-	-	-	-	-	-	-	-
	Heat	G	1.45	-	-	-	-	-	-	-	-	-
V		C	0.49	-	-	-	-	-	-	-	-	-
	Direct	O	1.87	-	-	-	-	-	-	-	-	-
	Heat	G	1.61	-	-	-	-	-	-	-	-	-
		C	0.55	-	-	-	-	-	-	-	-	-
	Indirect	O	2.09	-	-	-	-	-	-	-	-	-
	Heat	G	1.71	-	-	-	-	-	-	-	-	-
VI		C	0.17	-	-	-	-	-	-	-	-	-
	Direct	O	2.14	79	75	65	55	45	39	35	31	26
	Heat	G	1.28	-	-	-	-	-	-	-	-	-
		C	0.19	-	-	-	-	-	-	-	-	-
	Indirect	O	2.39	83	79	72	68	56	51	40	38	34
	Heat	G	1.35	-	-	-	-	-	-	-	-	-

[1]C = Coal
O = Oil
G = Gas

[2]PE LCC = Present Equivalent Life-Cycle Cost in 1976 Dollars
\- = Solar system is not competitive

TABLE I-7

OPTIMUM PERCENT ANNUAL LOAD

AS FUNCTION OF FUEL TYPE AND SOLAR REGION - 1985

Assumed Solar System: Tracking Parabolic Trough Collector

Solar Region		Fuel Type[1]	PE LCC[2] @ 15% $/10^6 Btu	Desired Temperature, °F 150	200	250	300	350	400	450	500	550
I	Direct Heat	C	1.04	-	-	-	-	-	-	-	-	-
		O	3.25	-	-	-	-	-	-	-	-	-
		G	4.56	-	-	-	-	-	-	-	-	-
	Indirect Heat	C	1.18	-	-	-	-	-	-	-	-	-
		O	3.64	-	-	-	-	-	-	-	-	-
		G	4.82	52	38	29	23	17	15	14	13	11
II	Direct Heat	C	0.88	-	-	-	-	-	-	-	-	-
		O	3.17	-	-	-	-	-	-	-	-	-
		G	3.12	-	-	-	-	-	-	-	-	-
	Indirect Heat	C	0.99	-	-	-	-	-	-	-	-	-
		O	3.54	56	48	35	30	20	18	16	15	13
		G	3.31	-	-	-	-	-	-	-	-	-
III	Direct Heat	C	0.83	-	-	-	-	-	-	-	-	-
		O	3.01	-	-	-	-	-	-	-	-	-
		G	2.00	-	-	-	-	-	-	-	-	-
	Indirect Heat	C	0.94	-	-	-	-	-	-	-	-	-
		O	3.36	63	56	47	41	32	27	23	21	19
		G	2.12	-	-	-	-	-	-	-	-	-

[1]C = Coal
O = Oil
G = Gas

[2]PE LCC = Present Equivalent Life-Cycle Cost in 1976 Dollars
- = Solar system is not competitive

TABLE I-7 (CONT'D)

OPTIMUM PERCENT ANNUAL LOAD

AS FUNCTION OF FUEL TYPE AND SOLAR REGION - 1985

Assumed Solar System: Tracking Parabolic Trough Collector

Solar Region	Fuel Type[1]		PE LCC[2] @ 15% $/10^6 Btu	Desired Temperature, °F 150	200	250	300	350	400	450	500	550
IV		C	0.84	-	-	-	-	-	-	-	-	-
	Direct	O	3.16	66	59	50	45	35	30	27	24	20
	Heat	G	2.81	-	-	-	-	-	-	-	-	-
		C	0.95	-	-	-	-	-	-	-	-	-
	Indirect	O	3.53	71	63	58	53	47	41	36	32	25
	Heat	G	2.98	64	55	46	40	31	28	23	20	18
V		C	0.72	-	-	-	-	-	-	-	-	-
	Direct	O	3.44	76	69	65	61	57	52	44	39	35
	Heat	G	3.30	75	67	63	59	54	48	40	36	31
		C	0.82	-	-	-	-	-	-	-	-	-
	Indirect	O	3.85	79	73	70	67	64	60	53	49	43
	Heat	G	3.49	76	69	66	62	58	53	45	40	36
VI		C	0.23	-	-	-	-	-	-	-	-	-
	Direct	O	3.92	90	89	87	85	82	81	80	78	72
	Heat	G	2.62	85	81	77	73	68	61	51	47	40
		C	0.26	-	-	-	-	-	-	-	-	-
	Indirect	O	4.38	92	90	89	87	85	84	83	81	77
	Heat	G	2.78	87	83	79	77	71	70	60	55	48

[1] C = Coal
O = Oil
G = Gas

[2] PE LCC = Present Equivalent Life-Cycle Cost in 1976 Dollars
- = Solar system is not competitive

TABLE I-8

OPTIMUM PERCENT ANNUAL LOAD

AS FUNCTION OF FUEL TYPE AND SOLAR REGION - 2000

Assumed Solar System: Tracking Parabolic Trough Collector

Solar Region	Fuel Type[1]		PE LCC[2] @ 15% $/10^6 Btu	150	200	250	300	350	400	450	500	550
I		C	2.06	-	-	-	-	-	-	-	-	-
	Direct	O	9.59	75	72	70	66	62	59	55	51	46
	Heat	G	13.43	81	79	76	74	73	72	71	66	60
		C	2.33	-	-	-	-	-	-	-	-	-
	Indirect	O	10.72	77	75	72	69	66	63	60	56	51
	Heat	G	14.22	82	80	77	76	75	74	73	68	63
II		C	1.74	-	-	-	-	-	-	-	-	-
	Direct	O	9.35	84	82	80	78	76	74	73	70	65
	Heat	G	9.21	84	82	80	78	76	74	72	69	64
		C	1.96	-	-	-	-	-	-	-	-	-
	Indirect	O	10.45	86	84	82	79	78	77	75	73	69
	Heat	G	9.75	85	83	81	78	77	76	75	71	67
III		C	1.66	-	-	-	-	-	-	-	-	-
	Direct	O	8.87	87	86	84	83	78	77	75	73	71
	Heat	G	5.90	79	76	74	71	68	66	62	58	53
		C	1.87	-	-	-	-	-	-	-	-	-
	Indirect	O	9.92	89	88	86	84	81	78	76	74	72
	Heat	G	6.25	81	80	76	73	70	69	65	61	57

[1]C = Coal
O = Oil
G = Gas

[2]PE LCC = Present Equivalent Life-Cycle Cost in 1976 Dollars
- = Solar system is not competitive

TABLE I-8 (CONT'D)

OPTIMUM PERCENT ANNUAL LOAD

AS FUNCTION OF FUEL TYPE AND SOLAR REGION - 2000

Assumed Solar System: Tracking Parabolic Trough Collector

Solar Region	Fuel Type[1]		PE LCC[2] @ 15% $/10^6 Btu	150	200	250	300	350	400	450	500	550
IV	Direct Heat	C	1.68	-	-	-	-	-	-	-	-	-
		O	9.32	90	88	86	85	84	82	80	79	76
		G	8.29	88	87	85	83	81	80	78	76	73
	Indirect Heat	C	1.89	-	-	-	-	-	-	-	-	-
		O	10.41	91	89	87	86	85	83	82	81	79
		G	8.78	89	87	85	83	82	81	80	77	75
V	Direct Heat	C	1.43	-	-	-	-	-	-	-	-	-
		O	10.15	92	90	89	87	85	84	83	81	79
		G	9.73	91	89	88	86	84	83	82	81	78
	Indirect Heat	C	1.61	-	-	-	-	-	-	-	-	-
		O	11.39	93	91	89	87	86	85	84	82	80
		G	10.31	92	90	88	86	85	84	83	81	79
VI	Direct Heat	C	0.46	-	-	-	-	-	-	-	-	-
		O	11.55	96	96	95	94	93	93	92	91	90
		G	7.73	95	94	93	92	91	90	89	89	88
	Indirect Heat	C	0.52	-	-	-	-	-	-	-	-	-
		O	12.91	97	96	95	95	94	94	93	92	91
		G	8.19	95	94	93	92	91	90	90	89	88

[1]C = Coal
O = Oil
G = Gas

[2]PE LCC = Present Equivalent Life-Cycle Cost in 1976 Dollars
\- = Solar system is not competitive

To summarize the process heat data, a table of specific process heat applications in specific processes included in the data base has been prepared together with the required process temperature and the total national annual use of process heat for each application. This table is Table I-9.

To present the data in a compact fashion in another format, they have been put into the form of a cumulative process heat spectrum, which shows the percent of industrial process heat used as a function of terminal process temperature required. This cumulative process heat spectrum is shown in Figure I-4. Particularly interesting is the percent of process heat needed at terminal process temperatures below a temperature of 212°F (100°C)--about 7-1/2 percent--which could perhaps be provided by low-temperature solar thermal energy systems, and the percent of process heat needed below a temperature of 550°F (288°C)--about 28 percent--which could perhaps be provided by concentrating solar collectors.

Two observations should be noted about the terminal-termperature spectrum in Figure I-4. First, the temperature indicated is from the point of view of the process requirement, as opposed to the temperature of the present heat-delivering medium, which may be much higher--and the greater the difference between the process temperature and the temperature of the heat-delivering medium, the greater is the amount of lost work or inefficiency in the heat-transfer process.

Second, in getting the temperature of the heat-delivering medium or the process material itself, up to the terminal temperature, part of the heat may well be supplied by solar at a lower temperature as preheat. Thus, solar should be able to supply a greater percentage of the process heat required at a particular temperature than is shown by the terminal-temperature curve. To evaluate the possibility of using solar as a preheat, the terminal-temperature curve was recalculated with the assumption that the amount of heat for each application could

TABLE I-9

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
1. Iron Ore-1011				
Pelletizing of Concentrates	2350-2500	1288-1371	37.2	39.2
2. Copper Concentrate-1021				
Drying	250*	121	1.7	1.8
3. Bituminous Coal-1211				
Drying (including lignite)	150-220*	66-104	18.	19.
4. Sand & Gravel-1442			None	
5. Potash-1474				
Drying Filter Cake	250*	121	1.03	1.09
6. Phosphate Rock-1475				
Calcining	1400-1600	760-871	0.71	0.75
Drying	450*	232	10.5	11.1
7. Sulfur-1477				
Frasch Mining	325-340	163-171	60.	63.
8. Meat Packing-2011				
Sausages & Prepared Meats-2013				
Scalding, Carcass Wash, and Cleanup	140	60	43.7	46.1
Singeing Flame	500	260	1.06	1.12
Edible Rendering	200	93	0.52	0.55
Smoking/Cooking	155	68	1.16	1.22
9. Poultry Dressing-2016				
Scalding	140	60	3.16	3.33
10. Natural Cheese-2022				
Pasteurization	170	77	1.28	1.35
Starter Vat	135	57	0.02	0.02
Make Vat	105	41	0.47	0.50
Finish Vat	100	38	0.02	0.02
Whey Condensing	160-200	71-93	10.2	10.8
Whey Drying	120*	49	2.94	3.10
Process Cheese Blending	165	74	0.07	0.07

TABLE I-9(Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
11. Condensed & Evaporated Milk-2023				
Stabilization	200-212	93-100	2.93	3.09
Evaporation	160	71	5.20	5.48
Spray Drying	350-400	177-204	3.58	3.78
Sterilization	250	121	0.54	0.57
12. Fluid Milk-2026				
Pasteurization	162-170	72-77	1.44	1.52
13. Canned Specialities-2032				
Beans				
Precook (Blanch)	180-212	82-100	0.40	0.42
Simmer Blend	170-212	77-100	0.24	0.25
Sauce Heating	190	88	0.20	0.21
Processing	250	121	0.38	0.40
14. Canned Fruits and Vegetables-2033				
Blanching/Peeling	180-212	82-100	1.88	1.98
Pasteurization	200	93	0.15	0.16
Brine Syrup Heating	200	93	1.02	1.08
Commercial Sterilization	212-250	100-121	1.67	1.76
Sauce Concentration	212	100	0.44	0.46
15. Dehydrated Fruits and Vegetables-2034				
Fruit and Vegetable Drying	165-185	74-85	5.84	6.16
Potatoes				
Peeling	212	100	0.33	0.35
Precook	160	71	0.47	0.50
Cook	212	100	0.47	0.50
Flake Dryer	350	177	1.09	1.15
Granule Flash Dryer	550	288	1.09	1.15

TABLE I-9(Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
16. Frozen Fruits and Vegetables-2037				
Citrus Juice Concentration	190	88	1.33	1.40
Juice Pasteurization	200	93	0.27	0.28
Blanching	180-212	82-100	2.26	2.38
Cooking	170-212	77-100	1.41	1.49
17. Wet Corn Milling-2046				
Steep Water Evaporator	350	177	3.66	3.86
Starch Dryer	120*	49	3.03	3.20
Germ Dryer	350	177	1.92	2.03
Fiber Dryer	1000	538	2.93	3.09
Gluten Dryer	350	177	1.32	1.39
Steepwater Heater	120	49	0.77	0.81
Sugar Hydrolysis	270	132	1.89	1.99
Sugar Evaporator	250	121	2.74	2.89
Sugar Dryer	120*	49	0.16	0.17
18. Prepared Feeds-2048				
Pellet Conditioning	180-190	82-88	2.28	2.40
Alfalfa Drying	400*	204	16.8	17.7
19. Bread & Baked Goods-2051				
Proofing	100	38	0.84	0.89
Baking	420-460	216-238	6.40	6.75
20. Cane Sugar Refining-2062				
Mingler	125-165	52-74	0.59	0.62
Melter	185-195	85-91	3.30	3.48
Defecation	160-185	71-85	0.44	0.46
Revivification	750-1110	399-599	3.96	4.18
Granulator	110-130	43-54	0.44	0.46
Evaporator	265	129	26.39	27.84

TABLE I-9(Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
21. Beet Sugar-2063				
Extraction	140-185	60-85	4.63	4.88
Thin Juice Heating	185	85	3.08	3.25
Lime Calcining	1000	538	2.98	3.14
Thin Syrup Heating	212	100	6.68	7.05
Evaporation	270-280*	132-138	30.8	32.5
Granulator	150-200	66-93	0.15	0.16
Pulp Dryer	230-280*	110-138	16.5	17.4
22. Soybean Oil Mills-2075				
Bean Drying	160	71	4.05	4.27
Toaster Desolventizer	215	102	6.08	6.41
Meal Dryer	350*	177	4.36	4.60
Evaporator	225	107	1.62	1.71
Stripper	212	100	0.30	0.32
23. Animal and Marine Fats-2077				
Continuous Rendering of Inedible Fat	330-350	166-177	16.5	17.4
24. Shortening and Cooking Oil-2079				
Oil Heater	160-180	71-82	0.72	0.76
Wash Water	160-180	71-82	0.12	0.13
Dryer Preheat	200-270	93-132	0.60	0.63
Cooking Oil Reheat	200	93	0.32	0.34
Hydrogenation Preheat	300	149	0.37	0.39
Vacuum Deodorizer	300-400	149-204	0.35	0.37
25. Malt Beverages-2082				
Cooker	212	100	1.53	1.61
Water Heater	180	82	0.53	0.56
Mash Tub	170	77	0.60	0.63
Grain Dryer	400*	204	9.18	9.68
Brew Kettle	212	100	3.98	4.20
26. Distilled Liquor-2085				
Cooking (Whiskey)	212	100	3.16	3.33
Cooking (Spirits)	320	160	6.27	6.61
Evaporation	250-290*	121-143	2.32	2[illegible]
Dryer (Grain)	300-400	149-204	1.94	2[illegible]
Distillation	230-250	110-121	7.69	8.11

TABLE I-9 (Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
27. Soft Drinks-2086				
Bulk Container Washing	170	77	0.21	0.22
Returnable Bottle Washing	170	77	1.27	1.34
Nonreturnable Bottle Warming	75-85	24-29	0.43	0.45
Can Warming	75-85	24-29	0.52	0.55
28. Cigarettes-2111				
Drying	220*	104	0.43	0.45
Rehumidification	220*	104	0.43	0.45
29. Tobacco Stemming & Redrying-2141				
Drying	220*	104	0.50	0.26
30. Finishing Plants, Cotton-2261				
Washing	200	100	15.4	16.2
Dyeing	200	100	4.5	4.7
Drying	275	135	22.2	23.4
31. Finishing Plants, Synthetic-2262				
Washing	200	93	35.9	37.9
Dyeing	212	100	15.2	16.0
Drying and Heat Setting	< 275	135	23.2	24.5
32. Logging Camps-2411			None	
33. Sawmills & Planing Mills-2421				
Kiln Drying of Lumber	300	149	63.4	66.9
34. Plywood-2435				
Plywood Drying	250	121	50.6	53.4
35. Veneer-2436				
Veneer Drying	212	100	57.8	61.0

TABLE I-9 (Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
36. Wooden Furniture-2511				
Makeup Air and Ventilation	70	21	5.7	6.0
Kiln Dryer and Drying Oven	150	66	3.8	4.0
37. Upholstered Furniture-2512				
Makeup Air and Ventilation	70	21	1.4	1.5
Kiln Dryer and Drying Oven	150	66	0.9	0.9
38. Pulp Mills-2611				
Paper Mills-2621				
Paperboard Mills-2631				
Building Paper-2661				
Pulp Digestion	370	188	253	267
Pulp Refining	150	66	175	185
Black Liquor Treatment	280	138	164	173
Chemicals Recovery-Calcining	1900	1038	96	101
Pulp and Paper Drying	290	143	383	404
39. Solid and Corrugated Fiber Boxes-2653				
Corrugating and Glue Setting	300-350	149-177	21.6	22.8
40. Alkalies & Chlorine-2812				
Mercury Cell (to be phased out by 1983)			6.4	6.8
Diaphragm Cell	350	177	82.1	86.6
41. Cyclic Intermediates-2865				
Ethylbenzene	350	177	3.	3.
Styrene	250-350	121-177	35.	37.
Phenol	250	121	0.45	0.47
42. Alumina-28195				
Digesting, Drying, Heating	280	138	113.2	119.4
Calcining	2200	1204	35.3	37.2

TABLE I-9 (continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr
43. Plastic Materials and Resins-2821				
Polystyrene, suspension process				
Polymerizer Preheat	200-215	93-102	0.102	0.107
Heating Wash Water	190-200	88-93	0.064	0.068
Drying	200	93	0.034	0.036
44. Synthetic Rubber-2822				
Cold SBR Latex Crumb				
Bulk Storage	80-100	27-38	0.179	0.189
Emulsification	80-100	27-38	0.086	0.091
Blowdown Vessels	130-145	54-63	0.865	0.912
Monomer Recovery by Flashing & Stripping	120-140	49-60	4.095	4.319
Dryer Air Temperature	150-200	66-93	3.663	3.864
Cold SBR, Oil-Carbon Black Masterbatch				
Dryer Air Temperature	150-200	66-93	0.506	0.534
Oil Emulsion Holding Tank	80-100	27-38	0.028	0.030
Cold SBR, Oil Masterbatch				
Dryer Air Temperature	150-200	66-93	1.09	1.15
Oil Emulsion Holding Tank	80-100	27-38	0.090	0.095
45. Cellulosic Man-made Fibers-2823				
Polyester	< 550	< 288	48.9	51.6
Nylon	≤ 535	< 279	41.7	44.0
Acrylic	< 250	< 121	23.5	24.8
Polypropylene	< 540	< 282	3.9	4.1
46. Noncellulosic Fibers-2824				
Rayon	< 212	< 100	37.8	39.9
Acetate	< 212	< 100	37.6	39.7
47. Pharmaceutical Preparations-2834				
Autoclaving & Cleanup	250	121	18.85	19.88
Tablet & Dry-capsule Drying	250	121	1.00	1.05
Wet Capsule Formation	150	66	0.05	0.05

TABLE I-9 (Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
48. Soaps and Detergents-2841				
Soaps:				
Various Processes in Soap Manufacture	180	82	0.50	0.53
High-temperature Processes	490	254	0.002	0.002
Spray Drying	500*	260	0.001	0.001
Detergents:				
Various Low-temperature Processes	180	82	0.36	0.38
High-temperature Processes	500	260	0.001	0.001
Drum-Dried Detergents	350*	177	0.31	0.33
Spray-Dried Detergents	500*	260	0.019	0.020
49. Organic Chemicals, N.E.C.-2869				
Ethanol	200-250	93-121	6.	6.
Isopropanol	200-350	93-177	11.	12.
Cumene	250	121	1.	1.
Vinyl Chloride Monomer	250-350	121-177	9.	9.
50. Urea-2873215				
High-Pressure Steam-Heated Stripper	375	191	5.07	5.35
Low-Pressure Steam-Heated Stripper	290	143	0.89	0.94
51. Explosives-2892				
Dope (Inert Ingredients)				
Drying	300	149	0.006	0.006
Wax Melting	200	93	0.118	0.124
Nitric Acid Concentrator	250	121	0.070	0.074
Sulfuric Acid Concentrator	200	93	0.027	0.028
Nitric Acid Plant	200	93	0.223	0.235
Blasting Cap Manufacture	200	93	0.016	0.017

TABLE I-9(Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
52. Petroleum Refining-2911				
Crude distillation				
Atmospheric topping	650	343	275	290
Vacuum distillation	440-800	227-427	183	193
Thermal operations	555-1010	291-543	154	162
Catalytic cracking	1125	607	447	471
Delayed coking	900	482	225	237
Hydrocracking	515-810	268-432	91	96
Catalytic reforming	925	496	498	525
Catalytic hydrorefining	700	371	52	55
Hydrotreating	700	371	124	131
Alkylation	45-340	7-171	59	62
Hydrogen plant	1600	871	124	131
Olefins and aromatics	1200	649	124	131
Lubricants	Unavailable	--	25	26
Asphalt	"	--	96	101
Butadiene	250-350	121-177	60	63
53. Paving Mixtures-2951				
Aggregate Drying	275-325*	135-163	88.1	92.9
Heating Asphalt	325	163	4.93	5.20
54. Asphalt Felts & Coatings-2952				
Saturator	400-500	204-260	1.52	1.60
Asphalt Coating	300-400	149-204	1.23	1.30
Drying (Steam)	350	177	3.32	3.50
Sealant	300-400	149-204	0.57	0.60
55. Tires and Inner Tubes-3011				
Vulcanization	250-340	121-171	6.18	6.52
56. Plastics Products-3079				
Blow-molded Bottles				
High-Density Polyethylene	425	218	3.52	3.71

TABLE I-9 (Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
57. Leather Tanning and Finishing-3111				
Bating	90	32	0.094	0.099
Chrome Tanning	85-130	29-54	0.060	0.063
Retan, Dyeing, Fat Liquor	120-140	49-60	0.15	0.16
Wash	120	49	0.034	0.036
Drying	110*	43	2.05	2.16
Finishing Drying	110*	43	0.13	0.14
58. Flat Glass-3211				
Melting	2300-2700	1260-1482	50.1	52.8
Fabrication (including Tempering and Laminating)	1470-2000	799-1093	3.5	3.7
Annealing	930	499	5.9	6.2
59. Glass Containers-3221				
Melting-Firing	2700-2900	1482-1593	98.60	104.0
Conditioning	1500-2000	816-1093	42.25	44.56
Annealing	1200	649	12.81	13.51
Post Forming	1200	649	1.42	1.50
60. Hydraulic Cement-3241				
Drying	275-325*	135-163	8.0	8.
Calcining	2300-2700	1260-1482	468.0	494.
61. Brick and Structural Tile-3251				
Brick kiln	2500	1371	70.4	74.2
62. Clay Refractories-3255				
Refractories firing	3300	1816	9.0	9.5
63. Concrete Block-3271				
Low-Pressure Curing	165*	74	12.29	12.96
Autoclaving	360	182	5.42	5.72
64. Ready-Mix Concrete-3273				
Hot Water for Mixing Concrete	120-190	49-88	0.34	0.36
65. Lime-3274				
Calcining	1800	982	129.9	137.0
66. Gypsum-3275				
Kettle Calcining	330	166	10.0	10.5
Wallboard Drying	300	149	11.18	11.79

TABLE I-9 (Continued)

LIST OF INDUSTRIAL PROCESS HEAT

APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr
67. Treated Minerals-3295				
Expanded Clay & Shale				
Bloating Process	1800	982	29.1	30.7
Fuller's Earth				
Drying & Calcining	1100	593	6.37	6.72
Kaolin				
Calcining	1900	1040	1.4	1.5
Drying	230*	110	12.7	13.4
Expanded Perlite				
Drying	160*	71	0.22	0.23
Expansion Process	1600	871	1.7	1.8
Barium				
Drying	230*	110	0.34	0.36
68. Blast Furnaces and Steel Mills-3312				
High-Temperature Uses	2700	1482	3300	3480
69. Ferrous Castings				
Gray Iron Foundries-3321 (73% of heat)				
Malleable Iron Foundries-3322 (10% of heat)				
Steel Foundries-3323 (17% of heat)				
Melting in Cupola Furnaces	2700	1482	146	154
Mold and Core Preparation	300-475	149-246	117.7	124.1
Heat Treatment and Finishing	900-1800	482-982	16	17
Pickling	100-212	38-100	151	160
70 Primary Copper-3331				
Smelting and Fire-Refining	2000-2500	1095-1371	32.58	34.37
71. Primary Zinc-3333				
Pyrolytic Reduction	2400	1300	1.0	1.1
72. Primary Aluminum-3334				
Prebaking anodes	2000	1093	8.14	8.59
73. Galvanizing-3479				
Cleaning, Pickling	130-190	54-88	0.011	0.012
Galvanizing (melting zinc)	850	454	0.014	0.015

TABLE I-9 (Continued)

LIST OF INDUSTRIAL PROCESS HEAT

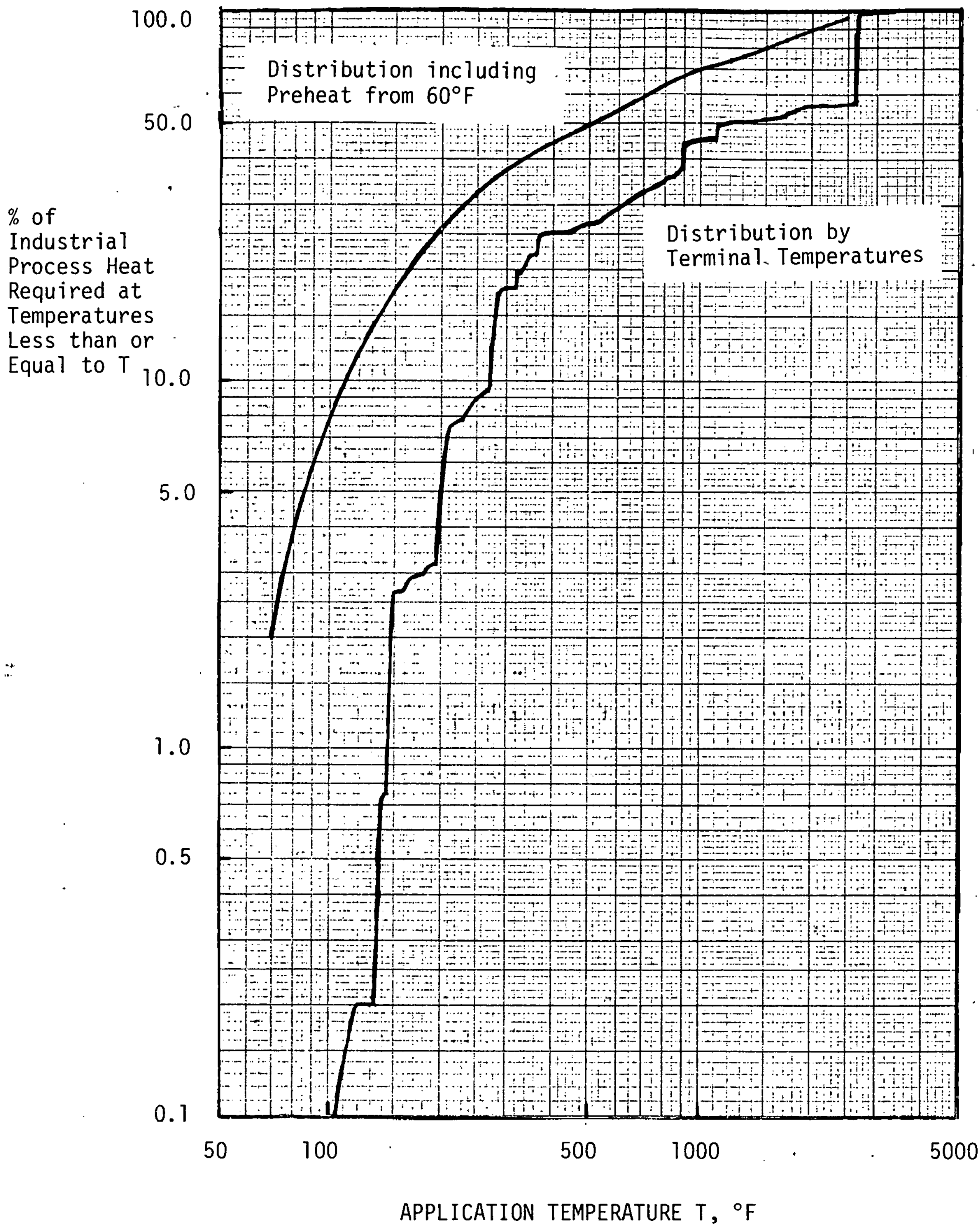
APPLICATIONS AND ANNUAL REQUIREMENTS (1974) FOUND FROM SURVEY

Industry - S.I.C. Group	Application Temperature Requirement °F	°C	Process Heat Used for Application 10^{12} Btu/Yr.	10^{12} kJ/Yr.
74. Motors and Generators-3621				
Drying and Preheat	150	66	0.043	0.045
Baking	350	177	0.133	0.140
Oxide Coat Laminations	1500-1700	816-927	0.72	0.76
Annealing	1500	816	0.67	0.71
75. Motor Vehicles-3711				
Baking-Prime and Paint Ovens	250-300	121-149	0.29	0.31
Casting Foundry	2650	1454	23.	24.
76. Inorganic Pigments-2816				
Drying Chrome Yellow	200	93	0.075	0.079

* No special temperature required; requirement is simply to evaporate water or to dry the material.

FIGURE I-4

CUMULATIVE DISTRIBUTION OF PROCESS HEAT REQUIREMENTS



be supplied over a temperature range from a base of 60°F (16°C) up to the terminal temperature required. It should be possible to visualize a method of utilizing preheat in some manner in essentially every application. This heat distribution curve which allows for the use of preheat shows that, based on the data sample used to calculate the curve, preheat up to 212°F, (100°C) could supply about 27 percent of industrial process heat, and preheat up to 550°F (288°C) about 52 percent.

Although these two curves indicate that there appears to be a sizable potential market for solar thermal energy systems for industrial process heat, the actual impact of solar thermal energy will be a function of many variables. Such variables include energy recovery opportunities, particularly in industries which use and have available high-temperature heat; economics of solar thermal energy systems, design considerations in actually applying such systems, and nontechnical issues. Other tasks in this project address these other variables.

Finally, to illustrate the composition of the data base by industry, Table I-10 shows the amount of process heat included in the data base for each 2-digit SIC group, with SIC groups 10-14 lumped together in the mining industry.

8. Assessment of Potential Applications of Solar Process Heat

Each application in the data base in which solar process heat could potentially be used was analyzed for the potential impact of solar. This analysis was done quantitatively according to the procedure in 6. above, and a table showing the results of this analysis is included in the discussion of the 4-digit SIC group or subindustry. The analysis showed how much process heat could be supplied by solar for the application, depending on location (solar region) and time frame.

To illustrate the potential impact of solar process heat upon each industry, the application analyses for each 2-digit SIC group were summed. A summary of

TABLE I-10

SUMMARY OF PROCESS HEAT DATA BASE BY INDUSTRY

SIC Group	Industry	Process Heat Included Within Data Base 10^{12} Btu	10^{12} kJ
10-14	Mining	129.14	136.22
20	Food & Kindred Products	318.93	336.41
21	Tobacco Products	1.36	1.43
22	Textile Mills	116.40	122.78
23	Apparel		
24	Lumber & Wood Products	171.80	181.21
25	Furniture	11.8	12.45
26	Paper & Allied Products	1,092.60	1,152.47
27	Printing & Publishing		
28	Chemicals	534.17	563.44
29	Petroleum Products	2,636.67	2,781.16
30	Rubber	9.70	10.23
31	Leather	2.52	2.66
32	Stone, Clay & Glass	990.94	1,045.24
33	Primary Metals	3,772.42	3,979.15
34	Fabricated Metal Products	0.03	0.03
35	Machinery		
36	Electrical Equipment	1.57	1.66
37	Transportation	23.29	24.57
38	Instruments		
39	Miscellaneous		
	TOTAL	9,813.34	10,351.11

these industry assessments, to show the potential for solar process heat by industry in the data base for the different time frames of interest, is shown in Table I-11. This table points out where solar process heat would appear to have the most potential in industries whose applications appear in the data base. Potential applications of solar process heat are to be found virtually across the board with respect to major industry. Comments and discussion with respect to the feasibility of individual applications of solar process heat are found in each profile of a specific 4-digit SIC group or subindustry.

Finally, the assessment tables for all of the application analyses were totaled for the entire data base. The summary is shown in Table I-12. Of course, since the data base represents only 59.1 percent of the total use of process heat in industry, the results in Table I-12 must be scaled up to estimate the impact on industry as a whole.

Thus, in 1985 solar should have the potential to supply 0.59×10^{15} Btu (0.62×10^{15} kJ) of process heat. In 2000, solar should be able to provide 7.27×10^{15} Btu (7.67×10^{15} kJ). This detailed assessment of the potential of solar process heat has been made only for those applications whose terminal temperature falls within the range which can be provided by solar.

As indicated by Figure I-4, which shows the cumulative process heat temperature spectrum with the assumption of preheat, a significantly larger proportion of process heat is used at a given temperature than is indicated by the terminal-temperature spectrum. The potential of solar to provide preheat must be significant, and it is an important potential use of solar because by undergirding the process heat demand with low-temperature solar heat, solar can save high-quality fossil fuels. However, this potential is difficult to assess quantitatively. Many variables are involved, including the opportunity for economic waste heat recovery in a given process and industry which have high-temperature waste heat available.

TABLE I-11

SUMMARY OF ASSESSMENT OF SOLAR PROCESS HEAT POTENTIAL BY INDUSTRY FOR DATA BASE

SIC Group	Industry	Solar Process Heat Potential - 10^{12} Btu/Yr Time Frame 1976	1985	2000
10-14	Mining	0.05	1.49	42.84
20	Food & Kindred Products	0.51	42.87	291.86
21	Tobacco Products		0.03	3.48
22	Textile Mills		2.05	162.22
23	Apparel			
24	Lumber & Wood Products	0.10	22.35	199.96
25	Furniture		1.30	25.02
26	Paper & Allied Products	0.27	118.92	1,847.94
27	Printing & Publishing			
28	Chemicals	0.22	83.40	1,003.90
29	Petroleum Products	0.06	54.84	403.00
30	Rubber		0.46	9.42
31	Leather		0.10	1.90
32	Stone, Clay & Glass	0.06	8.86	94.24
33	Primary Metals		13.00	209.36
34	Fabricated Metal Products		0.004	0.06
35	Machinery			
36	Electrical Equipment		0.01	0.13
37	Transportation Equipment		0.01	0.14
38	Instruments			
39	Miscellaneous			
	TOTAL	< 1.27	349.69	4,295.47

To obtain a quick estimate of the order of magnitude of solar's potential to provide preheat economically, however, the assumption can be made that solar can provide the same fraction of the required preheat under 550°F (288°C) that solar can provide for applications whose terminal temperature is less than this limit. In the year 2000, the cost of fossil fuels will be high enough that the main limitation on solar potential is technical (such as providing more, cheaper storage) and not with respect to either temperature or cost of competing fuels (except coal, of course). After all, for preheat solar will be competing against fossil fuels on the same basis as it competes against fossil fuels to provide terminal heat within its range of capability.

Thus, in 2000 solar can provide 7.27×10^{15} Btu (7.67×10^{15} kJ) or 70 percent of the 10.4×10^{15} Btu (11.0×10^{15} kJ) needed for applications at less than 550°F (288°C). Of the additional 8.6×10^{15} Btu (9.1×10^{15} kJ) required for preheat below this limit, solar can perhaps provide 70 percent or about 6.0×10^{15} Btu (6.3×10^{15} kJ). As noted, there is a certain degree of uncertainty associated with this estimate.

Thus, the total potential for solar process heat in industry in the year 2000 is about 13.3×10^{15} Btu (14.0×10^{15} kJ) or about 36 percent of the total use of process heat (36.6×10^{15} Btu, 38.6×10^{15} kJ) in that year.

9. Conceptualized Designs of Solar Process Heat Systems

The design of a solar process heat system and the integration of a solar thermal energy system with a conventional fuel backup system are influenced by a number of considerations. Some of these influences are due to process operational requirements and process materials. The characteristics of the various solar thermal energy systems also play a part in designing integrated energy supply

TABLE I-12

QUANTITATIVE ASSESSMENT OF POTENTIAL OF SOLAR PROCESS HEAT FOR DATA BASE

YEAR	SOLAR REGION	TOTAL PROCESS HEAT DEMAND FOR APPLICATIONS * BTU	OIL TOTAL DEMAND	OIL SOLAR HEAT * BTU	GAS TOTAL DEMAND	GAS SOLAR HEAT * BTU	TOTAL SOLAR HEAT * BTU
1976	I	0.524	0.123	0.000	0.285	0.000	0.000
	II	0.694	0.126	0.000	0.419	0.000	0.000
	III	0.414	0.041	0.000	0.245	0.000	0.000
	IV	0.721	0.056	0.000	0.621	0.000	0.000
	V	0.354	0.012	0.000	0.338	0.000	0.000
	VI	0.028	0.003	0.001	0.025	0.000	0.001
YEARLY TOTALS		2.736	0.360	0.001	1.934	0.000	0.001
1985	I	0.704	0.165	0.000	0.383	0.000	0.000
	II	0.894	0.162	0.000	0.540	0.000	0.000
	III	0.590	0.059	0.000	0.349	0.000	0.000
	IV	0.996	0.078	0.033	0.858	0.000	0.033
	V	0.524	0.017	0.010	0.501	0.283	0.293
	VI	0.036	0.003	0.003	0.032	0.021	0.024
YEARLY TOTALS		3.744	0.484	0.046	2.662	0.304	0.350
2000	I	1.164	0.272	0.178	0.633	0.470	0.648
	II	1.379	0.250	0.193	0.833	0.644	0.837
	III	1.112	0.111	0.089	0.657	0.446	0.535
	IV	1.738	0.136	0.114	1.496	1.227	1.341
	V	1.049	0.035	0.030	1.002	0.855	0.885
	VI	0.053	0.005	0.005	0.048	0.044	0.049
YEARLY TOTALS		6.495	0.808	0.609	4.669	3.687	4.295

* QUADRILLION BTU

systems for industrial processes. Because the performance of solar energy systems is influenced by climate, climate also plays a part in determining system design as well as the impact of solar thermal energy upon the process heat requirements for a particular industry.

The requirements of the process obviously play a major role in determining how solar thermal energy systems may be used to provide process heat. The temperature level of the required heat determines the type of solar system that conceivable could be used. Not only is the level important, but so is the required temperature tolerance. The amount of solar energy collected is a function of time and varying conditions of insolation; it is a function of the time during the day, the time of the year, and the weather conditions. Thus, the termperature of the heat collected is also a function of these variables, and for a process requiring closely controlled temperature conditions, an elaborate control system may be required to provide a constant-temperature source of heat to the process.

Integration of solar systems with conventional heat-supplying systems can be accomplished by a number of methods, and the process heat requirements have to be analyzed carefully to see how this integration can best be accomplished for an individual application. Because solar energy is an intermittent energy source, an auxiliary energy storage system is generally needed, depending on the requirements of the process. Many industrial processes are continuous and operate around the clock. It may be more efficient to operate the process continuously, or it may be difficult or costly to shut the process down intermittently. In this case, the solar thermal energy system must have a certain amount of storage associated with it and an adequate backup system to supply the needed heat continuously.

The characteristics of the various systems for collecting solar thermal energy also may influence the method by which a solar energy system is integrated into a process. For example, an ordinary flat-plate collector typically supplies hot air or hot water, but if the need is for steam at above atmospheric pressure, a concentrating type of system with a different type of storage is required. The integration of a steam-supplying concentrating system into a process may be quite different from the way a hot-water-supplying collector would be used. If very high-temperature heat is required, a solar furnace may be used. However, extensive process modification might be required because of the characteristics of the solar furnace--the relatively small area in which the energy is available and the requirements of the tracking system, for example. Also, energy storage is a significant problem in the case of a solar furnace.

Although all of these influences--and others--must be considered in developing a design for a specific application, it is possible to conceive of basic generalized designs which would be suitable for many diverse applications. The same type of process operation--e.g., heating a liquid or a gas, drying a solid, providing steam, etc.--is common to many processes, although the hot liquid or gas, or steam may then be used in many ways. If designed as a plant utility system to provide simply the hot liquid, hot gas, hot air, or steam, a solar process heat system design should find numerous applications in many different processes and industries.

This is the basic philosophy behind the effort in this study to develop generalized designs of solar process heat systems, including the method by which the solar system is integrated with the conventional fuel system used for backup. Seven basic generalized system designs were developed in this project, including a design for a system to: 1) preheat boiler feedwater, 2) preheat combustion air, 3) provide once-through hot water, 4) heat process liquid, 5) heat process gas, 6) provide hot air, and 7) provide steam. In each case, a schematic block diagram has been drawn for the system, including the controls and the interface with the conventional fuel system. The operation of each system is described and analyzed. A specific example for an application is discussed, as well as potential problems which might be involved in operating the system.

The underlying purpose in developing these designs is to stimulate the thinking of potential industrial users of solar energy, who may then adapt these designs to their own particular applications and requirements.

10. Identification of Nontechnical Issues

There are a number of nontechnical issues associated with the widespread use of solar thermal energy systems. Many of these issues have been assessed previously with particular reference to the use of solar systems for the heating and cooling of buildings. The literature commenting upon these issues is routinely oriented to the use of solar energy in general, as opposed to its use for industrial process heat. Nevertheless, nearly all of the issues relating to the use of solar energy in general may be applied to the industrial context. Accordingly, each nontechnical issue is discussed according to its influence on the widespread implementation of solar energy in general and, where appropriate, on its particular use for industrial process heat. In addition, industrial solar systems present other issues which must be identified and assessed. The influence of each issue is analyzed to the extent that it may provide either an incentive or a disincentive to such implementation.

Central among the economic and financial issues affecting the use of solar thermal energy is the comparatively high initial system cost, coupled with a certain degree of public and institutional inertia. The amortization of a system's cost over its anticipated useful life, however, improves the competitive merit of solar energy usage in many installations. This competitive margin can be extended, however, and the degree of public acceptability enhanced, by reducing the effective system cost through the use of a variety of financial incentives applying to manufacturers as well as consumers. Although other nontax financial mechanisms are available such as direct subsidies or outright grants, incentives may be readily employed within the nation's existing tax structure through the use of such traditional mechanisms as tax credits, accelerated depreciation and tax abatement. The relative cost of solar energy use may also be reduced through the use of similar mechanisms to increase the cost of competitive energy sources such as fossil fuels. Other suggested financial incentives include government-assisted or low-interest loans, mandated life-cycle costing and government-guaranteed markets. In short, many mechanisms are available to implement policy decisions favoring the use of financial incentives to spur the development of widespread use of solar energy in industry.

The growing implementation of solar technology also creates a host of legal, environmental and institutional issues. Of the several or so broad areas of legal inquiry which have been identified as related to the industrial use of solar energy, it would appear that several will require a degree of specialized societal response and planning, while the remainder may well resolve themselves without such intensive effort. The former category would include issues concerned with: the establishment and protection of solar rights; the development of effective programs of standardization and certification for solar energy systems and components; and the resolution of labor-related issues engendered by the new solar technology. Other legal issues, such as those pertaining to the fields of antitrust, public liability, and certain public utilities matters, are somewhat independent of the peculiar solar-related technologies, and are expected to be resolved in a somewhat more *laissez-faire* fashion.

On balance, it appears that the general environmental effects of widespread solar usage would be highly beneficial. Due primarily to the decreased reliance on fossil fuels, these beneficial effects will include the reduced emission of airborne pollutants and the greater degree of flexibility which may be allowed for industrial siting as a result of the availability of the option to use solar energy. Although the land-use, demographic and other environmental effects of large-scale solar development have not yet been fully explored in the literature, it would appear that a similarly beneficial environmental impact could be anticipated to emerge from that scenario as well.

Institutions of all kinds, including governmental, educational and financial, possess a growing awareness of the need to deal with solar energy usage, and they are responding to that awareness in positive directions. Governments at many levels are sponsoring and encouraging solar energy usage; educational institutions are beginning to nourish the public's growing need for information regarding this new energy source; and the financial community is overcoming its initial inertia of conservatism by becoming more fully informed on the technology itself, as well as on such important evaluation techniques as life-cycle costing. The report explores the current status of these institutional attitudes, and outlines many of the directions in which such institutional efforts appear to be headed.

In this study, the nontechnical issues which may influence the use of solar thermal energy to provide industrial process heat have been identified. Critical issues which may impede or even prevent such use can then be investigated further and perhaps resolved before they begin to hinder the installation of solar systems which otherwise would be technically feasible. In addition, it is imperative to identify potential constraints and pitfalls in applying solar energy to specific processes because the failure of inappropriately applied solar energy systems would have a significant negative impact on the acceptance of such systems during the near-future trial period. In other words, the potential for failure of these systems must be minimized if the potential for widespread application of solar energy systems is to be maximized in the near future. The effort on identification of critical nontechnical issues was directed towards this end.

C. Conclusions

1. Our collector performance calculations have shown that for equal solar fractions, greater than 2.5 times more collector area is required in Region I than in Region VI. Looked at another way, for equal collector areas a substantially greater solar fraction can be expected in Region VI than in Region I. Since the collector area versus solar fraction curve is nonlinear, it is difficult to generalize with respect to the expected increase in performance. These results lead one to expect that solar energy for process heat will first become economical in Regions IV, V and VI with Region VI being the best.

2. One of the significant conclusions of our results is that for all temperatures greater than 125°F (52°C), the polar-axis mounted, single-axis tracking concentrating collectors gave a far superior performance to all other collectors evaluated. In particular, the parabolic trough type collector with its low loss coefficient looked especially good at temperatures greater than about 250°F (121°C) and even at 500°F (260°C) was providing significant amounts of energy (> 300 kBtu/ft^2/yr, 3,400 MJ/m^2/yr) in many regions.

In a number of cases, we found it necessary to develop thermal models of the performance of concentrating collectors. In addition, collector efficiency data in cases where they existed did not extend over the range of temperatures considered in our study. Furthermore, very little work on systems conceptual design has been done using these collectors. In view of the superior performance of these collectors, we strongly recommend further work in these areas.

3. Below delivery temperatures of about 175°F (79°C), the best performing flat-plate collector deserves serious consideration. Our calculations have shown a single-glazed collector with a black chrome selective surface to be the best performing and most cost-effective flat-plate collector. The lower cost of this collector in comparison with the concentrating collectors may allow it to produce less costly energy at these temperatures.

4. An interesting result of our calculations is that on a relative basis, the polar-axis mounted, single-axis tracking concentrating collectors compared with the best flat-plate collector look better in Region I than in Region VI. This is contrary to intuition which would guess that the higher proportion of diffuse radiation in Region I would tend to make the flat-plate collector look relatively better. It appears that this effect arises because of the relatively lower ambient temperatures in the northern regions combined with the lower heat-loss coefficient of the concentrating collector.

5. At temperatures of less than approximately 125°F (52°C), a shallow solar pond appears to be the most economical solar system in Regions IV, V and VI. This is the case because of the higher ambient temperatures and lower latitude angles in these regions and because of the much lower installed cost of solar ponds than any other solar system (by a factor of about 2).

6. To provide process heat for its production processes, industry--including manufacturing and mining--consumed 16.6 quadrillion Btu (17.5 quadrillion kJ) in 1974 as heat delivered to processes, either directly or in the form of steam. This usage of process heat is expected to increase to 23.0 quadrillion Btu (24.3 quadrillion kJ) in 1985 and 36.6 quadrillion Btu (38.6 quadrillion kJ) in 2000.

7. As the result of a detailed survey of the uses of process heat by specific application, a total of 59 percent of the use of process heat has been characterized by specific application including required process temperature.

8. Put into the form of a spectrum of cumulative process heat requirements as a function of terminal process temperature required, the survey data indicate that 7-1/2 percent of process heat is used below 212°F (100°C), and 28 percent is used below 550°F (288°C), which is taken in the study as the highest practical temperature which can be reached by a concentrating solar collector system having practical potential to provide a significant amount of process heat.

9. If the assumption is made that all heat involves preheat of some material in some way or other, then 27 percent of process heat is used at 212°F (100°C) or below, and 52 percent is used at 550°F (288°C) or below.

10. A quantitative assessment of the potential of solar thermal energy systems to provide process heat technically, practically and economically indicates that solar has a maximum potential to provide 0.6 quadrillion Btu (0.6 quadrillion kJ) per year in 1985, and 7.3 quadrillion Btu (7.7 quadrillion kJ) per year in 2000--for applications having a maximum required temperature of 550°F (288°C).

11. If the potential opportunity for economic waste heat recovery is not considered, then solar has an additional maximum potential to provide 6.0 quadrillion Btu (6.3 quadrillion KJ) per year in 2000 as preheat of some material in some way or other.

12. On the basis of a simple life-cycle cost analysis in competition with the cost of fossil fuels, solar process heat provided by a tracking parabolic trough collector system might be cost effective now in competition with oil heat in the region of the country with the highest insolation (Arizona and New Mexico).

13. By 1985, solar process heat should be cost competitive with oil in all locations in indirect heat applications and some locations in direct heat applications.

14. By 2000, solar process heat should be able to compete with the fuel cost of oil and gas anywhere in any application.

15. Because the cost of coal is not expected to escalate as rapidly as the cost of oil or natural gas, solar process heat does not appear to be able to compete against the fuel cost of coal even in 2000.

16. Specific industries which should have significant potential for solar process heat for a variety of reasons include food, textiles, chemicals and primary metals. Lumber and wood products, and paper and allied products also appear to have significant potential but these industries also have the potential to use great quantities of self-generated fuels which solar would have to compete with.

17. However, good potential applications for solar process heat can be found across the board thoughout industry.

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UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545

MAY 23 1977

Doris Brooks, TIC
Oak Ridge Operations

Dear Doris:

We found the reproducible copy of Intertechnology report entitled "Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat," number COO/2829-76/1, at the patent reviewers office in Germantown, Maryland.

As we discussed on the telephone, only Volume I is for distribution to UC-59b, with a notification that Volumes II and III are available at the appropriate price. Information regarding the place of purchase should be included.

We would appreciate having a small supply (20-25 copies) of Volume I for both the ITC report (COO/2829-76/1) and the Battelle report (TID-27348) for local distribution.

Your cooperation is very much appreciated.

Sincerely,

Bill

William W. Auer
Program Manager
Agricultural & Industrial Process Heat Branch
Division of Solar Energy

Bill Auer 376-9455

Number as ↓ or COO/2829-1 for Vol 1, -2 for Vol 2, -3 for Vol 3.

I ckd w/Auer on 6/1/77 and he ok'd the numbering (the ITC contract is dead) ∴ the 3 parts will be numbered -1, -2, -3.

Auer says its cleared for patents, if not you call back & he will send it. OK to print & MF

OK to Unlimited

add Footnote for Vols II & III in Table of Contents. Avail. from NTIS as Report COO/2829-76/1 Vols II & III

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C. Bruce: Vol. 2 and 3 of this report are not to be printed; they will be fiched and sent to NTIS for sale as fiche blowback or paper copy. Please add following note to Table of Contents in Volume 1. (Under Vol II ...)