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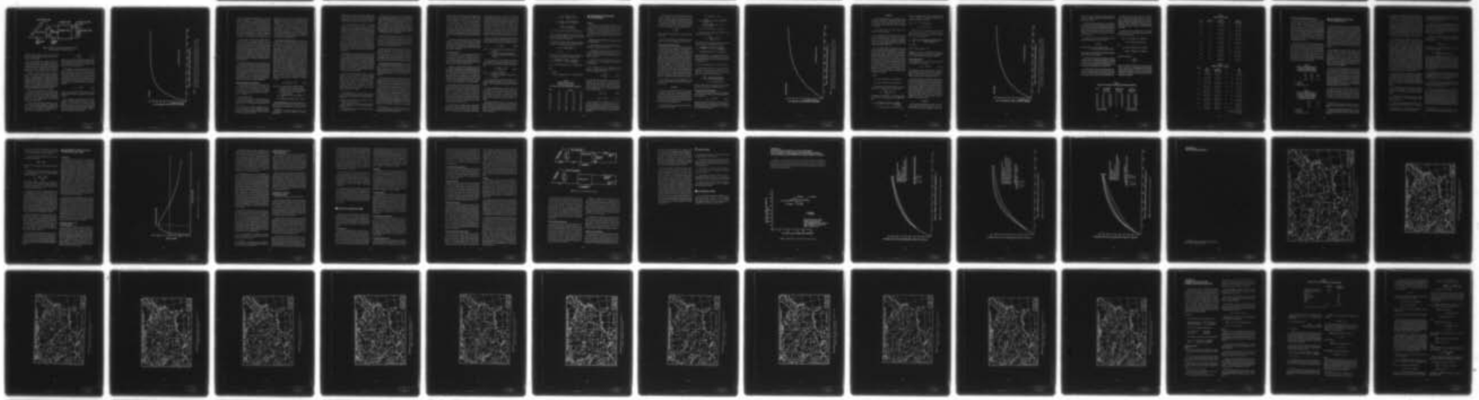

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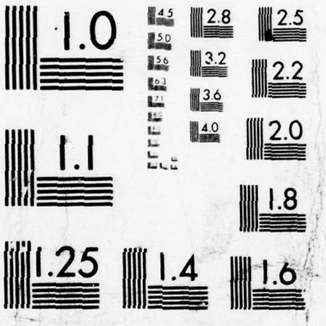

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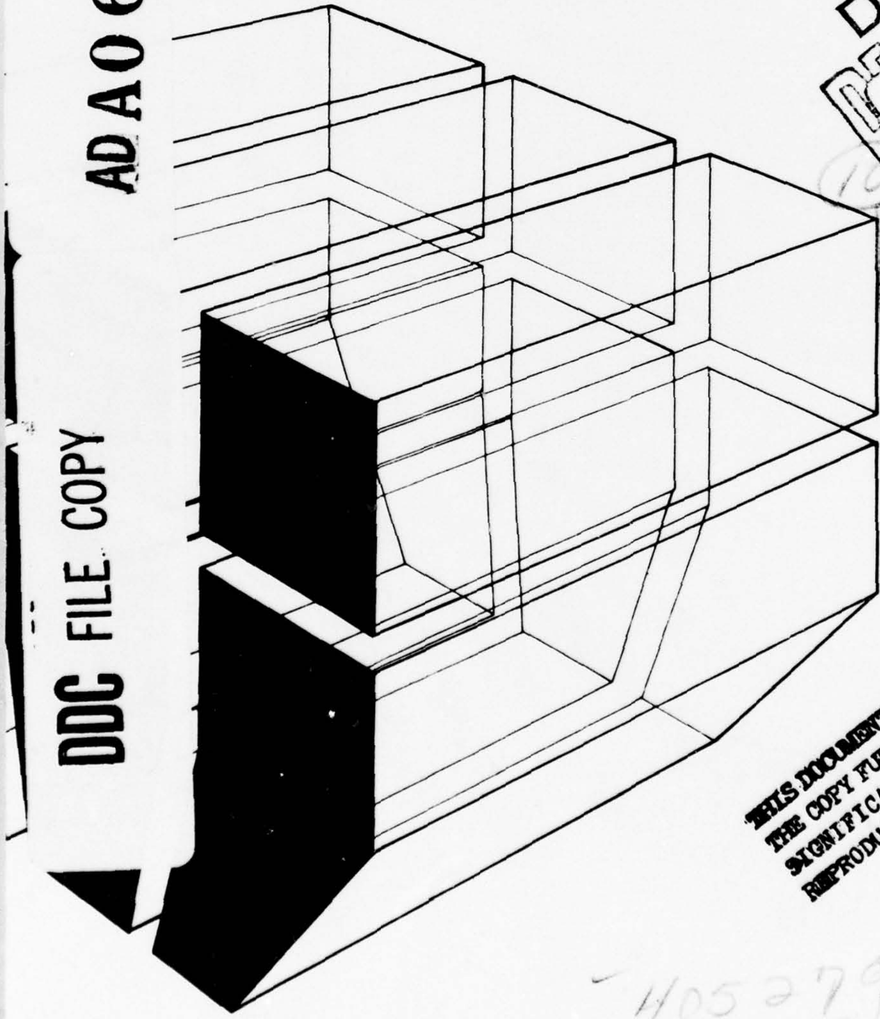

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This report presents a method for making an energy and an economic cost/benefit analysis of solar energy systems. A graphical method is presented for evaluating the performance of solar domestic hot water systems, solar heating systems, and solar heating and cooling systems. Methods for selecting the optimum collector area based on benefit-to-cost ratio and for systematically making detailed design calculations using the Building →

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Block 20 continued.

Loads Analysis and System Thermodynamics (BLAST) computer simulation program are also presented. Practical considerations for solar system designs are discussed.

The methods presented provide the required accuracy for both initial evaluations and final design calculations. Examples are provided throughout the text to aid in using the methods described.

FOREWORD

This work was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task T6, "Energy Systems"; Work Unit 021, "Solar Energy for Heating and Cooling of Buildings." Mr. S. Hiratsuka, DAEN-MCE-U, served as the OCE Technical Monitor.

This study was performed by the Energy and Habitability Division (EH), U.S. Army Construction Engineering Research Laboratory (CERL). Mr. R. G. Donaghy is Chief of EH.

Appreciation is expressed to Mr. Sheng-dar Lee for assistance in preparing the universal curves, and to Mr. L. Randal Rippy for his contribution to the development of the example problems.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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DESIGN OF SOLAR HEATING AND COOLING SYSTEMS

1 INTRODUCTION

Background

The technical feasibility of heating and cooling buildings using flat-plate solar collectors has been established both in theory and practice. Although improvements in component and system design are forthcoming, one can approach solar heating and cooling technology with full confidence that a practical, reliable system can be constructed. The construction phase of solar systems requires little more skill than is presently required to install conventional heating and cooling systems; the design phase, however, is considerably more complex.

Sunlight is inherently an intermittent source of energy at the earth's surface. For this reason, solar energy systems for heating domestic hot water or for heating and cooling buildings are not and frequently cannot be designed to meet the full demands of the building or buildings being served. System design is therefore uncoventional in that solar energy supplies some but not all of the building's energy requirements. The fundamental problem in analyzing solar energy systems is determination of the collector array area which will provide the greatest cost benefit in meeting the highest fraction of the building's energy load. In the past, because of the uncontrolled nature of solar energy, extensive and costly computer studies (taking into account hourly weather data from the site in question) have been required to evaluate proposed solar projects and to design solar energy systems. The tools used for these studies have generally been proprietary and thus not available to Corps of Engineers Districts. Those which have been available have generally been difficult to use and are not ready for general use by design engineers.

Hence, there is a basic need for a simple, convenient method for making the necessary design calculations and for assessing energy and economic benefits. In particular, simplified techniques for making preliminary energy and economic analyses are needed to minimize the number of expensive computer studies required. Where computer studies are required, user-oriented computer programs are necessary.

Objective

The objective of this study was to develop and field test a straightforward procedure that would allow District Engineers to perform energy and cost benefit analysis as well as final design calculations for individual solar energy system applications. The procedure would permit (1) preliminary solar energy system performance assessment from charts and graphs, and (2) the computer-aided evaluations of solar energy system performance necessary for final design. The procedure was to be applicable to solar domestic hot water, solar heating only, and to heating and cooling systems. This report describes how to use the graphical and computer tools developed in response to the study objective.

Approach

The approach used in this research consisted of the following steps:

1. Develop a computer simulation program for analyzing the performance of solar energy systems.

2. Use the solar simulation program to determine the performance of typical solar systems in meeting predetermined hourly building loads at each of five sites in the continental United States using hourly incident radiation data.

3. Study the effects on solar system performance of varying solar system design parameters (including collector area, collector tilt angle, storage tank volume, and heat exchanger effectiveness).

4. Based on the results of the parametric studies, develop a graphical method for estimating solar system performance.[1,2]

5. Develop a user-oriented computer simulation program for making rigorous solar system performance calculations during the final design phases.[3]

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[1] D. C. Hittle, D. F. Holshouser, and G. N. Walton, *Interim Feasibility Assessment Guidance for Solar Heating and Cooling of Army Buildings*, Technical Report E-91/ADA026588 (U.S. Army Construction Engineering Research Laboratory [CERL], May 1976).

[2] D. C. Hittle, G. N. Walton, D. F. Holshouser, and D. J. Leverenz, *Predicting the Performance of Solar Energy Systems*, Technical Report E-98/ADA035608 (CERL, January 1977).

[3] D. C. Hittle, *Building Loads Analysis and System Thermodynamics (BLAST) Program: Vol I, Users Manual*, Technical Report E-119/ADA048734 (CERL, November 1977); and *Building Loads Analysis and System Thermodynamics (BLAST) Program: Vol II, Reference Manual*, Technical Report E-119/ADA048982 (CERL, December 1977).

6. Develop recommended procedures for using the graphical and computer simulation techniques for making solar system energy and economic analyses, and for optimizing solar system designs based on the highest benefit-to-cost ratio.

7. Field test the graphical and computer procedures for making a solar system energy and economic analysis at a Corps District to insure that the procedures are clear and user-oriented, and that the original input data are available.

8. Publish the graphical and computer procedures, modified after the field test, as an Engineer Technical Letter.

Organization of Report

Chapter 2 introduces the graphical method for computing expected performance of solar collector arrays, and Chapter 3 presents examples of its use. Chapter 4 describes a method for optimizing the solar energy system on the basis of highest benefit-to-cost ratio. Chapter 5 describes the computer-aided method for solar energy systems which is recommended for performing design calculations on larger projects. Chapter 6 outlines some practical considerations relevant to the application of solar technology.

Mode of Technology Transfer

The evaluation procedures and information in Chapters 2 through 6 will be furnished to District and Facilities Engineers as an Engineer Technical Letter.

2 THE UNIVERSAL SOLAR SYSTEM PERFORMANCE CURVE–A GRAPHICAL APPROACH

Introduction

During the development of a solar system simulation model and design methodology, the U.S. Army Construction Engineering Research Laboratory (CERL) performed several hundred solar system simulations for typical Army buildings in various parts of the country. Analysis of the solar system performance curves for these systems indicated that with proper normalization, the performance of a given solar system for the various buildings in all locations could be represented by a single universal performance curve.

Figure 1 is a schematic of the type of system studied in developing the universal curve. Solar radiation, when available, is converted to thermal energy at the collector and storage pumps. The heat exchanger, which isolates the collection and storage loops, allows the collector fluid to be freeze-protected. Normal operation of this system permits heating of the storage tank whenever sufficient solar energy is available.

Heat is taken from the tank by the load pump whenever there is a demand for heat, whether it is at a heating coil or at the generator of an absorption air conditioner. As shown, this system is representative of a large class of liquid solar energy systems, and all the simulations run at CERL were based on such a system.

The universal curve may be consulted to determine the overall performance of the system pictured in Figure 1. Three such curves are presented in this report: one for solar domestic hot water, one for solar heating only, and one for solar heating and cooling applications. It should be pointed out that the development of these curves was based on several assumptions. First, a single-cover, flat-plate collector with an emissivity of .10 and an absorptivity of .90 was used as the reference collector. The tilt of these collectors from the horizontal depended on the particular application. For solar domestic hot water, this angle was assumed to be equal to the latitude; for solar space heating, the angle was taken as the latitude plus 10 degrees; for solar heating and cooling, it was latitude minus 10 degrees. These collection tilt angles were found to be near optimum for these applications. All collectors were unshaded and facing south. The heat exchanger effectiveness was taken to be .8, and the storage tank held 16 lb of water per square foot of collector (78 kg/m^2 or about 2 gal/sq ft). The tank insulation had an "R" value of 19. (These values of heat exchanger effectiveness, tank volumes, and tank insulation were considered reasonable for this type of system.) Line losses were assumed to be negligible in all cases.

While variations in all these parameters will affect system performance (see Appendix A), it was found that the assumed collector efficiency is by far the dominant factor. A method for adjusting collector area for types other than the reference collector is presented in Chapter 3. Variations in the other parameters can be evaluated in the final design phase using the computer simulation model (see Chapter 5). Since one purpose of this report is to present a simple method to be used for

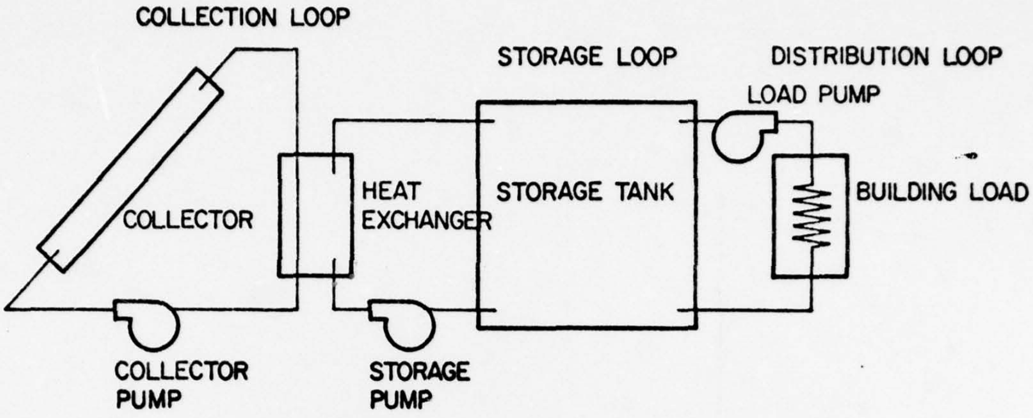

Figure 1. Schematic of the liquid solar energy system used in the development of the universal curves.

feasibility studies, explicit correction factors for the effects of varying parameters other than the collector type have been excluded.

Use of the universal curves requires calculation of building energy loads and compilation of on-site weather data. Once this information is available, the curve relates solar system performance to the collector array area. In order to apply the curve, however, an understanding of the following terms is required:

1. Annual or monthly incident solar radiation flux density, Q_c. This is the solar flux density on the tilted collector array in Btu/square foot/month or Btu/square foot/year (langleys/month or langleys/year). Solar radiation data are normally given in terms of horizontal radiation densities. Thus, these numbers must be corrected for the tilt angle of the collector array. The method for making these corrections is presented in the *Solar Radiation Data* section of this chapter.

2. Annual and monthly energy requirements, Q_L. For the purposes of the universal curve, these energy requirements are defined as the total thermal energy in the form of hot water required by the building's domestic hot water heating system, space heating system, or absorption chiller.

3. Solar system performance parameter, P_s. The solar system performance parameter is defined as the ratio of annual (or monthly) radiation incident on the collector array to the annual (or monthly) energy requirements of the building, as given by Eq 1:

$$P_s = \frac{Q_c A_c}{Q_L} \qquad \text{[Eq 1]}$$

where A_c is the collector area. This quantity is essentially a measure of the available solar energy (incident on the collector array of the system in question) compared to the total energy required.

4. Percentage of the energy requirements met by solar, ρ. This term is the fraction of Q_L met by the solar energy system. The quantity ρ may be calculated from the appropriate universal curve of solar system performance. Figure 2 shows the form of this curve for solar domestic hot water. From the figure, it can be seen that the relationship between P_s and ρ allows calculation of the solar system performance. For domestic hot water,

$$\rho = 1 - e^{-.78 P_s^{.93}}. \qquad \text{[Eq 2]}$$

Closed form expressions of the universal curve for solar heating and cooling and solar heating only are given in Chapter 3.

As an example of the application of the method, consider a 200-man barracks in Topeka, KS, which requires 1.73×10^9 Btu (1.83×10^9 kJ) of energy annually to heat hot water. Use of the universal curve permits determination of the percentage of this load which can be met by 2400 sq ft (223 m^2) of collectors tilted at 39 degrees from the horizontal.

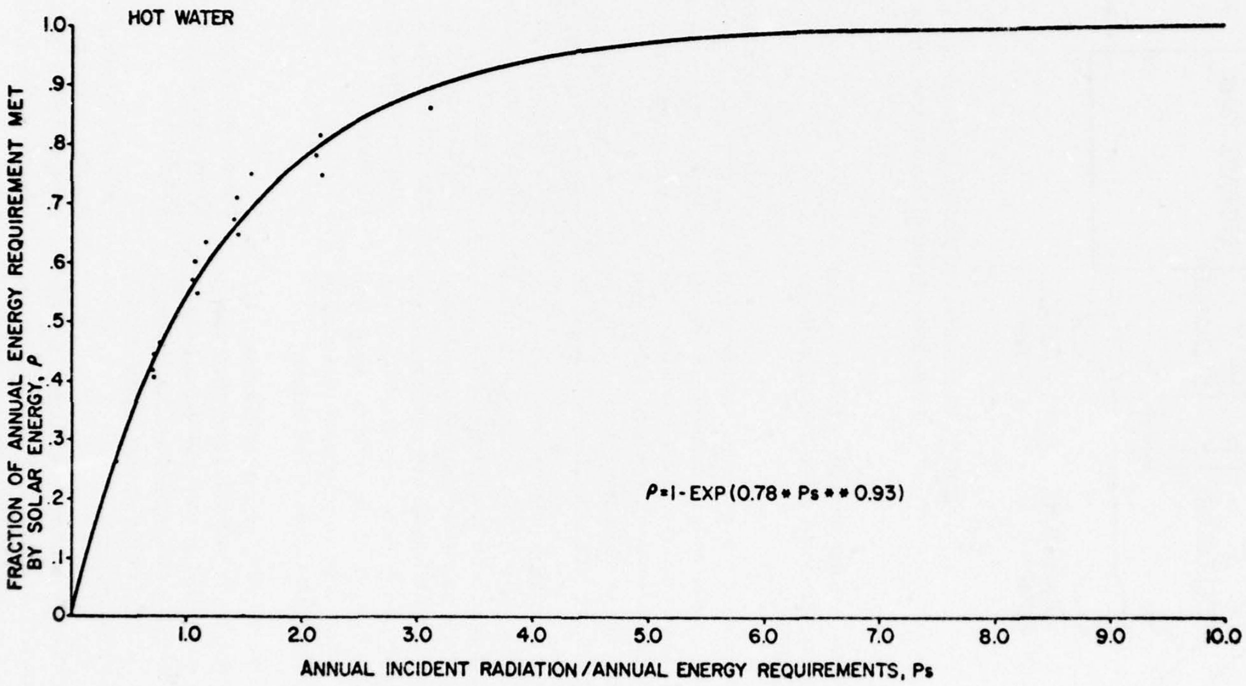

Figure 2. Universal curve for solar domestic hot water. (From D. C. Hittle, G. N. Walton, D. F. Holshouser, and D. J. Leverenz, *Predicting the Performance of Solar Energy Systems*, Technical Report E-98/ADA035608 [CERL, January 1977]).

The solar radiation flux density, Q_c, on a collector tilted at 39 degrees is 6.0×10^5 Btu/sq ft (6.8×10^6 kJ/m^2). (The method for obtaining solar flux density on a tilted surface is described in the *Solar Radiation Data* section.) From Eq 1, $P_s = .83$; from Eq 2, ρ is .48. Thus, 2400 sq ft (223 m^2) of collector would meet 48 percent of the load; i.e., the collector array would supply $(.48)(1.73 \times 10^9$ Btu$) = 8.3 \times 10^8$ Btu (8.8×10^8 kJ), and the auxiliary system would have to supply the remaining 9.0×10^8 Btu (9.5×10^8 kJ) of hot water by means of a conventional hot water heating system.

If the efficiency of the auxiliary energy supply system (an oil boiler, for example) is 80 percent, the solar energy system would save 1.04×10^9 Btu (1.10×10^9 kJ) of fuel energy. If the heating value of oil is 138,000 Btu/gal (38,464 kJ/ℓ) at a cost of \$0.50/gal (\$0.14/ℓ), the annual dollar savings would be \$3,768. This savings could be used to offset the capital cost of the solar system. With this information, an economic cost benefit analysis of this candidate solar system can be made. The procedure can be repeated for different collector areas until the collector area giving the maximum cost benefit is found.

It should be pointed out that there is another class of solar systems which operate by warming and circulating air through the collectors rather than water. These, however, are not as widely used as liquid solar energy systems. (Air systems have been used with some success in residential-scale solar domestic hot water and heating-only applications, but are not suited for solar air-conditioning.) A study comparing the liquid and air systems has shown that for these heating applications, the performance of the two is almost identical.[4]

Obtaining Required Input Information

As the example in the previous section shows, two sets of input information in addition to collector area are required to use the universal curve: the thermal energy demand, Q_L, and the radiation flux density, Q_c. The following sections describe how this information can be obtained.

Energy Consumption Data

The type of data required to determine Q_L and the sources of that data depend on the type of system being considered. Since solar energy systems produce thermal energy in the form of hot water, consumption or energy requirements in any other terms—such as kilowatt hours supplied to or required by a centrifugal chiller, Btu's of chilled water required, gallons of oil or cubic feet of gas supplied to a boiler, or gallons of hot water used—must be converted to thermal energy in the form of hot water (or hot air if a hot air system is used.) This usually requires taking into account the efficiency of conversion equipment as well as the appropriate conversion factors. Determination of Q_L for the three types of systems is described below.

Solar Domestic Hot Water System. To use the universal curve for domestic hot water systems, the annual energy needed for heating the hot water is required. For the purpose of designing a solar energy system, the best source of this information is metered data from the building in question or from an identical or similar building at the same location. Metered consumption data for either energy or fuel input to the hot water heater or gallons of hot water consumed can be used. When fuel consumption is known, corrections for boiler efficiency must be taken into account as discussed above. When actual consumption data cannot be obtained, data can be derived from various handbooks (such as the section "Plumbing" in TM 5-810-1[5]) or from local or national plumbing codes. However, care must be exercised in using data from these sources, since they are usually developed for design purposes and thus are often more closely related to *peak* demand than to *average* hot water consumption. Whichever method is used, if annual hot water demand is determined, the annual energy consumption is obtained from Eq 3:

$$Q_L = DwC_p(T_{out} - T_{in}) \qquad \text{[Eq 3]}$$

where Q_L = annual energy consumption in Btu(J)
D = annual hot water demand in gal (ℓ)
w = density of water = 8.33 lb/gal (1.00 kg/ℓ)
C_p = specific heat of water = 1 Btu/1bm °F (4.1868 kJ/kg °K)
T_{out} = temperature of hot water supply in °F (°C)
T_{in} = temperature of supply water in °F (°C)

Solar Heating Systems. Solar energy incident upon a collector array in the summer is of little use for solar space heating the following winter. For this reason, the

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[4] George O. G. Löf, "Heating of Buildings with Solar Energy," *Solar Heating and Cooling of Buildings*, Vol 3, Joint Conference Proceedings of American Section, International Solar Energy Society and the Solar Energy Society of Canada, K. W. Böer, ed. (August 15-20, 1976).

[5] *Mechanical Design: Heating, Ventilating and Air Conditioning Changes 1-5*, TM 5-810-1 (Department of the Army, January 1956).

universal curve for solar heating must be applied on a monthly basis only for those months when a space heating load occurs. This, in turn, requires that the monthly energy demand for the heating be obtained.

Once again, the best source of data for estimating the amount of heat energy required for a particular building or set of buildings is measured data for the building in question or for similar or identical buildings at the same location. These data may only be available in terms of the amount of fuel oil used per month or the amount of gas consumed in heating the particular building or buildings. If so, the fuel consumption data must be adjusted to account for the efficiency of the boiler or furnace supplying the heat in the space. Typically, solar heating systems include both heating the building and the domestic hot water for the building. This can be accounted for in the energy requirement by adding the monthly domestic hot water load to the heating load.

If measured data for the building being considered are not available, the building's heating energy demand can be estimated using one of several methods. One such method, described in a CERL report entitled *Energy Utilization Index Method for Predicting Building Energy Use,*[6] provides a manual procedure to compute monthly and annual heating and cooling loads. This procedure was developed from extensive computer simulations and uses readily available building descriptions and weather data as its input.

The Carrier Rational Energy Analysis Procedure (REAP)[7] is another method for calculating building heating requirements. This is a modified bin method[8] which requires the calculation of heating loads at several different design points of the system. These loads, combined with frequency of occurrence of weather conditions, which can be obtained from Air Force Manual 88-8,[9] provide an estimate of the monthly energy requirements for heating.

Another source of loads data is the output from energy analysis computer programs such as the Building Loads Analysis and System Thermodynamics (BLAST) program.[10] Loads information obtained from a computer simulation of the building under construction could be used for the solar system analysis. However, if such a simulation had not been performed during the design phase, the additional effort required to prepare a building input deck would probably not be warranted for a solar energy feasibility study alone.

Montly energy consumption for domestic hot water heating, which is generally included in a solar heating system, can be determined by applying the methods described in the preceding section on a montly basis. It should be noted that measured data often have domestic hot water and space heating combined.

Design day calculations alone *cannot* be used to obtain heating loads, since they provide peak energy demands rather than the average demand required for estimating monthly energy consumption. Therefore, the methods for determining heating loads described in the ASHRAE *Handbook of Fundamentals* or in the Department of the Army's TM 5-810-1 should be avoided.

Solar Heating and Cooling Systems. The universal curve for solar heating and cooling systems is an annual curve, since there is a year-round demand for energy. The Q_L required is the sum of the heating and cooling energy requirements (plus the domestic hot water heating energy requirement if it is to be included in the system).

The annual energy required for heating and cooling is again best determined from measured data for the building in question or a similar or identical building at the same location. In determining the energy required for cooling, attention must be given to the differences in the coefficients of performance (COP) of the various chillers involved. For example, if measuring the consumption of electricity for a conventional chiller in the building indicates that 1,000,000 kWh are used annually, then this number must first be converted to Btu's by multiplying the 3412, giving 3.41×10^9 Btu (or converted to kilojoules by multiplying by 3600, giving 3.60×10^9 kJ), and then multiplied by the centrifugal chiller's mean COP. If the mean COP is 4, 13.6×10^9 Btu/yr (14.3×10^9 kJ/yr) are required to be delivered

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[6] L. M. Windingland and D. C. Hittle, *Energy Utilization Index Method for Predicting Building Energy Use*, Vols I & II, Interim Report E-105/ADA039913 and ADA040344 (CERL, May 1977).

[7] *Rational Energy Analysis Procedure (REAP)* (Carrier Air Conditioning Company, undated).

[8] *ASHRAE Handbook of Fundamentals* (American Society of Heating, Refrigerating and Air Conditioning Engineers [ASHRAE], 1972).

[9] *Engineering Weather Data*, AFM 88-8, Chapter 6 (Department of the Air Force, 1976).

[10] D. C. Hittle, *Building Loads Analysis and System Thermodynamics (BLAST) Program: Users Manual*, Technical Report E-119/ADA048734 (CERL, December 1977).

by the chiller to the cooling system. This chilled water demand, when divided by the COP of a solar energy system's absorption chiller (say .65) indicates that 21.0×10^9 Btu (22.2×10^9 kJ) must be supplied to the absorption chiller to meet the annual energy required for cooling. Since heating and cooling systems may also include domestic hot water heating, total demand for heat energy for heating domestic hot water can be summed with the total demand for heating and added to the annual demand for cooling energy in order to determine the annual building energy requirement, Q_L.

If measured consumption data are not available, the energy use index method, REAP method, or BLAST simulation program described in the previous section can be used to determine annual heating and cooling loads. Again, calculations based on peak cooling loads should not be performed.

Solar Radiation Data

The tilt angle of the collector plate greatly affects the amount of solar radiation striking the surface of the plate. Most measured and reported data are for solar radiation incident upon a horizontal surface. This section describes where to obtain this information and how to correct it for tilted collector arrays.

Average solar radiation data for many sites around the country are published in the National Oceanic and Atmospheric Administration's (NOAA) *Climatic Atlas of the United States.* Annual and monthly solar radiation maps from this document are reproduced in Appendix B. Since the radiation values on these maps are given in daily means, the annual and monthly values are obtained by multiplying by the number of days in the year or month, depending on the map being used.

The *Climatic Atlas of the United States* also contains tabulated summaries of radiation data for specific sites. More detailed summaries are frequently available from NOAA or from local weather services or state agencies. Data for the particular site in question should be obtained, if possible, since incident solar radiation frequently varies substantially over relatively small geographical distances. This is particularly true in coastal regions and in regions near mountains, where local climatological variations are severe.

Once the collector tilt angle is known, the radiation flux density on the tilted collector surface can be determined from horizontal radiation data. Fortunately, there is an optimum collector tilt angle (measured from horizontal) for each type of system. For heating and cooling systems, this optimum tilt angle, υ_c, is roughly the location latitude minus 10 degrees; for heating-only systems, it is roughly the latitude plus 10 degrees; and for domestic hot water systems, it is roughly equal to the latitude. These angles provide for collection of the greatest amount of solar energy in each application. Variations of ± 5 degrees affect performance only slightly. In all cases the optimum azimuth angle is due south and again, slight deviations from due south (± 10 degrees) do not significantly reduce system performance.

Once the optimum tilt angle has been determined, the annual or monthly radiation flux density, Q_c, on the optimally tilted surface can be estimated from Eq 4:

$$Q_c = KH_\upsilon \qquad \text{[Eq 4]}$$

where K = a correction factor depending on the collector tilt

H_υ = the annual or monthly radiation flux density on a horizontal surface (Btu/sq ft or J/m^2).

For solar systems for which annual solar radiation data are used (i.e., heating and cooling or domestic hot water), the correction factor, K, is given approximately by

$$K = \frac{\cos(\upsilon_L - 7 - \upsilon_c)}{\cos(\upsilon_L - 7)} \qquad \text{[Eq 5]}$$

where υ_L = the latitude in degrees

υ_c = the optimum angle from the horizontal in degrees.

Eq 5 is an empirically derived equation based on the results of simulation studies and is valid only for near-optimum collector tilt angles and annual solar radiation data.

For solar heating applications, where monthly radiation figures must be used, the correction factor may not be expressed in closed form. In this case, K must be determined from Table 1, which gives monthly values of this correction factor for four different latitudes. Table 1 is valid only for optimum collector tilt angles.

Recalling the example on page 11, the annual radiation for Topeka, KS, was found as follows: the annual radiation level on a horizontal surface obtained from Figure B1 of Appendix B is 380 langleys/day. The latitude, υ_L (also from Figure B1), is 39. Using Eqs 4 and 5, Q_c can be found.

$$Q_c = KH_\upsilon = \frac{\cos(\upsilon_L - 7 - \upsilon_c)}{\cos(\upsilon_L - 7)} H_\upsilon$$

$$Q_c = \frac{\cos(39 - 7 - 39)}{\cos(39 - 7)} \left(\frac{380 \text{ langleys}}{\text{day}}\right) \left(\frac{365 \text{ day}}{\text{yr}}\right) \left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$Q_c = 6.0 \times 10^5 \text{ Btu/sq ft/yr } (6.8 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

As an example of applying the monthly correction factor used for heating-only systems, find the solar radiation for January in Topeka, KS.

From Table 1, K is estimated by interpolation between 35 degrees and 40 degrees latitude for January. Thus,

$$K = 1.84 + \left(\frac{2.12 - 1.84}{40^\circ - 35^\circ}\right) \times 4^\circ$$

$$K = 2.06$$

From Figure B2 of Appendix B, the mean daily horizontal radiation in January is 190 langleys. Hence,

$$H_\upsilon = \left(\frac{190 \text{ langleys}}{\text{day}}\right) \left(\frac{31 \text{ days}}{\text{mo}}\right) \left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$H_\upsilon = 2.2 \times 10^4 \text{ Btu/sq ft/mo } (2.5 \times 10^6 \text{ kJ/m}^2\text{/mo})$$

Thus,

$$\begin{aligned} Q_c &= KH_\upsilon \\ &= 4.5 \times 10^4 \text{ Btu/sq ft/mo } (5.1 \times 10^5 \text{ kJ/m}^2\text{/mo}). \end{aligned}$$

Table 1
Monthly Correction Factors
for Heating-Only Systems
(for collector tilt equal to latitude plus 10 degrees)

Month	Latitude			
	30°	*35°*	*40°*	*45°*
Jan	1.64	1.84	2.12	2.49
Feb	1.42	1.55	1.71	1.93
Mar	1.18	1.25	1.33	1.44
Apr	.97	1.00	1.03	1.07
May	.84	.84	.85	.87
Jun	.78	.78	.78	.78
Jul	.80	.80	.80	.81
Aug	.90	.91	.93	.96
Sep	1.07	1.11	1.17	1.24
Oct	1.29	1.40	1.51	1.66
Nov	1.54	1.70	1.93	2.23
Dec	1.70	1.93	2.24	2.64

3 ESTIMATING SOLAR SYSTEM PERFORMANCE

General

A critical step in the economic analysis of a solar energy system is a determination of the solar system performance to find out how much of the energy requirement is met by solar energy and how much is met by auxiliary heat for a given size collector array. In order to make this determination, the universal curves are used.

Analyzing a given solar system performance requires the following steps:

1. Determine the annual or monthly energy requirement, Q_L, as described on pages 13-15.

2. Determine the annual or monthly solar radiation on the optimally tilted collector array, Q_c, for the location in question, using the method described beginning on page 15.

3. Determine the solar system performance using the universal curve. Two methods can be used to accomplish this:

a. If a collector area, A_c, is assumed, then the annual or monthly solar system performance parameter, P_s, can be found from Eq 1:

$$P_s = \frac{Q_c A_c}{Q_L} \qquad \text{[Eq 1]}$$

From this value and the equation for the appropriate universal curve, the annual or monthly fraction of energy met by the solar system, ρ, can be determined. Using this value in Eqs 6 and 7 yields the energy supplied by auxiliary heat, Q_{LA}, and the energy supplied by the solar system, Q_{LS}.

$$Q_{LS} = \rho Q_L \qquad \text{[Eq 6]}$$

$$Q_{LA} = (1 - \rho) Q_L \qquad \text{[Eq 7]}$$

If the analysis is for heating-only systems, the monthly Q_{LS} and Q_{LA} are obtained from Eqs 6 and 7 and must be summed to get the annual values required for determining optimal collector area and making the energy and economic cost/benefit analysis as described in Chapter 4.

b. The universal curve can also indicate what collector area is required to meet a given fraction, ρ, of the annual or monthly energy requirement. This information is useful in establishing a starting point for a solar system analysis. The collector area can be determined by using ρ to find P_s from the universal curve equations. For P_s, the collector area can be found from:

$$A_c = \frac{P_s Q_L}{Q_c}$$

Again, annual or monthly Q_{LS} and Q_{LA} is given by Eqs 6 and 7.

The next sections present the universal curves for the various systems and examples of how to use them.

Solar Domestic Hot Water Systems

The development of the universal curve for domestic hot water (Figure 2) was based on a two-tank system in which the solar-heated tank serves as a preheater for a conventional hot water generator. According to the control scheme in the simulation, the solar tank is always allowed to achieve the highest temperature possible under the given conditions of solar radiation. Auxiliary energy is provided to the conventional hot water tank as required to maintain a preset temperature. (In accordance with ETL 110-3-266, the actual measured temperature of hot water delivered to the user should not exceed 110°F [43°C]). A uniform annual hot water demand was assumed when generating the universal curve for domestic hot water; therefore, the curve should not be used if the system being considered has a highly seasonal demand. For seasonal demands, heating-only monthly analysis must be made.

The following example illustrates application of the procedure outlined above as applied to solar domestic water heating.

Example 1

Assume that a barracks at Fort Hood, TX, consumes 30 gal (114 ℓ) of hot water per day per person and that the average occupancy for the year is 200 people. The collector area which will meet 50 percent of the load assuming that the city water supply is 55°F (13°C) and that the water must be heated to 110°F (43°C), can be determined in the following manner:

1. First determine Q_L, the annual energy required to heat the water. Eq 3 gives:

$$Q_L = DwC_p(T_{out} - T_{in})$$

$$Q_L = \left(\frac{30 \text{ gal}}{\text{person-day}}\right)(200 \text{ persons})\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{8.33 \text{ lb}}{\text{gal}}\right)\left(\frac{1 \text{ Btu}}{\text{lb°F}}\right)(110°\text{F} - 55°\text{ F})$$

$$Q_L = 1.0 \times 10^9 \text{ Btu/yr} (1.1 \times 10^9 \text{ kJ/yr})$$

2. Estimate Q_c, the annual solar radiation on the array. From Eqs 4 and 5,

$$Q_c = \frac{\cos(\upsilon_L - 7 - \upsilon_c)}{\cos(\upsilon_L - 7)} H_\upsilon$$

From Figure B1, the mean daily horizontal solar radiation at this location is 445 langleys/day. Thus,

$$H_\upsilon = \left(\frac{445 \text{ langleys}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$= 6.0 \times 10^5 \text{ Btu/sq ft/yr} (6.8 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

Also from Figure B1, υ_L is 33 degrees (latitude of Fort Hood, TX). Since this is a domestic hot water system, the optimum tilt angle, υ_c, for hot water is equal to υ_L (33 degrees). Thus,

$$Q_c = 6.6 \times 10^5 \text{ Btu/sq ft/yr} (7.5 \times 10^6 \text{ kJ/m}^2\text{/yr}).$$

3. Use the universal curve to estimate the solar performance. To meet 50 percent of the load, ρ is .5. From Eq 2 (for ρ equal to .5) P_s is .88. The required collector area can now be found from Eq 1.

$$A_c = \frac{P_s Q_L}{Q_c} = \frac{(.88)(1.0 \times 10^9 \text{ Btu/yr})}{(6.6 \times 10^5 \text{ Btu/sq ft-yr})}$$

$$= 1.3 \times 10^3 \text{ sq ft} (120 \text{ m}^2)$$

The area required to meet 50 percent of the annual domestic hot water load is 1300 sq ft (120 m²).

Solar Heating and Cooling Systems

Figure 3 shows the universal curve for solar heating and cooling systems. Here the relationship between P_s and ρ is given by

$$\rho = 1 - e^{-.32P_s^{1.07}} \qquad \text{[Eq 8]}$$

Analysis of the system's performance proceeds exactly as described for solar domestic hot water. The following example illustrates an application of the method for solar heating and cooling.

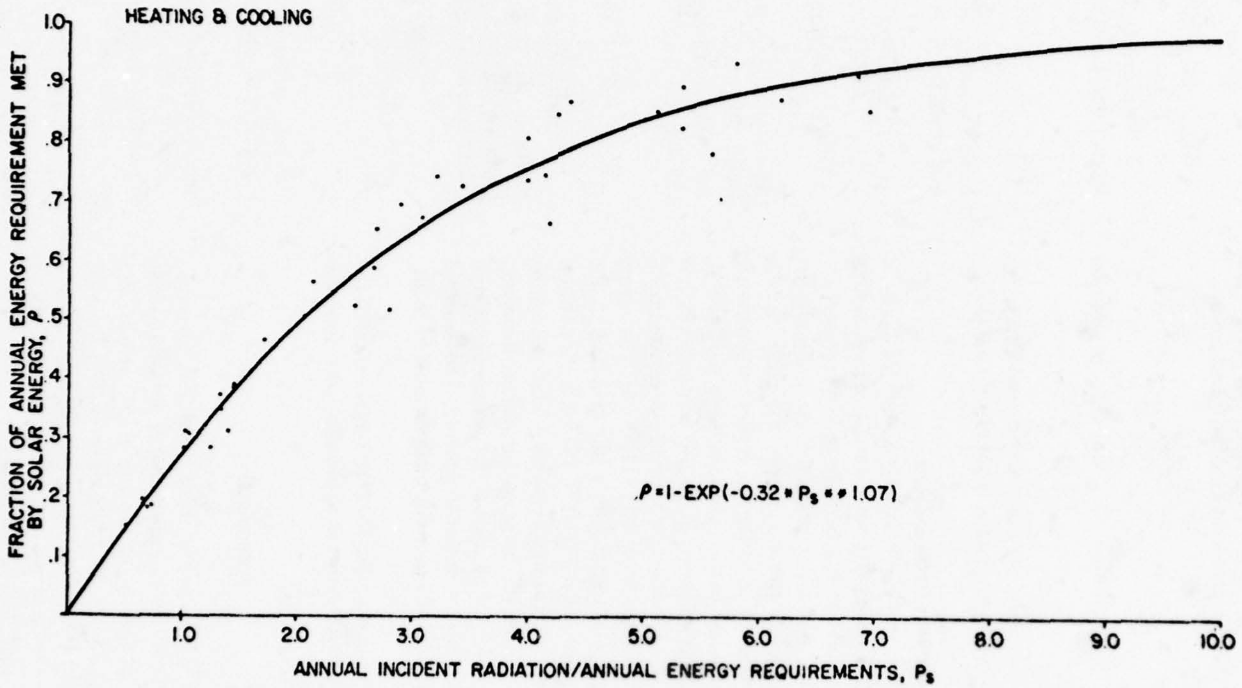

Figure 3. Universal curve for solar heating and cooling systems. (From D. C. Hittle, G. N. Walton, D. F. Holshouser, and D. J. Leverenz, *Predicting the Performance of Solar Energy Systems*. Technical Report E-98/ADA035608 [CERL, January 1977]).

Example 2

The following example is for an administrative building housing 300 people in Champaign, IL (latitude 40 degrees). The energy consumption data were taken from monthly utility billings. The steps in the analysis are as follows:

1. First determine Q_L, the annual energy requirement for heating and cooling.

a. For heating, power records indicate that for the months of October through June, 144 × 10^8 Btu (152 × 10^8 kJ) of gas were consumed for heating and domestic hot water. When multiplied by a boiler efficiency of .75, the building heating load is found to be 108 × 10^8 Btu (114 × 10^8 kJ).

b. For cooling, utility records show that for the months of April through November, 82 × 10^4 kWh (28 × 10^8 Btu [29.5 × 10^8 kJ]) were consumed by the centrifugal chiller. The chiller load was found by subtracting the average winter electrical load from the average summer electrical load to account for other, noncooling loads. Thus, chiller electrical load, when multiplied by the COP of the centrifugal chiller (found from manufacturer's literature to be 4), gives a cooling load for the building of 112 × 10^8 Btu (118 × 10^8 kJ). Dividing by the COP of the absorption chiller (.65) indicates that 172 × 10^8 Btu (181 × 10^8 kJ) must be supplied to the absorption chiller to meet the annual cooling energy demand.

Hence,

$$Q_L = 108 \times 10^8 \text{ Btu/yr} + 172 \times 10^8 \text{ Btu/yr}$$

$$Q_L = 280 \times 10^8 \text{ Btu/yr} \; (295 \times 10^8 \text{ kJ/yr}).$$

2. Estimate the annual solar radiation, Q_c, on the optimally tilted collector array. From Eqs 4 and 5,

$$Q_c = \frac{\cos(\upsilon_L - 7 - \upsilon_c)}{\cos(\upsilon_L - 7)} H_\upsilon .$$

Interpolating from Figure B1, the mean daily annual solar radiation for Champaign, IL, is 355 langleys/day. Thus,

$$H_\upsilon = \left(\frac{355 \text{ langleys}}{\text{day}}\right)\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{3.69 \text{ Btu}}{\text{sq ft-langley}}\right)$$

$$= 4.8 \times 10^5 \text{ Btu/sq ft/yr} \; (5.5 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

since υ_L = 40 degrees (the latitude of Champaign), and $\upsilon_c = \upsilon_L$ − 10 degrees = 30 degrees (optimum collector tilt angle for heating and cooling).

Thus, $Q_c = 5.7 \times 10^5$ Btu/sq ft/yr

$$(6.4 \times 10^6 \text{ kJ/m}^2\text{/yr})$$

3. Determine the solar system performance from the equation for the universal curve for heating and cooling (Eq 8), assuming a collector area of 50,000 sq ft (4645 m^2). From Eq 1, P_s is given by

$$P_s = \frac{A_c Q_c}{Q_L} = \frac{(5 \times 10^4 \text{ sq ft})(5.7 \times 10^5 \text{ Btu/sq ft/yr})}{(280 \times 10^8 \text{ Btu/yr})}$$

$$P_s = 1.02$$

For P_s = 1.02, Eq 8 gives ρ = .28.

Roughly 28 percent of the building's annual energy requirement for heating and cooling can be supplied by the sun, using 50,000 sq ft (4645 m^2) of collectors.

Solar Heating Systems

The universal curve for solar heating systems (Figure 4) is given by the expression

$$\rho = 1 - e^{-.46 P_s^{.92}} . \qquad \text{[Eq 9]}$$

Eq 9 is applied by using a method similar to those for the previous two systems, except that the analysis is carried out month by month. Here, the monthly results are summed to give a seasonal solar percent.

Since the domestic hot water load for a heating system is small in comparison to the space heating requirements, it can be assumed that the total hot water load is met by solar energy during the nonheating season. This somewhat simplifies the calculations, in that the monthly analysis needs to be performed only for those months with significant space heating loads. The hot water energy requirements for the other months can be summed and added directly to Q_{LS}. The following example shows how this monthly analysis is accomplished for heating-only systems.

Example 3

The administrative building of Example 2 was used in this example to determine what percent of the heating load could be met by the 50,000 sq ft (4645 m^2)

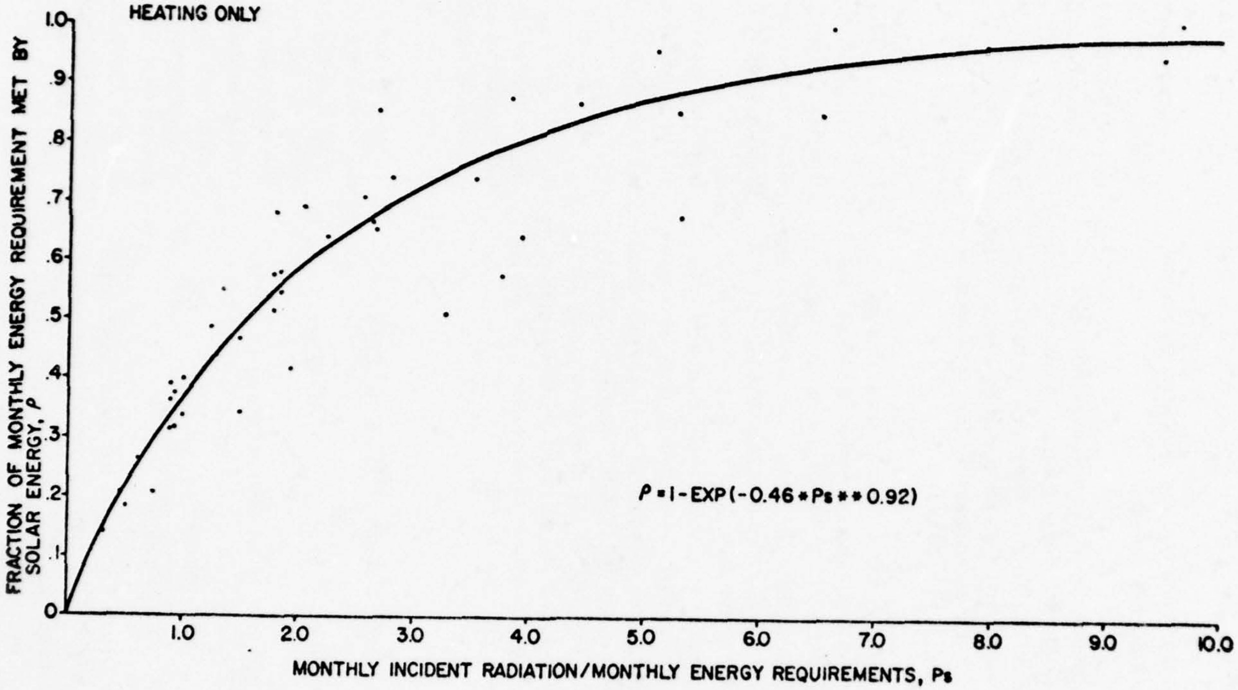

Figure 4. Universal curve for solar heating systems. (From D. C. Hittle, G. N. Walton, D. F. Holshouser, and D. J. Leverenz, *Predicting the Performance of Solar Energy Systems,* Technical Report E-98/ADA035608 [CERL, January 1977]).

of collectors. Again the energy consumption data were taken from monthly utilities bills. The steps in the analysis are as follows:

1. Determine the monthly loads, Q_L, for the heating season. Table 2 presents the building's natural gas consumption indicated by the monthly utility records. The values of Q_L in the table have been corrected for a boiler efficiency assumed as .75. Note that the 108 × 10^8 Btu/yr (114 × 10^8 kJ/yr) total load is the same as found in Example 2.

2. Estimate Q_c, the annual solar radiation on the optimally tilted collector array. From Eq 4,

$$Q_c = KH_\upsilon$$

where H_υ and Q_c = monthly radiation values
K = the correction factor from Table 1.

H_υ is obtained from the figures in Appendix B. Monthly values for Q_c are listed in Table 3.

3. Determine the solar system performance from the universal curve for heating only (Figure 4), assuming a collector area, A_c, of 50,000 sq ft (4645 m^2). From Eq 1, P_s for each month can be calculated from the monthly Q_L and Q_c presented in Tables 2 and 3.

From these values of P_s, the monthly values of ρ can then be obtained from the equation for the universal curve. Finally, from Eq 6, the load met by the solar system, Q_{LS}, can be found for each month (Table 4).

The figures in Table 4 show that 53.7 × 10^8 Btu (51.6 × 10^8 kJ) of heating is supplied by the solar system during October through June. The total heating Q_L for October through June (from part 1 of this example) is 108 × 10^8 Btu (114 × 10^8 kJ). Hence, the solar system provides 50 percent of the annual heating requirement.

For the 3 months not considered above, it is assumed that all domestic hot water heating is performed by the solar energy system. Thus,

$$Q_{LS} = 53.7 \times 10^8 \text{ Btu} + 3(.6 \times 10^8 \text{ Btu})$$

$$= 55.5 \times 10^8 \text{ Btu} \ (63.5 \times 10^8 \text{ kJ})$$

and

$$Q_L = 107.9 \times 10^8 \text{ Btu} + 3(.6 \times 10^8 \text{ Btu})$$

$$= 109.7 \times 10^8 \text{ Btu} \ (115.7 \times 10^8 \text{ kJ}).$$

Hence, the annual ρ is

$$\rho = \frac{Q_{LS}}{Q_L} = .51$$

Thus, the 50,000 sq ft (4645 m^2) of collectors will meet 51 percent of the heating and hot water load for a total energy savings of 56 × 10^8 Btu (53.4 × 10^8 kJ) compared with Example 2, where the same 50,000 sq ft (4645 m^2) of collectors met only 28 percent of the heating and cooling load.

Table 2
Natural Gas Consumption for Example Administration Building

Month	Q_L (Heating) Btu × 10^8 (kJ × 10^8)		Q_L (Hot Water) Btu × 10^8 (kJ × 10^8)		Total Q_L Btu/mo × 10^8 (kJ/mo)	
Oct	2.0	(2.1)	.6	(.6)	2.6	(2.7)
Nov	7.8	(8.2)	.6	(.6)	8.4	(8.9)
Dec	12.3	(13.0)	.6	(.6)	12.9	(13.6)
Jan	19.9	(21.0)	.6	(.6)	20.5	(21.6)
Feb	18.5	(19.5)	.6	(.6)	19.1	(20.2)
Mar	16.3	(17.2)	.6	(.6)	16.9	(17.8)
Apr	12.9	(13.6)	.6	(.6)	13.5	(14.2)
May	8.8	(9.3)	.6	(.6)	9.4	(9.9)
Jun	4.0	(4.2)	.6	(.6)	4.6	(4.9)
	102.5 × 10^8 Btu/yr (108.1 × 10^8 kJ/yr)				107.9 × 10^8 Btu/yr (113.8 × 10^8 kJ/yr)	

Table 3
Monthly Values for Q_C

Month	H_υ Langley/day	H_υ Btu/sq ft/mo (kJ/m²/mo)	K	Q_C Btu/sq ft/mo (kJ/m²/mo)
Oct	275	3.1×10^4 (3.5×10^5)	1.51	4.7×10^4 (5.3×10^5)
Nov	175	1.9×10^4 (2.2×10^5)	1.93	3.7×10^4 (4.2×10^5)
Dec	135	1.5×10^4 (1.7×10^5)	2.24	3.4×10^4 (3.8×10^5)
Jan	155	1.8×10^4 (2.0×10^5)	2.12	3.8×10^4 (4.3×10^5)
Feb	240	2.5×10^4 (2.8×10^5)	1.71	4.3×10^4 (4.9×10^5)
Mar	330	3.8×10^4 (4.3×10^5)	1.33	5.1×10^4 (5.7×10^5)
Apr	400	4.4×10^4 (5.0×10^5)	1.03	4.5×10^4 (5.1×10^5)
May	510	5.8×10^4 (6.6×10^5)	.85	4.9×10^4 (5.6×10^5)
Jun	550	6.1×10^4 (6.9×10^5)	.78	4.8×10^4 (5.4×10^5)

Table 4
Monthly Values of e and Q_{LS}

Month	Q_L Btu/mo (kJ/mo)	Q_c Btu/sq ft/mo (kJ/m²/mo)	P_s	e	Q_{LS} Btu (kJ)
Oct	2.6×10^8 (2.7×10^8)	4.7×10^4 (5.3×10^5)	9.0	.97	2.5×10^8 (2.6×10^8)
Nov	8.4×10^8 (8.9×10^8)	3.7×10^4 (4.3×10^5)	2.2	.61	5.1×10^8 (5.4×10^8)
Dec	12.9×10^8 (13.6×10^8)	3.4×10^4 (4.0×10^5)	1.3	.44	5.7×10^8 (6.0×10^8)
Jan	20.5×10^8 (21.6×10^8)	3.8×10^4 (4.5×10^5)	.93	.35	7.2×10^8 (7.6×10^8)
Feb	19.1×10^8 (20.2×10^8)	4.3×10^4 (5.1×10^5)	1.1	.39	7.4×10^8 (7.8×10^8)
Mar	16.9×10^8 (17.8×10^8)	5.1×10^4 (5.6×10^5)	1.5	.49	8.3×10^8 (8.7×10^8)
Apr	13.5×10^8 (14.2×10^8)	4.5×10^4 (5.0×10^5)	1.7	.53	7.2×10^8 (7.6×10^8)
May	9.4×10^8 (9.9×10^8)	4.9×10^4 (5.6×10^5)	2.6	.67	6.3×10^8 (6.6×10^8)
Jun	4.6×10^8 (4.9×10^8)	4.8×10^4 (5.5×10^5)	5.2	.87	4.0×10^8 (4.2×10^8)
				Total Q_{LS}	53.7×10^8 Btu $(57 \times 10^8$ kJ)

Corrections for Different Collector Types

As previously described, the universal curves were developed for the reference solar collector. For collectors with different absorber plate characteristics and different numbers of covers, Tables 5 and 6 can be used to correct the results of the universal curve. These tables give values for a collector area multiplication factor which can be applied when a particular collector other than the reference collector is used. In these tables, α is the absorptivity and ϵ is the emissivity of the absorber plate. The transmittance of each cover was assumed to be 0.9, so that for two covers, the transmittance equals 0.81.

These tables are useful because they permit application of the performance curves for the reference flat-plate collector (a single-cover collector with an absorptivity of 0.9 and an emissivity of 0.10) to other flat-plate collectors. For example, in order to achieve equivalent performance for heating and cooling from a two-cover (N = 2), nonselective collector ($\alpha = \epsilon = .96$), consulting Table 5, one would multiply the appropriate collector area for the reference collector by 1.09 or increase the collector area by 9 percent.

Table 5
Collector Area Multiplying Factor for Different Collector Designs for Heating and Cooling Systems

α		0.96	0.94	0.90
ϵ		0.96	0.30	0.10
N	1	1.55	1.09	1
	2	1.09	0.97	0.93

α = Absorptivity
ϵ = Emissivity
N = Number of glass covers

Table 6
Collector Area Multiplying Factor for Different Collector Designs for Domestic Hot Water Heating and Heating-Only Systems

α		.96	.90
ϵ		.96	.10
N	1	1.26	1
	2	.96	.93

α = Absorptivity
ϵ = Emissivity
N = Number of glass covers

4 DETERMINING THE OPTIMAL COLLECTOR AREA

This chapter describes a method for determining the collector area with the maximum economic payback over the life of the facility for which it is being considered. The method is based on the computation of a benefit-to-cost ratio (B/C) for the solar energy system, the performance of which is determined from the appropriate universal curve. The benefit associated with the incorporation of solar energy is the fuel savings; the cost is the increased first cost of the solar energy system itself. If the benefits outweigh the costs, B/C is greater than 1, and the system is economically feasible.

Basic standards and guidelines for the conduct of all economic studies by and for the Department of the Army are contained in AR 11-28.[11] Supplemental guidelines for performing an economic analysis of energy-related systems may be obtained in the ECIP guidelines.[12] Further clarifications of the basic criteria may be obtained through normal channels from the Office of the Chief of Engineers, Department of the Army (ATTN: DAEN-MPE-T).

The first step in determining the optimal collector area is to estimate the initial capital costs (IC) of the solar energy system components in present-year dollars. Only the cost of components that are not normally part of the conventional heating and cooling system should be included. For example, the cost of the building's air-handling system would not be considered, but the difference between the cost of a more expensive absorption chiller and a less expensive centrifugal chiller should be charged to the solar system.

Certain cost elements for solar energy systems vary according to the size of the system, while others are relatively fixed, regardless of collector area or tank size. The costs of the collector and storage tank are obvious examples of items which are dependent on collector area. (The tank volume is assumed to be 16 lb of water

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[11] *Economic Analysis and Program Evaluation for Resource Management*, AR 11-28 (Department of the Army, 2 December 1975).

[12] Letter from David M. Crabtree, Chief, Util. Engr. and Ops. Div., Facilities Engineering (DAEN-FEU), Subject: Energy Conservation Investment Program (ECIP) Guidance (7 November 1977).

per square foot of collector [78 kg/m^2].) Other examples include heat exchanger, pump, and piping costs. Central system costs associated with the solar energy system, however, are largely independent of collector area. The cost difference associated with the purchase and installation of an absorption chiller is also relatively independent of solar collector area, since the selection of an appropriate absorption chiller is dictated by peak building cooling load for all but the smallest collector areas. It is important that these costs be apportioned accurately, since the benefit-to-cost ratio is computed as a function of the area of the solar collector array.

When determining the capital cost of the solar system, the user must specify the type of auxiliary energy system to be used. For example, most solar systems have a complete conventional system as an auxiliary. For solar systems containing an absorption chiller, the auxiliary source of cooling can either be a boiler (to drive the absorption chiller) or a redundant centrifugal chiller. In the first case, the capital cost is low, since a credit can be taken for the centrifugal chiller and the boiler is always required for the heating system. However, the fuel costs may be high, since the absorption chiller COP is approximately .65. In the second case, the capital costs are higher, since credit for the centrifugal chiller cannot be taken; however, since this chiller operates with a COP of approximately 4, the fuel costs may be considerably lower. Note that in the first case, heating fuel is the source of auxiliary energy, while in the second case, the source is electrical power.

If the project under consideration is programmed for funding in the future, the initial capital cost (IC) of the system, expressed in today's dollars, must be escalated to the value of dollars at that date. The escalated IC is called the current wording estimate (CWE); the factors for converting IC to CWE are given in the ECIP guidance.

Once the CWE has been determined, the second step in the economic analysis is to establish the annual fuel cost for the conventional energy system (FC) as follows:

1. Determine the annual heating and/or cooling energy requirement for conventional equipment as described in Chapter 2.

2. Convert the cooling energy load to kilowatt hours and multiply by the local electrical rate* to obtain the cost of cooling energy (note that the COP of the conventional electrical chilling device must be considered when making this conversion).

3. Divide the required input heating energy and/or domestic hot water energy by the heating value of the fuel used and multiply by the unit fuel price* to determine the cost of heating (note that in determining the heat energy required, the efficiency of the boiler or furnace must be considered).

4. Convert the amount of fuel cost to the present worth fuel cost for the conventional system, $PWFC_c$, which is given by

$$PWFC_c = MF_c,$$

where M is the cumulative, discounted single amount factor, and is expressed by

$$M = 1/2 \sum_{n=0}^{n} \left[\frac{1}{(I-i)^n} + \frac{1}{(I-i)^{n-1}} \right]$$

Here, n is the facility life, I the discount rate, and i is the long-term differential inflation factor for the fuel being considered. (Values for I and i are also listed in the ECIP guidance.) If more than one type of fuel is being used, the $PWFC_c$ must be calculated for each type, and the results summed to give the total $PWFC_c$. The ECIP guidance provides tables of values of M for various fuel types.

The third step in the economic analysis is to calculate the present worth fuel cost for energy required by the conventional system if the solar energy equipment is present, $PWFC_s$. To do this it is necessary to:

1. Determine the total annual energy requirement, Q_{LA}, for a given collector area and systems type using the methods described in Chapter 3.

2. Determine the annual cost for this auxiliary energy, F_s.* For heating and cooling systems, assume that solar energy is used first to meet the domestic hot water demand, then the heating load, and then the cooling load. Note in particular that if centrifugal or other electrical chilling devices are used to augment the solar cooling equipment, the appropriate COPs for absorption and electrical refrigeration equipment must be used to determine the auxiliary energy that will be

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*Energy costs here are fuel prices escalated to the end of the year in which the project is programmed for funding.

*Energy costs are based on fuel prices escalated to the end of the year in which the project is programmed for funding.

required to meet the cooling demand not met by the solar system. If a boiler is used to drive the absorption chiller, the boiler efficiency must be considered.

3. Convert the annual auxiliary fuel cost to present worth fuel cost as before:

$$PWFC_s = MF_s$$

where M is the cumulative, discounted single amount factor.

The final step in the economics analysis is calculation of the benefit-to-cost ratio, B/C, for various collector areas. B/C is given by

$$B/C = \frac{PWFC_c - PWFC_s}{CWE}$$

where $PWFC_c$, $PWFC_s$, and CWE are as defined previously. Systems are cost-effective only if this ratio is greater than one. Figure 5 is a hypothetical plot of B/C as a function of collector area.

The shape of this curve is readily explained. For very small collector areas, very little fuel is saved to offset the fixed costs of the system, such as for controls, added piping, and pumps. As the collector area increases, however, the fuel savings begin to offset the fixed costs, and B/C increases. As more collectors are added, a point of diminishing returns is reached; additional collector area provides very little added fuel savings. Thus, the added cost of these collectors and tank cannot be offset by their fuel savings, and therefore the benefits are outweighed by the added costs of these components. Hence, B/C begins to decrease.

When B/C is plotted for the solar system being considered (as in Figure 5), the optimum collector area becomes obvious—the area at which B/C is maximized. Note that Figure 5 concisely summarizes the economics of solar systems. Only when B/C is greater than 1 can the solar energy system be economically justified. In fact, if the collector and tank costs are too high, the fuel savings will never offset the fixed costs and the B/C will never achieve a value of 1.

An application of the methodology presented in the preceding three chapters enables an energy and economic analysis of the solar energy system being considered. If, based on this analysis, the solar system is found to be feasible, then a detailed design analysis can be made using the computer-aided method described in Chapter 5.

5 PERFORMING COMPUTER-AIDED DESIGN CALCULATIONS

Introduction

The previous chapter described a method for graphically estimating the performance of candidate solar domestic hot water, building heating, or building heating and cooling systems. This method is sufficiently accurate for a preliminary energy and economic analysis of solar energy systems. For most projects, however, selecting the optimum collector area and type and insuring the selection of the appropriate collector tilt angle and storage tank volume may require a more detailed design analysis. The methods described in this chapter are based on the application of the BLAST program developed at CERL. This program permits hourly simulation of building loads, air-handling systems meeting these loads and simulation of central energy plan equipment, including solar energy systems, supplying the air-handlers. Designers who wish to use this program should obtain the users and reference manuals which describe the preparation of the input required for using the program and the algorithms employed in performing the simulation.

The optimum design using the simulation model is again determined by performing the economic analysis as described in Chapter 4. The simulation tools, however, allow better determination of system performance and, thus, a more accurate measure of ρ, the fraction of the load met by the solar system for a given collector array. Also, other variables such as collector tilt angle, storage tank volume, and type of collector can be varied to maximize solar system performance. In addition, the BLAST program allows for the analysis to be performed using more accurate values of the building energy requirements, Q_L, since assumptions concerning average efficiency and COP do not have to be made.

Information Required to Use the BLAST Program

To use BLAST, hourly weather data, including solar radiation, must be acquired in the necessary format as input to the computer program. While several versions (National Weather Service Series 280 Solar Data Tapes, National Weather Service Series 1440 Climatological Data Tapes, NBS-NOAA-ASHRAE Test Reference Year Tapes, and SOLMET Tapes) of suitable weather tapes exist; obtaining this information may take up to 6 weeks. Therefore, users should anticipate use of the BLAST program and request the tapes early enough so they will be available when required.

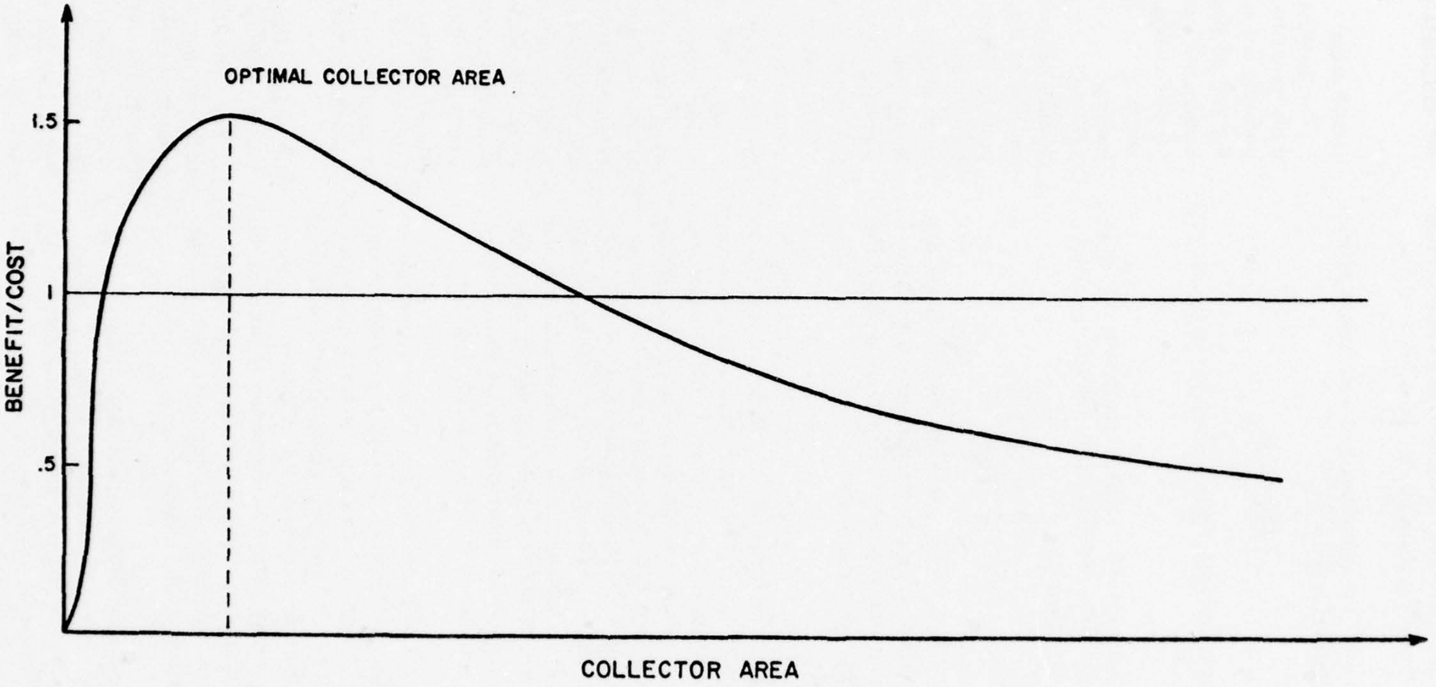

Figure 5. Benefit-to-cost ratio (B/C) vs. the collector area (A).

The BLAST program requires a description of the building as input. The user's manual describes the exact form of this input. The program uses such information as the type of wall construction, window area and construction, building orientation, schedule for occupancy, and electrical demands in determining the hourly building zone loads and hourly total load of the building. If measured data are available, they can frequently be used to check the building loads to insure that parameters were properly defined and reflect the actual building, since some parameters, such as infiltration and occupancy, are hard to determine.

The air-handling systems used in the building must also be described. In this case, such information as the zone air flow rate, type of coil, type of air-handling system, and type of control system used is specified by the user. The output from the air distribution system simulations is the hourly energy demand on the boilers and chillers serving the air handlers in the building. These hourly demands form the input to the central plant simulation program which determines the expected performance of conventional and solar energy system components. In performing the central energy plant simulation, the user can specify the performance of the solar collector, the collector area, and the storage tank volume being used in the system. The type of performance data required for solar collectors is identical to that described in National Bureau of Standards' publication NBSIR-74-635.[13] The slope and intercept of solar collector efficiency curves are the input parameters required.

Note that in the analysis of the solar energy systems, the BLAST program should first be used to minimize the energy required by each zone by studying such effects as added insulation and changes in window area and orientation. This should be followed by a comparison of various air-handling systems and control schemes to minimize the energy demanded by the boilers and chillers, assuming these design changes can be made to the building. Once this analysis has been performed, various collector systems must be simulated to optimize the performance of the candidate systems and to establish the optimum system configuration.

Once the load profiles for the boilers and chillers have been determined, the optimization of the solar energy system can be initiated.

Setting Up the Solar Energy Detailed Design Study

The computer-aided design should not be initiated until the graphical economic analysis described in the previous chapter has been completed, since the results of that study provide the starting point for the computer-aided study. If the economic study has been completed, but the loads determined from the BLAST program are considerably different than those used for analysis, the analysis should be repeated. The graphical method serves to bracket the area of consideration.

In order to optimize the design, certain variables not previously considered should be varied to establish their optimum value, as discussed in the following section. The starting point should be the solar system obtained from the universal curve analysis which set the optimum collector area. The collector array should be set with an azimuth angle of 180 degrees (i.e., facing due south) and tilted at the optimum angle as described in Chapter 2. The tank volume should be set at 16 lb/sq ft of collector (78 kg/m^2).

Methodology for Optimizing the Solar System Design

The optimization proceeds in the following steps:

1. First, several simulations may be run using the BLAST solar simulation package with different tilt and azimuth angles for the collector array. Figure A1 illustrates how the output from such a parametric study can be plotted to establish the optimum tilt for a given azimuth. A similar plot of system performance versus azimuth angle will indicate the optimum azimuth. This step would be required only if dictated by architectural considerations, such as building siting.

2. The next step is to vary the collector area while keeping the collector-area-to-tank-volume ratio constant (start with 16 lb/sq ft of collector [78 kg/m^2]) and repeat the economic analysis described in Chapter 4, obtaining a curve similar to Figure 5. The collector area with the greatest B/C ratios is the optimum collector area for this collector-area-to-tank-volume ratio. (Note that this is a repeat of the universal curve analysis using the more precise computer analysis tools.)

3. The third step is to repeat the previous step for different collector-area-to-storage-tank-volume ratios. All B/C ratios can be plotted on the same graph. Sufficient runs should be performed to determine the curve with the greatest B/C. If no other information is available, 8 and 32 lb/sq ft (39 and 156 kg/m^2) are good

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[13] J. S. Hill and T. Kusuda, *Methods of Testing for Rating Solar Collectors Based on Thermal Performance*, NBSIR-74-635 (National Bureau of Standards, 1974).

second and third tries. Subsequent tries are based on the results of these simulations. The curve with the highest ratio gives the optimum tank-volume-to-collector-area ratio, while the point at which the maximum occurs establishes the optimum collector area. In spite of the fact that higher values of tank insulation will lead to larger optimum tank volumes, high tank insulation (especially for buried tanks) is difficult to achieve in practice. Therefore, tank-volume-to-collector-area ratios which greatly exceed 16 lb/sq ft (78 kg/m^2) should be examined critically to insure that the specified tank insulation values can be obtained.

4. The final step is to vary the type of collector to see what effect this has on system life-cycle costs. The optimum tank-volume-to-collector-area ratio found in Step 3 should not be significantly affected by the type of collector. The curves of B/C ratio versus collector area should be constructed as before by simulating several different areas for each collector type being considered.

Note that the only differences between the graphical and computer-aided methods for determining system performance and optimal collector configuration are that the simulation model provides a more accurate estimate of the performance of a candidate solar energy system and permits a more refined study of the secondary effects of collector tilt, azimuth angle, and storage tank capacity.

6 PRACTICAL CONSIDERATIONS

Discussions in the previous chapters focused on estimating performance of solar collector systems. This chapter deals with some practical considerations involved in the final design, installation, and operation of solar energy systems and is based on experience gained in the construction and operation of the CERL solar facility.

Freeze Protection

Because the components in the collector loop are sometimes exposed to conditions of low outdoor temperature, provision must be made in many locations for freeze protection of the heat transfer fluid. One approach to this problem is to drain the collectors each time the ambient temperature approaches freezing; however, in some climates, particularly for the larger systems, this method may not be practical. More often, a fluid other than pure water, such as ethylene glycol, propylene glycol, or silicones, is circulated in any exposed component. A heat transfer penalty may be paid, however, since these liquids may have a higher viscosity and a lower specific heat than pure water. In addition, for domestic hot water systems, local building codes should be consulted before the heat transfer fluid is chosen, since it is possible to contaminate the potable water supply. In many areas, two walls must separate any toxic fluid from potable water supplies.

Stagnation

A malfunction of the collector pump or system controls can lead to stagnation of the fluid in the collection loop. Under conditions of high solar insolation, temperatures as high as 350° (177°) can be attained in some flat plate collectors. The possibility of stagnation must be anticipated in the design of any system. First, the collector must be able to withstand these high temperatures. Second, the collector fluid should not decompose if stagnation occurs. In addition, provision (e.g., an expansion tank) must be made for thermal expansion of the collector fluid under these conditions.

Thermal Expansion

Temperature variations in the collector loop are often greater than those encountered in normal hydronic heating systems. This is because the collector piping is subjected to conditions ranging from the coldest ambient to the highest fluid temperatures. For this reason, additional caution must be taken to insure that some type of mechanical strain relief is provided to allow for differential thermal expansion between the collector piping and the collector supports. This relief commonly consists of expansion loops at intercollector connections.

Flow Balancing in the Collectors

In some of the larger solar systems it is not uncommon to have 20 collectors in a single array. In such a case, there may be a significant flow imbalance from one collector to another. Any collectors operating at a lower than design flow will exhibit a higher than design temperature difference across them. This, in turn, lowers the collection efficiency. Two common methods for addressing this problem are the incorporation of flow-balancing valves or the use of a two-pipe reverse-return strategy.

Venting the Collector Loop

Particular attention must be given to the possibility of air accumulating in the collector array. A frequent problem encountered in the past has been accumulation of pockets of air at the top of the collector bank. These air pockets prevent the fluid from passing over the collector absorber plate, thus reducing the area over which solar energy is collected. Such "vapor locking" can be prevented by generous use of automatic or manual vents in the collector system and by avoiding sharp bends or other piping arrangements which can trap air. Use of air separators in the collector loop is also recommended.

Prevention of Natural Convection

Free convection should be prevented from dissipating solar heat through the collector bank when the solar energy system is not in operation. This can be prevented by using two-position valves which close when the collector system is de-energized, but are opened if the system is in operation.

Piping of Hot Fluids

Pumps in the system should be positioned carefully, particularly when the storage tank is to be maintained at or near atmospheric pressure. A potential cause of system failure is the cavitation of pumps used to pump hot fluids. Piping considerations should insure that at the collection and storage loops, pumps are positioned so that there is always a net positive suction. This will prevent flashing when the pumps are energized. Whenever possible, circulating pumps should be used for closed loops, and self-priming pumps for open loops.

Storage Tank Insulation

Practical experience indicates that heat loss from insulated tanks is frequently higher than predicted. For buried tanks in particular, special care must be taken to insure that an impenetrable vapor barrier surrounds the insulation of the tank. In addition, storage containers with a high volume to area ratio should be considered to minimize the heat loss. During the heating season, this consideration is less important for tanks located inside the building, since any heat loss from the storage tank heats the mechanical room. However, in the summer such a tank may contribute to the building's cooling load, in addition to occupying valuable floor space. These factors should be considered when designing and placing the storage tank.

Piping of the Auxiliary Energy Supply

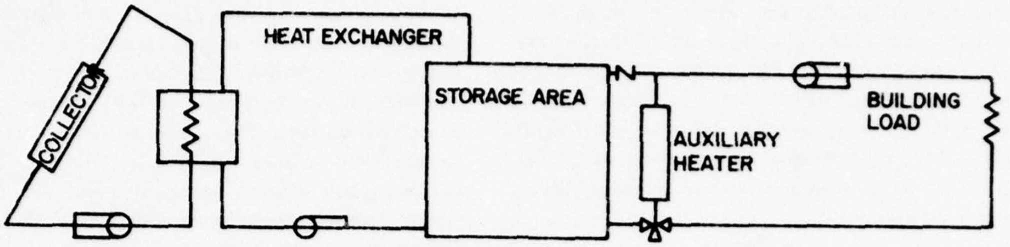
For practical solar energy systems, some auxiliary energy supply will be required. Since there are many possible configurations, individual cases must be examined to determine where auxiliary energy can be derived. However, any auxiliary supply boiler or other device should be piped parallel with the solar energy solar tank. Figure 6 illustrates examples of a correct and incorrect method for piping an auxiliary energy supply. If the auxiliary supply is piped in series with the tank, under conditions of low tank temperature the auxiliary supply will not only be required to meet the heat energy demands of the building, but will also begin to add energy to the tank. This is particularly undesirable because it will require an unnecessarily large auxiliary heater capable of meeting instantaneous demand while simultaneously supplying an added demand by delivering energy to the storage tank. It is also undesirable because the stored energy should be derived only from the solar energy system; application of auxiliary heat to the stored energy raises the tank temperature, which reduces collector efficiency and increases tank heat losses.

Controls

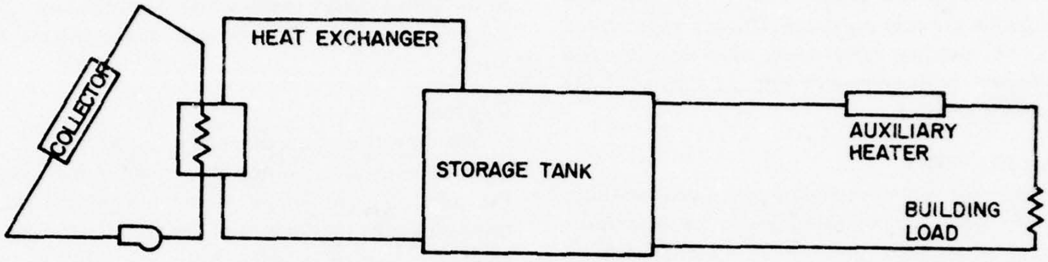
The objective of a solar energy system, whether it is used for hot water, heating, or cooling, is to maximize the collection and storage of energy from the sun. In this regard, the importance of the control strategy and equipment cannot be overemphasized. While the control of these systems typically does not require new technology, special care must be exercised in determining when the collector pump is actuated, because it is this unit which allows energy to be transferred to the storage tank.

The most straightforward method for initiating flow in the collection loop would be to sense the temperature difference between the collector plate surface and the storage tank. If a positive difference existed (i.e., the collector is hotter than the tank), solar energy would be available and the collector system could be energized. Unfortunately, if this strategy were adopted, the system would cycle excessively as the collector temperature oscillated above and below the tank temperature.

This problem is commonly attacked through the use of hysteresis in the turn-on, turn-off temperatures; that is, the collector pump is activated when the collector plate is 15°F (8.3°C) warmer than the tank, but it is de-energized when it is only 3°F (17°C) warmer. In this strategy it is important that the control system have the capability for sensing temperature differences accurately over the entire region of control. When the tank is at 180°F (82.2°C) during the summer, for example, collection would be initiated at a plate temperature of 195°F (90.6°C). During the winter, when the storage is 100°F (43.3°C), pumping should begin when the plate reaches 125°F (51.7°C). Sensing these temperature differences accurately over this wide operating range places an additional burden on the system control electronics.



a. CORRECT



b. INCORRECT

Figure 6. Piping the auxiliary energy supply.

While the use of hysteresis is the most common approach to the problem of differential temperature control, another method–proportional control–has been employed. Here, the speed of pumping is varied in proportion to the difference in plate-tank temperature. The advantage in this case is that energy is collected on days when the solar insolation is high enough to heat the plate, but not to a temperature 15°F (8.3°C) greater than the storage. The disadvantage lies in the fact that large, variable-speed pumps are not common. Proportional control is used most frequently in residential-scale systems.

Sizing of Auxiliary Equipment

As stated previously, solar energy systems are normally backed by auxiliary equipment capable of meeting a building's heating and cooling loads. (This requirement of a redundant HVAC system is one reason that the initial cost of using solar energy is so high.) For heating-only applications, the first cost and part-load characteristics of boilers are such that the economic penalty paid for having a full-sized auxiliary is not too great. Because this is not necessarily the case for absorption air conditioning, the sizing of the chiller back-up system becomes more critical.

During the cooling season, there will be times when the auxiliary cooling system, in supplementing the solar air-conditioner, will be operating at a small fraction of its full load capacity. In terms of energy saved, the low efficiency of the auxiliary chiller under these conditions refutes the performance of the overall system. However, if the back-up chiller has been sized too small, it might not be able to meet the load during extended periods of hot, cloudy weather.

One approach to the problem of equipment size has been to have both a large and small back-up chiller. This allows both units to be operated efficiently over a wide range of cooling loads. (The first cost would be higher here too.) At the very least, it is important to realize that an effort should be made to insure that auxiliary chilling equipment is not greatly oversized.

Absorption Air Conditioning

The performance of systems involving solar absorption air-conditioning has sometimes been less than expected. At least two factors account for this. The first of these, excessive machine cycling, is essentially a control problem. (Cycling penalizes the equipment performance by not allowing the machine sufficient time to reach its full-rated capacity.) For example, if the absorption chiller is activated when the tank temperature is greater than 185°F (85°C), but de-energized at temperatures less than 180°F (82.2°C), a five-degree hysteresis or dead band is said to exist in this control parameter. If the hysteresis is increased (i.e., the on-off temperature difference is made larger), the chiller will come on less frequently, but for longer periods of time, thereby reducing the ill effects of cycling.

The second problem associated with solar cooling arises when the absorption chiller is underfired. (For a given condensing water temperature, there is a required minimum generator water temperature, below which the unit is said to be underfired.) The penalty under these conditions is that the capacity of the chiller is reduced greatly. Underfiring can best be avoided by altering the control strategy so that the minimum temperature of water pumped to the generator is raised. For example, the tank cut-off temperature for cooling could be raised from 180°F to 185°F (82.2°C to 85°C). Strictly speaking, raising the tank cut-off temperature is not the best approach, since there may be a range of condensing water temperatures for which a tank temperature of 180°F (82.2°C) does not cause the unit to be underfired. A more accurate method would be to have a control system capable of measuring condensing and generating water temperature simultaneously, and subsequently running the chiller within its specified operating region.

7 CONCLUSIONS

The following conclusions can be drawn concerning the methods presented in this report:

1. The graphical method of evaluating solar energy systems is based on established technology and calculation methods, and provides sufficient accuracy for use in feasibility studies.

2. The method for economic analysis includes all cost factors which must be considered in evaluating solar energy systems.

3. The computer simulation method is based on established calculation methods and can be used in preparing design instructions and evaluating final designs.

4. The input data required for both the graphical and computer simulation methods can be readily obtained by District personnel.

8 RECOMMENDATIONS

It is recommended that District Engineers use the procedures contained in this report for use in designing solar energy systems; in addition, it is recommended that Facilities Engineers use these procedures for preparing DD 1391 submissions on solar projects.

APPENDIX A:
EFFECTS OF COLLECTOR TILT, HEAT EXCHANGER EFFECTIVENESS, TANK VOLUME, AND TANK INSULATION ON THE THEORETICAL PERFORMANCE OF SOLAR ENERGY SYSTEMS

In Chapter 2 it was stated that the single most important factor in determining the performance of a solar energy system is the assumed collector efficiency. In support of that statement, Figures A1 through A4 present graphs of percent solar, ρ, versus P_s which explicitly shows the dependence of ρ on collector array tilt, heat exchanger effectiveness, tank volume, and tank insulation.

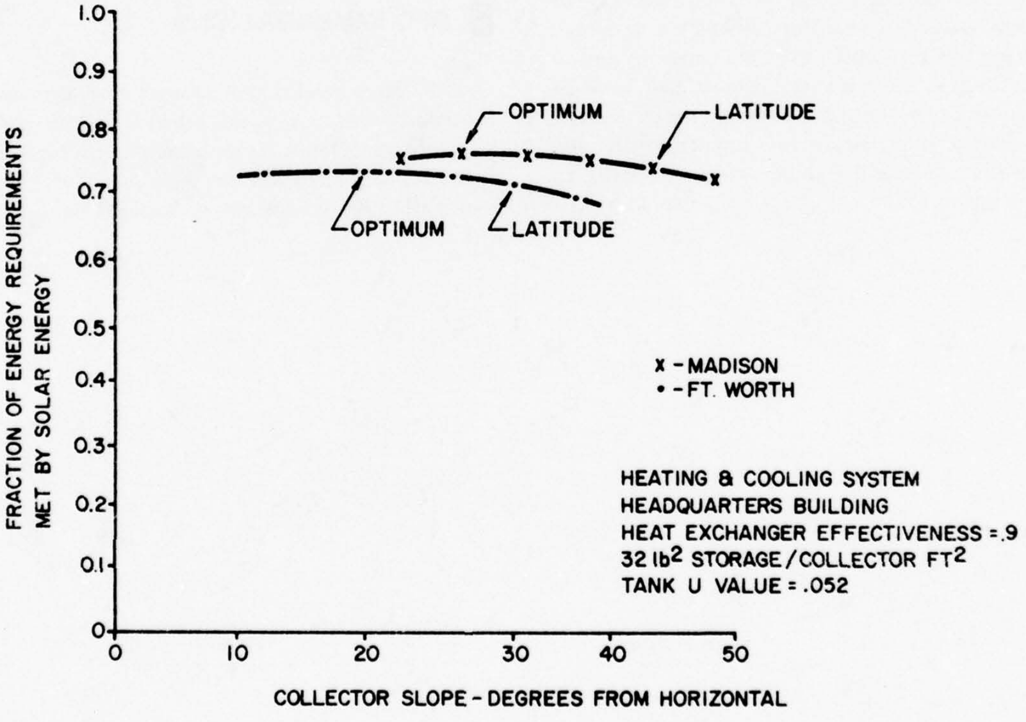


Figure A1. Dependence of solar fraction on collector slope.

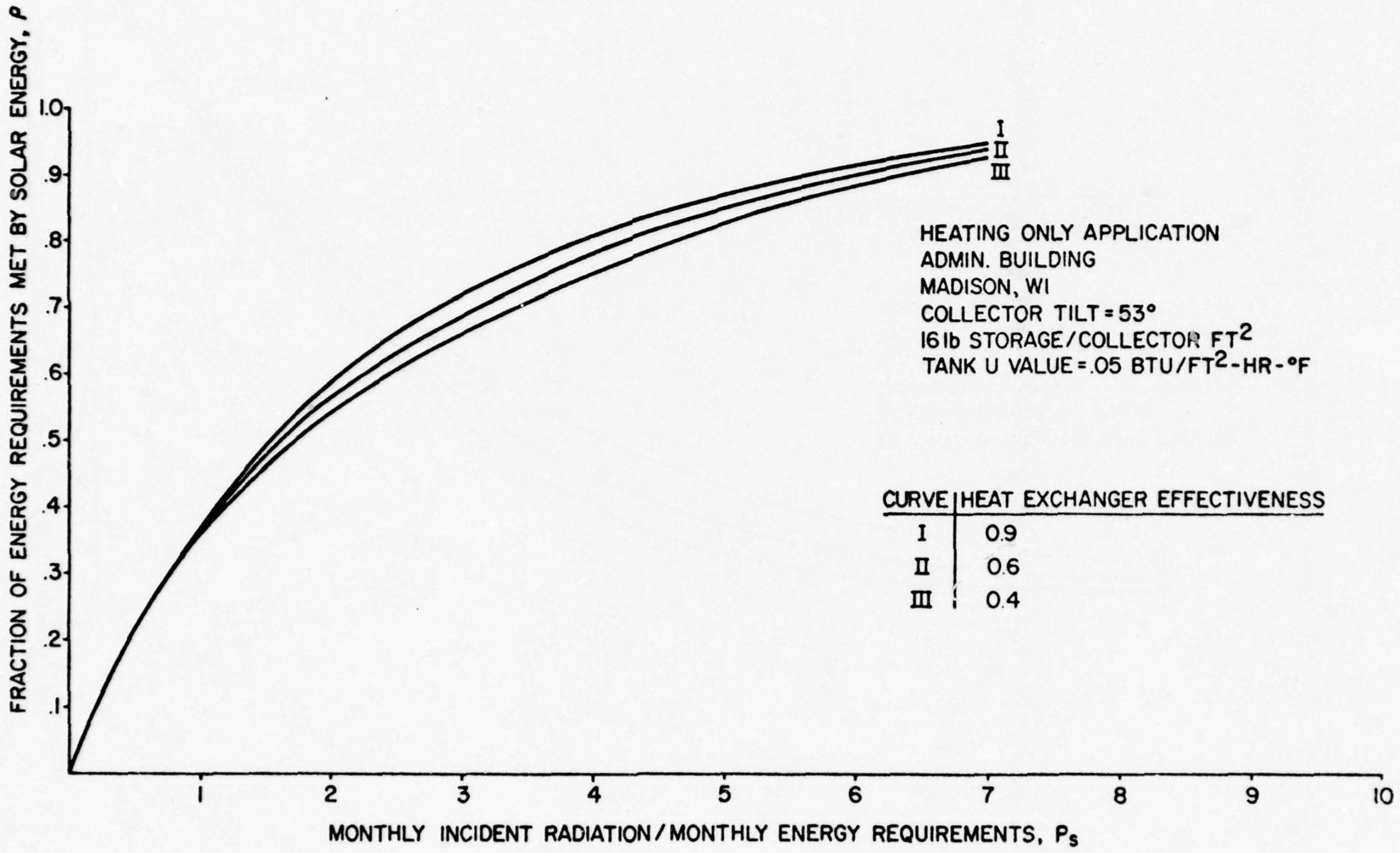


Figure A2. Dependence of solar fraction on heat exchanger efficiencies.

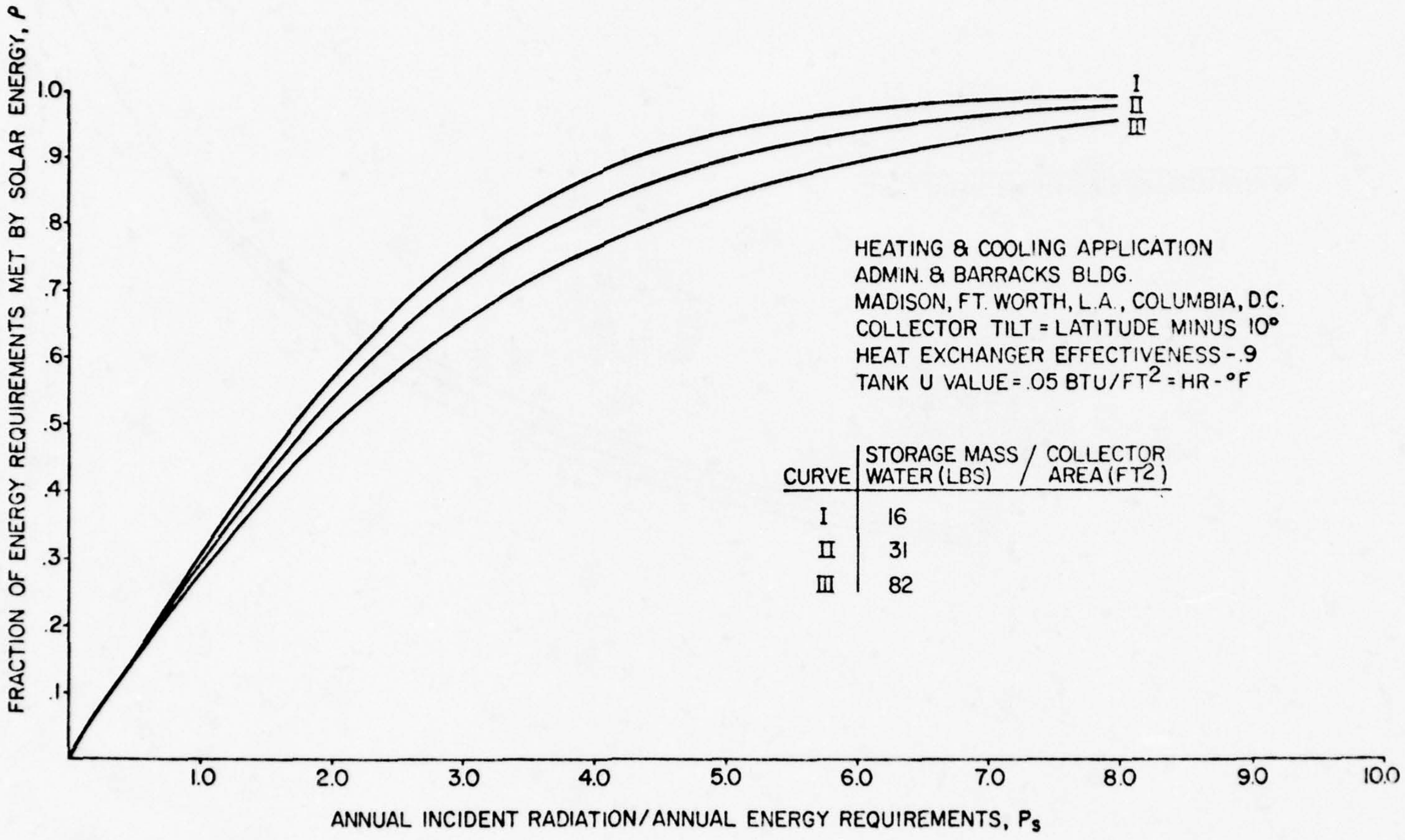


Figure A3. Dependence of solar fraction on storage tank volume.

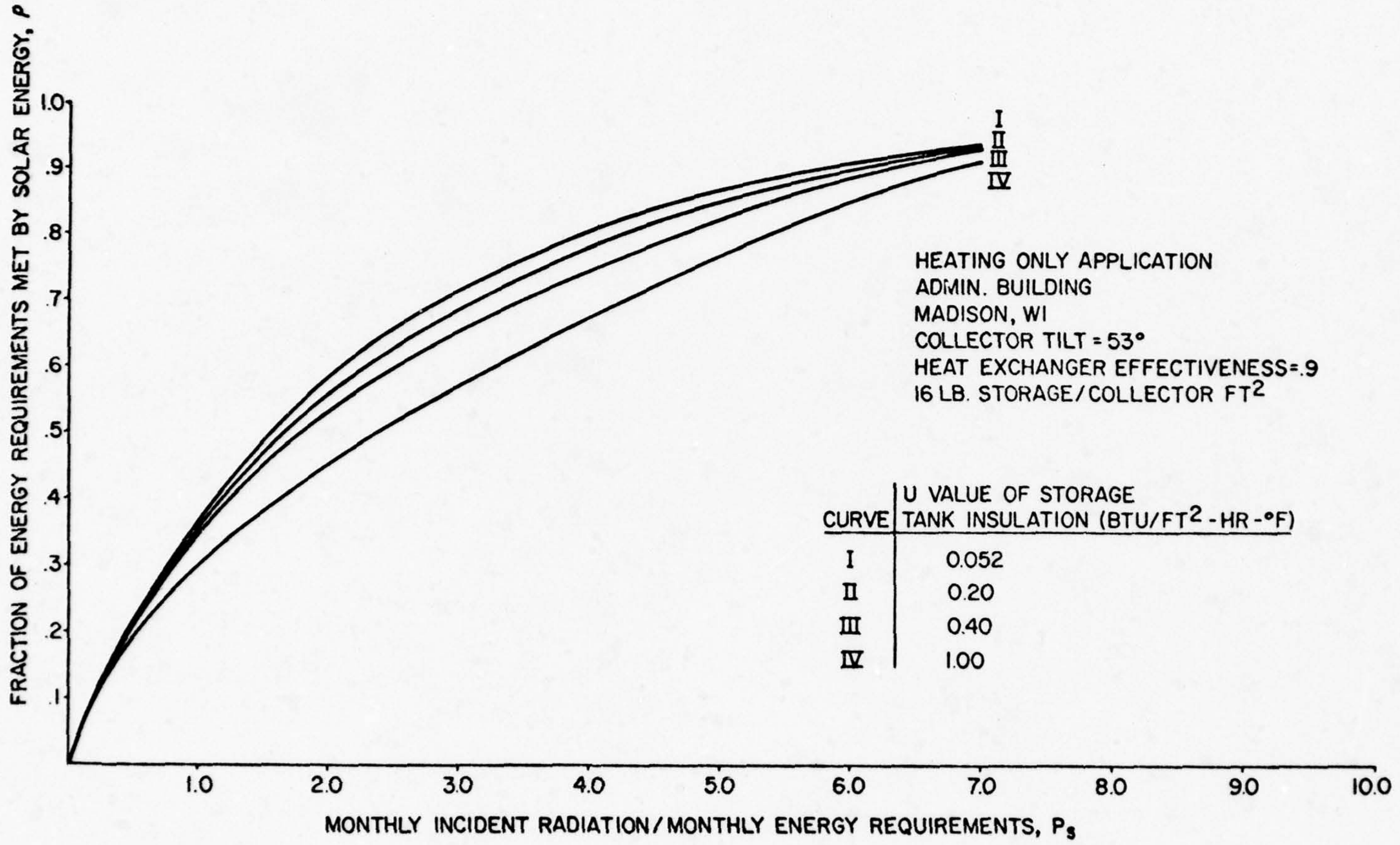


Figure A4. Dependence of solar fraction on storage tank insulation.

APPENDIX B:
SOLAR RADIATION DATA*

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*From *Climatic Atlas of the United States* (National Oceanic and Atmospheric Administration, 1968).

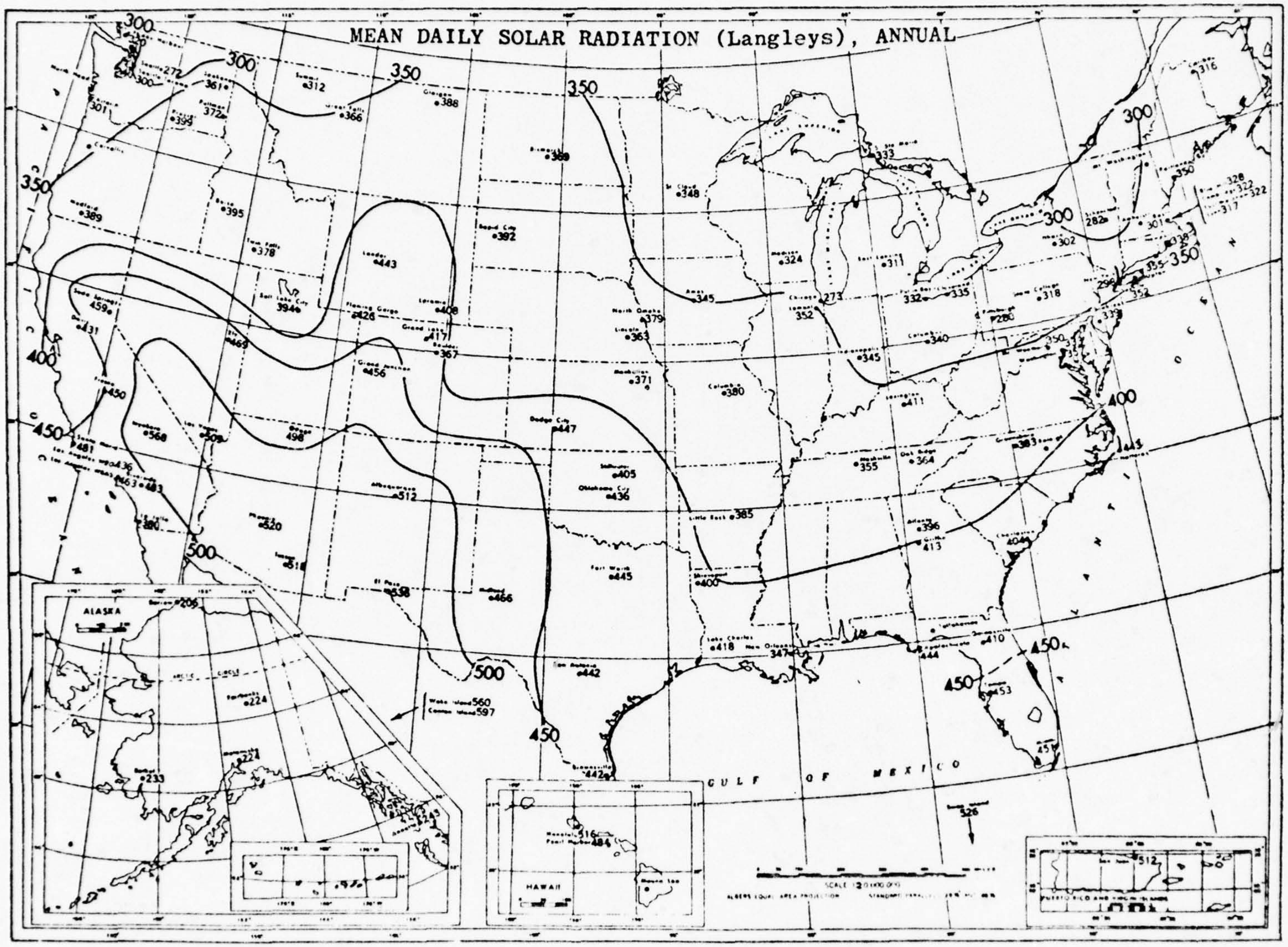

Figure B1. Annual mean daily solar radiation. Conversion factor:
1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

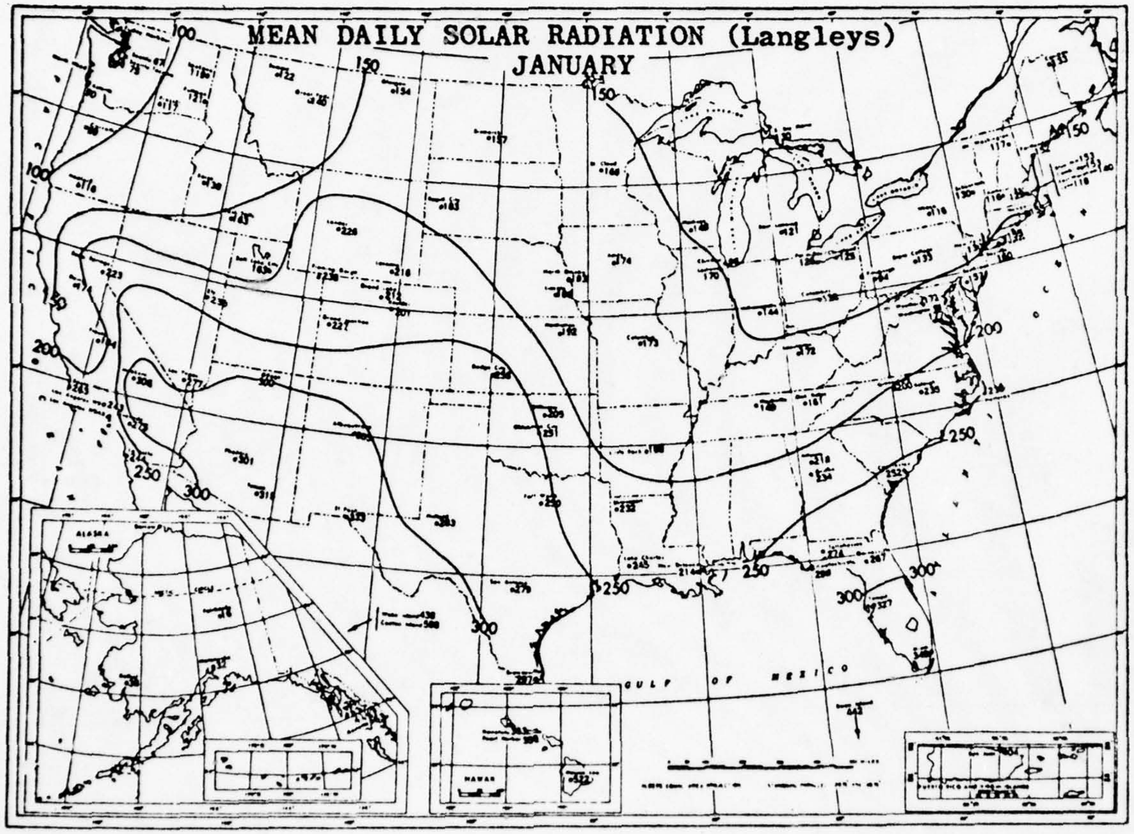

Figure B2. Mean daily solar radiation for January. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

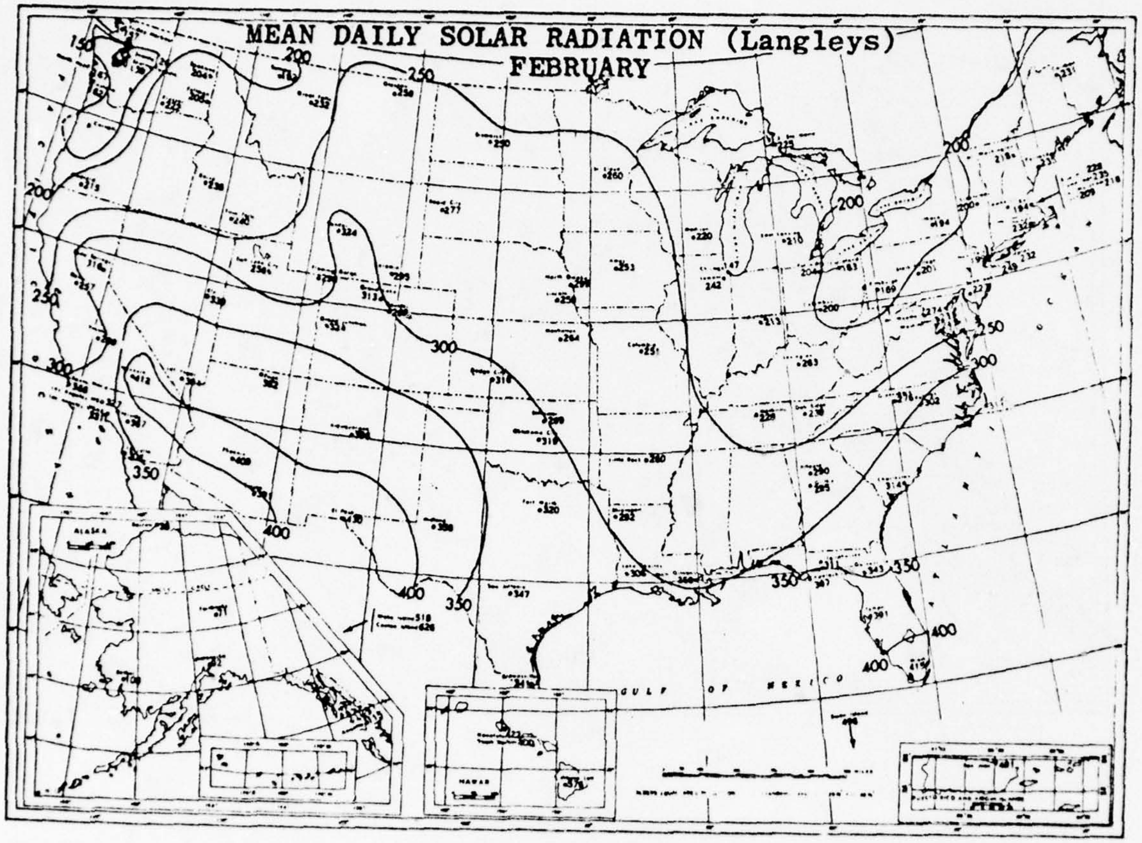

Figure B3. Mean daily solar radiation for February. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

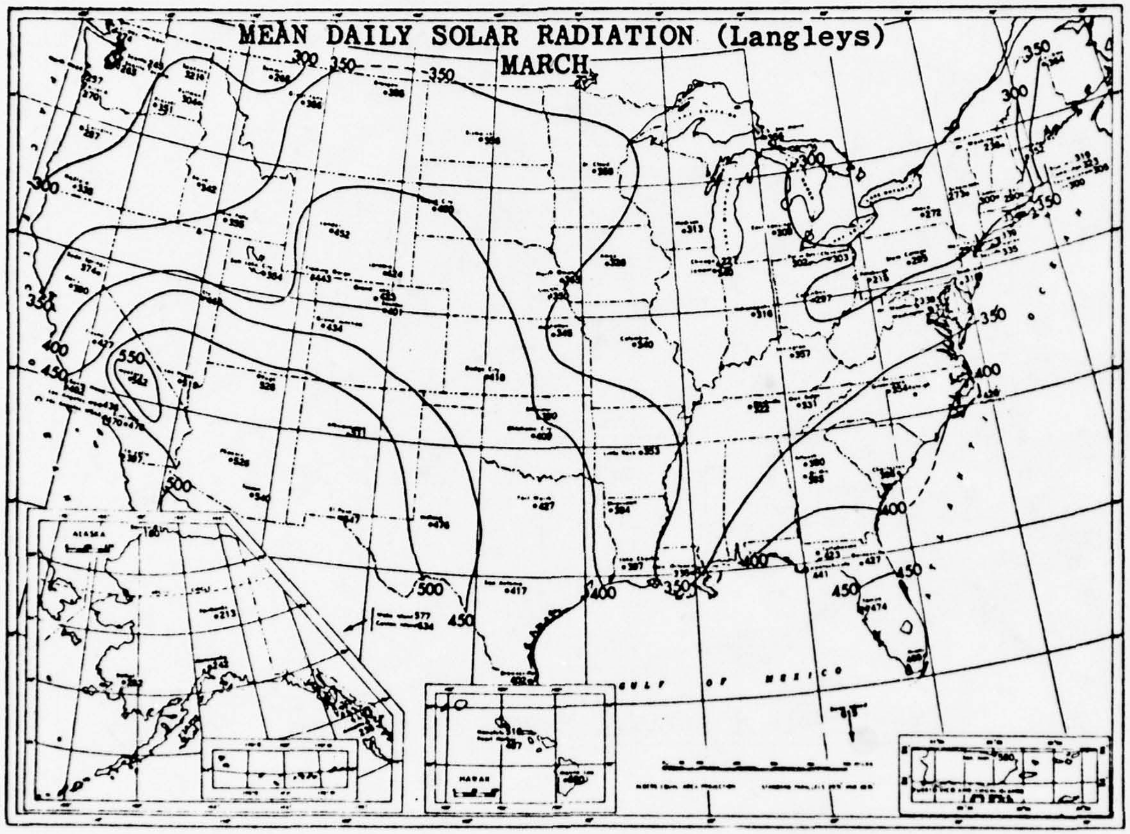

Figure B4. Mean daily solar radiation for March. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

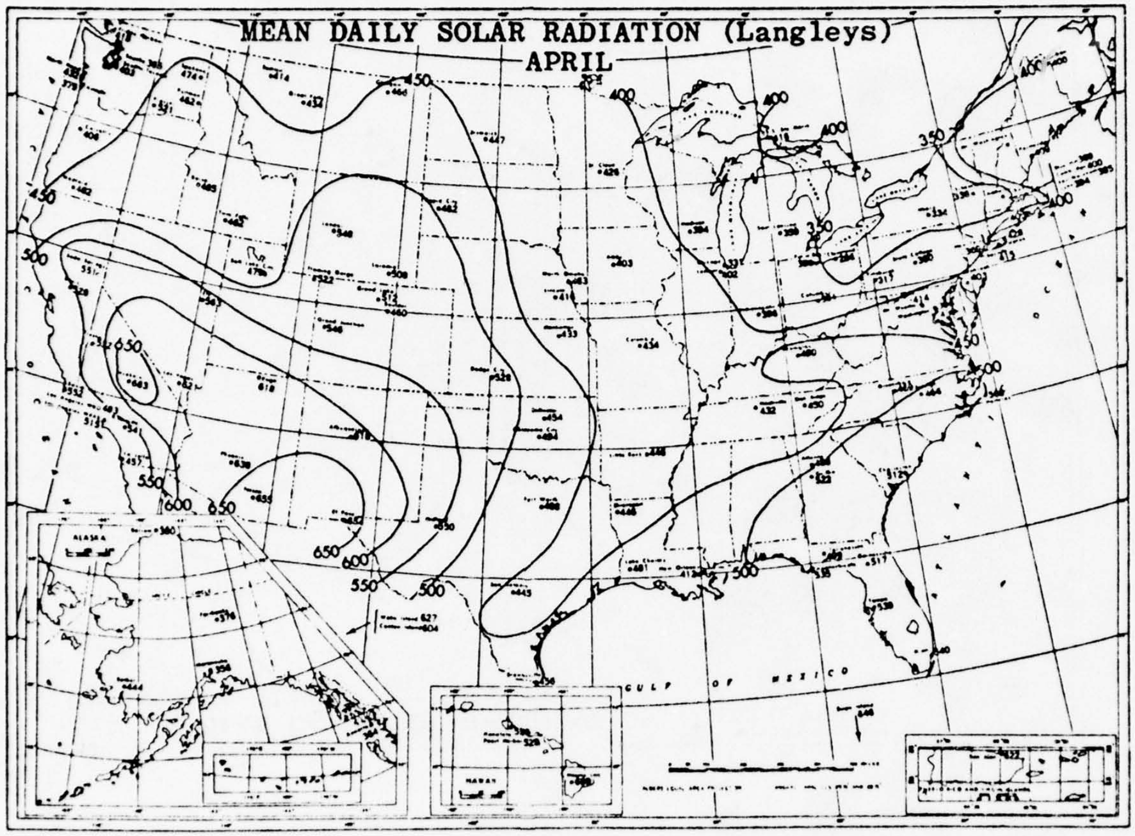

Figure B5. Mean daily solar radiation for April. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

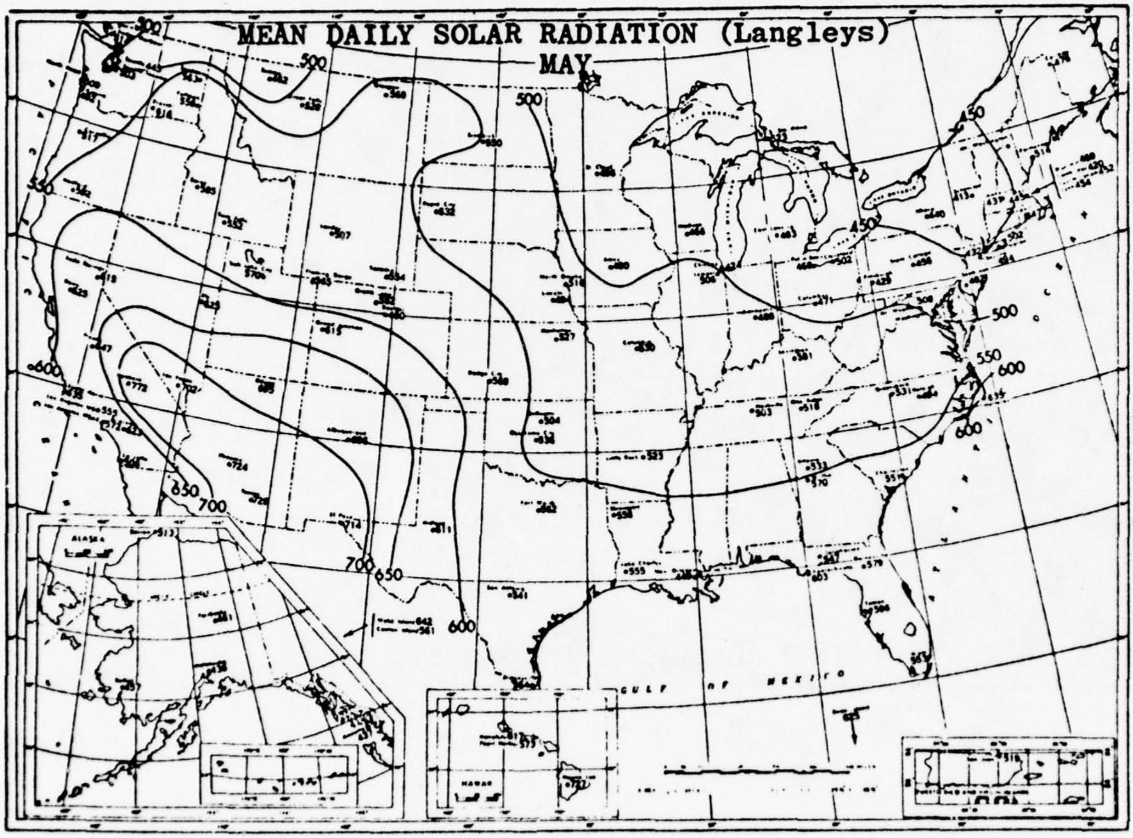

Figure B6. Mean daily solar radiation for May. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

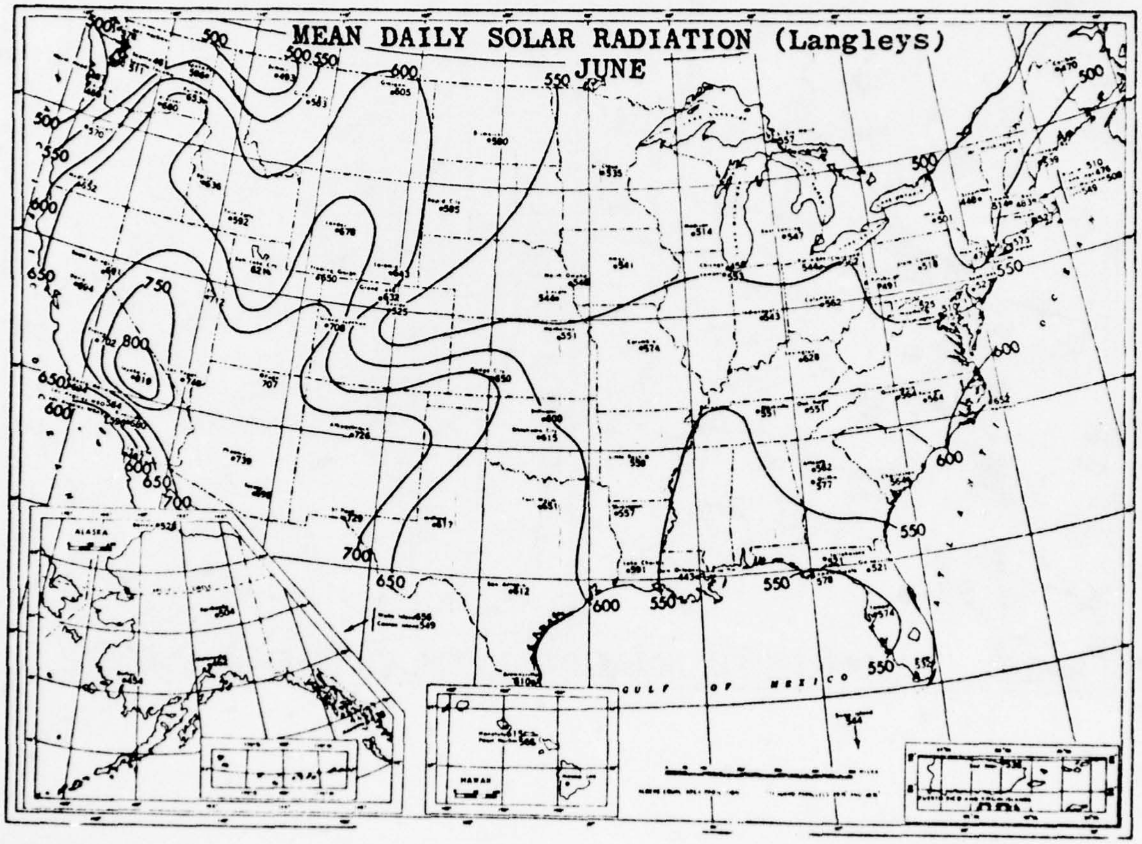

Figure B7. Mean daily solar radiation for June. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

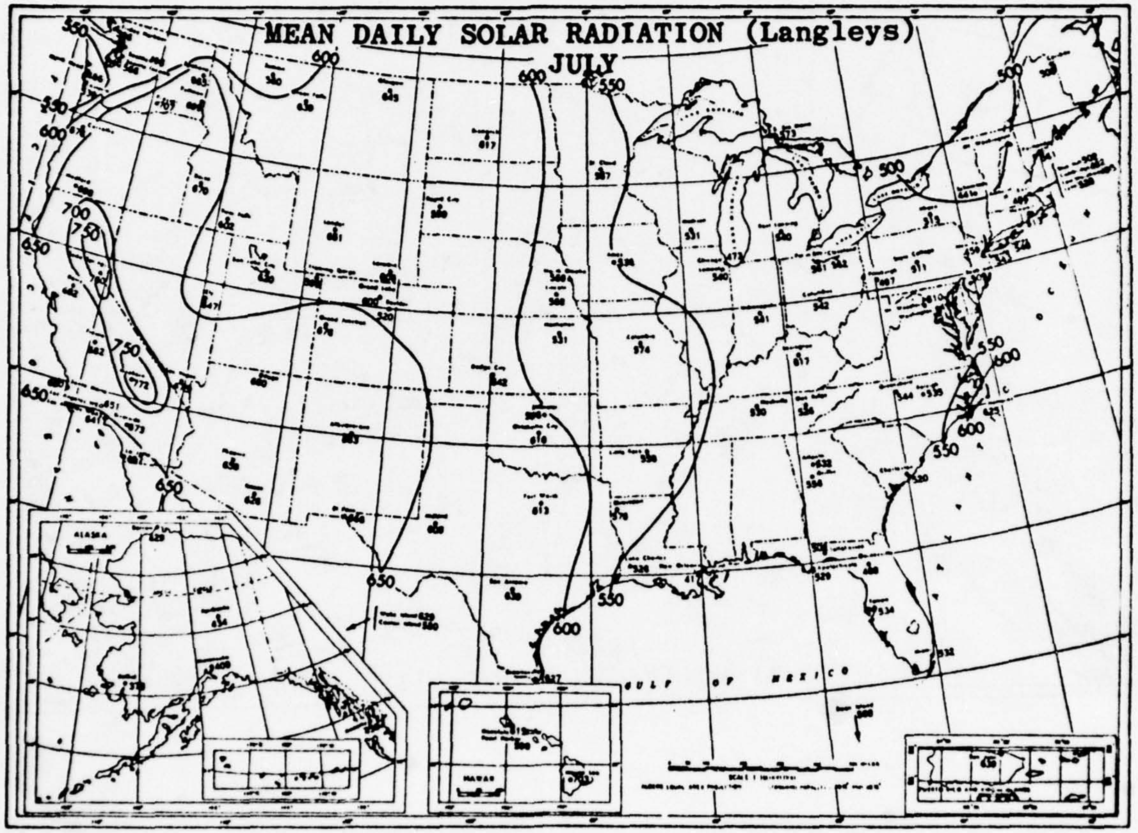

Figure B8. Mean daily solar radiation for July. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

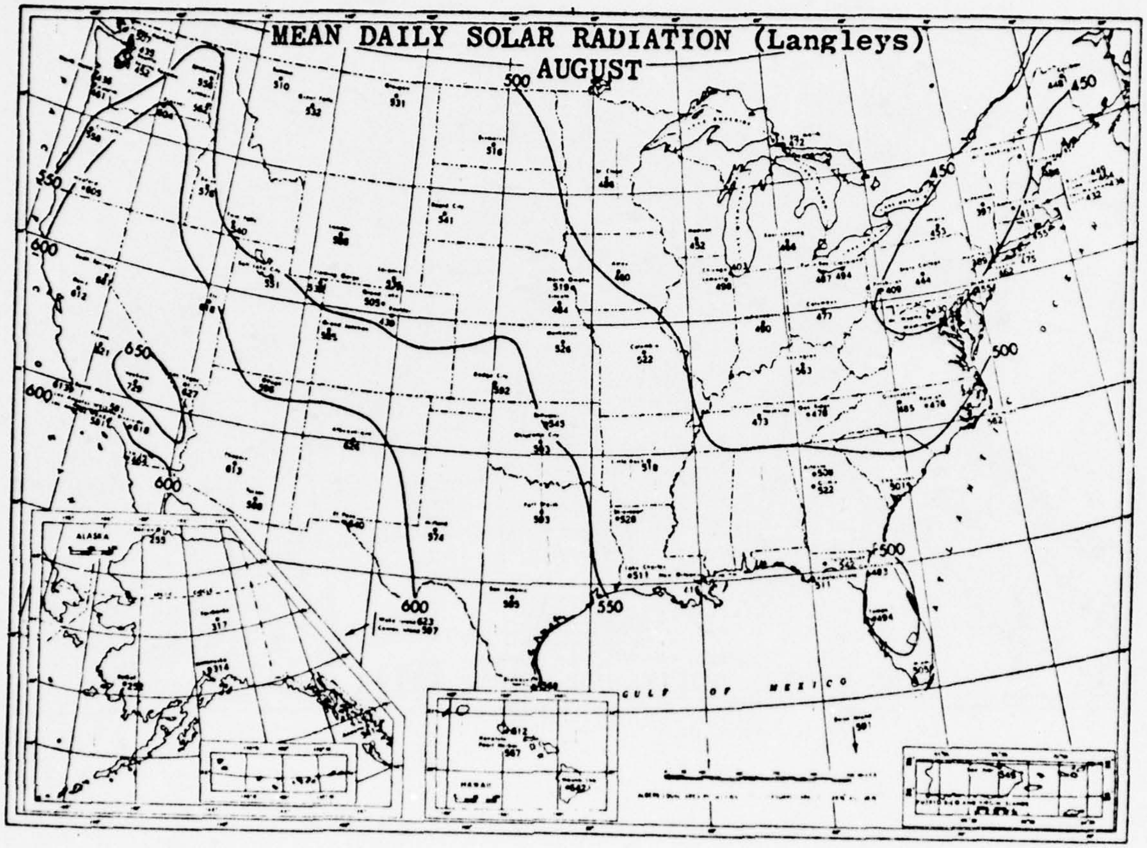

Figure B9. Mean daily solar radiation for August. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m².

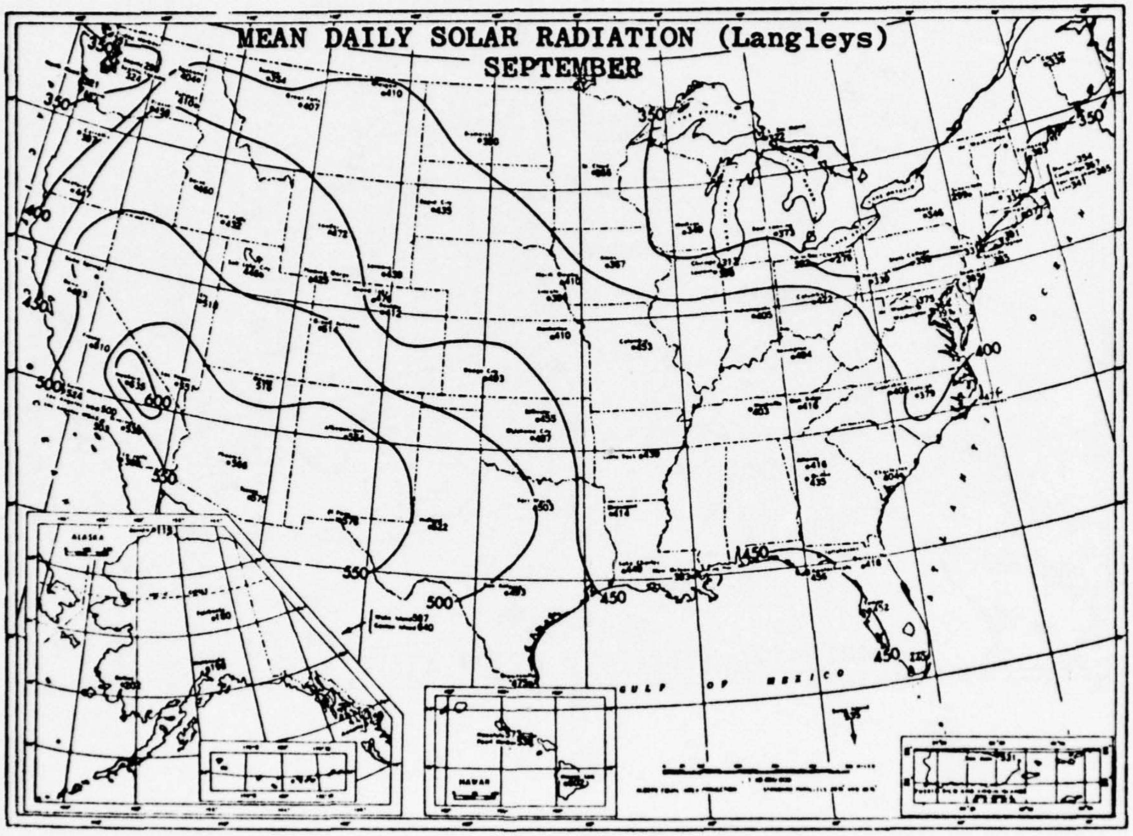

Figure B10. Mean daily solar radiation for September. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

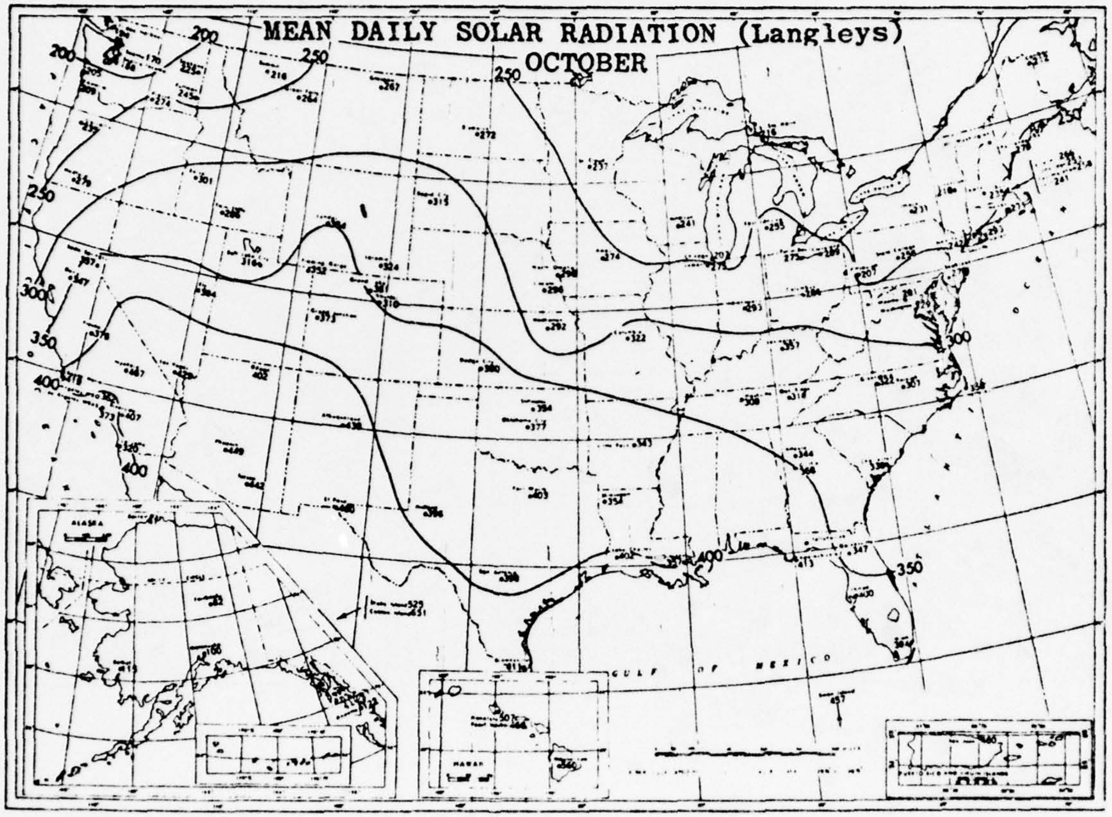

Figure B11. Mean daily solar radiation for October. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

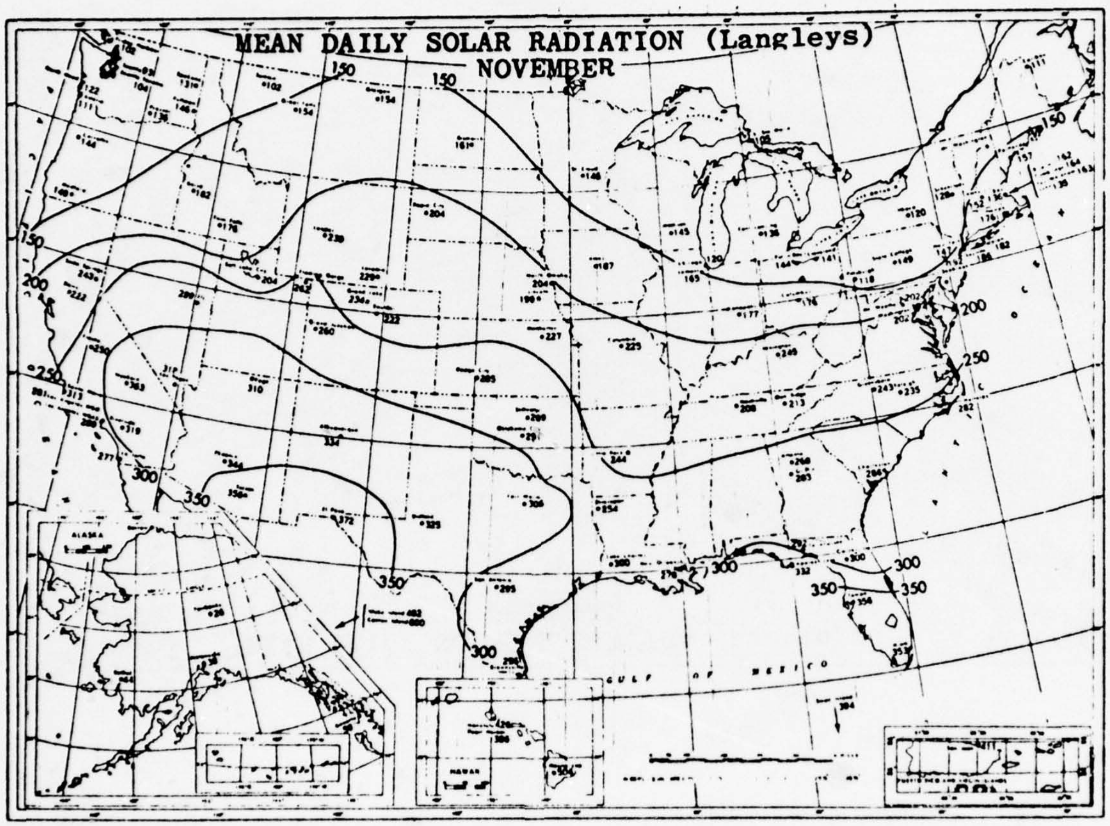

Figure B12. Mean daily solar radiation for November. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

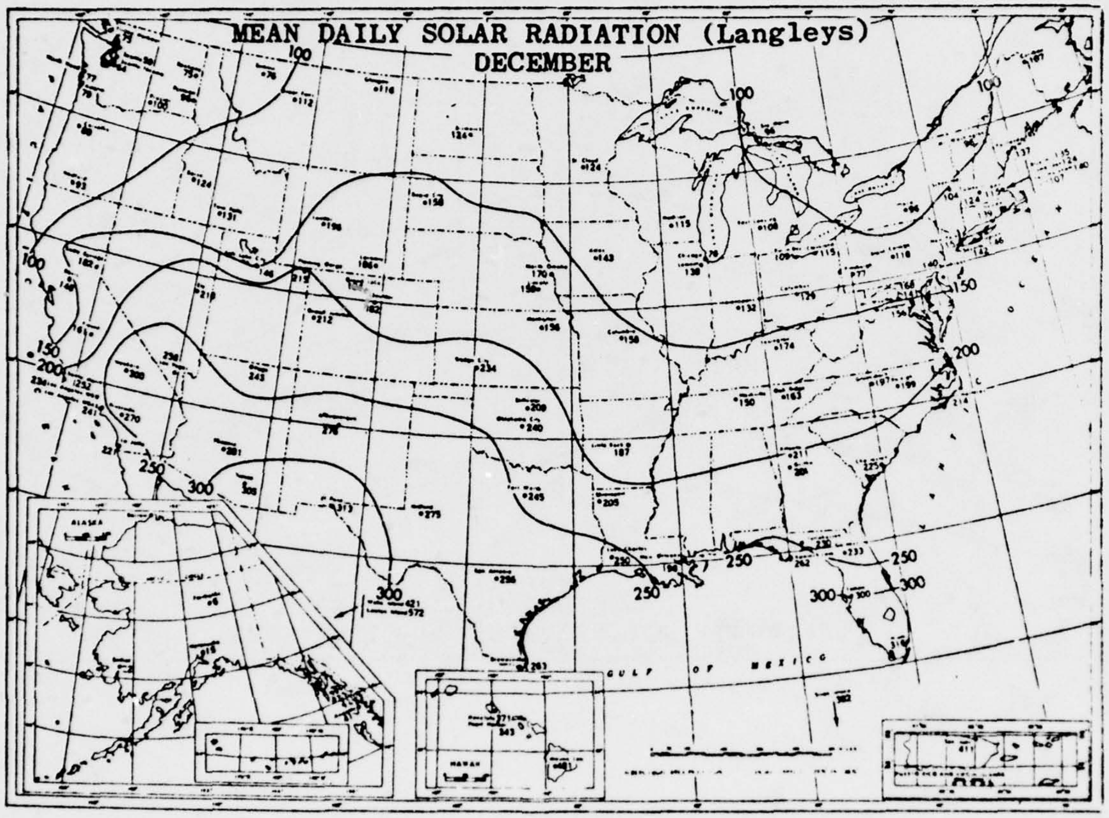

Figure B13. Mean daily solar radiation for December. Conversion factor: 1 langley = 3.69 Btu/sq ft or 41.84 kJ/m^2.

APPENDIX C: EXAMPLE OF SOLAR SYSTEM PRESENT WORTH COST ANALYSIS

A design engineer wants to determine the collector area which has the greatest economic B/C ratio[14] for solar heating and cooling of a new administration building similar to the one used for Examples 2 and 3 in Chapter 3. For the purpose of this example, he/she is to compare the costs of a building with conventional oil heating and electric centrifugal cooling to a building heated and cooled by a solar energy system. In the solar case, auxiliary heating is supplied by an oil-fired boiler and auxiliary cooling is provided by an electric centrifugal chiller. For this example, it is assumed that the analysis is being performed in FY78 for a project programmed for funding in FY80.

Input Data:

From Examples 2 and 3, the annual loads are

Building Heating Load	10.8×10^3 mBtu/yr*
Building Cooling Load	11.2×10^3 mBtu/yr

The FY78 cost of energy is assumed to be

Price of Electricity	\$.027/kWh
Price of Oil	\$.50/gal**†

The energy costs escalated to the end of FY80[15] are

Electricity	$(\$.027)(1.16)^2 = \$.036$/kWh
Oil	$(\$.50)(1.16)^2 = \$.673$/gal

Heating and Cooling

Step 1

Following the procedures in Chapter 4, the capital costs of the solar system components must be determined. Since in this case the absorption chiller is redundant, its entire price is charged to the solar system. Table C1 summarizes estimated costs; design costs have been ignored for the purposes of this example.

Since the building of Examples 2 and 3 contains a 385-ton cooling unit, the cost of an absorption chiller (\$20,000) is listed in the table.

The cost of controls, sensors, valves, and minimal piping is nearly independent of system size and is estimated at roughly \$30,000.

The remainder of the items in the table are dependent on collector area (A_c). These values are meant as estimates for the purposes of the example only. Thus, the initial capital costs (IC) are

$$IC = 5.0 \times 10^4 + 14.18\, A_c .$$

Escalating this cost to the end of FY80[16] gives the current working estimate (CWE)

$$CWE = (5 \times 10^4 + 14.18\, A_c)(1.07)(1.065)$$

$$CWE = 5.7 \times 10^4 + 16.2\, A_c$$

Step 2

Once the cost data and CWE have been determined, the second step in the comparison procedure is the establishment of the annual fuel cost for the conventional energy systems. As described in Chapter 4, conventional system annual fuel costs are estimated as follows:

1. Determine the annual heating and/or cooling energy requirement for conventional equipment as described in Chapter 2.

For this example the heating load is 10.8×10^3 mBtu/yr and the cooling load is 11.2×10^3 mBtu/yr (shown in Examples 2 and 3 of Chapter 3).

2. Convert the cooling energy load to kilowatt hours and multiply by the local electrical rate to obtain the cost of cooling energy (note that the coefficient of performance of the conventional electrical chilling device must be considered in making this conversion).

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[14] Letter from David M. Crabtree, Chief, Util. Engr. and Ops. Div., Facilities Engineering (DAEN-FEU), Subject: Energy Conservation Investment Program (ECIP) Guidance (7 November 1977).

*SI conversion factor: 1 Btu = 1.055 kJ. (To avoid confusion, SI equivalents are not given in this example; instead, an SI conversion factor is given the first time a particular unit is used.)

**SI conversion factor: 1 gal = 3.785 ℓ.

†This price is used for example purposes only; it may be somewhat higher than the actual fuel cost.

[15] Letter from David M. Crabtree (7 November 1977).

[16] Letter from David M. Crabtree, Chief, Util. Engr. and Ops. Div., Facilities Engineering (DAEN-FEU), Subject: Energy Conservation Investment Program (ECIP) Guidance (7 November 1977).

Table C1
Estimated FY78 Costs for Heating and Cooling Example

	Fixed Costs $	Cost/sq ft* of Collector, $
Absorption Cooling System	2×10^4	
Controls, Sensors, Valves, Piping	3×10^4	
Heat Exchanger		.5
Fluid		.18
Storage Tank		1.0
Additional Plumbing		.75
Pumps		.75
Collector		10.0
Labor		1.0
	5.0×10^4	$14.18 A_c$

*SI Conversion factor: 1 sq ft = 0.0929 m².

For a cooling load of 11.2×10^3 mBtu/yr and a chiller COP of 4, the FY80 cost of cooling energy (at $.036/kWh) is:

$$(11.2 \times 10^3 \text{ mBtu/yr})(1/4)\left(\frac{\text{kWh}}{3.412 \times 10^{-3} \text{ mBtu}}\right)\left(\frac{\$.036}{\text{kWh}}\right)$$

$$= 29.5 \times 10^3/\text{yr}$$

3. Divide the input heating energy and/or domestic hot water heating required by the heating value of the fuel used and multiply by the unit fuel price to determine the cost of heating (note again that in determining the heat energy required, the efficiency of the boiler or furnace must be considered).

For a boiler which is 75 percent efficient, using a heating value of .138 mBtu[17]/gal for oil, the FY80 cost of heating (at $.673/gal for oil) is:

$$(10.8 \times 10^3 \text{ mBtu/yr})\left(\frac{1}{.75}\right)\left(\frac{\$.673}{\text{gal}}\right)\left(\frac{1 \text{ gal}}{.138 \text{ mBtu}}\right)$$

$$= 70.2 \times 10^3/\text{yr}$$

4. Convert the annual fuel cost to present worth fuel cost (PWFC). This value provides the baseline for comparison of conventional and solar energy systems. The PWFC for the conventional system ($PWFC_c$) is given by

$$PWFC_c = MF_c$$

where M is the single amount factor for energy prices over the life of the facility. If the facility life is 25 years, M is 19.72 for oil[18] and 17.67 for electricity.[19] Hence, for the cooling system,

$$\text{PWFC (elec)} = (17.67)(29.5 \times 10^3/\text{yr})$$

$$= .52 \times 10^6$$

and for heating,

$$\text{PWFC (oil)} = (19.72)(70.2 \times 10^3/\text{yr})$$

$$= 1.38 \times 10^6$$

The total $PWFC_c$ is the sum of these two.

$$PWFC_c = 1.9 \times 10^6$$

Step 3

The third step is to calculate the amount of auxiliary fuel or electrical energy required annually by the solar system for various collector array sizes based on the methods described in Chapter 3. Procedures for determining the present worth of auxiliary fuel cost for various solar energy systems are as follows:

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[17] Letter from David M. Crabtree, Chief, Util. Engr. and Ops. Div., Facilities Engineering (DAEN-FEU), Subject: Energy Conservation Investment Program (ECIP) Guidance (7 November 1977).

[18] Letter from David M. Crabtree (7 November 1977).

[19] Letter from David M. Crabtree (7 November 1977).

1. Determine the total annual energy supplied by the solar energy system, Q_{LS}, by the method prescribed in Chapter 3. Following Example 2 of Chapter 3, Q_L is 28×10^3 mBtu/yr and Q_c is .57 mBtu/sq ft/yr. For a collector area, A_c, of 5×10^4 sq ft (a guess), Eq 1 may be used to find P_s

$$P_s = 1.02$$

For this P_s, the equation for the heating and cooling universal curve gives a ρ of .28. Hence,

$$Q_{LS} = \rho Q_L = .28(28 \times 10^3 \text{ mBtu})$$

$$Q_{LS} = 7.8 \times 10^3 \text{ mBtu/yr}$$

This is the amount of energy supplied by the solar energy system.

2. Determine the annual energy cost, F_s, for auxiliary fuel.

As stated in Chapter 4, solar energy is used first to satisfy the building heating load, then the cooling load. In order to calculate the annual energy cost for auxiliary fuel, the total annual building thermal demand, Q_L, must be separated into the thermal requirements for heating and cooling, respectively, and compared with the amount of solar energy, Q_{LS}, supplied.

Following Example 2 of Chapter 3, the thermal energy requirements for heating and cooling for this case are 10.8×10^3 mBtu and 17.2×10^3 mBtu, respectively. (Note that these sum to the total requirement, Q_L.) For a collector area of 5×10^4 sq ft, Q_{LS} has been calculated to be 7.8×10^3 mBtu. This energy is first used to meet the heating requirement. Because Q_{LS} is less than the heating demand, a total of $(10.8 - 7.8) \times 10^3$ mBtu must be purchased for heating auxiliary and 17.2×10^3 mBtu for cooling.

The annual cost for each fuel type may now be computed. For heating,

$$F_s(\text{oil}) = \left(\frac{3 \times 10^3 \text{ mBtu}}{\text{year}}\right)\left(\frac{\$.673}{\text{gal}}\right)\left(\frac{1 \text{ gal}}{.138 \text{ mBtu}}\right)\left(\frac{1}{.75}\right)$$

Where .75 is the estimated boiler efficiency

$$F_s(\text{oil}) = \$1.95 \times 10^4/\text{year}$$

Because a centrifugal chiller (COP of 4) supplies the cooling backup, the cost of auxiliary fuel for cooling is

$$F_s(\text{elec}) = \left(\frac{17.2 \times 10^3 \text{ mBtu}}{\text{year}}\right)\left(\frac{.65}{4}\right)$$

$$\left(\frac{\$.036}{\text{kWh}}\right)\left(\frac{\text{kWh}}{3.412 \times 10^{-3} \text{ mBtu}}\right)$$

$$F_s(\text{elec}) = \$2.95 \times 10^4/\text{yr}$$

The factor of .65 comes from the fact that the thermal demand for cooling (17.2×10^3 mBtu) was computed on the basis of absorption air conditioning. Now that the backup system is assumed to be conventional, this factor is regained.

3. Convert the annual fuel cost to present worth fuel cost, $PWFC_s$. As in the conventional case,

$$PWFC_s(\text{oil}) = MF_s(\text{oil})$$

$$= (19.72)(1.95 \times 10^4)$$

$$PWFC_s = \$3.85 \times 10^5$$

and

$$PWFC_s(\text{elec}) = MF_s(\text{elec})$$

$$= (17.67)(2.95 \times 10^4)$$

$$= \$5.21 \times 10^5$$

The total $PWFC_s$, for a collector area of 5×10^4 sq ft, is the sum of:

$$PWFC_s = \$3.85 \times 10^5 + \$5.21 \times 10^5$$

$$PWFC_s = 9.06 \times 10^5$$

Step 4

The total B/C ratio for the solar heating and cooling system is given by

$$B/C = \frac{PWFC_c - PWFC_s}{CWE}$$

The solar energy system represents a savings over the conventional system *only if B/C is greater than 1.0.*

From Step 1, for an A_c of 5×10^4 sq ft

$$CWE = 5.7 \times 10^4 + 16.2(5 \times 10^4)$$

$$CWE = 8.67 \times 10^5$$

Using $PWFC_c$ and $PWFC_s$ from Steps 2 and 3, B/C can now be computed.

$$B/C = \frac{1.9 \times 10^6 - 9.06 \times 10^5}{8.67 \times 10^5}$$

$$B/C = 1.15$$

for a collector area of 50,000 sq ft.

If the previous calculation is repeated for an A_c of 1×10^5 sq ft, it is found that

$$P_s = 2.04$$

The universal curve gives a ρ of .50 for this P_s; thus,

$$Q_{LS} = 14.0 \times 10^3 \text{ mBtu}$$

Since this amount of energy exceeds the heating demand, all backup must be supplied for cooling. Thus,

$$F_s(\text{elec}) = (14 \times 10^3)\left(\frac{.65}{4}\right)\left(\frac{.036}{3.412 \times 10^{-3}}\right)$$

$$= \$24.0 \times 10^3.$$

This implies that

$$PWFC_s = (17.67)(24.0 \times 10^3) = \$4.2 \times 10^5$$

For an A_c of 1×10^5 sq ft. Also,

$$CWE = 5.7 \times 10^4 + 16.2(1 \times 10^5) = 1.68 \times 10^6.$$

Using the same $PWFC_c$ as before,

$$B/C = \frac{1.9 \times 10^6 - 4.2 \times 10^5}{1.68 \times 10^6}$$

$$B/C = .88$$

for a collector area of 100,000 sq ft. The larger collector area has resulted in a lower B/C ratio.

If a collector area of 25,000 sq ft is considered, B/C is computed to be 1.11. Since a maximum has been found in B/C, a more exact analysis of the problem is indicated. Hence, the computer simulation program should probably be consulted.

Heating Only

Experience indicates that a high percentage of the auxiliary fuel requirement is normally used for cooling. This seems to suggest that a heating-only system might (from an economic standpoint) be more feasible. Thus, the previous example is repeated considering only the heating load.

Step 1

Determine capital costs. Table C2 summarizes estimated costs. For this case, the absorption chiller cost is saved, and the current working estimate, CWE (FY80), is given by

$$CWE = \$3.42 \times 10^4 + \$10.46\, A_c.$$

Step 2

The computation of conventional fuel costs is based on the heating load alone. For a building heating load of 10.8×10^3 mBtu/yr, with a .75 boiler efficiency, the FY80 annual fuel costs, as in the last example, are,

$$F_c = (10.8 \times 10^3 \text{ mBtu/yr})(1/.75)(\$.673/\text{gal})$$

$$(1 \text{ gal}/.138 \text{ mBtu})$$

$$F_c = \$70.2 \times 10^3/\text{yr}$$

Hence,

$$PWFC_c = (19.72)(70.2 \times 10^3)$$

$$PWFC_c = 1.38 \times 10^6$$

Step 3

To compute the cost of auxiliary fuel for the solar system, Q_{LA} must be determined from monthly Q_L and Q_c data. The values for Q_L and Q_c for the heating months are given in Example 3, Chapter 3. This information (along with an assumed collector area) allows calculation of a P_s for each month. The universal curve for heating (Figure 4) then gives the ρ for each P_s. Finally a monthly Q_{LS} can be figured (ρQ_L) and summed to get a yearly Q_{LS}.

Table C3 summarizes the procedure using the Q_L and Q_c from Example 3 of Chapter 3, with a collector area of 4×10^4. The Q_{LA} can be determined from

$$Q_{LA} = Q_L - Q_{LS} = 10.8 \times 10^3 - 4.69 \times 10^3 \text{ mBtu/yr}$$

$$Q_{LA} = 6.2 \times 10^3 \text{ mBtu/yr}$$

The solar auxiliary fuel cost, F_s, is given (assuming a boiler efficiency of .75) by

$$F_s = (6.2 \times 10^3 \text{ mBtu/yr})(1/.75)(\$.673/\text{gal})$$

$$(1 \text{ gal}/.138 \text{ mBtu})$$

$$F_s = \$40.3 \times 10^3$$

Table C2
Estimated (FY78) Costs for Heating-Only Example

	Fixed Costs $	Cost/sq ft of Collector, $
Controls, Valves, Sensors, Piping	3×10^4	
Heat Exchanger		.5
Fluid		.18
Tank		1.0
Additional Plumbing		.75
Pumps		.75
Collector		5.0
Labor		1.0
	3×10^4	$9.18 A_c

Table C3
Summary of Procedures Used to Determine Q_{LS}

Month	Q_L MBtu/mo	Q_c Btu/sq ft/mo	P_s	e	Q_{LS} MBtu/mo
Oct	2.6×10^2	4.7×10^4	7.23	.94	244
Nov	8.4×10^2	3.7×10^4	1.76	.54	454
Dec	12.9×10^2	3.4×10^4	1.05	.38	490
Jan	20.5×10^2	3.8×10^4	.74	.29	595
Feb	19.1×10^2	4.3×10^4	.90	.34	649
Mar	16.9×10^2	5.1×10^4	1.21	.42	710
Apr	13.5×10^2	4.5×10^4	1.34	.45	608
May	9.4×10^2	4.9×10^4	2.09	.60	564
Jun	4.6×10^2	4.8×10^4	4.17	.82	377
					4.69×10^3

Hence,

$$PWFC_s = MF_s = (19.72)(40.3 \times 10^3)$$

$$PWFC_s = \$.794 \times 10^6$$

Step 4

Determine B/C, where,

$$B/C = \frac{PWFC_c - PWFC_s}{CWE}$$

For an A_c of 4×10^4 sq ft

$$CWE = 3.42 \times 10^4 + 10.46\,A_c$$

$$= 3.42 \times 10^4 + 10.46(4 \times 10^4) = \$4.53 \times 10^5$$

Thus,

$$B/C = \frac{1.38 \times 10^6 - .794 \times 10^6}{4.53 \times 10^5}$$

$$B/C = 1.29$$

for a collector area of 40,000. The price of the solar energy system compares favorably to the cost of the conventional system.

Table C4 shows results of the analysis for other collector areas. A maximum benefit-to-cost ratio is seen to exist. At this point the computer simulation program should be consulted for a more exact analysis.

Table C4
Benefit-to-Cost Ratio for Various Collector Areas

Collector Area (sq ft)	B/C
0	0
5,000	1.35
15,000	1.50
40,000	1.29
85,000	.99

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