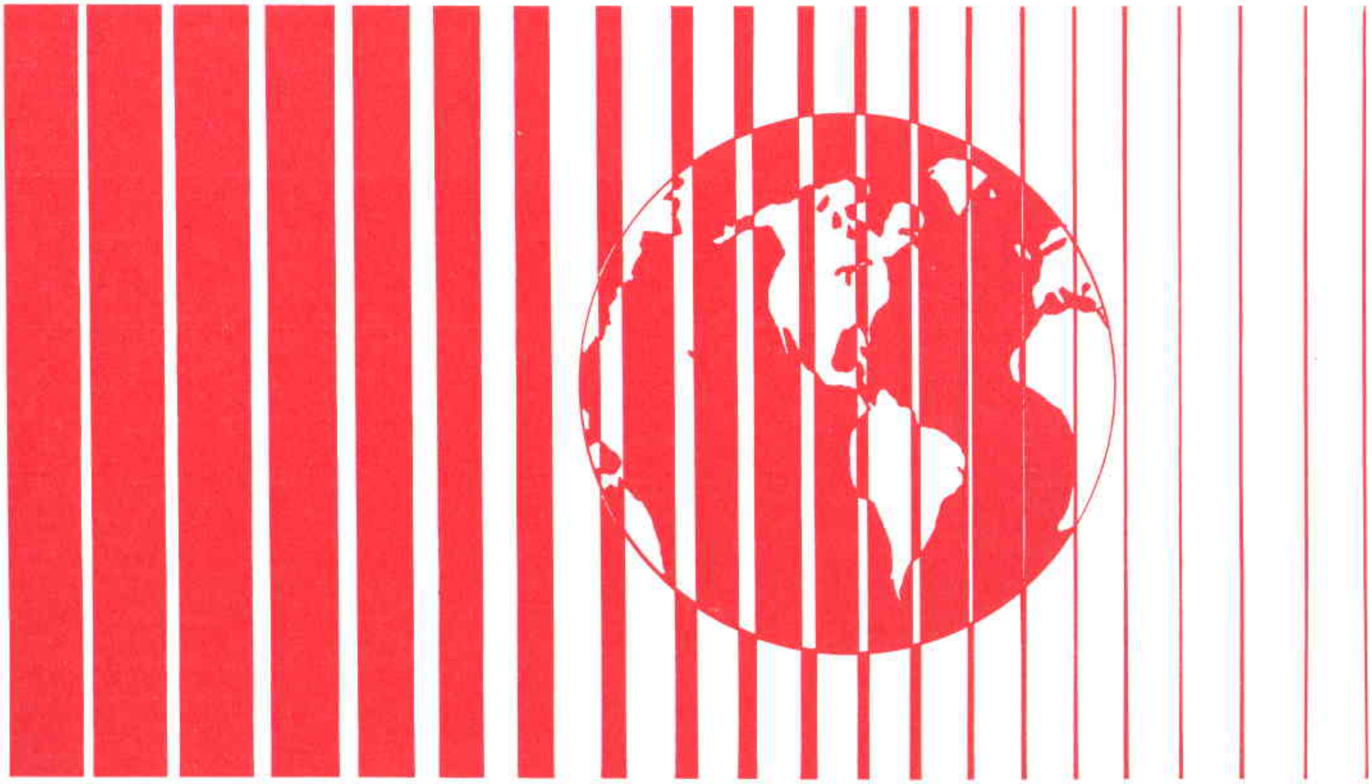
LA-7995-TASE

The Characterization and Assessment of Selected Solar Thermal Energy Systems for Residential and Process Heat Applications

technology assessment of solar energy



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The Characterization and Assessment of Selected Solar Thermal Energy Systems for Residential and Process Heat Applications

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PREFACE

The Office of the Department of Energy's Assistant Secretary for Environment, through its Division of Technology Assessment, has initiated a comprehensive plan relating to the extensive use of solar energy technologies. The resultant program, entitled "Technology Assessment of Solar Energy (TASE)," will determine the long-range environmental and socioeconomic impacts of distributed (decentralized) solar energy systems plus several other distributed selected nonsolar technologies. The solar technologies include (1) space heating and cooling and domestic hot water, (2) agricultural and industrial process heat, (3) photovoltaics, (4) wind, and (5) biomass. The nonsolar technologies are (1) cogeneration, (2) urban waste utilization, and (3) district heating. The latter technologies were included in Phase 1 because they are complementary to the distributed solar systems being studied; that is, they are scaled to local energy needs compared to large capital-intensive centralized power sources. In the next fiscal year, these nonsolar technologies will continue to be studied as part of an assessment study other than TASE.

The scope of TASE includes national, regional, and community levels. The Los Alamos Scientific Laboratory (LASL) was the lead laboratory during FY 1978 for the national and regional studies. Lawrence Berkeley Laboratory (LBL) led the community studies and also assisted with the national and regional studies. Two other major contributors to the studies were Argonne National Laboratory and Oak Ridge National Laboratory.

This report is presented in partial fulfillment of the Phase 1 requirements outlined under the TASE program. The results of investigations of selected solar thermal energy systems for residential and process heat applications are given. Emphasis has been placed on the selection and use of specific applications and conceptual models to develop and quantify the data. Technical system characterizations plus material, land, and water requirements have been included. The existing reference literature has been used extensively.

In order to meet TASE program requirements, two reports were melded into one paper. The editorial changes, revisions, and modifications required were made at LASL by John H. Altseimer with the assistance of Ellen L. Heckler and Milton C. Krupka.

In addition to the technical data reported herein, cost data have been generated for the various processes and components used in each solar technology. The requirements for costing information basically arise from the need to compute parameters such as demands, residual levels, material investment demands, and employment patterns (associated with each technology) for several national and regional scenarios. The specific cost data have been arranged in special format for input to the Strategic Environmental Assessment Simulation (SEAS) model computer program. These data have been compiled and coordinated by LASL. Operating residual data, such as are presented in this report, also are required for these computations. After all of these types of data are entered in the SEAS computer system, computations will be made through DOE by the Mitre Corporation.

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THE CHARACTERIZATION AND ASSESSMENT OF SELECTED SOLAR THERMAL ENERGY SYSTEMS FOR RESIDENTIAL AND PROCESS HEAT APPLICATIONS

by

Jack C. Hyde

ABSTRACT

The environmental data presented in this report are in partial response to the Technology Assessment of Solar Energy (TASE) program. TASE is an assessment of the potential environmental, socioeconomic, and institutional impacts of solar technologies on the national, regional, and local community levels.

The results of studies of seven solar thermal energy applications are presented. Five of these are residential applications: space heating--active liquid, space heating--active air, domestic hot water--active, space heating--passive, and space heating and cooling--active liquid. Denver, Colorado, was selected as a representative location for each of the above applications. The remaining two applications produce industrial process heat: a flat-plate collector system producing 50°C - 100°C hot water for a commercial laundry in Indianapolis, Indiana; and a concentrating collector system that could produce 100°C - 300°C process heat adequate to the needs of a pulp mill in Madison, Wisconsin.

For each application, a representative system model and preliminary designs of major system elements were established. Then the following data were generated: annual useful energy produced, type and weight of the basic component materials, environmental residuals generated during system operation, and land and water requirements. These data were generalized for other TASE study purposes by expressing them as quantities per 10^{15} Btu of useful energy. This report discusses the system characteristics and evaluates the environmental impacts. To allow the reader to estimate system performance at other geographic locations than those studied, insolation and other pertinent data are provided.

There is an almost unlimited variety of solar and conservation elements that can be combined in a system for any application. Also, there are many potential improvements that can be speculated upon, but which were not included in these studies. Therefore the data developed here must be regarded as a "first-cut" at the subject area and it is recommended that more model systems be added for future TASE studies.

For solar space heating and cooling, the direct operating residuals were found to be minimal. Material requirements are high, however, and indirect residuals and impacts may be significant. The latter were not addressed in these studies but will be included in future TASE studies.

The same comments apply to the industrial process heat systems. The potential for the application of solar energy to meet industrial process heat loads appears very favorable. This is because industrial demand is approximately constant throughout the year, competent maintenance and operating personnel would be available as an inherent element of industrial operations, and the systems would be both larger and fewer in number, probably making it easier for the government to develop effective incentives for commercialization.

I. INTRODUCTION

This report is presented in partial fulfillment of the Phase I requirements outlined under the Technology Assessment of Solar Energy (TASE) Program. It is comprised of two major parts: the results of the investigation on solar space heating and cooling and domestic hot water heating, and several applications of industrial process heat. These are published in a single report because the technologies are so nearly similar, except for scale, that each study augments the materials in the other report. The combined appendicies provide enough information to compute the performance of applications at any location in the United States.

Emphasis has been placed upon the selection and use of specific applications and conceptual models to develop and quantify the data. Technical system characterizations plus material, land, and water requirements have been included. Direct operating residuals (the materials or things discharged into or otherwise impacting on the environment) are also estimated. Not included are the indirect residuals, e.g., those that might be generated in mining, ore processing, component fabrication, and transportation, etc. These will be included in a later report planned by LASL.

II. RESIDENTIAL APPLICATIONS

A. Introduction

In keeping with the general intent of the TASE Program, i.e., to emphasize the decentralized types of solar applications, five residential applications have been studied: (1) space heating--active liquid, (2) space heating--active air, (3) domestic hot water--active, (4) space heating--passive and, (5) space heating and cooling--active liquid. A general discussion of the basic required data and calculation procedures is presented, followed by discussions of each specific system.

B. Basic Data and Methods

An objective of this report is to provide the information for computing estimated environmental residuals for various solar energy applications at any location in the United States. Environmental residuals are those materials that are discharged into the environment as a result of the existence and operation of the system being considered.

The mass of residuals produced per quad (10^{15} Btu) of useful energy obtained from solar radiation can be readily computed. However, the credibility of the predictions depend upon the five key system elements which are discussed below.

1. Percent Solar. The designer selects the fraction of the total energy needed that, according to his calculations, will be supplied by solar. This is ultimately an economic decision and depends on such things as the available insolation at the location, the amount of energy required, the cost of the solar system,* collector life, and the cost of the fuel being replaced. The useful energy collected per unit area of collector decreases as collector area increases. For a very small collector, almost all of the energy collected would be useful when any load was required.
For a very large collector, only on the days of heaviest load would all of the energy collected be immediately useful. On other days, much of the collected energy would be surplus and would be dumped or stored. These things in turn depend on the type of system selected. For example, in regions with a long, cold heating season, having only expensive fuel available, but having bright clear winters, it might be economically reasonable to design for a solar fraction approaching 100%. For marginal regions where solar heating can barely be justified economically, the design point for an active system might be less than 50%. In general, for active systems, if solar heating is feasible at all, the optimum solar fraction would be greater than 50%, because the cost of items not dependent on collector area make small systems uneconomical. The cost of passive systems is more linear as size goes to zero and therefore can optimize at solar fractions of less than 50%.

The economic complexities associated with a rigorous determination of the optimum percent solar are not required for the TASE study. Acceptable results can be obtained by grouping regions based on whether the factors present would tend to warrant a high, medium or low solar fraction. The solar fraction would be determined from the region designation and the solar energy system. For

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*The cost of the solar system is a function of collector area needed and is not linear, especially as the area approaches zero.

example, a passive system in a medium solar fraction region might have an 80% solar fraction, whereas an active system in the same location might use 60% solar.

2. System Life. The life of the system, unfortunately, must be assigned without the benefit of an extensive historical data base. Most people assign life estimates of 20 to 30 years for active systems. Others feel that these estimates are overly optimistic. Passive system life estimates would possibly be considerably longer.

3. Environmental Residuals Predictions. The residuals calculation method consists of a fairly direct combination of the elements just described. Figure 1 outlines the method. First, a region is selected. Next, a system is chosen, for example, space heating, active, liquid, flat plate collector. The system selection may depend to some extent on the region and its climate. Having made these two selections, the rest of the process should go ahead automatically to produce the desired residuals data. The design of the system and percent of solar heating is determined by the region and solar equipment selected. The regional data and percent solar determine the useful energy per unit collector area. The selected system and the percent solar supply the reference design calculation, which generates the weight of each significant material per unit collector area. The selected system and, possibly, the region determine the system life. The life, the total useful energy generated per unit collector area, and materials per unit collector area are combined to compute the weight of each type of material required by the system per unit of useful energy per year. Using a data base that supplies the weight of residuals per weight of material used, we then obtain the residuals information in weight per unit energy per year by multiplying these ratios together.

There are two basic kinds of residuals: operating and indirect. Operating residuals can be easily estimated for each system and are included in this report. However, the indirect residuals are a different matter. These will be obtained in a follow-on study (outside of the scope of the work reported herein) by using the data base contained in the computer program called the Strategic Environmental Assessment System (SEAS). SEAS is theoretically capable of generating a balanced national economy for any given scenario and contains a detailed residual data base that can be used to generate the indirect residuals data needed for the TASE studies.

4. Regional Data. For any geographic location, the hour-to-hour, day-to-day clear sky flux of solar energy is a function only of latitude and altitude. In addition, climatic data is required that includes the degree days (for heating or cooling), the fraction of sunshine correction for cloud cover, and the effects of air purity. Using a representative assumed building load and collector characteristics, this information can be conveniently expressed in terms of delivered useful energy per unit area of collector per year. A major factor in the residuals calculation scheme are the regional data adjustments to the above estimate of the useful energy delivered per unit collector area per year. For example, if we know how many Btu of the annual heat load a solar heater

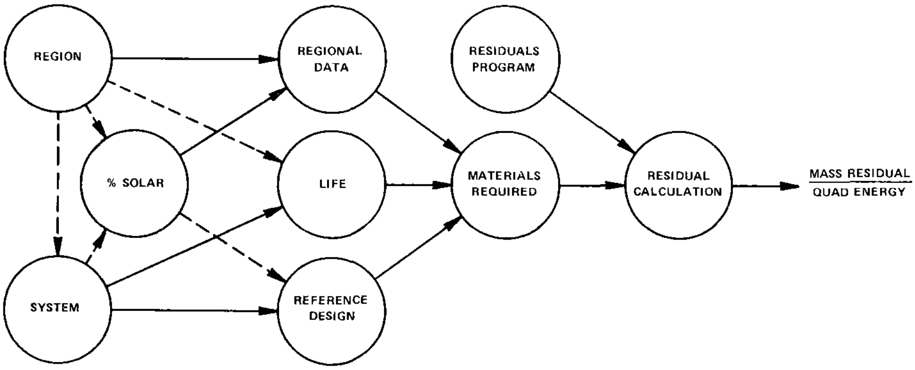

Fig. 1. Residuals calculation method.

would supply to a house in Chicago per square foot of collector area, we could determine the materials and auxiliary energy required per Btu delivered, and therefore the operating and indirect residuals per Btu delivered.

a. Space Heating. The space heating data was obtained from Ref. 1 and is presented in terms of a load-collector ratio LC, where

$$LC = \frac{\text{Building Load}}{\text{Collector area/Building floor area}}, \ \frac{\text{Btu}}{\text{DD ft}^2}$$

Ac = solar collector area (ft^2)

A_f = floor area in heated space (ft^2)

BL = building load, expressed as heat required (Btu) per A_f floor area, (ft^2) and per annual degree days (DD or ^oFd).

These load collector ratios for active space heating and hot water are tabulated for various regions and for three solar fractions in Appendix A.

Collector size increases non-linearly as the fraction of the total load supplied by solar increases. LC values for the solar fractions of 25%, 50%, and 75% listed, show this effect. The cost of items not dependent on the system size partially offsets the effect of non-linearly increasing collector area with increasing solar fraction. These opposing effects result in solar fractions of 50% to 80% being most economic for most cases. Using the 75% LC data will be fairly representative for most residuals calculations. The reference system used for the LC calculations was a liquid collector system with single glazing and a non-selective absorber coating. Corrections for double glazing, selective coatings and air collectors are relatively small. Methods of estimating these corrections are described in Ref. 1.

The hot water data shown in Appendix A was obtained from unpublished data computed by Jim Hedstrom of the LASL Solar Group. Appendix B shows LC values for passive heating with water walls (WW), water walls with night insulation (WWNI), Trombe Wall (TW), and Trombe Wall with night insulation (TWNI). (Appendix B was extracted from Ref. 2.) The LC data were generated for a particular building with size and insulation properties typical of a single-story, single family residence, e.g., 2000 ft^2 floor area. The computer code used this building's characteristics, together with weather data and solar information from each of the cities considered, to generate LC values allowing comparisons between geographic locations. A distribution of building size and characteristics occur at any location and this distribution changes from place to place. A small retirement community in Florida might consist mostly of lightly-insulated single family bungalows. Most of the new construction in large cities consists of multi-story, multi-unit dwellings which are relatively well insulated and have low heat loads per unit area of living space. LC values have not been computed for various building characteristics at each location, and it would require a large effort to generate them.

The parameter LC depends strongly on weather conditions, (e.g., is the insolation high or low; is the heating load constant over a long period; or is it concentrated into a short period?) and less on building characteristics. This can be seen by looking at the definition of LC and at the LC data in Appendix B. For a given location, if we increase building load, we must also increase the ratio of collector area to building area to obtain the same fraction of the total heating load from solar. The increase will not be exactly one-to-one, so LC is some function of load, but is a fairly weak function for many cases.

b. Space Cooling. Detailed regional analysis of solar cooling requirements, similar to the LC data for heating, were not available. An estimate of collector area per Btu of cooling can be obtained by using information from LASL's "ERDA Facilities' Solar Design Handbook" (Ref. 3) in conjunction with some simplifying assumptions. Any approach short of an economic analysis requires some assumption about what fraction of the total load is supplied by solar. For heating, we assume that 75% of the load would come from the solar collectors. For cooling we assume that the collector size is such that all of the solar energy collected in June, July, and August and half of the energy collected in May and September is used and none of the energy in the remaining months is used for cooling. This is a rather broad assumption but may be reasonable for residuals estimates, and it does allow use of available regional data. The assumption is most inaccurate in extreme places when cooling and heating are combined. For example, in Maine a system large enough to supply 75% of the heat would collect much more energy than would be required to handle the complete cooling load. In this case we overestimate the end use energy derived from solar. At the other end, a system sized to handle 75% of the heating load in Tucson may not provide 100% of the energy required for cooling in July, hence all of the energy collected would be used, as assumed. However, more than half the energy collected in September would probably be required for cooling in which case the end use energy would be underestimated. In Tucson the system would probably be sized based on cooling requirements instead of sizing it to handle 75% of the heating, as assumed. In any case, the assumption isn't very bad for estimating cooling energy collected per year per square foot of collector for residuals estimates. Figs. C-1 - C-11 in Appendix C are daily mean horizontal surface insolation maps for the United States in langleys per day (3.69 Btu/ft^2 = 1 langley) and are taken from Ref. 3. Additional assumptions are: the collector tilt angle = latitude + 10°, the average collector efficiency = 50%, and the cooling system coefficient of performance = 0.7. The selected tilt angle is pretty good for combined heating and cooling, but not necessarily for cooling only. The horizontal surface insolation can be corrected for collector tilt of latitude plus 10° by

$$H_\beta = C\ H_o - 8200$$

where

H_β is insolation at a tilt angle of β = latitude + 10° Btu/ft^2/mo

H_o is the horizontal surface insolation at the site, Btu/ft^2/mo

C is a correction factor from Table I (obtained from Ref. 4).

Table I and Figs. C-1 - C-11 (Appendix C) can be used to compute the cooling energy supplied per square foot of collector at any selected location using the assumptions listed.

TABLE I

TILTED SURFACE INSOLATION CORRECTION FACTORS

$$H_\beta = (C)\ (H_o) - 8200,$$

where

H_β is insolation at β = latitude + 10° in Btu/ft^2/month.

C = correction values shown below.

H_o = horizontal insolation in Btu/ft^2/month.

	Latitude						
Month	34°N	36°N	38°N	40°N	42°N	44°N	46°N
Jan.	1.8135	1.9122	2.0247	2.1541	2.3041	2.4799	2.6882
Feb.	1.5349	1.5984	1.6691	1.7486	1.8384	1.9404	2.0570
Mar.	1.2811	1.3163	1.3552	1.3983	1.4460	1.4990	1.5580
Apr.	1.1295	1.1487	1.1701	1.1938	1.2199	1.2488	1.7945
May	1.0625	1.0734	1.0858	1.0999	1.1158	1.1335	1.1532
June	1.0433	1.0508	1.0598	1.0703	1.0823	1.0959	1.1112
July	1.0496	1.0583	1.0685	1.0803	1.0937	1.1088	1.1256
Aug.	1.0900	1.1046	1.1210	1.1393	1.1597	1.1922	1.2072
Sept.	1.1976	1.2241	1.2535	1.2858	1.3216	1.3611	1.4047
Oct.	1.4053	1.4537	1.5075	1.5675	1.6345	1.7096	1.7945
Nov.	1.6925	1.7750	1.8683	1.9746	2.0963	2.2369	2.4010
Dec.	1.8960	2.0062	2.1327	2.2793	2.4506	2.6533	2.8963

Source: Energy Research and Development Administration,"ERDA Facilities Solar Design Handbook," ERDA 77-65, Aug. 1977.

c. <u>Regional Variation Estimates</u>. Figure 2 presents the information contained in the LC tables in a form that allows easy comparison of the "efficiency" of solar heating on a regional basis. The dashed curves are lines of constant useful energy per unit collector area, normalized with respect to Grand Junction, Colorado. If the cost of building the solar heating system and the cost of fuel replaced were the same everywhere, and the cost of the system were linear with size, the map would show the relative economic feasibility of solar energy. For example, one square foot of collector replaces almost three times as much alternate heating energy in Santa Monica, California, as in Cleveland for a 75% solar fraction heating system. The variation in the cost of fuel from place to place strongly affects the economics of solar heating, but the regional output variations are equally important. The very high cost of fuel in New York may make it economic to heat with solar there, but the system required will be much larger and more expensive than if it were located in Albuquerque. Albuquerque has the same heating load but obtains roughly 75% more useful heating energy per square foot of collector. In other words, solar heating will be expensive in New York, but possibly less expensive than the available alternatives.

It is interesting to estimate the amount of energy that can be supplied by solar. If solar heating were only feasible in sparsely populated areas with very mild winters, the amount of conventional fuel saved would not be very large. Figure 3 shows a heating load map. Some of the highest output areas, such as coastal California, are low load areas but densely populated. New

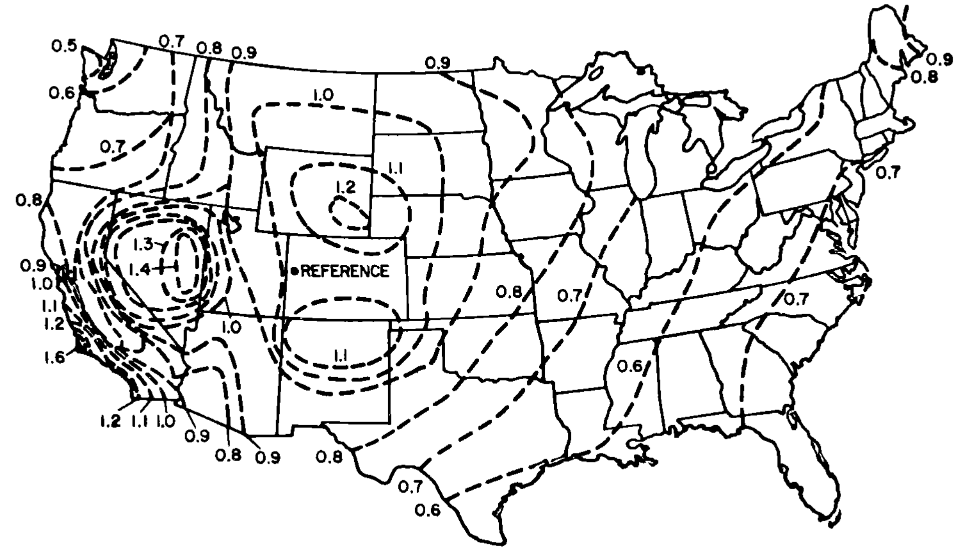

Fig. 2. Useful energy per unit collector area, normalized to Grand Junction, Colorado. (93,000 Btu/ft^2/yr at 75% solar)

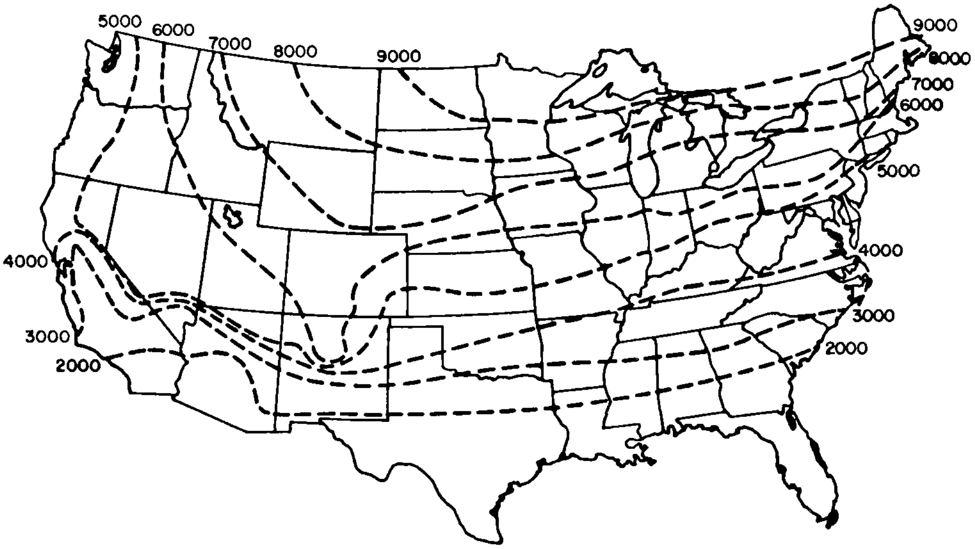

Fig. 3. Heating degree days across the US.

England is densely populated and has high loads, but the solar output is low. The Denver area has high load, large population, and high output. The whole regional problem is complex and requires consideration of many aspects to obtain reasonable results.

5. Reference Designs. Preliminary design concepts were developed for each system selected. The purpose of the designs was to estimate weights of component materials, land, and water requirements, and operating residuals for representative reference systems. With fair accuracy, we can estimate the components for some solar systems, e.g. typical active liquid or air heating designed for today's installations. Because solar energy is a rapidly developing technology, we have less confidence in designs for application in 20 years.

Assuming an ongoing, healthy solar industry in the U.S., the systems in the year 2000 should be considerably modified and improved over today's. Solar powered cooling is even less well established than heating, and many feel that none of the schemes being considered today show much promise of becoming economically feasible in the foreseeable future. Thus, the accuracy of the assessment of a solar powered cooling system designed for 10 or 20 years in the future is very questionable. For the TASE study system, designs have been generated using the best information presently available.

C. Selected Application

Several types of solar energy systems are presently being used to provide space heating and cooling of both residential and commercial buildings. These include active air and liquid systems as well as various types of passive systems. Solar hot water heaters for providing domestic hot water are another important application. This study concentrates on a limited set of applications that typify the most important systems for space heating and cooling and domestic hot water. These systems are:

1. Active, liquid flat plate collectors, space heating,
2. Active, liquid flat plate collectors, domestic hot water,
3. Active, air flat plate collectors, space heating,
4. Passive, storage wall, space heating,
5. Active, liquid flat plate collectors, space heating and cooling.

The method used to characterize each of these systems consisted of generating a reference design for each system for a nominal collector area of 500 ft^2 for heating and cooling and of 50 ft^2 for domestic hot water. The materials required for each reference design, for example, the pounds of glass needed per 500 ft^2 of collector, were then determined. The final step was to determine the useful energy delivered per 500 ft^2 of collector.

The above sizes are approximately correct for a typical residence in the Denver/Boulder, Colorado area, which is a good representative location. The representative solar performance was assumed as 75% of the demand load. The data discussed in Section II-B substantiates these assumptions and also can be used by the reader to study the effects of other assumptions.

1. Space Heating - Liquid. Figure 4 shows a schematic of the selected reference design system. The significant items are the collectors, an insulated water storage tank, two heat exchangers, and the system piping. Expansion tanks, valves, pumps, vents, and controls were assumed to be negligible with respect to residuals. A glycol/water mixture removes heat from the collector and transfers it to the water in the storage tank. Water from the tank supplies heat to the load as required.

The collector design in use at the LASL National Security and Resources Study Center was used as a model for this design. The Study Center has 66,000 ft^2 of floor area and is being used to

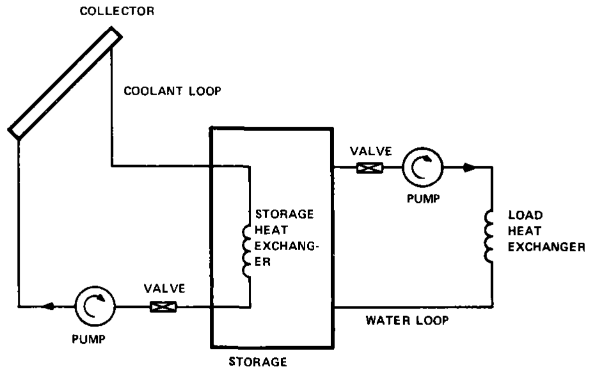

Fig. 4. Reference design - space heating, liquid.

monitor the performance of several types of solar heating and cooling systems. The flat plate collectors used in the 8000 ft^2 array are considered typical of current well-designed liquid cooled types and include such features as high performance, selective absorber surfaces and the ability to support high roof loadings. Thus, the collector assumed for this study has a double-walled steel body with coolant passages between the walls. The structure is steel. It is single glazed with 0.125-inch glass and insulated with urethane. In some areas double glazing would be preferable, in which case the amount of glass should be multiplied by two.

The reference system also has a single wall storage tank with a capacity of 900 gallons (15 Btu/°F/Ac, where Ac is the collector area in ft^2). The tank is steel with a wall thickness based on a working pressure of 150 psi and an allowable stress of 30,000 psi (0.125 inch wall thickness). A two-inch-thick layer of 3 lbs/ft^3 density urethane insulates the tank. The system has water service copper tubing (0.050-inch wall thickness) from the collectors to the storage tank and from the storage tank to the load. Both the storage tank heat exchanger and the load heat exchanger are copper. The collector coolant flow rate provides 15 Btu/hr/°F/Ac (1200 gallons per hour). One-inch diameter lines give a coolant velocity of 10 feet per second (pressure drops 0.1 psi per foot). The reference system has 100 feet of one-inch tubing. For an average gap of 0.25 inches between the collector plates and an expansion tank volume equal to 40% of the collector volume (tank half full of coolant), the system requires 100 gallons of coolant for 500 ft^2 of collector.

The assumptions and the annual performance of the active-liquid heating system are:

Space heating, active liquid, Ac = 500 ft^2
75% solar, Denver/Boulder, CO, 20-yr life
5509 degree days, LC = 23 Btu/DD ft^2
Yield = 95,000 Btu/yr ft^2 or 47.5×10^6 Btu/yr.

2. Domestic Hot Water. Figure 5 shows the schematic for the reference two-tank domestic hot water system. It is almost identical to the liquid space heating schematic, but the system is smaller. The hot water reference system has 50 ft^2 of collector. Optimum storage is 1.8 gal/ft^2 of collector. The steel tank was sized for a working stress of 150 psi and an allowable stress of 30,000 psi. Three inches of urethane insulation were used to minimize heat losses to the surrounding living area. The tank is five-feet high with a 1.5-foot diameter.

The assumptions and the annual performance of the domestic hot water system are:

Domestic hot water, active liquid Ac = 50 ft^2
75% solar, Denver/Boulder, CO, 20-yr life
Yield = 139,000 Btu/yr ft^2 or 7.0×10^6 Btu/yr

3. Space Heating - Air. Figure 6 shows a schematic of the reference design for space heating using air cooled collectors. The major elements of the system are the collector array, the energy storage system, and the ducting. The blower and dampers are negligible compared to the rest of the system. The collector and collector support structure are the same as for the liquid cooled design with respect to the materials required. Optimum storage for air systems using a rock bed with a bed density of about 100 lbs/ft^3 is 0.75 ft^3 of storage per ft^2 of collector. The reference storage system has four-inch-thick concrete walls, floor, and top covered with a two-inch thick layer of urethane insulation on all surfaces and a sheet of plastic to prevent moisture from migrating into the rock bed.

The ducting system was sized to handle 2 cubic feet per minute of air per ft^2 of collector at a velocity of 10 feet per second, which corresponds to 1.5-ft diameter ducts for a 500 ft^2 collector array. The system has 100 ft^2 of 0.028-inch wall galvanized sheet steel

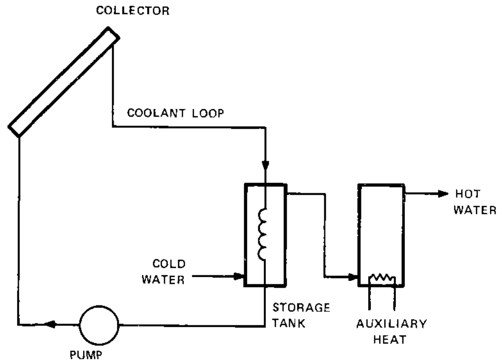

Fig. 5. Reference design - hot water.

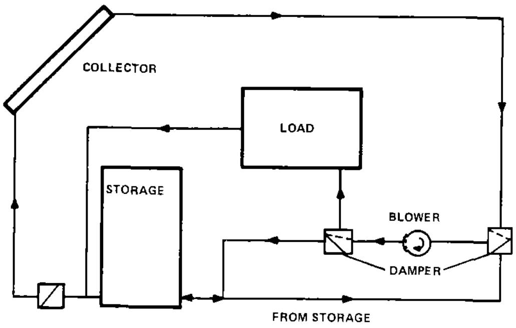

Fig. 6. Reference design - space heat, air.

galvanized sheet steel (24-gauge sheet metal) insulated with a one-inch thickness of urethane.

The assumptions and the annual performance of the active-air systems are:

Space heating, air, active, Ac = 500 ft^2

75% solar, Denver/Boulder, CO, 20-yr life

5509 degree days, LC = 23 Btu/DD ft^2.

Yield = 95,000 Btu/yr ft^2 or 47.5 x 10^6 Btu/yr.

4. Passive System - Storage Wall. The reference design for the passive heating system consists of a single glazing in front of a concrete storage wall (Fig. 7). The glazing is 1/8-inch thick and the storage wall thickness is 18 inches. This is a high density concrete wall with the wall thickness determined more by human comfort requirements than by just heat capacity to absorb the incident insolation. The selected system includes insulation that can be positioned between the glass and the masonry at night to reduce heat losses when the wall is not being heated by the sun. The insulation approximately doubles the effective gain of the system, and requires only a small amount of additional materials.

The assumptions and the annual performance of the passive storage wall heating system are:

Space heating, passive, storage wall with night insulation, Ac = 500 ft^2

75% solar, Denver/Boulder, CO, 20-yr life

5509 degree days LC = 23 Btu/DD ft^2

Yield = 95,000 Btu/yr ft^2 or 47.5 x 10^6 Btu/yr.

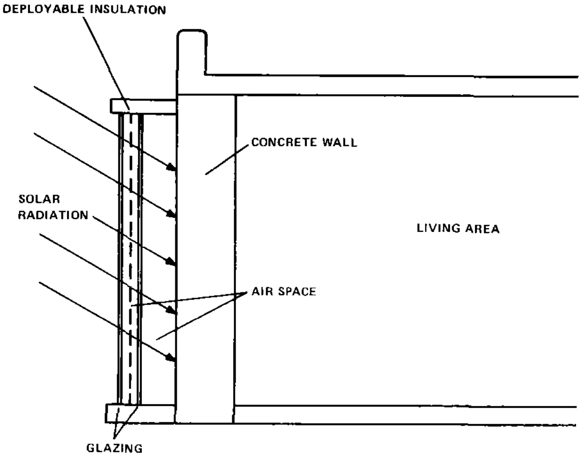

Fig. 7. Reference design - passive heating.

5. Solar Heating and Cooling. The reference design consists of the same collector, coolant loop, and storage as the active liquid space heating system with the water loop modified to provide heat to either the heating load heat exchanger or the refrigeration system, depending on the building requirements. Figure 8 is a diagram of the system. An absorption refrigeration system serves as the cooler for the reference system. The materials for heating and cooling are essentially the same as for space heating (see Space Heating - Liquid), but the energy collected is much greater because the system is used all year.

The yield estimate for the heating and cooling system was more approximate than were the space heating yield estimates which were based on hour-by-hour computer calculations. For a 500 ft^2 collector and a 75% solar heating fraction, the energy delivered for the heating is the same as for heating alone. A cooling yield was estimated and added to the heating yield to get the total annual yield.

The assumptions and the annual performance of the active-liquid heating and cooling systems are:

Space heating and cooling, active, liquid, Ac = 500 ft^2

75% solar, Denver/Boulder, CO, 20-yr life

Absorption refrigeration cooling

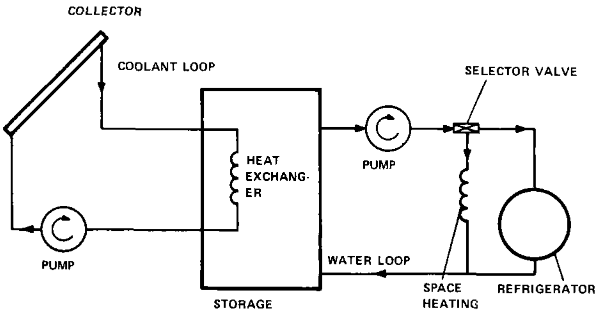

Fig. 8. Reference design - heating and cooling.

Heating load 5509 DD, LC = 23 Btu/DD ft^2

Heating yield = 47.5×10^6 Btu/yr

Cooling yield = 23×10^6 Btu/yr

Total yield = 70.5×10^6 Btu/yr.

D. Environmental Data

1. Materials Required. The materials required for each of the reference design systems were computed for a nominal system size of 500 ft^2 of collector area for heating and cooling, and 50 ft^2 of collectors for domestic hot water. Residuals associated with producing the materials and building the systems will be much larger than residuals generated in the normal operation of these systems. Operating residuals are, in fact, negligible for the systems described.

a. Active, liquid flat plate collectors, space heating. Materials required to produce 500 ft^2 of collector array are:

800 lbs. glass
3050 lbs. steel
300 lbs. urethane.

The structure required to support the collectors depends on the building and installation design. For this study, we assumed that 1000 lbs. of steel were used to support the collectors. Storage tank materials are:

800 lbs. steel
70 lbs. urethane.

The reference system has 100 feet of one-inch tubing. Materials required are:

Piping	60 lbs. of copper
Heat exchangers	100 lbs. of copper (est.).

For an average gap of 0.25 inches between the collector plates and an expansion tank volume equal to 40% of the collector volume (tank half full of coolant), the system requires 100 gal of coolant mix (50% glycol) for 500 ft^2 of collector. Summary of materials for the liquid space heating system:

3850 lbs. steel
800 lbs. glass
370 lbs. urethane
160 lbs. Copper
100 gal. coolant mix.

b. Active, liquid flat plate collectors, domestic hot water. The reference two-tank domestic hot water system is almost identical to the liquid space heating schematic, but the system is about 1/10 as large. (The hot water reference system has 50 ft^2 collectors.) The collector array is simply scaled down to 50 ft^2 and requires, including the mounting structure:

80 lbs. glass
305 lbs. steel
30 lbs. urethane.

The storage tank was five feet high with a 1.5 foot diameter. Materials for the storage system are:

65 lbs. steel
24 lbs. copper.

Summary of materials for the hot water system:

370 lbs. steel
80 lbs. glass
54 lbs. urethane
29 lbs. copper
10 lbs. coolant mix.

c. Active, air flat plate collector, space heating. The major elements of the air system are the collector array, the energy storage system, and the ducting. The blower and dampers are negligible compared with the rest of the system. The collector and collector support structure are the same as for the liquid cooled design with respect to the materials required. Materials required for a 500 ft^2 collector array and its support are, as before:

800 lbs. glass
3050 lbs. steel
300 lbs. urethane.

Optimum storage for air systems using a rock bed with a bed density of about 100 lbs/ft^3 is 0.75 ft^3 of storage per ft^2 of collector.

The storage system materials for a 500 ft^2 collector are:

37,500 lbs. rock
15,000 lbs. concrete
150 lbs. urethane.

The ducting system has 460 ft^2 of 0.028-inch wall galvanized sheet steel (24 gauge sheet metal) insulated with a one-inch thickness of urethane.

Materials for ducting are

500 lbs. steel
60 lbs. zinc (on galvanized ducting)
120 lbs. urethane.

Summary of materials for the reference air space heating system:

3600 lbs. steel
800 lbs. glass
570 lbs. urethane
37,500 lbs. rock
15,000 lbs. concrete
60 lbs. zinc.

d. Passive, storage wall, space heating. The reference design for the passive heating system consists of single glazings in front of an 18 inch concrete storage wall with removable night insulation. Materials for this system are:

800 lbs. glass
112,000 lbs. concrete
100 lbs. insulation.

e. Solar Heating and Cooling. The reference design consists of the same collector, coolant loop, and storage as the active liquid space heating system with the water loop modified to provide heat to either the heating load heat exchanger or to the refrigeration system, depending on the building requirements. Add 500 lbs. of steel and 100 lbs. of copper to account for the refrigerator.

2. Ancillary Energy Requirements We also estimated ancillary energy requirements. Ancillary energy consists of the electrical power required to circulate the collector fluid and to distribute the heat throughout the building. Collector fluid power requirements per 500 ft^2 of collector area were computed from pipe line and heat exchange pressure drops and flow rates. The heat distribution power is not very closely tied to collector area, but is dependent on the building size. A very large house in Florida might have the same collector area for heating as a very small house in Maine. The house in Florida would use more power for heat distribution. In order to estimate distribution power, it is assumed that the distribution power is proportional to the building area, and 0.3 kW, running half time, is required for 2000 ft^3 of heated area. A 500 ft^2 collector will provide about 50% of the heating load for a 2000 ft^2 house in a region where $LC_{50\%} = 40$. (Building load was assumed to be 10 Btu/ft^2DD). Distribution power per 500 ft^2 of collector for any region is, then

$$P_{distribution} = 0.3\frac{LC_{50\%}}{40}\,kW/500\ ft^2.$$

Assuming that the distribution system runs 12 hours per day, 30 days per month or six months, the energy used to distribute the energy collected is

$$E_D = 16.2\ LC_{50\%} \qquad kWh/yr/500\ ft^2.$$

This estimate was used for both air and liquid systems. Power estimates for collector fluid circulation are:

$$P = 0.7\ kW/500\ ft^2 \qquad \text{liquid space heating and hot water}$$
$$P = 0.13\ kW/500\ ft^2 \qquad \text{air space heating.}$$

Assuming that the circulation system operates 30 days per month, 4 hours per day, 6 months per year, circulation energy per year is,

$$E_c = 504\ kWh/yr/500\ ft^2 \text{ liquid}$$

$$E_c = 94\ kWh/yr/500\ ft^2 \text{ air.}$$

3. Reference Case The factors that determine the performance of solar heating or cooling systems vary from one geographic location to another. Therefore, we must select a location before we can compute the characteristics of a solar heating or cooling installation. This regional dependence is necessary because the performance of solar heating and of cooling systems varies a great deal from place to place. Detailed information, like the pounds of glass per million Btu of solar heating delivered for an active liquid residential space heating system in San Francisco, can be computed, or at least estimated, using the methods and information presented in this report. (See Appendix C for some examples.) Instead of considering various locations, for this report we chose a reference case and worked out the materials required per quad of useful energy delivered for each of the reference designs.

The selection of a reference case requires many judgemental factors. The first choice that must be made is the geographic location used in the study. Denver, Colorado was chosen because it has a significant heating load, has a moderately large population, and is a better-than-average site for solar energy. It could be argued that an average site should be used; however, we expect that in the near future most of the solar installations will be constructed in the more favorable areas. Denver is estimated to be about average for sites using solar energy by the year 2000.

The second issue is the solar fraction. A purely economic method could be used to determine what fraction of the load should be supplied by solar, but the information required is not available or is available in the form of a guess. For example, what will the price of natural gas be in Denver in 20 years? If the same question were asked 20 years ago about Cleveland, many experts are unlikely to have anticipated a freeze on hookups at this time. Rather than attempt such an analysis we selected a 75% solar fraction. This was based on the assumption that if solar energy were used at all, a large fraction would be used even in locations where a balanced solar/fossil fuel ratio might be a little more economic.

The reference system selected was:

Denver, Colorado

75% solar

Single family dwelling--single story, conventional construction, typical present day insulation, average size.

We used data and performance calculations for Boulder, Colorado, because good weather data was not available for Denver.

The performance data from Appendices A, B, & C and the materials requirements for each of the reference designs were used to compute the materials required per quad (10^{15} Btu) of energy for a 20-year system life for each of the systems. The results are listed in Table II.

TABLE II

MATERIALS SUMMARY FOR REFERENCE CASES

1. Space Heating, Active Liquid, 75% Solar, LC = 23
Denver, CO, 5509 Degree Days, 20 yr life,
Yield = 95,000 Btu/ft^2/yr

Materials	lbs/500 ft^2	lbs/quad/yr	lbs/quad
Steel	3850	8.10×10^{10}	4.05×10^{9}
Glass	800	1.68×10^{10}	0.84×10^{9}
Urethane	370	0.78×10^{10}	0.39×10^{9}
Copper	160	0.34×10^{10}	0.17×10^{9}
Coolant	800	1.68×10^{10}	0.84×10^{9}

2. Domestic Hot Water, Active Liquid, 75% Solar
Denver, CO, 20 year life
Yield = 1.02 gal/ft^2/day
Yield = 139,000 Btu/ft^2/yr

Materials	lbs/500 ft^2	lbs/quad/yr	lbs/quad
Steel	370	5.32×10^{10}	2.66×10^{9}
Glass	80	1.15×10^{10}	0.58×10^{9}
Urethane	54	0.78×10^{10}	0.39×10^{9}
Copper	29	0.42×10^{10}	0.21×10^{9}
Coolant	80	1.15×10^{10}	0.58×10^{9}

3. Space Heating, Active Air, 75% Solar, LC = 23
Denver, CO, 5509 Degree Days, 20 yr life,
Yield = 95,000 Btu/ft^2/yr

Materials	lbs/500 ft^2	lbs/quad/yr	lbs/quad
Steel	3600	7.57×10^{10}	3.78×10^{9}
Glass	800	1.68×10^{10}	0.84×10^{9}
Urethane	570	1.20×10^{10}	0.60×10^{9}
Rock	37500	78.90×10^{10}	39.50×10^{9}
Concrete	15000	31.50×10^{10}	11.70×10^{9}
Zinc	60	0.13×10^{10}	0.06×10^{9}

4. Space Heating, Passive, Storage Wall, 75% Solar
Denver, CO, 5509 Degree Days, 20 yr life,
LC = 23
Yield = 95,000 Btu/ft^2/yr

Materials	lbs/500 ft^2	lbs/quad/yr	lbs/quad
Glass	800	1.68×10^{10}	0.84×10^{9}
Concrete	112000	235×10^{10}	117×10^{9}
Insulation	100	0.21×10^{10}	0.10×10^{9}

5. Space Heating and Cooling, Active Liquid
75% Solar, Denver, CO
Yield = 142,000 Btu/ft^2/yr

Materials	lbs/500 ft^2	lbs/quad/yr	lbs/quad
Steel	4350	6.12×10^{10}	3.06×10^{9}
Glass	800	1.13×10^{10}	0.57×10^{9}
Urethane	370	0.52×10^{10}	0.26×10^{9}
Copper	260	0.37×10^{10}	0.18×10^{9}
Coolant	800	1.13×10^{10}	0.57×10^{9}

E. Conclusions

A characteristic of small scale decentralized solar energy applications for heating and cooling of buildings is that each application will consist of a unique combination of solar and conservation components. Therefore, the categorization into 5 separate types in this report of the system is only a first-cut approach to their characterization. This was consistent with the time and funds available for the study.

Another aspect of the first-cut approach is that for the most part, near-term design concepts were used to formulate each system design. There was a minimal amount of speculation as to the many advances that could occur by the year 2000. A few examples of potential improvements are: (1) collector covers with better insulation and cost characteristics, (2) better and cheaper insulation, (3) more integration into building structures, (4) automatic night insulation for the transparent collector covers, (5) evacuated tube collectors or equivalent, (6) new solid or liquid absorbers, (7) more efficient heat storage materials, (8) other passive heating systems such as direct gain greenhouses, roof ponds, (9) passive cooling techniques, (10) optimum integration of active, passive, and conservation components, and (11) integration with other solar technologies such as wind and photovoltaics, etc.

The size of each solar system depends upon its location and the assumed solar fraction. In a free market situation, the solar fraction would depend on the economics of solar versus alternative energy supplies (i.e., high insolation plus high alternative costs may equate to high solar fractions). However, future scarcities of alternative energy supplies due to uncontrollable national or international events may be more influential than economics. Our estimate of 75% solar fraction appears reasonable at this time.

The environmental impacts associated with the use of solar heating and cooling will result mostly from the large quantities of materials (glass, steel, insulation, etc.) required to build these systems. Direct operating residuals are negligible compared to most energy generation methods. Indirect impacts derived from mining, ore processing, chemical processing, component manufacturing, transportation, etc., will be more important. The indirect impacts were not defined in this report but will be addressed in a follow-on TASE study.

For the active systems, operating residuals are obviously small with the exception of questions associated with the coolant fluids. Still open to speculation are: how these fluids will be disposed of; how often they must be changed; and how much will be spilled during changes, deactivations, and failures (earthquakes, etc.).

Indirect residuals per unit of energy are directly proportional to the system life. System life depends on many things, but based on engineering judgements, it was estimated that by the year 2000, systems with at least 20-year lifetimes will be available.

III. INDUSTRIAL AND PROCESS HEAT

A. Introduction

Industrial and process heat applications of solar energy are fundamentally very similar to the active space heating applications discussed in the preceding section. The sun's energy heats a fluid in an array of collectors and the fluid is pumped to a load or to storage for later use. There are, however, two major differences between the applications. First, the heating temperature range for industrial applications spans a much larger range than for space heating. Process heat temperatures range from near room temperature to several thousand degrees centigrade (C). The collectors for the lower temperatures are similar to those for residential space heating. The collectors for the higher temperatures must have concentrating configurations and many require tracking systems to allow them to adjust their orientation as the earth rotates relative to the sun. Most of today's space heating collectors are non-concentrating, flat plate configurations and do not track. Collectors for process heat tend to be more complex because the performance requirements are more complex than those for simple space heating.

The second major difference between space heating and process heat is the load variation with time of day and time of season. In space heating, the load is poorly matched to the supply. The maximum loads occur during the winter when the useful insolation is minimum and during the summer, insolation is wasted. Thus, the costs of space heating tend to be high because large collection and storage systems are required to compensate for the above mismatch. The process heat applications are more favorable and the systems can be sized such that all of the energy collected is used, 365 days per year. In the winter, when the insolation is reduced, the backup system can make up the difference. This is a very favorable match between supply and load. Even with space heating and cooling, a large fraction of the yearly available solar energy occurs when there is no need to heat or cool, and is dumped or stored. With a plant operating single shift, the sun is providing energy at exactly the time it is required and storage or backup requirements are minimized. If the processes operate continuously, storage or backup energy (fossil or some other solar technology) is usually required to handle the time from sunset to sunrise. Because of the potential excellent match between load and supply, process heat may be one of the first applications of solar energy to become economically feasible.

An example illustrates the advantages of the favorable load to supply match in process heating. Indianapolis, Indiana, is about an average solar site by United States standards. It receives an annual horizontal average insolation of 350 langleys per day or 470,000 Btu/ft^2/yr. A 45^o tilted surface would receive an annual horizontal average insolation of 700,000 Btu/ft^2/yr. A flat plate fixed collector with an all day efficiency of 30% would deliver 210,000 Btu/ft^2/yr of 65.5^{o}C (150^{o}F) process heat. In the same location, a system for space heating, sized to provide 50% of the load, would deliver 90,000 Btu/ft^2/yr or only 43% of the comparable process heat system output. The above space heating estimation was based on the LC data and methods described in Section II.

The belief that the technology that is barely economic for residential use could provide real savings for many industries is shared by others. For example, Reference 5 states that industrial process heat is one of the several applications that is at or very near the economic breakeven point and is likely to become even more practical in the near future.

B. Potential Applications

Table III lists some of the volumes and temperature ranges at which process steam is used by the various two-digit Standard Industrial Code (SIC) industry groups who use process heat at temperatures below 250^{o}C (482^{o}F). Current solar technology can readily provide any and all of these temperature ranges and include enough storage capability to provide three shift operations where needed.

While this paper discusses only two solar applications in detail, each of the groups of industries shown on Table III represents hundreds of potential industrial applications for solar produced process heat. Both the primary metals and petroleum sectors could and should provide most of their "low" temperature steam by recycling heat from much higher temperature processes. The chemical, food, and paper industries in their many ramifications presently use oil or natural gas to produce most of the Btu's needed for these temperatures, as do most of the "other industries" on Table III. Volume II of Reference 5 divides food processing (SIC 20) into 18 component sectors and each step of each process is analyzed for its

TABLE III

ESTIMATED USES OF PROCESS STEAM
(AT VARIOUS TEMPERATURES) IN INDUSTRIAL SECTORS

Industry	Temperature Range (^{o}C)	Total Steam Use (% of Sector)	Energy Use (10^{12} Btu)
Primary Metals	>250	∿100	350.0
Chemical and Allied Products Products	>250	5.0	54.7
	225-249	7.5	82.0
	200-224	7.5	82.0
	175-199	25	273.5
	150-174	25	273.5
	125-149	30	328.2
		100	1093.9
Petroleum	225-249	7	67.2
	200-224	7	67.2
	175-199	6	57.6
	150-174	40	384.0
	125-149	40	384.0
		100	960.0
Food and Kindred Products	150-174	10	90.0
	125-149	45	405.0
	100-124	45	405.0
		100	900.0
Paper and Allied Products	175-199	70	703.5
	150-174	30	301.5
		100	1005.0
Other Industries*	>250	7	407.6
	225-249	2	116.5
	200-224	2	116.5
	175-199	19	1106.4
	150-174	19	1106.4
	125-149	21	1222.8
	100-124	7	407.6
	75-99	2	116.5
	50-74	21	1222.8
		100	5823.1

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*Other Industry data are divided according to steam use in other categories, except for the space heating component because all space heating appears in this category. Space heating is classified as heating in the 50^o to 74^{o}C temperature range.

SOURCE: LASL, D. P. Grimmer, K.C. Herr, "Solar Process Heat from Concentrating Flat Plate Collectors," UC-62, (December 1976). Los Alamos Scientific Laboratory, Los Alamos, NM; page 13, Table III (a).

temperature and volume which are then projected for the years 1976, 1985, and 2000. Examples of these summary tables for three food processing industries are included as Appendix D as are illustrative process heat requirements flow charts.

The food processing industry is one of the more disaggregated of the major industries in this country. Because of the need to minimize the handling and transport of their raw materials, even the largest corporations operate relatively small plants at widely scattered locations. The disaggregation of food processors and the proximity of these plants to the relevant agricultural producers improves the economics of applying solar solutions to their process heat needs. A small plant can use its roof and the area above its parking lots as the sites needed for its collectors. This minimizes the need to acquire the extra land area for collectors likely to be needed for the more vertically oriented operations of larger plants.

The "chemicals and allied products" group of industries are slightly less obvious candidates for solar process heat. Refiners use high temperature process steam and associated chemical plants could use recycled steam from the refineries for many of their hot water and low pressure steam needs. This also applied to other industries.

Solar evaporators, however, could be very useful to the entire complex of chemical industries, either directly, via lenses, or be creating steam for conventional dryers. The sun has been used to lower the water content of brines for centuries and is still used this way in California and Nevada. But solar evaporators much more complex than open pools could also use the sun effectively.

Among the "other industries" of Table III are the textiles group (SIC 22). More than 700 companies operate more than 7000 textile plants in the United States. Most of these are located in the Sun Belt, and have been using natural gas as their heat source for moisture control, washing, dying, texturizing, and drying as well as space heating and cooling. None of the processes presently used by these textile industries require heat greater than that created by the current generation of the trough-type concentrating collectors designed to produce low pressure steam. The concentrators expected to be available in the 1980's should prove even more effective for any segment of this industry.

The lumber and wood products industries (SIC 24) are also prime candidates for solar process heat. While many of these companies already use wood wastes to produce part of their heat needs, other solar heat systems could provide almost all of their supplemental requirements for the kiln drying of lumber, the heating of vats for soaking and mixing and the curing of paint and lacquer and resins. These needs are valid for plywood and other building materials and for furniture and fixtures of hundreds of kinds. More than 9000 companies produce furniture of one variety or another. Those that produce wood furniture could readily use the sun instead of natural gas or oil or coal to supply the heat not adequately supplied by the burning of wood wastes.

The particular example detailed in this report postulates a pulp mill in Wisconsin as an appropriate use of solar energy. Most of the other industries that are part of SIC 26 are also good candidates for the installation of solar industrial process heat. Like the lumber industries, many of the paper and pulp mills burn wood wastes for much of their heat needs, but must supplement this source with fossil fuels. The use of solar concentrating collectors would permit not only the replacement of the fossil fuels, but the release of a good deal of the wood waste now used as fuel for higher value competing uses such as fiberboard and methanol production.

In the paper fabricating industries such as the mills that make roofing papers, shingles, and insulation board, tissues, milk cartons, paper plates, corrugated boxes, etc., the proportion of oil and gas used for forming and drying purposes is even greater since the waste available for producing heat is smaller. Again, these industries should find concentrating collector solar heating systems a very good alternative energy source.

C. Selected Applications and General Design Features

For the TASE study, we assume that industrial process heat can be divided into two temperature regimes, 50°C to 100°C (122°F to 212°F), provided by conventional flat plate collectors, and 100°C to 300°C (212°F to 572°F), provided by concentrating collectors. We further assume that the plant capacity is sized to use all of the energy delivered by the collectors in any 24-hour period. This problem is less complicated than the space heating problem where the solar input is matched with the residence heating load, which varies a great deal, making it impractical to use even half of the energy that could be delivered by the collectors. For the industrial process heat calculations, all we need to know is the local insolation and the efficiencies associated with collection and storage. Some storage would probably be used in industrial applications to spread the time period during which energy would be available. For this study we assume that the solar storage system combined with an alternative energy backup will be sized to provide 24-hour-per-day operation year around.

1. 50°C to 100°C Process Heat. The selected typical application for 50°C to 100°C process heat is a commercial laundry located in Indianapolis, Indiana. If we normalize the system to a 500 ft^2 collector area the system is identical to the active, liquid flat plate collector space heating system described in Section II. A conventional low pressure water storage system is adequate.

2. 100° C to 300° C Regime Process Heat. In 1975, wood pulp manufacturers used slightly more than one quad of fossil fuel to produce process heat at temperatures of 140°C to 300°C (284°F to 572°F). A recent study of cogeneration and wood pulp production (Ref. 4) determined that a typical mill produces 200,000 tons of pulp per year and, even if all of the combustible waste products were used as fuel, still requires 0.27×10^{12} Btu/yr of fossil fuel. Thus, the wood pulp industry was selected as the application for the 100°C to 300°C solar process heat system. Further, it is estimated that a reasonable compromise between the use of solar energy and fossil fuel (or some other energy source) is to assume that 50% of the energy, other than that from combustible waste products, is solar.

The type of collectors and storage systems used for space heating applications cannot be used for the high temperature regime. The efficiency of conventional flat plate collectors approaches zero at output temperatures of higher than 100°C under most conditions. The simplicity of flat plate collectors is attractive for low temperature applications, but some sort of concentrating collector is required for temperatures exceeding 100°C (212°F). Concentrating collectors in general require some degree of tracking to operate properly, and higher concentration ratios, which give higher efficiencies at high temperatures, require more elaborate tracking than low concentration ratio designs. Axi-symmetric parabolic concentrators (dish collectors) provide high concentrations (up to 1000) but require accurate tracking in both altitude and azimuth. The collector must point directly at the sun at all times, or the concentrated energy doesn't reach the absorber and is lost. The required tracking accuracy increases with concentration ratio. Various types of trough collectors offer the advantage of requiring only single axis tracking but provide more modest concentration ratios (up to about 50). The compound parabolic concentrator was selected for the reference design. This configuration produces good efficiencies at high temperatures and requires minimal adjustment of the collector position. A conventional parabolic concentrator could also be used for this application. It would produce a higher efficiency but would require a more elaborate positioning mechanism to obtain full time altitude tracking of the sun. The compound parabolic collector information described here is from Ref. 1 which contains a detailed description of this collector type and the performance calculations.

Figure 9 shows the collector for the reference design. A single glass glazing covers the steel box that contains the polished aluminum reflectors and the absorber. The box is evacuated to reduce convection heat losses and the absorber is coated with black chrome to reduce radiation heat losses. The collector axes are oriented east to west with the normal to each axis oriented exactly south. A simple timing mechanism is used to continuously adjust the tilt angle of the

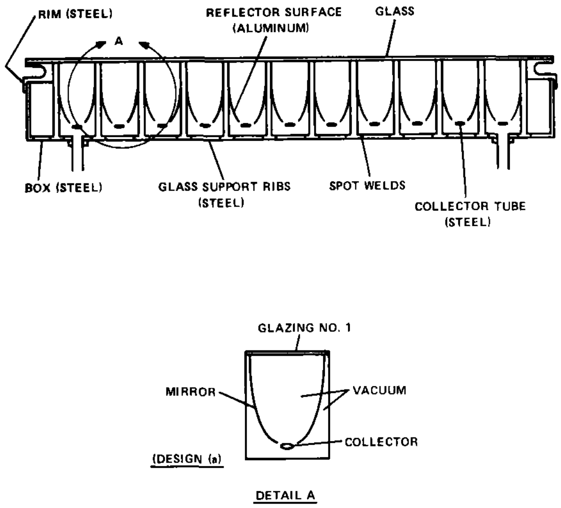

Fig. 9. Reference design - Compound parabolic collector.

collector to account for the seasonal change in the solar altitude (about 50^o summer to winter), thereby providing the equivalent of a daily adjustment of the tilt angle. (A monthly adjustment would be adequate but a little less efficient). It is not necessary to track the sun with this configuration. If no tilt adjustment were made, the largest concentration ratio that could be used is 2.4. Daily adjustment makes it possible to use a concentration ratio of 30. The reference design collector has a concentration ratio of 9.2 which provides an outlet fluid temperature of 300^oC (572^oF) with a theoretical efficiency of 44% of the annual solar flux incident on a constantly maintained normal to the solar flux surface at 40^oN latitude (Ref. 1). The actual efficiency will, of course, be somewhat less.

Figure 10 is a sketch of the system. The design arrangement is basically the same as the liquid space heating system. A maximum storage temperature of 249^oC (480^oF) was selected. A high pressure storage tank stores energy collected in liquid phase water at 600 psi (saturation temperature = 480^oF). Low pressure steam is produced by throttling the hot water.

D. Basic Data and Methods

1. Collector Performance. For the low temperature, flat plate collector used in Indiana, an average daily collection efficiency of 50% is assumed. For the high temperature concentrating collectors in Wisconsin, allowance is made for higher heat losses compared to the low temperature devices and an efficiency of 40% is assumed.

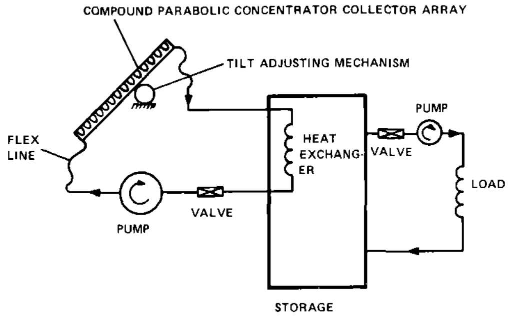

Fig. 10. Reference design - Concentrator collector array.

For both of the above applications the collector operation can be stabilized by a simple collector coolant flow control slaved to the desired output temperature. Such controllers are not usually used for simple space heating systems but would not be incompatible with the more sophisticated industrial heat systems.

2. Storage Performance. For process heating, the collectors deliver more heat to the system in the summer months, but the coast period that the storage system must provide is shorter, compared with the winter. A reasonable estimate of the storage requirements can be obtained by sizing the systems to store 70% of the average daily energy delivered by the collectors (30% is used during the time the collectors are collecting energy).

For the low temperature systems, a storage efficiency of 80% was estimated. The combining of this efficiency with the 70-30% assumption given above, results in a storage efficiency of 86% for the overall system.

For the high temperature system a maximum storage temperature of 249^oC (480^oF) was selected as was discussed in Sec. C-2, above. Because of greater heat losses in the high pressure storage system, compared to the low temperature system, the storage efficiency was decreased to 70% resulting in an overall storage efficiency of 79%.

3. System Life. In all cases, it is assumed that the system life will be at least 20 years, with a reasonable amount of maintenance. Such

durability cannot be expected immediately but will be the result of perhaps 10 years of learning experiences with basic designs, materials, installation, operating techniques, etc.

4. Regional Effects. Solar process heat is subject to only half the regional variations that affect space heating. In space heating, both the supply and load are dependent on the region. For process heat, the load is essentially regionally independent. Further information is given below.

An important variable affecting the amount of incident solar energy is the cloud cover and air purity. For the reader's information, Fig. 11 shows annual incident energy on a surface normal to the beam radiation versus latitude. In the 48 contiguous states, the normal-surface insolation for clear sky is about 10^6 Btu/ft^2/yr. A greater fraction of the energy is delivered in the summer as latitude increases. At 64°N, only 3% of the annual normal insolation occurs during December. Also, Table IV gives fractions of possible sunshine for selected cities in the US. Percentages range from 30% to 45% in Alaska and 40% to 50% in Washington to more than 90% in Yuma, Arizona.

One can calculate the energy collected using equations that incorporate data given in the previous paragraph. However, it is suggested that the procedure given below may be more convenient.

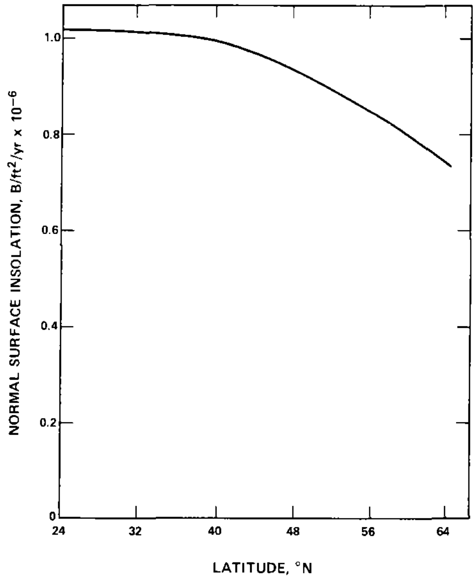

Fig. 11. Annual incident energy on a normal surface.

Figure 12 can be used to estimate the energy incident on the collectors for either temperature regime. To convert the mean annual daily insolation, I_o, presented in Fig. 11 from langleys per day to British thermal units per year per square feet, use:

$$I = I_o \times 3.69\ \text{Btu/ft}^2 \times 365\ \text{days/yr},\quad \text{Btu/ft}^2\text{/yr}.$$

I_o is based on actual measurements and therefore climatic effects are included. To correct I_o to a collector tilted at an angle equal to the local latitude plus 10° use Table V and the method previously described in Section II-D-1-b.

E. Performance of the Selected Systems

1. T = 50°C - 100°C at Indianapolis, Indiana. Obtain the horizontal insolation, I_o from Fig. 12 and convert to new units.

Then, I_o = 350 langleys/day

$= 470{,}000$ Btu/ft^2/yr.

The latitude is about 38°, which gives an average C = 1.4 where C is averaged from Table V data. Use the equation given with Table V and remember to convert from monthly to annual data. Then, the average annual energy incident on a tilted collector is

$$I_\beta = 1.4\ (470{,}000) - 12\ (8200)$$

$$= 560{,}000\ \text{Btu/ft}^2\text{/yr}.$$

The energy delivered to the process, Q, is

$$Q = I_\beta\, \eta_c\, \eta_{store},$$

where we assume

collector efficiency η_c = 50%

storage efficiency η_{store} = 86%

and,

$$Q = 560{,}000 \times 0.5 \times 0.86 = 241{,}000\ \text{Btu/ft}^2\text{/yr}.$$

2. T = 100°C - 300°C at Madison, Wisconsin. The method for handling regional variations for the 100°C - 300°C application is the same as for the lower temperature case. The annual incident energy for a horizontal surface is obtained from Fig. 12. Table V is used to correct for latitude and tilt. It is assumed that all of the energy delivered is useful. The

TABLE IV

MEAN PERCENTAGE OF POSSIBLE SUNSHINE FOR SELECTED LOCATIONS

MEAN PERCENTAGE OF POSSIBLE SUNSHINE FOR SELECTED LOCATIONS

STATE AND STATION	YEARS	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	ANNUAL
ALA. BIRMINGHAM	56	43	49	56	63	66	67	62	65	66	67	58	44	59
MONTGOMERY	49	51	53	61	69	73	72	66	69	69	71	64	48	64
ALASKA, ANCHORAGE	19	39	46	56	58	50	51	45	39	35	32	33	29	45
FAIRBANKS	20	34	50	61	68	55	53	45	35	31	28	38	29	44
JUNEAU	14	30	32	39	37	34	35	28	30	25	18	21	18	30
NOME	29	44	46	48	53	51	48	32	26	34	35	36	30	41
ARIZ. PHOENIX	64	76	79	83	88	93	94	84	84	89	88	84	77	85
YUMA	52	83	87	91	94	97	98	92	91	93	93	90	83	91
ARK. LITTLE ROCK	66	44	53	57	62	67	72	71	73	71	74	58	47	62
CALIF. EUREKA	49	40	44	50	53	54	56	51	46	52	48	42	39	49
FRESNO	55	46	63	72	83	89	94	97	97	93	87	73	47	78
LOS ANGELES	63	70	69	70	67	68	69	80	81	80	76	79	72	73
RED BLUFF	39	50	60	65	75	79	86	95	94	89	77	64	50	75
SACRAMENTO	46	44	57	67	76	82	90	96	95	92	82	65	44	77
SAN DIEGO	68	68	67	68	66	60	60	67	70	70	70	76	71	68
SAN FRANCISCO	64	53	57	63	69	70	75	68	63	70	70	62	54	66
COLO. DENVER	64	67	67	65	63	61	69	68	68	71	71	67	65	67
GRAND JUNCTION	57	58	62	64	67	71	79	76	72	77	74	67	58	69
CONN. HARTFORD	48	46	55	56	54	57	60	62	60	57	55	46	46	56
D. C. WASHINGTON	66	46	53	56	57	61	64	64	62	62	61	54	47	58
FLA. APALACHICOLA	26	59	62	62	71	77	70	64	63	62	74	66	53	65
JACKSONVILLE	60	58	59	66	71	71	63	62	63	58	58	61	53	62
KEY WEST	45	68	75	78	78	76	70	69	71	65	65	69	66	71
MIAMI BEACH	48	66	72	73	73	68	62	65	67	62	62	65	65	67
TAMPA	63	63	67	71	74	75	66	61	64	64	67	67	61	68
GA. ATLANTA	65	48	53	57	65	68	68	62	63	65	67	60	47	60
HAWAII. HILO	9	48	42	41	34	31	41	44	38	42	41	34	36	39
HONOLULU	53	62	64	60	62	64	66	67	70	70	68	63	60	65
LIHUE	9	48	48	48	46	51	60	58	59	67	58	51	49	54
IDAHO, BOISE	20	40	48	59	67	68	75	89	86	81	66	46	37	66
POCATELLO	21	37	47	58	64	66	72	82	81	78	66	48	36	64
ILL. CAIRO	30	46	53	59	65	71	77	82	79	75	73	56	46	65
CHICAGO	66	44	49	53	56	63	69	73	70	65	61	47	41	59
SPRINGFIELD	59	47	51	54	58	64	69	76	72	73	64	53	45	60
IND. EVANSVILLE	48	42	49	55	61	67	73	78	76	73	67	52	42	64
FT. WAYNE	48	38	44	51	55	62	69	74	69	64	58	41	38	57
INDIANAPOLIS	63	41	47	49	55	62	68	74	70	68	64	48	39	59
IOWA. DES MOINES	66	56	56	56	59	62	66	75	70	64	64	53	48	62
DUBUQUE	54	48	52	52	58	60	63	73	67	61	55	44	40	57
SIOUX CITY	52	55	58	58	59	63	67	75	72	67	65	53	50	63
KANS. CONCORDIA	52	60	60	62	63	65	73	79	76	72	70	64	58	67
DODGE CITY	70	67	66	68	68	68	74	78	78	76	75	70	67	71
WICHITA	46	61	63	64	64	66	73	80	77	73	69	67	59	69
KY. LOUISVILLE	59	41	47	52	57	64	68	72	69	68	64	51	39	59
LA. NEW ORLEANS	69	49	50	57	63	66	64	58	60	64	70	60	46	59
SHREVEPORT	18	48	54	58	60	69	78	79	80	79	77	65	60	69
MAINE, EASTPORT	58	45	51	52	52	51	53	55	57	54	50	37	40	50
MASS. BOSTON	67	47	56	57	56	59	62	64	63	61	58	48	48	57
MICH. ALPENA	45	29	43	52	56	59	64	70	64	52	44	24	22	51
DETROIT	69	34	42	48	52	58	65	69	66	61	54	35	29	53
GRAND RAPIDS	56	26	37	48	54	60	66	72	67	58	50	31	22	49
MARQUETTE	55	31	40	47	52	53	56	63	57	47	38	24	24	47
S. STE. MARIE	60	28	44	50	54	54	59	63	58	45	36	21	22	47
MINN. DULUTH	49	47	55	60	58	58	60	68	63	53	47	36	40	55
MINNEAPOLIS	45	49	54	55	57	60	64	72	69	60	54	40	40	56
MISS. VICKSBURG	66	46	50	57	64	69	73	69	72	74	71	60	45	64
MO. KANSAS CITY	69	55	57	59	60	64	70	76	73	70	67	59	52	65
ST. LOUIS	68	48	49	56	59	64	68	72	68	67	65	54	44	61
SPRINGFIELD	45	48	54	57	60	63	69	77	72	71	65	58	48	63
MONT. HAVRE	55	49	58	61	63	63	65	78	75	64	57	48	46	62
HELENA	65	46	55	58	60	59	63	77	74	63	57	48	43	60
KALISPELL	50	28	40	49	57	58	60	77	73	61	50	28	20	53
NEBR. LINCOLN	55	57	59	60	60	63	69	76	71	67	66	59	55	64
NORTH PLATTE	53	63	63	64	62	64	72	78	74	72	70	62	58	68
NEV. ELY	21	61	64	68	65	67	79	79	81	81	73	67	62	72
LAS VEGAS	19	74	77	78	81	85	91	84	86	92	84	83	75	82
RENO	51	59	64	69	75	77	82	90	89	86	76	68	56	76
WINNEMUCCA	53	52	60	64	70	76	83	90	90	86	75	62	53	74
N. H. CONCORD	44	48	53	55	53	51	56	57	58	55	50	43	43	52
N. J. ATLANTIC CITY	62	51	57	58	59	62	65	67	66	65	54	58	52	60
N. MEX. ALBUQUERQUE	28	70	72	72	76	79	84	76	75	81	80	79	70	76
ROSWELL	47	69	72	75	77	76	80	76	75	74	74	74	69	74
N. Y. ALBANY	63	43	51	53	53	57	62	63	61	58	54	39	38	53
BINGHAMTON	63	31	39	41	44	50	56	54	51	47	43	29	26	44
BUFFALO	49	32	41	49	51	59	67	70	67	60	51	31	28	53
CANTON	43	37	47	50	48	54	61	63	61	54	45	30	31	49
NEW YORK	83	49	56	57	59	62	55	66	64	64	61	53	50	59
SYRACUSE	49	31	38	45	50	58	64	67	63	56	47	29	26	50
N. C. ASHEVILLE	57	48	53	56	61	64	63	59	59	62	64	59	48	58
RALEIGH	61	50	56	59	64	67	65	62	62	63	64	62	52	61
N. DAK. BISMARCK	65	52	58	56	57	58	61	73	69	62	59	49	48	59
DEVILS LAKE	55	53	60	59	60	59	62	71	67	59	56	44	45	58
FARGO	39	47	55	56	58	62	63	73	69	60	57	39	46	59
WILLISTON	43	51	59	60	63	66	66	78	75	65	60	48	48	63
OHIO, CINCINNATI	44	41	46	52	56	62	69	72	68	68	60	46	39	57
CLEVELAND	65	29	36	45	52	61	67	71	68	62	54	32	25	50
COLUMBUS	65	36	44	49	54	63	63	71	68	66	60	44	35	55
OKLA, OKLAHOMA CITY	62	57	60	63	64	65	74	78	78	74	68	64	57	68
OREG. BAKER	46	41	49	56	61	63	67	83	81	74	62	46	37	60
PORTLAND	69	27	34	41	49	52	55	70	65	55	42	28	23	48
ROSEBURG	29	24	32	40	51	57	59	79	77	68	42	28	18	51
PA. HARRISBURG	60	43	52	55	57	61	65	68	63	62	58	47	43	57
PHILADELPHIA	66	45	56	57	58	61	62	64	61	62	61	53	49	57
PITTSBURGH	63	32	39	45	50	57	62	64	61	62	54	39	30	51
R. I. BLOCK ISLAND	48	45	54	47	56	58	60	62	62	60	59	50	44	56
S. C. CHARLESTON	61	58	60	65	72	73	70	66	66	67	68	68	57	66
COLUMBIA	55	53	57	62	68	69	68	63	65	64	68	64	51	63
S. DAK. HURON	62	55	62	60	62	65	68	76	72	66	61	52	49	63
RAPID CITY	53	58	62	63	62	61	66	73	73	69	66	58	54	64
TENN. KNOXVILLE	62	42	49	53	59	64	66	64	59	64	64	53	41	57
MEMPHIS	55	44	51	57	64	68	74	73	74	70	69	58	45	64
NASHVILLEE	63	42	47	54	60	65	69	69	68	69	65	55	42	59
TEX. ABILENE	14	64	68	73	66	73	66	83	85	73	71	72	66	73
AMARILLO	54	71	71	75	75	75	82	81	81	79	76	76	70	76
AUSTIN	33	46	50	57	60	62	72	76	79	70	70	57	49	63
BROWNSVILLE	37	44	49	51	57	65	73	78	78	67	70	54	44	61
DEL RIO	36	53	55	61	63	60	66	75	80	69	66	58	52	63
EL PASO	53	74	77	81	85	87	87	78	78	80	82	80	73	80
FT. WORTH	33	56	57	65	66	67	75	78	78	74	70	63	58	68
GALVESTON	66	50	50	55	61	69	76	72	71	70	74	62	49	63
SAN ANTONIO	57	48	51	56	58	60	69	74	75	69	67	55	49	62
UTAH, SALT LAKE CITY	22	48	53	61	68	73	78	82	82	84	73	56	49	69
VT. BURLINGTON	54	34	43	48	47	53	59	62	59	51	43	25	24	46
VA. NORFOLK	60	50	57	60	63	67	66	66	66	63	64	60	51	62
RICHMOND	56	49	55	59	63	67	66	65	62	63	64	58	50	61
WASH. NORTH HEAD	44	28	37	42	48	48	48	50	46	48	41	31	27	41
SEATTLE	26	27	34	42	48	53	48	62	56	53	36	28	24	45
SPOKANE	62	26	41	53	63	64	68	82	79	68	53	28	22	58
TATOOSH ISLAND	49	26	36	39	45	47	46	48	44	47	38	26	23	40
WALLA WALLA	44	24	35	51	63	67	72	86	84	72	59	33	20	60
YAKIMA	18	34	49	62	70	72	74	86	86	74	61	38	29	65
W. VA. ELKINS	55	33	37	42	47	55	55	56	53	55	51	41	33	48
PARKERSBURG	62	30	36	42	49	56	60	63	60	60	53	37	29	48
WIS. GREEN BAY	57	44	51	55	56	58	64	70	65	58	52	40	40	55
MADISON	59	44	49	52	53	58	64	70	66	60	56	41	38	56
MILWAUKEE	59	44	48	53	56	60	55	73	67	62	56	44	39	57
WYO. CHEYENNE	63	65	66	64	61	59	68	70	68	69	69	65	63	66
LANDER	57	66	70	71	66	65	74	76	75	72	67	61	62	69
SHERIDAN	52	56	61	62	61	61	67	76	74	67	60	53	52	64
YELLOWSTONE PARK	35	39	51	55	57	56	63	73	71	65	57	45	38	56
P. R. SAN JUAN	57	64	69	71	66	59	62	65	67	61	63	63	65	65

Based on period of record through December 1959, except in a few instances.

These charts and tabulation derived from "Normals, Means, and Extremes" table in U.S. Weather Bureau publication *Local Climatological Data*.

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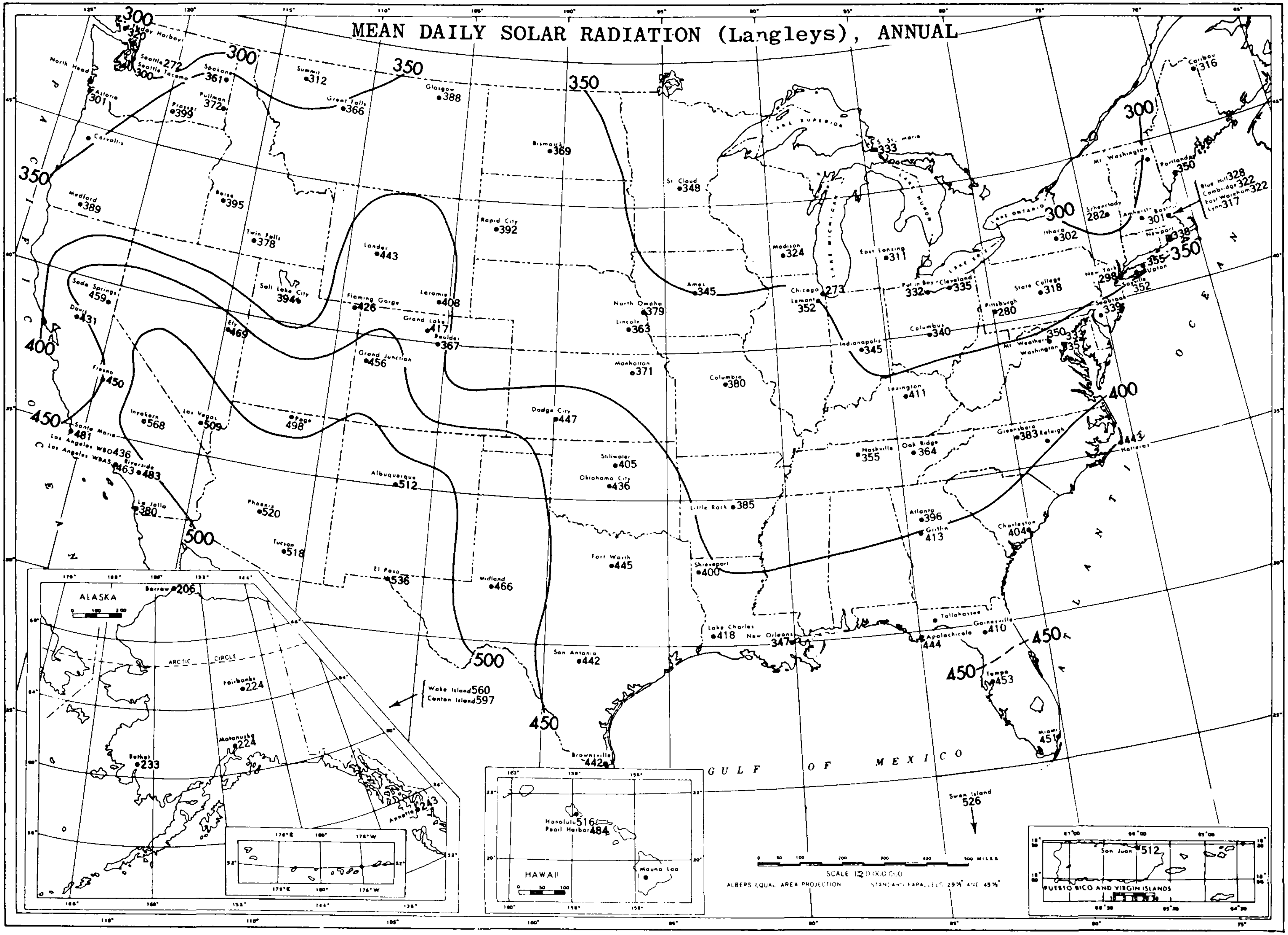

Fig. 12. Mean annual daily insolation.

collector efficiency is, however, 40% for the 100°C - 300°C application. Storage efficiency is 79%.

For our pulp mill, Fig. 12 shows that Madison has an average annual flux of about 320 langleys per day of 430,000 Btu/ft^2/yr for horizontal surfaces. A factor of 1.5 from Table III corrects for a tilted surface, giving 650,000 Btu/ft^2/yr incident on a tilted collector. Using 79% storage efficiency and 40% collector efficiency (all year average) the energy delivered is 650,000 x 0.4 x 0.79 = 205,000 Btu/ft^2/yr. Normalized to a 500 ft^2 collector, the reference system delivers 102.5 x 10^6 Btu/yr of process heat energy per 500 ft^2 of collector.

The selected pulp plant application typically requires 0.27 x 10^{12} Btu/yr of fossil fuel. A solar system sized to provide 50% of the fossil fuel load would deliver 0.13 x 10^{12} Btu/yr. The collector data for this load is

$$\frac{.13 \times 10^{12} \text{ Btu/yr}}{102.5 \times 10 \text{ Btu/yr/500 ft}^2} = 634{,}000 \text{ ft}^2.$$

F. Environmental Data

1. Materials Required.

a. 50 C - 100 C Process Heat. For a materials breakdown, see the discussion in Section II, of active, liquid flat plate collectors--space heat. There, weights were given for systems with 500 ft^2 of collector area.

TABLE V

TILTED SURFACE INSOLATION CORRECTION FACTORS

$$H_\beta = (C)\ (H_o) - 8200,$$

where

H_β is insolation at β = latitude + 10° in Btu/ft^2/month.

C = correction values shown below.

H_o = horizontal insolation in Btu/ft^2/month.

Month	Latitude 34°N	36°N	38°N	40°N	42°N	44°N	46°N
Jan.	1.8135	1.9122	2.0247	2.1541	2.3041	2.4799	2.6882
Feb.	1.5349	1.5984	1.6691	1.7486	1.8384	1.9404	2.0570
Mar.	1.2811	1.3163	1.3552	1.3983	1.4460	1.4990	1.5580
Apr.	1.1295	1.1487	1.1701	1.1938	1.2199	1.2488	1.7945
May	1.0625	1.0734	1.0858	1.0999	1.1158	1.1335	1.1532
June	1.0433	1.0508	1.0598	1.0703	1.0823	1.0959	1.1112
July	1.0496	1.0583	1.0685	1.0803	1.0937	1.1088	1.1256
Aug.	1.0900	1.1046	1.1210	1.1393	1.1597	1.1922	1.2072
Sept.	1.1976	1.2241	1.2535	1.2858	1.3216	1.3611	1.4047
Oct.	1.4053	1.4537	1.5075	1.5675	1.6345	1.7096	1.7945
Nov.	1.6925	1.7750	1.8683	1.9746	2.0963	2.2369	2.4010
Dec.	1.8960	2.0062	2.1327	2.2793	2.4506	2.6533	2.8963

Source: Energy Research and Development Administration,"ERDA Facilities Solar Design Handbook." ERDA 77-65, Aug. 1977.

Let, W_{500} = material weight in each system (lb)

W_Q = material per quad of useful energy proproduced (lb/quad)

Q = one quad = 10^{15} Btu

E = useful energy produced annually per unit collector area (Btu/ft^2/yr)

L = system life (yr)

Ac = collector area per system (ft^2).

Then,

$$W_Q = \frac{W_{500} \times Q}{E \times L \times Ac}$$

$$= \frac{W_{500} \times 10^{15}}{241{,}000 \times 20 \times 500} \ .$$

Using the above equation, we get the following:

Materials	Weights Per System	Weights Per Quad (lb/10^{15}Btu)
Steel	3850 lbs.	1.60 x 10^9
Glass	800 lbs.	0.332 x 10^9
Urethane	370 lbs.	0.154 x 10^9
Copper	160 lbs	0.066 x 10^9
Coolant	100 gal.	0.041 x 10^9

b. 100° C - 300° C Process Heat. The collector has a steel body with a single glass cover and polished aluminum reflectors. Materials per 500 square feet of collector area are:

Glass	800 lbs.
Steel	2500 lbs.
Aluminum	700 lbs.
Urethane	300 lbs.

The collector support structure and tilting mechanism require 1500 lbs. of steel per 500 ft^2. For 15 lbs. of water per ft^2, a 900-gallon storage tank is required. The tank pressure is 600 psi and, for a double wall design, uses 3500 lbs. of steel. The tank has 200 lbs. of insulation. Pipes and heat exchangers require 500 lbs. of steel and 100 lbs. of insulation. Applying the same equation for the derivation of weight per quad that was used above, total materials for 500 ft^2 of collectors with a yield of 205,000

Btu/ft^2/yr and a 20 year life are:

Materials	Weights Per System	Weights Per Quad (lb/10 Btu)
Steel	7900 lbs.	3.85×10^9
Glass	800 lbs.	0.390×10^9
Aluminum	700 lbs.	0.341×10^9
Urethane	600 lbs.	0.293×10^9

2. Operating Residuals. Operating residuals for solar industrial and process heat are the same as for the residential space heating application, essentially negligible, except for the residual associated with periodic changing of the heat transfer fluid, as described in Section II. The main difference in process heat is that for 100°C - 300°C the heat transfer fluid is an oil such as Therminol 66 (Monsanto Corp.) and, therefore, represents a different type of hazard if it is spilled. It is relatively expensive, however, and would not be spilled if at all possible.

3. Land Requirements. Most envisioned solar heating installations would place collectors on roof tops and would not require additional land. Large process heat users such as pulp plants may represent an exception because of the very large collector areas required. The reference application pulp plant, with an annual output of 200,000 tons of pulp per year required 14.5 acres of collectors. We estimate 19 acres of land for the collector system for 200,000 tons per year output. For large process heat applications assume that the land area required equals about 1.3 times the collector area.

4. Water Requirements. The primary water requirement is for washing collector glazing. If one gallon of water is used per square foot of collector area each washing, and 10 washings are required per year, the system requires 10 gallons/ft^2/yr. The laundry collector yield was 241,000 Btu/ft^2/yr. Water requirements for the laundry were 41.5 gal/10^6 Btu. Collector yield for the pulp mill was 205,000 Btu/ft^2/yr which corresponds to 48.8 gal of water/10 Btu.

G. Conclusions

1. Environmental effects associated with the operation of solar industrial process heat systems are very small. The indirect residuals resulting from the production of the materials and components and the construction of the systems will probably be more significant. The latter was not characterized in this report.

2. Regional solar considerations make areas that are reasonably close to large urban areas, such as California's Mojave Desert, potentially attractive sites for energy intensive process plants. Since present heavy industrial areas in the Great Lakes Region and Northeast are not as well suited for solar energy, some industry location changes may take place, causing new environmental consequences that may be undesirable.

3. Industrial and process heat could be an early use of solar energy because: (a) the load and supply are well matched, making it more economic than space heating, (b) many of the systems would be large, permitting the use of trained operating and maintenance people on site to maintain consistent operation, and (c) the government can more easily exert pressures on the relatively few and large users to change over to solar.

REFERENCES

1. Balcomb, J. D., and Hedstrom, J. C., "Solar Heating Maps," LA-UR-76-2722.
2. Balcomb, J. D., and McFarland, R. D., "A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type," LA-UR-78-1159.
3. "ERDA Facilities Solar Design Handbook," ERDA 77-65 (August 1977).
4. Harper, J., Sobek, A., and Antonopoulos, A., "Environmental Residual and Capital Cost Evaluation for Energy Recovery From Agricultural and Forestry Residues," Argonne National Laboratory (August 1978).
5. Inter-Technology Corporation, "Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat," prepared for Energy Research and Development Administration, Intertech Report No. 0028-1 (February 7, 1977).

APPENDIX A

TABLE A-1

REGIONAL DATA FOR SPACE HEATING (ACTIVE) AND HOT WATER

	Altitude (ft^2)	Degree Days/yr (DD)	Space Heat Active LC = Btu/DD/ft^2			Hot Water Only Gal/day/ft^2 at 60°F		
			Solar Fraction 25%	50%	75%	Solar Fraction 25%	50%	75%
Alabama								
Arizona								
Page	4280	6632	128	48	23	5.72	2.36	1.49
Phoenix	1139	1765	300	118	59	8.85	3.86	2.08
Tucson	2440	1800	301	118	59	8.71	3.80	2.05
Arkansas								
Little Rock	276	3219	126	48	24	6.50	2.83	1.51
California								
Davis	50	2502	198	72	33	7.97	3.43	1.80
El Centro	12	1458	547	206	97	8.02	3.50	1.88
Inyokern	2186	3528	232	88	42	10.50	4.58	2.46
Los Angeles	540	2061	416	157	75	7.70	3.35	1.80
Riverside	1050	1803	391	152	74	8.34	3.64	1.96
Santa Monica	289	2967	353	142	67	8.29	3.61	1.94
Fresno	336	2492	195	70	32	7.78	3.35	1.76
Colorado								
Boulder	5350	5509	119	47	23	3.92	1.62	1.02
Grand Junction	4832	5641	119	46	22	5.90	2.44	1.53
Connecticut								
Delaware								
Florida								
Apalachicola	46	1308	324	129	65	7.30	3.19	1.72
Gainesville						7.15	3.13	1.69
Miami						7.18	3.14	1.70
Tallahassee	64	1485	283	113	57	7.15	3.12	1.68
Georgia								
Atlanta	1018	2961	154	59	29	6.53	2.85	1.53
Griffin	1001	2136	217	84	42			
Idaho								
Boise	2895	5809	108	39	17	5.24	2.17	1.35
Illinois								
Lamont	750	6155	79	30	14	4.22	1.74	1.10
Indiana								
Indianapolis	819	5699	86	32	15	4.34	1.79	1.13
Iowa								
Ames						4.40	1.82	1.14
Kansas								
Dodge City	2625	4986	126	49	24	7.99	3.49	1.87
Manhattan						4.52	1.87	1.18

TABLE A-1 (Continued)

Region	Altitude	DD	Space Heat-Active LC			Hot Water Only		
			25%	50%	75%	25%	50%	75%
Kentucky								
Lexington						5.69	2.46	1.30
Louisiana								
Lake Charles	39	1459	261	104	53	6.35	2.77	1.48
Rushton						5.97	2.59	1.38
Shreveport	220	2184	179	70	35			
Maine								
Caribou	640	9767	68	26	12	4.31	1.78	1.12
Portland						4.55	1.88	1.18
Maryland								
Silver Hill	892	4224	111	43	21			
Massachusetts								
Blue Hill	670	6368	82	31	15	4.16	1.72	1.08
Boston	157	5624	86	33	16	4.12	1.70	1.07
East Wareham	50	5891	97	37	18	4.23	1.75	1.10
Michigan								
East Lansing	878	6909	76	28	13	4.31	1.78	1.12
Sault Ste. Marie	724	9048	74	27	12	4.49	1.86	1.17
Minnesota								
St. Cloud	1062	8879	71	27	13	4.70	1.94	1.22
Mississippi								
Missouri								
Columbia	814	5046	102	38	18	4.75	1.96	1.24
Montana								
Glasgow						6.49	2.68	1.69
Great Falls	3962	7750	93	35	16	5.08	2.10	1.31
Nebraska								
Lincoln	1316	5864	104	39	19	4.89	2.02	1.27
North Omaha	1323	6612	89	34	16	4.95	2.04	1.29
Nevada								
Ely	6279	7733	119	47	23	6.07	2.51	1.58
Las Vegas	2188	2709	218	84	42	9.31	4.06	2.18
Reno	4400	6632	125	47	22	5.05	2.09	1.32
New Hampshire								
New Jersey								
Seabrook	110	4812	97	37	18	6.21	2.69	1.43
New Mexico								
Albuquerque	5327	4348	161	64	31	9.23	4.03	2.17
Los Alamos	7200	6600	107	41	21			
New York								
Ithaca	951	6914	68	24	11	3.83	1.58	0.98
New York	187	4871	88	34	16	5.91	2.56	1.36
Sayville	56	4811	98	38	18	6.32	2.75	1.46
Schenectady	490	6650	63	24	11	3.56	1.47	0.93
Upton						4.75	1.97	1.24

TABLE A-1 (Continued)

Region	Altitude	DD	Space Heat-Active LC 25%	50%	75%	Hot Water Only 25%	50%	75%
North Carolina								
Cape Hatteras	27	4612	189	74	36	7.23	3.15	1.69
Greensboro	914	3805	128	50	24	6.60	2.88	1.55
Hatteras	27	2612	204	79	39	8.03	3.49	1.87
Raleigh	440	3393	133	52	25	6.55	2.85	1.53
North Dakota								
Bismark	1677	8851	78	29	14	5.18	2.14	1.35
Ohio								
Cleveland	871	6351	71	26	12	3.94	1.63	1.01
Columbus	760	5211	77	29	13	3.63	1.50	0.94
Put-In-Bay	580	5796	68	24	11	3.97	1.64	1.01
Oklahoma								
Oklahoma City	1317	3725	134	53	26	7.17	3.13	1.68
Stillwater	910	3725	132	52	25	7.15	3.12	1.68
Oregon								
Astoria	22	5186	127	45	19	3.86	1.59	0.98
Corvallis	236	4726	120	42	18	6.19	2.62	1.33
Medford	1321	5008	107	38	16	4.90	2.02	1.23
Pennsylvania								
State College	1230	5934	78	29	14	4.07	1.68	1.06
Rhode Island								
Newport	50	5804	97	37	18	4.26	1.76	1.11
South Carolina								
Charleston	69	2033	210	82	41	6.86	2.99	1.61
South Dakota								
Rapid City	3180	7345	97	37	18	5.13	2.12	1.33
Tennessee								
Nashville	614	3578	117	44	21	6.33	2.74	1.46
Oak Ridge	940	3817	111	42	20	6.01	2.61	1.39
Texas								
Brownsville	48	600	517	218	110	7.01	3.05	1.63
El Paso	3954	2700	228	88	44	9.41	4.11	2.21
Fort Worth	574	2405	186	73	37	7.32	3.19	1.71
Midland	2885	2591	202	79	39	8.06	3.52	1.90
San Antonio	818	1546	262	103	52	7.04	3.07	1.65
Utah								
Flaming Gorge	6273	6929	111	43	21	5.50	2.27	1.43
Salt Lake City	4238	6052	107	40	19	5.79	2.39	1.51
Vermont								
Burlington	385	8269	63	24	11	3.93	1.62	1.02
Virginia								
Washington								
Prosser	840	4805	117	41	18	7.46	3.19	1.64
Pullman	2583	5542	100	36	16	4.83	1.99	1.21

TABLE A-1 (Continued)

Region	Altitude	DD	Space Heat-Active LC 25%	50%	75%	Hot Water Only 25%	50%	75%
Washington (continued)								
Richland						5.10	2.11	1.32
Seattle	110	4785	94	33	13	5.03	2.13	1.07
Spokane	2356	6655	90	31	14	4.88	2.02	1.24
West Virginia								
Wisconsin								
Madison	889	7863	76	28	13	4.58	1.89	1.19
Wyoming								
Lander	5574	7870	108	42	21	5.92	2.45	1.54
Laramie	7240	7381	106	42	21	5.20	2.15	1.35

APPENDIX B

PERFORMANCE PARAMETERS FOR PASSIVE SOLAR HEATING SYSTEMS USING THERMAL STORAGE WALLS

Load Collector Ratio (BTU/DD-ft^2) for particular values of Solar Heating Fraction (SHF)

Page, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	196	88	54	37	27	19	13	7	
6632 DD	WWNI	312	145	91	65	49	38	29	22	15
	TW	195	94	56	37	25	17	11	6	
37°N	TWNI	304	141	89	63	46	35	26	28	12

Phoenix, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	626	294	188	135	102	78	60	44	29
1765 DD	WWNI	863	407	261	189	145	114	90	69	49
	TW	577	287	179	123	88	64	47	33	21
33°N	TWNI	819	386	247	176	132	101	76	56	38

Tucson, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	631	291	184	132	100	77	59	43	29
1800 DD	WWNI	871	403	256	185	142	112	89	68	49
	TW	578	284	176	121	87	63	46	33	21
32°N	TWNI	825	383	243	173	130	99	75	56	38

Little Rock, Arkansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	239	108	66	46	33	24	17	11	
3219 DD	WWNI	365	172	107	76	57	44	35	26	18
	TW	232	112	67	44	30	21	14	9	
35°N	TWNI	356	165	103	73	54	40	30	22	14

Davis, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	409	187	115	79	57	42	30	21	11
2502 DD	WWNI	585	272	170	120	89	68	52	39	26
	TW	376	183	111	74	51	36	25	16	9
39°N	TWNI	556	259	161	112	82	61	45	32	21

El Centro, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	1028	482	301	214	161	125	97	72	50
1458 DD	WWNI	1375	649	407	290	221	175	139	107	77
	TW	916	458	284	194	140	103	75	54	36
33°N	TWNI	1294	608	382	270	202	154	117	87	60

Fresno, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	405	186	113	77	55	40	29	19	10
2492 DD	WWNI	577	271	168	117	87	66	50	37	25
	TW	370	181	109	72	49	34	24	15	8
37°N	TWNI	550	257	159	110	79	59	43	31	20

Inyokern, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	453	209	129	90	66	50	37	26	16
3528 DD	WWNI	641	300	188	132	100	77	60	46	32
	TW	419	204	124	84	59	42	30	20	12
36°N	TWNI	613	284	177	124	92	69	52	38	25

Los Angeles, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	763	362	225	158	118	91	70	52	35
2061 DD	WWNI	1032	498	310	219	165	131	103	80	57
	TW	687	344	213	145	103	75	55	39	26
34°N	TWNI	979	464	291	205	153	116	88	65	45

Riverside, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	767	356	224	160	121	94	72	53	36
1803 DD	WWNI	1039	488	308	221	169	134	106	82	58
	TW	692	344	214	146	105	77	56	40	26
34°N	TWNI	984	459	290	207	155	118	90	67	46

Santa Maria, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	544	272	176	126	96	74	56	41	27
2967 DD	WWNI	752	376	247	179	137	108	86	66	45
	TW	514	264	167	115	83	61	44	31	20
35°N	TWNI	720	358	231	166	126	96	73	54	36

Boulder, Colorado	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	196	90	56	39	28	20	14	8	
5524 DD	WWNI	313	146	94	67	51	40	31	23	15
	TW	197	96	58	38	26	18	12	7	
40°N	TWNI	303	143	91	65	48	36	27	19	13

Grand Junction, Colorado	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	199	92	56	39	28	20	13		
5641 DD	WWNI	317	150	95	67	51	39	30	22	15
	TW	201	97	58	38	26	17	11	6	
39°	TWNI	310	145	91	64	48	36	26	19	12

Washington, D.C.	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	179	79	47	32	22	15	9		
4224 DD	WWNI	292	135	83	58	44	33	25	18	12
	TW	180	85	50	32	21	13	8		
39°N	TWNI	285	131	81	57	41	31	22	16	10

Apalachicola, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	700	322	204	145	110	85	65	48	32
1308 DD	WWNI	956	444	281	203	155	123	97	75	53
	TW	635	313	194	133	95	70	51	36	24
30°N	TWNI	906	240	266	189	142	108	82	61	42

Gainesville, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	731	333	212	152	116	90	69	51	35
1239 DD	WWNI	1000	457	292	211	162	129	102	79	56
	TW	662	326	202	139	100	73	54	39	25
39°N	TWNI	943	435	276	197	148	113	86	64	44

Tampa, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	1147	573	374	272	210	166	129	98	69
683 DD	WWNI	1520	760	500	365	283	227	182	141	102
	TW	1059	548	351	245	179	134	100	73	49
28°N	TWNI	1443	717	467	339	258	199	152	114	80

Atlanta, Georgia	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	301	136	83	58	43	31	23	15	8
2961 DD	WWNI	448	207	129	91	69	54	42	32	22
	TW	286	138	83	55	38	27	18	12	7
34°N	TWNI	431	198	123	87	64	48	36	26	17

Boise, Idaho	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	185	83	48	31	20	12	6		
5809 DD	WWNI	299	139	86	59	43	31	23	16	10
	TW	182	86	50	31	20	12	6		
44°N	TWNI	290	135	83	56	40	29	21	14	8

Lemont (ANL) Illinois	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	120	51	29	18	11				
6155 DD	WWNI	219	100	61	42	31	24	18	13	8
	TW	129	59	33	20	12	7			
42°N	TWNI	216	99	61	42	30	22	16	11	7

Indianapolis, Indiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	136	58	33	21	14	7			
5699 DD	WWNI	239	109	67	46	34	26	19	14	9
	TW	142	65	37	23	14	8			
40°N	TWNI	235	107	66	45	33	24	17	12	7

Ames, Iowa	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	117	50	29	18	11				
6588 DD	WWNI	215	99	61	42	31	23	18	12	8
	TW	127	58	33	20	12	6			
42°N	TWNI	213	98	60	41	30	22	16	11	7

Dodge City, Kansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	214	99	61	43	31	23	16	10	
4986 DD	WWNI	335	160	101	72	54	42	33	25	17
	TW	214	104	63	41	28	20	13	8	
38°N	TWNI	327	154	97	69	51	38	29	21	14

Manhattan, Kansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	165	74	44	30	21	14	8		
5182 DD	WWNI	274	128	80	56	42	32	25	18	12
	TW	214	80	47	30	20	13	8		
39°N	TWNI	327	125	78	54	40	30	22	15	10

Lexington, Kentucky	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	143	63	36	24	16	10			
4683 DD	WWNI	246	114	70	49	36	28	21	15	10
	TW	148	70	40	25	16	10	5		
38°N	TWNI	242	112	69	48	35	26	19	13	8

Lake Charles, Louisiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	522	239	152	109	82	63	48	35	23
1459 DD	WWNI	730	338	214	155	119	94	74	57	40
	TW	481	237	146	100	71	52	38	26	17
30°N	TWNI	695	322	204	146	109	83	63	46	32

Shreveport, Louisiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	361	166	104	74	65	42	31	22	14
2184 DD	WWNI	524	245	154	111	85	67	53	40	28
	TW	340	167	103	69	49	35	25	17	10
32°N	TWNI	500	234	148	105	79	60	45	33	22

Caribou, Maine	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	83	34	17	8					
9769 DD	WWNI	172	78	48	33	24	17	13	8	
	TW	97	43	23	12	5				
47°N	TWNI	172	79	48	33	23	17	12	8	4

Portland, Maine	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	125	54	31	20	13	7			
7511 DD	WWNI	223	103	64	45	33	25	19	14	8
	TW	133	62	35	22	14	8			
44°N	TWNI	221	102	63	44	32	23	17	12	7

Boston, Massachusetts	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	137	60	35	23	15	9			
5634 DD	WWNI	241	110	68	48	36	27	21	15	9
	TW	145	67	39	24	15	9	5		
42°N	TWNI	238	108	67	47	34	25	18	13	8

East Lansing, Michigan	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	111	46	25	15	8				
6909 DD	WWNI	208	94	57	39	29	22	16	11	7
	TW	120	54	30	18	10	4			
43°N	TWNI	206	93	57	39	28	20	15	10	6

Sault St. Marie, Michigan	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	100	40	21	11					
9048 DD	WWNI	193	87	53	36	26	19	13	9	5
	TW	110	49	26	15	7				
46°N	TWNI	192	87	53	36	25	18	13	8	5

St. Cloud, Minnesota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	96	39	21	11					
8879 DD	WWNI	189	85	52	36	26	19	14	9	5
	TW	108	49	26	15	7				
46°N	TWNI	189	86	52	36	25	18	13	8	5

Columbia, Missouri	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	175	77	46	31	21	14	8		
5046 DD	WWNI	287	133	82	57	43	33	25	18	12
	TW	177	83	49	31	20	13	8		
39°N	TWNI	281	129	80	55	41	30	22	15	10

Glasgow, Montana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	168	75	44	29	19	12	6		
8996 DD	WWNI	277	130	81	56	41	31	23	17	10
	TW	171	80	47	30	19	12	7		
48°N	TWNI	272	126	78	54	39	29	21	14	9

Great Falls, Montana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	143	63	37	23	14	8			
7750 DD	WWNI	246	115	71	49	36	27	20	14	8
	TW	149	69	40	25	15	9			
47°N	TWNI	243	112	69	48	34	25	18	12	7

Lincoln, Nebraska	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	175	77	45	30	21	14	8		
5864 DD	WWNI	288	133	82	57	42	33	25	18	12
	TW	176	83	48	31	20	13	8		
41°N	TWNI	280	129	79	55	40	30	22	16	10

Ely, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	172	80	50	35	25	18	12	6	
7733 DD	WWNI	282	134	85	61	47	36	28	21	14
	TW	178	86	52	34	23	16	10	6	
39°N	TWNI	277	131	83	59	44	33	25	18	11

Las Vegas, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	448	209	130	92	68	52	39	28	17
2709 DD	WWNI	632	300	188	134	102	80	63	48	33
	TW	414	205	126	85	60	43	31	21	13
36°N	TWNI	603	284	179	126	94	71	53	39	26

Reno, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	192	88	54	37	26	18	12	6	
6332 DD	WWNI	307	145	91	65	49	37	28	21	13
	TW	192	93	55	36	24	16	10	5	
39°N	TWNI	298	141	89	62	46	34	25	18	11

Seabrook, New Jersey	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	163	72	43	29	20	13	8		
4812 DD	WWNI	271	126	78	55	41	31	24	17	11
	TW	167	78	46	29	19	12	7		
39°N	TWNI	267	123	76	53	39	29	21	15	9

Albuquerque, New Mexico	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	278	133	83	59	44	33	24	16	9
4348 DD	WWNI	414	201	128	92	70	55	43	33	23
	TW	271	135	83	56	39	28	19	13	7
35°N	TWNI	402	193	123	87	65	49	37	27	18

Los Alamos, New Mexico	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	179	84	52	36	26	18	12	7	
6604 DD	WWNI	288	139	89	64	48	37	29	21	14
	TW	183	89	54	36	24	16	11	6	
36°N	TWNI	283	136	86	61	45	34	25	18	12

Ithaca, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	93	36	18	9					
6914 DD	WWNI	189	83	50	34	24	18	13	9	5
	TW	106	46	24	13	6				
42°N	TWNI	188	83	50	34	24	17	12	8	4

New York City, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	147	64	38	25	17	11	5		
4871 DD	WWNI	250	117	72	51	38	29	22	16	10
	TW	152	71	42	26	17	11	6		
41°N	TWNI	247	114	71	49	36	27	20	14	9

Sayville, L.I. New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	165	74	45	30	21	14	9		
4811 DD	WWNI	272	129	80	57	43	33	25	18	12
	TW	169	81	48	31	20	13	8	4	
41°N	TWNI	268	125	78	55	40	30	22	16	10

Schenectady, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	84	34	18	9					
6650 DD	WWNI	174	79	48	33	24	18	13	9	5
	TW	98	43	23	13	6				
43°N	TWNI	175	79	49	33	24	17	12	8	5

Greensboro, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	237	107	66	46	33	24	17	11	
3805 DD	WWNI	367	170	107	75	57	44	35	26	18
	TW	231	112	67	44	30	21	14	9	
36°N	TWNI	354	165	103	72	54	40	30	22	14

Hatteras, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	412	189	118	82	61	46	34	24	15
2612 DD	WWNI	588	274	173	123	93	73	57	43	30
	TW	381	187	115	77	54	39	28	19	11
35°N	TWNI	560	261	164	115	86	65	49	36	24

Raleigh, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	256	117	71	50	37	27	19	12	7
3393 DD	WWNI	391	182	114	80	61	48	37	28	19
	TW	249	120	72	48	33	23	16	10	5
36°N	TWNI	378	175	109	77	57	43	32	23	15

Bismarck, North Dakota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	111	46	25	14	6				
8851 DD	WWNI	208	94	57	39	28	21	15	10	6
	TW	120	54	30	17	9				
47°N	TWNI	207	94	57	39	27	20	14	9	5

Cleveland, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	103	41	22	12					
6351 DD	WWNI	202	89	53	36	26	20	14	10	6
	TW	114	50	27	15	8				
41°N	TWNI	200	89	53	36	26	19	13	9	5

Columbus, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	120	51	29	18	11				
5211 DD	WWNI	218	100	61	42	31	23	17	12	7
	TW	128	59	33	20	12	6			
40°N	TWNI	199	87	52	35	25	18	12	8	4

Put-in-Bay, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	102	39	20	9					
5796 DD	WWNI	199	88	52	35	25	18	13	8	
	TW	112	48	26	14	6				
42°N	TWNI	199	87	52	35	25	18	12	8	4

Oklahoma City, Oklahoma	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	250	115	70	49	36	26	19	12	6
3725 DD	WWNI	382	179	112	80	60	47	37	28	19
	TW	243	118	71	47	32	23	15	10	5
35°N	TWNI	370	172	108	76	57	43	32	23	15

Astoria, Oregon	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	207	98	59	39	26	17	9		
5186 DD	WWNI	322	158	99	69	50	37	27	19	11
	TW	205	99	59	38	25	16	9		
46°N	TWNI	315	152	95	65	47	34	24	16	9

Corvallis, Oregon	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	224	96	57	37	24	16	9		
4726 DD	WWNI	352	158	97	67	48	36	26	18	11
	TW	217	100	58	36	24	15	9		
45°N	TWNI	341	153	93	63	45	33	23	16	9

Medford, Oregon	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	188	83	49	31	20	12			
5008 DD	WWNI	306	139	86	60	43	32	23	16	9
	TW	186	87	50	31	20	12	6		
42°N	TWNI	296	136	83	57	40	29	21	14	8

State College, Pennsylvania	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	117	50	28	18	11				
5934 DD	WWNI	214	98	61	42	31	23	17	12	7
	TW	126	58	33	20	12	6			
41°N	TWNI	213	97	60	41	30	22	16	11	6

Newport, Rhode Island	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	150	66	40	27	19	12	7		
5804 DD	WWNI	256	118	74	52	39	30	23	17	11
	TW	156	74	43	27	18	11	7		
41°N	TWNI	251	116	72	51	37	28	20	14	9

Charleston, South Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	442	204	127	90	67	52	39	28	18
2033 DD	WWNI	624	295	184	132	100	79	63	48	34
	TW	407	202	124	84	59	43	31	21	13
33°N	TWNI	594	279	176	124	93	71	53	39	27

Rapid City, South Dakota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	149	67	40	26	18	11	6		
7345 DD	WWNI	253	118	74	52	39	30	22	16	10
	TW	155	73	43	27	17	11	6		
44°N	TWNI	249	116	72	50	37	27	20	14	9

Nashville, Tennessee	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	227	99	59	40	28	20	13	8	
3578 DD	WWNI	355	161	98	68	51	39	30	23	15
	TW	219	103	61	39	26	18	11	7	
36°N	TWNI	343	155	95	66	48	36	27	19	12

Oak Ridge, Tennessee	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	204	90	54	36	26	18	12	6	
3817 DD	WWNI	325	149	92	64	48	37	29	21	14
	TW	201	95	56	36	24	16	6		
36°N	TWNI	315	145	89	62	46	34	25	18	11

Brownsville, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	1052	526	348	254	194	151	117	88	60
600 DD	WWNI	1399	700	465	342	265	209	165	127	90
	TW	976	506	324	226	165	123	91	66	44
26°N	TWNI	1330	664	435	315	238	183	140	104	71

El Paso, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	431	205	129	92	69	52	39	28	18
2700 DD	WWNI	608	295	187	134	103	80	63	48	34
	TW	402	202	125	85	60	44	31	22	13
32°N	TWNI	582	297	178	126	94	72	54	40	27

Fort Worth, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	364	171	108	76	57	43	32	23	14
2405 DD	WWNI	526	251	159	115	87	69	54	41	29
	TW	344	171	106	71	50	36	26	18	10
33°N	TWNI	503	239	152	108	81	61	46	34	23

Midland, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	385	184	115	82	61	47	35	25	16
2591 DD	WWNI	548	267	169	121	93	73	57	44	31
	TW	362	182	113	76	54	39	28	19	12
32°N	TWNI	527	253	161	115	86	65	49	36	24

San Antonio, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	547	253	159	114	86	66	50	37	24
1546 DD	WWNI	762	355	224	162	124	98	78	60	42
	TW	501	248	154	104	75	54	40	28	18
30°N	TWNI	722	337	213	152	114	87	66	49	33

Flaming Gorge, Utah	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	170	79	48	33	23	16	10	5	
6929 DD	WWNI	277	132	84	60	45	35	27	20	13
	TW	173	84	50	33	22	15	9	5	
41°N	TWNI	272	129	82	58	43	32	24	17	11

Salt Lake City, Utah	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	192	86	52	35	24	16	10		
6052 DD	WWNI	308	143	90	63	46	35	27	19	12
	TW	190	91	54	34	23	15	9	4	
41°N	TWNI	299	140	87	60	44	32	24	17	10

Burlington, Vermont,	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	80	30	15						
8269 DD	WWNI	171	75	46	31	23	17	12	8	4
	TW	94	41	21	11					
44°N	TWNI	172	77	46	31	22	16	11	7	4

Pullman, Washington,	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	178	78	44	27	17	9			
5542 DD	WWNI	291	134	82	56	40	29	21	14	8
	TW	175	81	46	28	18	10			
47°N	TWNI	282	130	79	53	37	27	19	13	7

Richland, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	179	77	43	25	15	7			
5941 DD	WWNI	293	133	81	54	38	27	19	13	7
	TW	176	80	45	27	16	9			
47°N	TWNI	285	130	78	52	36	26	18	12	7

Seattle, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	219	93	52	32	20	11			
4424 DD	WWNI	346	154	93	62	44	31	22	15	9
	TW	211	95	54	33	20	12	6		
48°N	TWNI	333	149	89	59	41	29	20	13	8

Spokane, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	149	63	34	20	10				
6655 DD	WWNI	255	116	70	47	33	23	17	11	6
	TW	151	68	38	22	13	6			
48°N	TWNI	251	114	68	45	32	22	16	10	5

Madison, Wisconsin	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	108	44	24	14	7				
7863 DD	WWNI	206	92	56	38	28	21	16	11	6
	TW	119	53	29	17	10				
43°N	TWNI	204	92	56	38	27	20	14	10	6

Lander, Wyoming	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	163	76	47	32	22	15	9		
7870 DD	WWNI	267	129	82	58	44	34	26	19	12
	TW	168	81	49	32	21	14	9	4	
43°N	TWNI	264	126	80	56	41	31	23	16	10

Laramie, Wyoming		SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW		157	72	44	31	22	15	10		
7381 DD	WWNI		263	124	79	56	43	33	26	19	13
	TW		164	79	47	31	21	14	9	4	
41°N	TWNI		259	122	77	55	41	30	23	16	10
Edmonton, Alberta		SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW		93	34							
10268 DD	WWNI		184	83	48	31	20	13	8	4	
	TW		102	42	20						
54°N	TWNI		184	83	48	31	20	14	9	5	
Ottawa, Ontario		SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW		91	35	17	7					
8735 DD	WWNI		185	81	49	33	24	17	12	8	4
	TW		103	45	23	13					
45°N	TWNI		184	82	49	33	24	17	12	8	4
Toronto, Ontario		SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW		103	42	23	14	6				
6827 DD	WWNI		198	89	55	38	27	21	15	10	6
	TW		114	51	28	16	9				
44°N	TWNI		197	89	55	37	27	19	14	9	5
Winnipeg, Manitoba		SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW		74	27							
10679 DD	WWNI		162	73	44	29	20	14	9	5	
	TW		88	37	18	7					
50°N	TWNI		164	74	44	29	20	14	9	5	

SOURCE: J. D. Balcomb and R. D. McFarland, "A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type," LA-UR-78-1159 (March 1978), Table I, p. 11.

APPENDIX C

The reference designs, estimated system life, and regional data tables can be used to calculate the amounts of various materials required to build solar heating or solar hot water systems to produce a given amount of useful energy, for instance pounds of concrete per 10^6 BTU. The materials data can be used to compute residuals associated with the production of the materials.

Example 1. Compute materials for an active space heating, air, in Atlanta, Georgia. Assume 75% of the heating load will be supplied by solar. Appendix A shows $LC_{75\%} = 29$ and DD = 2961 degree days for Atlanta.

$$LC_{75\%} \times DD \times 75\% = q \text{ in BTU/ft}^2\text{/yr}$$

$$q = 29 \times 2961 \times 0.75 = 64400 \quad \text{BTU/ft}^2\text{/yr}$$

For an estimated life of 20 years, the reference design materials and q give

MATERIAL	$lb/500\ ft^2$	USEFUL ENERGY $BTU/500\ ft^2$ YR	LIFE YRS	MASS/ENERGY $lb/10^6$ Btu
Steel	3600	500 x 64,400	20	5.6
Glass	800	500 x 64,400	20	1.2
Urethane	570	500 x 64,400	20	0.9
Rock	37500	500 x 64,400	20	58
Concrete	15000	500 x 64,400	20	23
Zinc	60	500 x 64,400	20	0.1

Collector fluid circulation energy used, $E_c = 194$ Kwh/yr/500 ft^2 = 2.9 Kwh/10^6 BTU. For this case $LC_{50\%} = 59$. The distribution system energy is

$$E_D = 16.2 \times 59 = 950 \text{ Kwh/yr/500 ft}^2$$

$$= 29.7 \text{ Kwh/yr/}10^6 \text{ BTU}$$

Example 2. Compute materials for space heating, active, liquid, in Bakersfield, California. Bakersfield is not listed in Appendix A. It is located near Los Angeles but across the mountains in the same central valley where Davis and Fresno are located. Note that LC & DD for Davis and Fresno are nearly identical although they are several hundred miles apart. They are quite different from Los Angeles. Santa Maria is not far from Bakersfield, but is a coastal city and again much different in climate. Use Fresno data. Assume 75% solar.

$$q = LC_{75\%} \times 0.75 = 32 \times 2492 \times 0.75 = 59800 \text{ BTU/ft}^2\text{/yr}$$

From the reference design and q,

	lb/500 ft^2		q	life	lb/10^6	BTU
Steel	3850	÷	500 x 59800 x 10^6	÷ 20	128	6.4
Glass	800				26.8	1.3
Urethane	370				12.4	0.6
Copper	160				5.4	0.3
Coolant	12				0.4	0.02

Collector fluid circulation energy used, E, = 504 $\frac{\text{kwh}}{\text{yr } 500 \text{ ft}^2}$ = 16.9 Kwh/10^6 BTU. $LC_{50\%} = 70$.

Distribution energy, E_D, = 16.2 x 70 = 1134 Kwh/yr/500 ft^2
= 37.9 Kwh/yr/10^6 BTU

The preceding examples show how the information in the reference designs and regional data can be used to compute materials requirements which can subsequently be used in an additional program to obtain residuals.

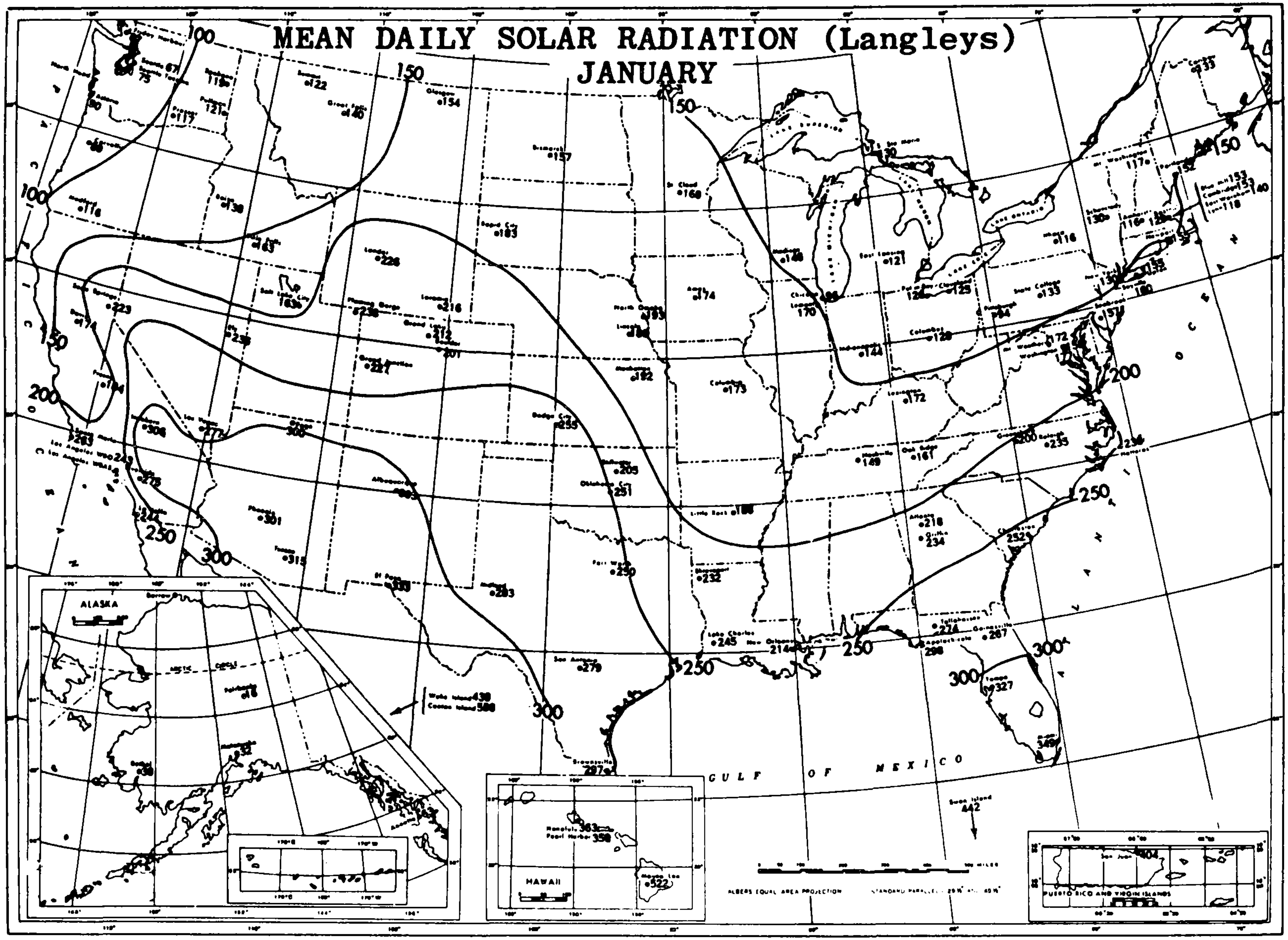

Fig. C-1.

Mean horizontal surface insolation in January. (Figures C-1 through C-12 are from the "Climatic Atlas of the United States--1968," US Depatment of Commerce, US GPO.)

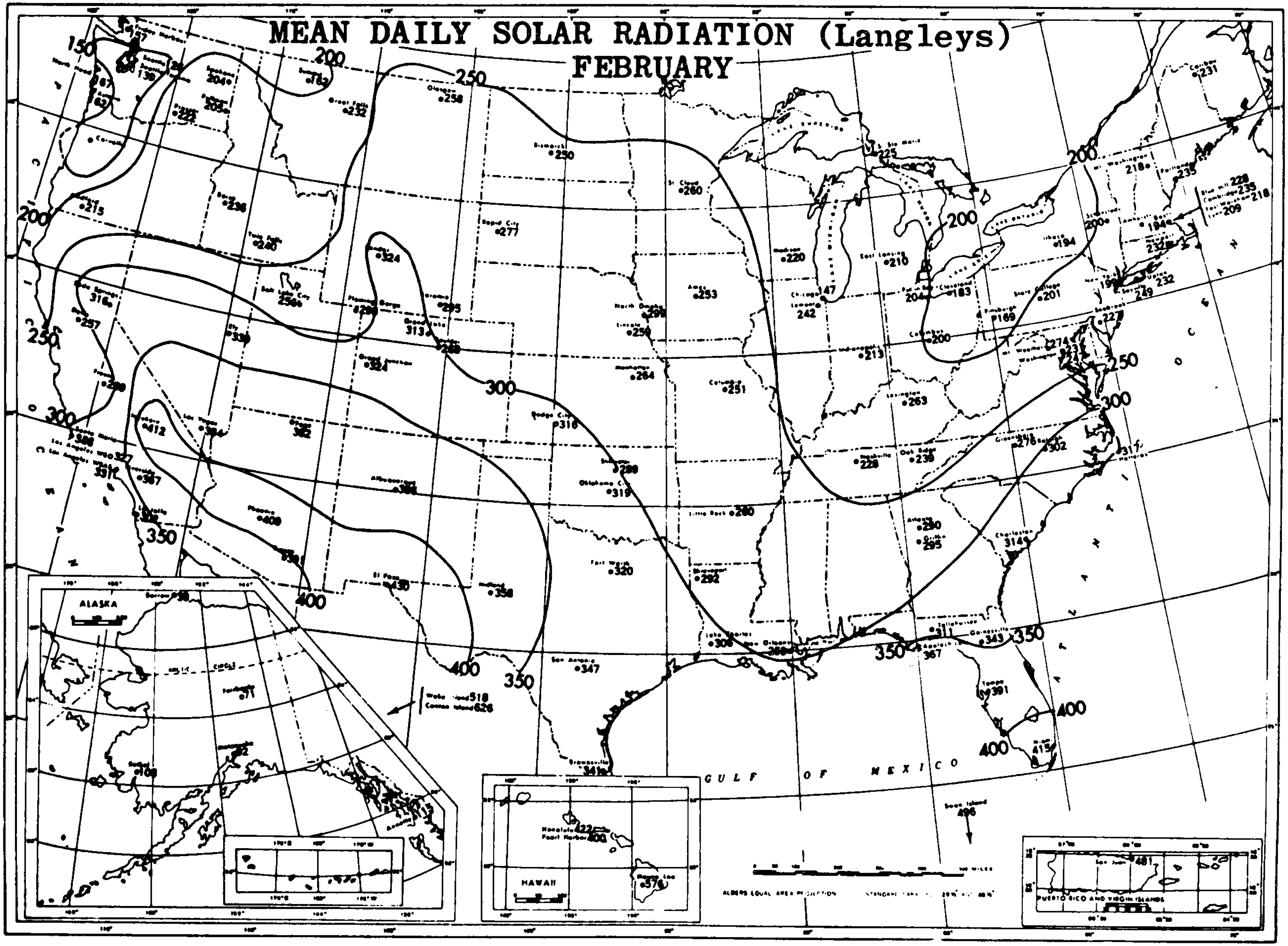

Fig. C-2.

Mean horizontal surface insolation in February.

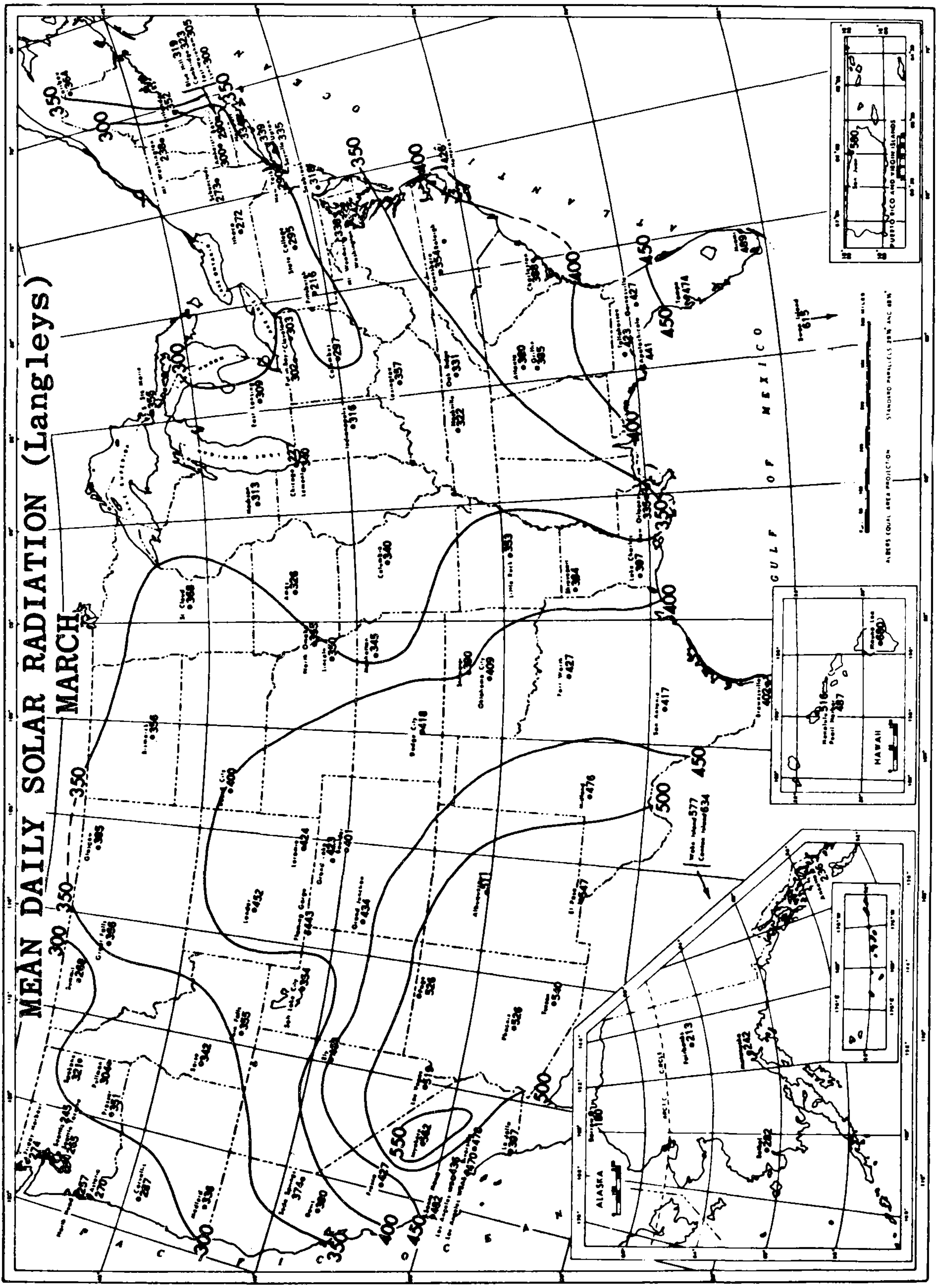

Fig. C-3.

Mean horizontal surface insolation in March.

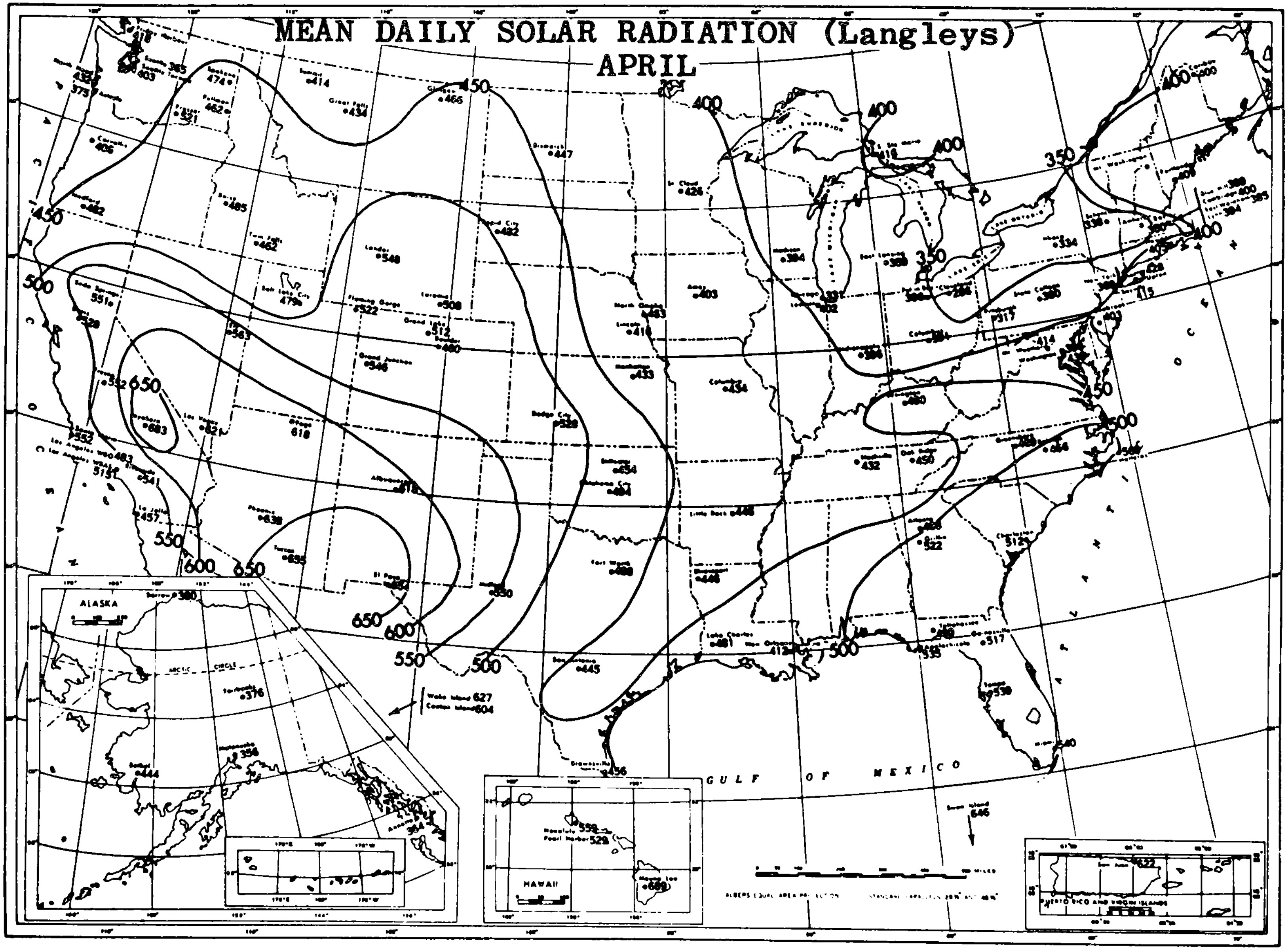

Fig. C-4.

Mean horizontal surface insolation in April.

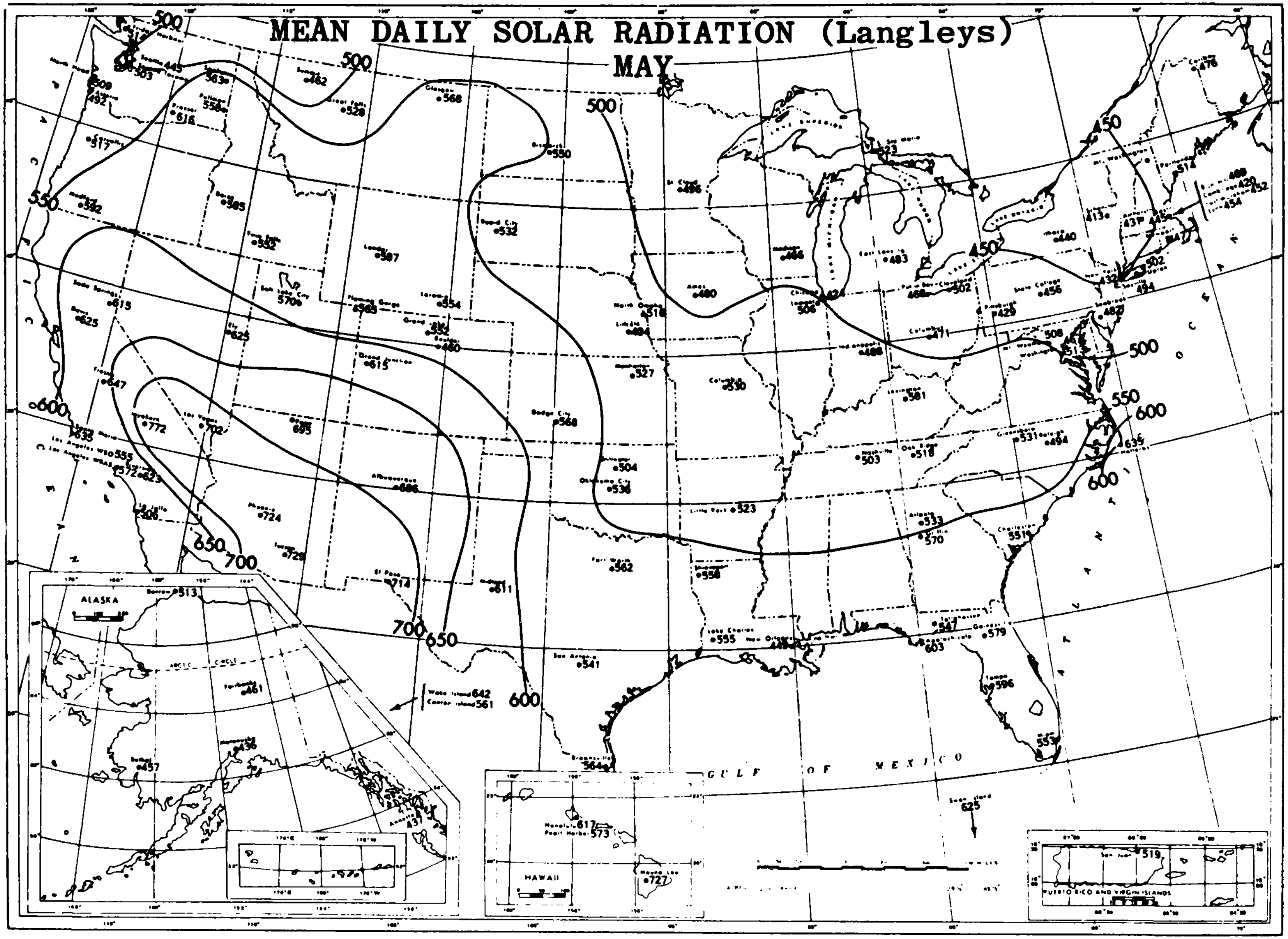

Fig. C-5.

Mean horizontal surface insolation in May.

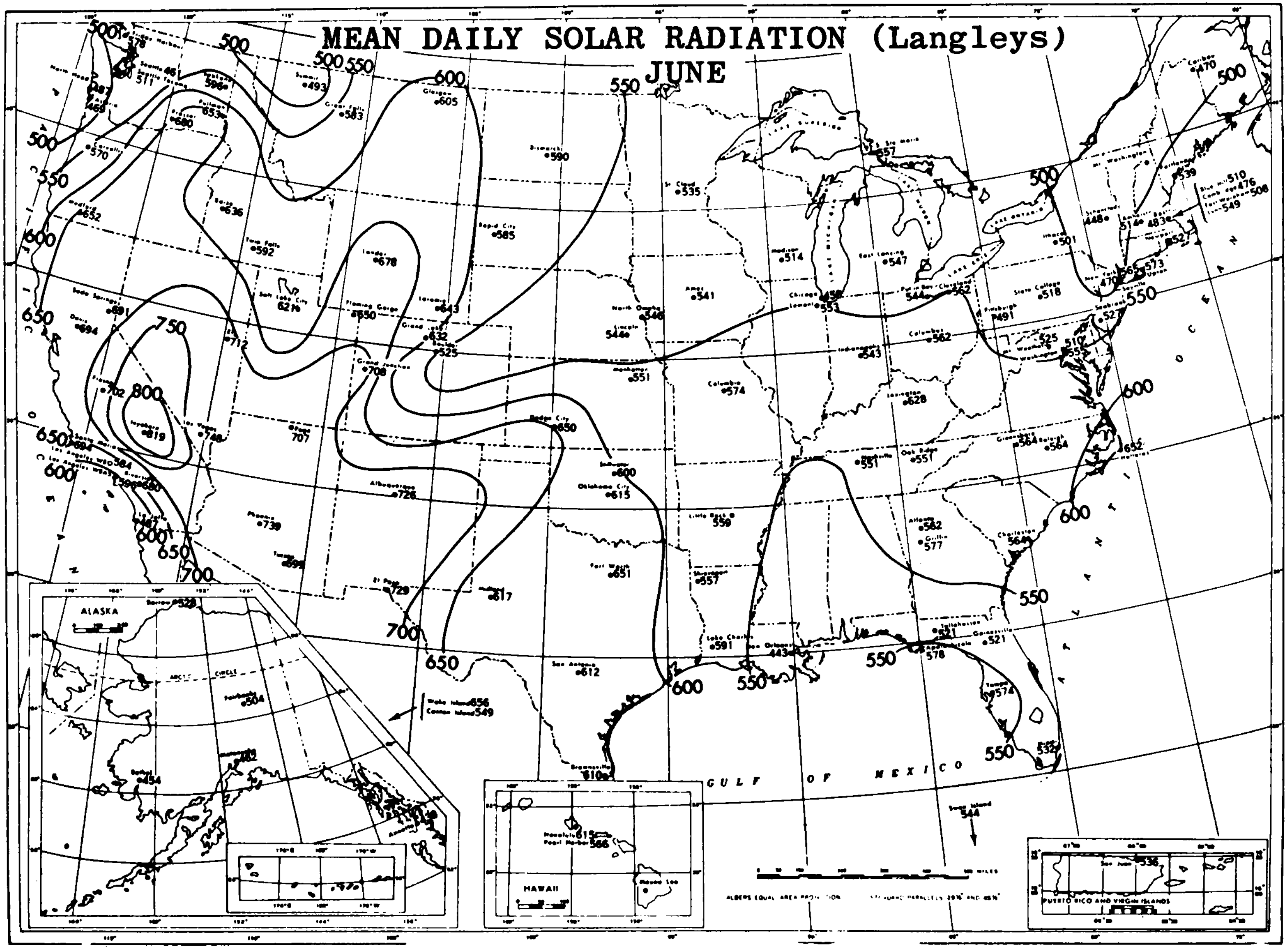

Fig. C-6.

Mean horizontal surface insolation in June.

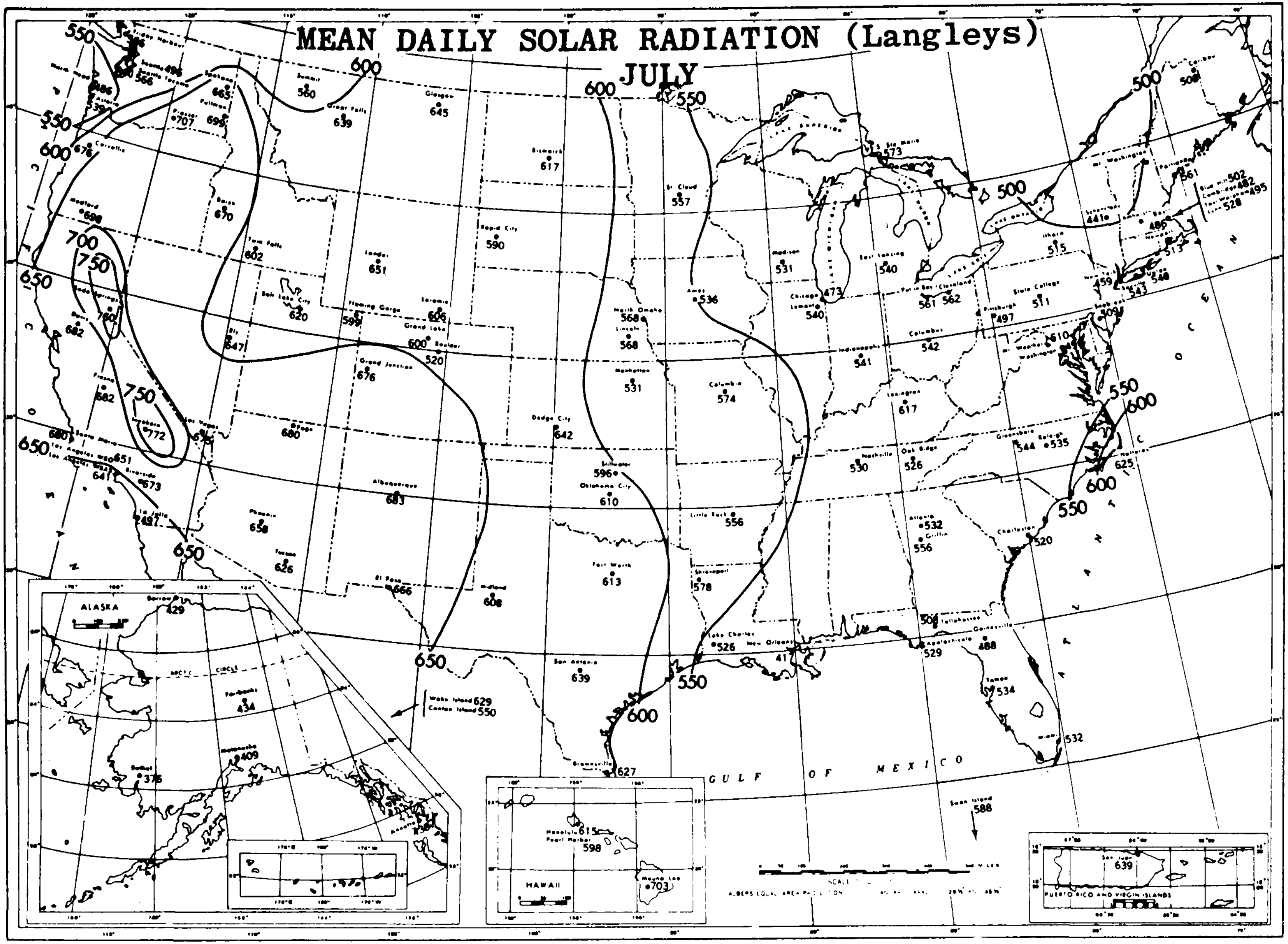

Fig. C-7.

Mean horizontal surface insolation in July.

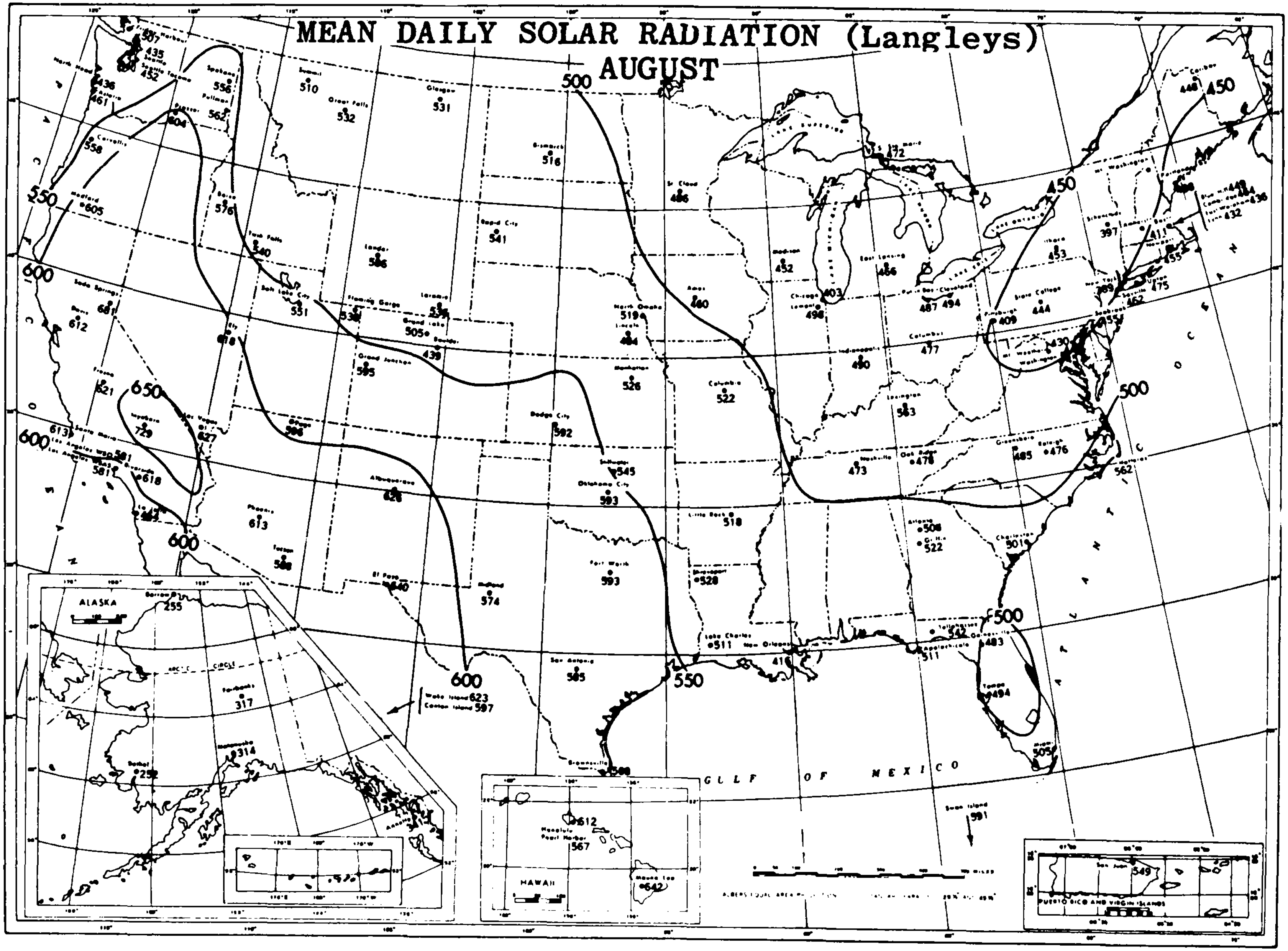

Fig. C-8.

Mean horizontal surface insolation in August.

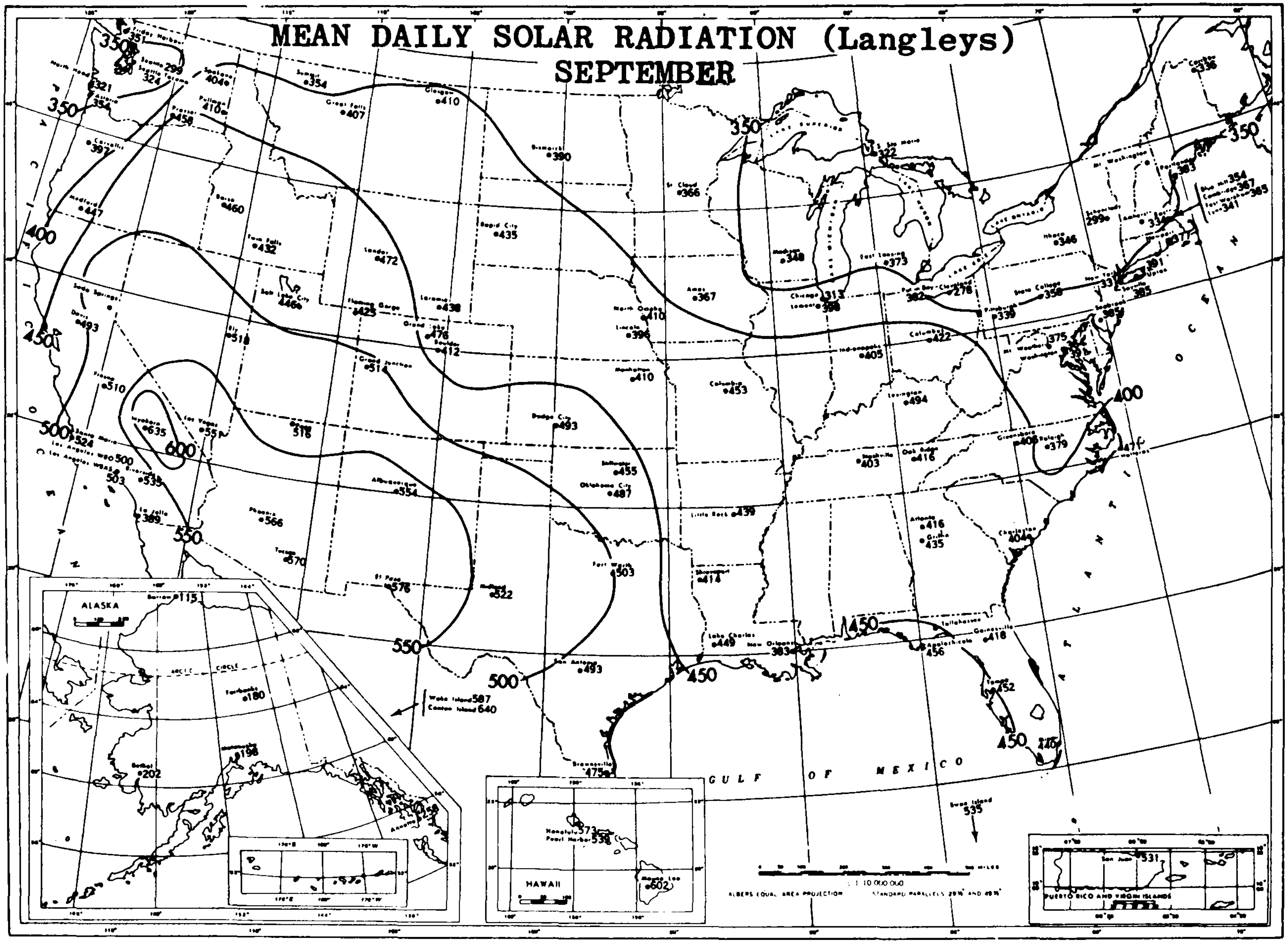

Fig. C-9.

Mean horizontal surface insolation in September.

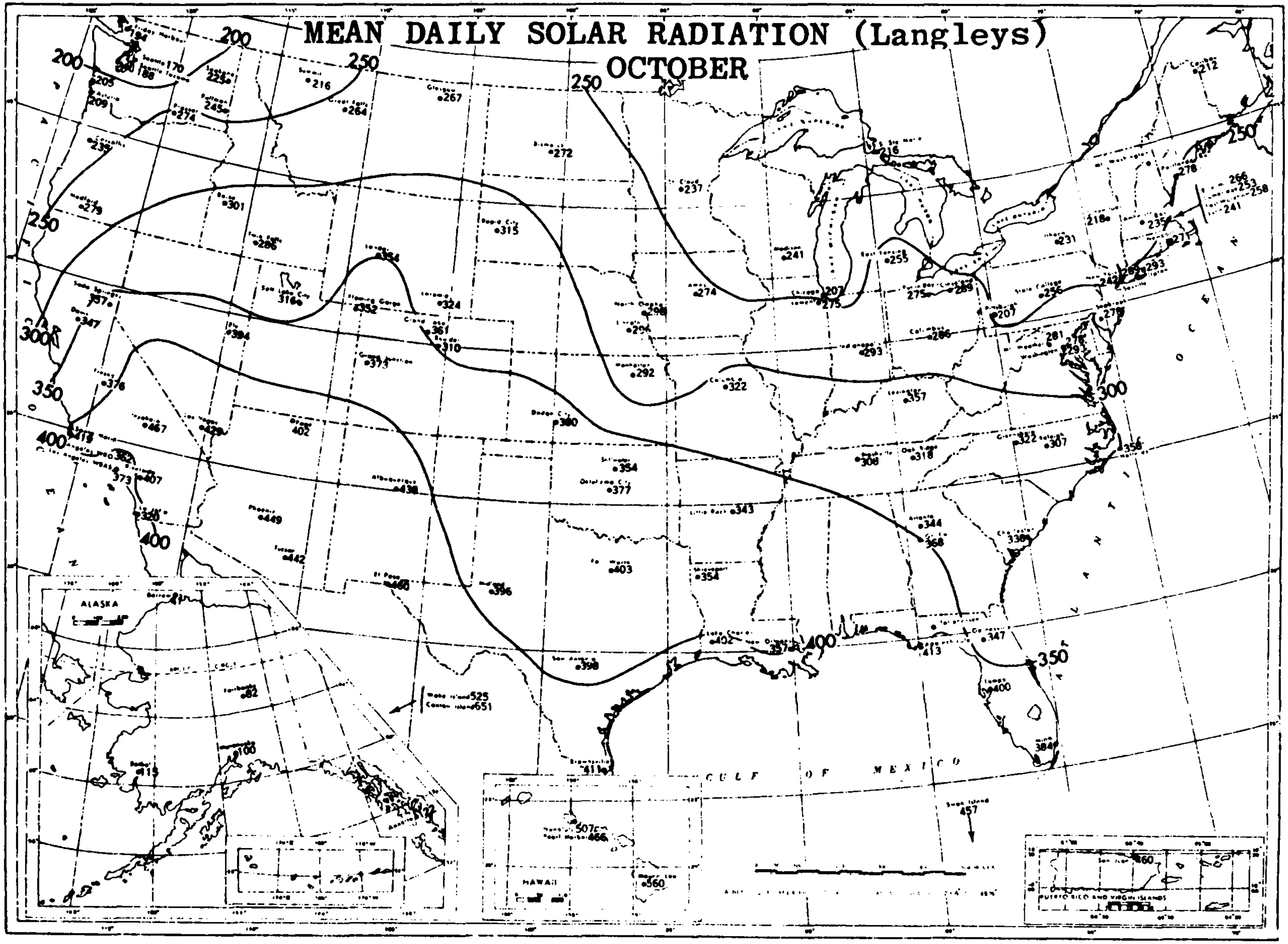

Fig. C-10.

Mean horizontal surface insolation in October.

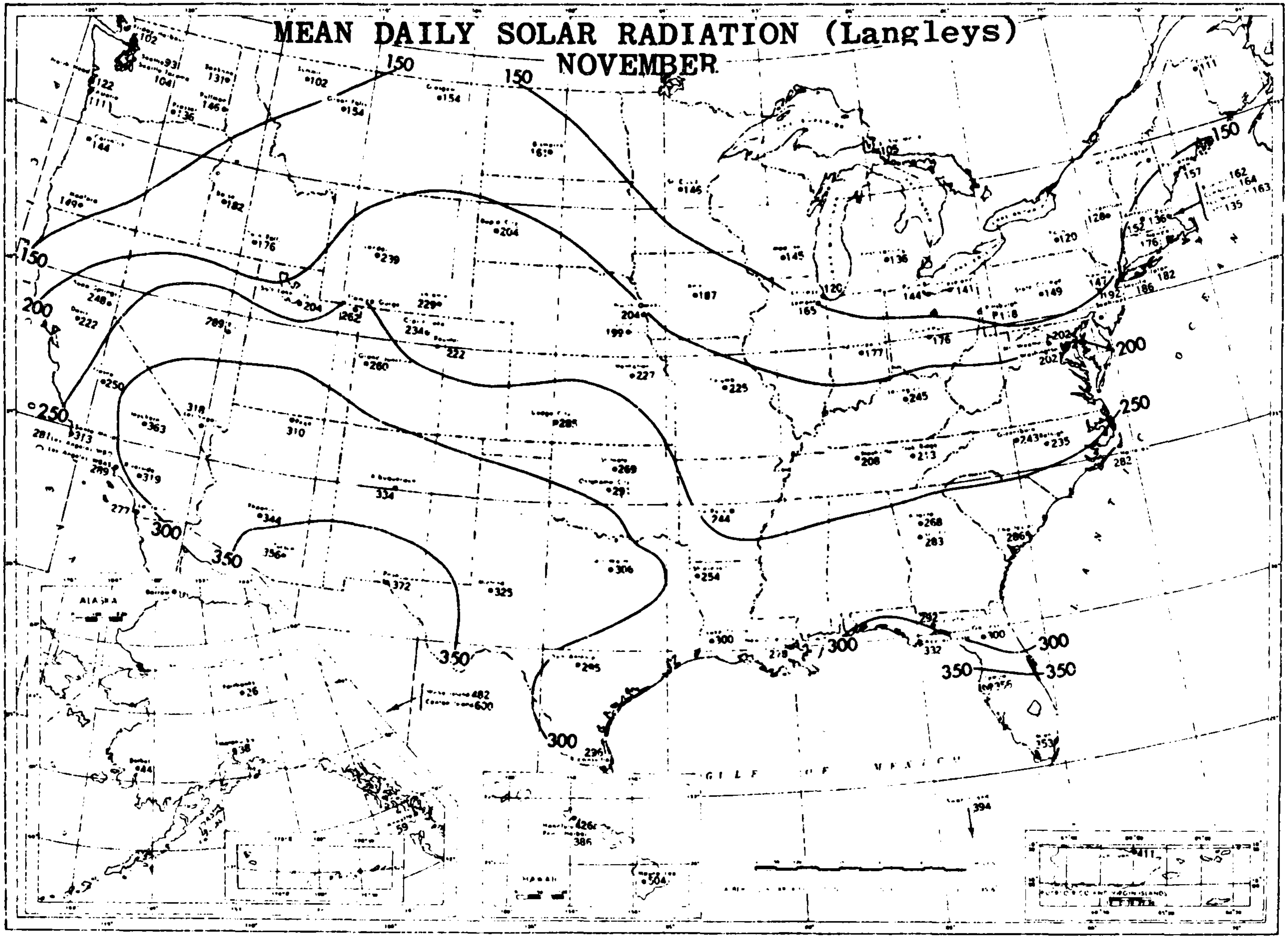

Fig. C-11.

Mean horizontal surface insolation in November.

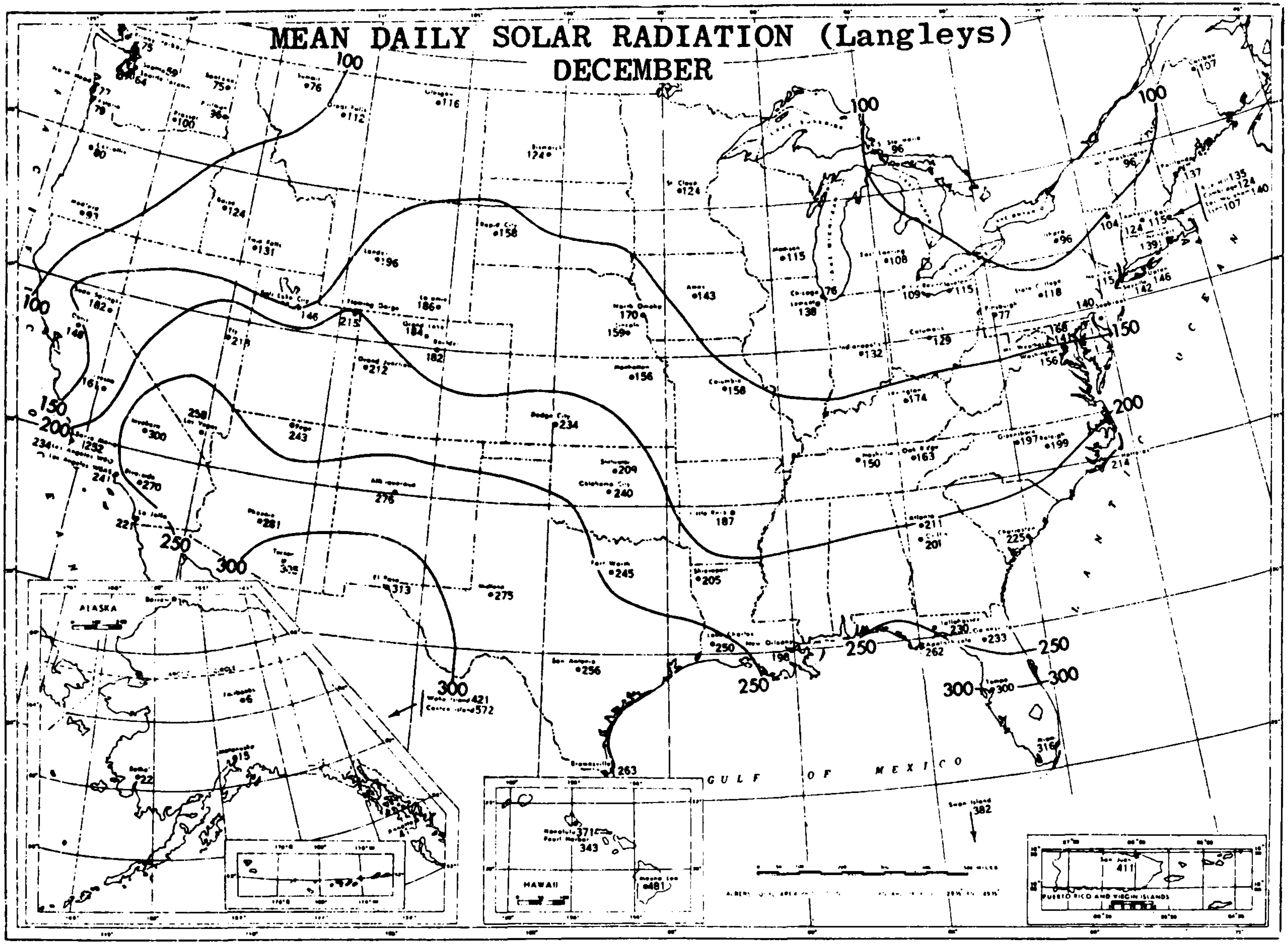

Fig. C-12.

Mean horizontal surface insolation in December.

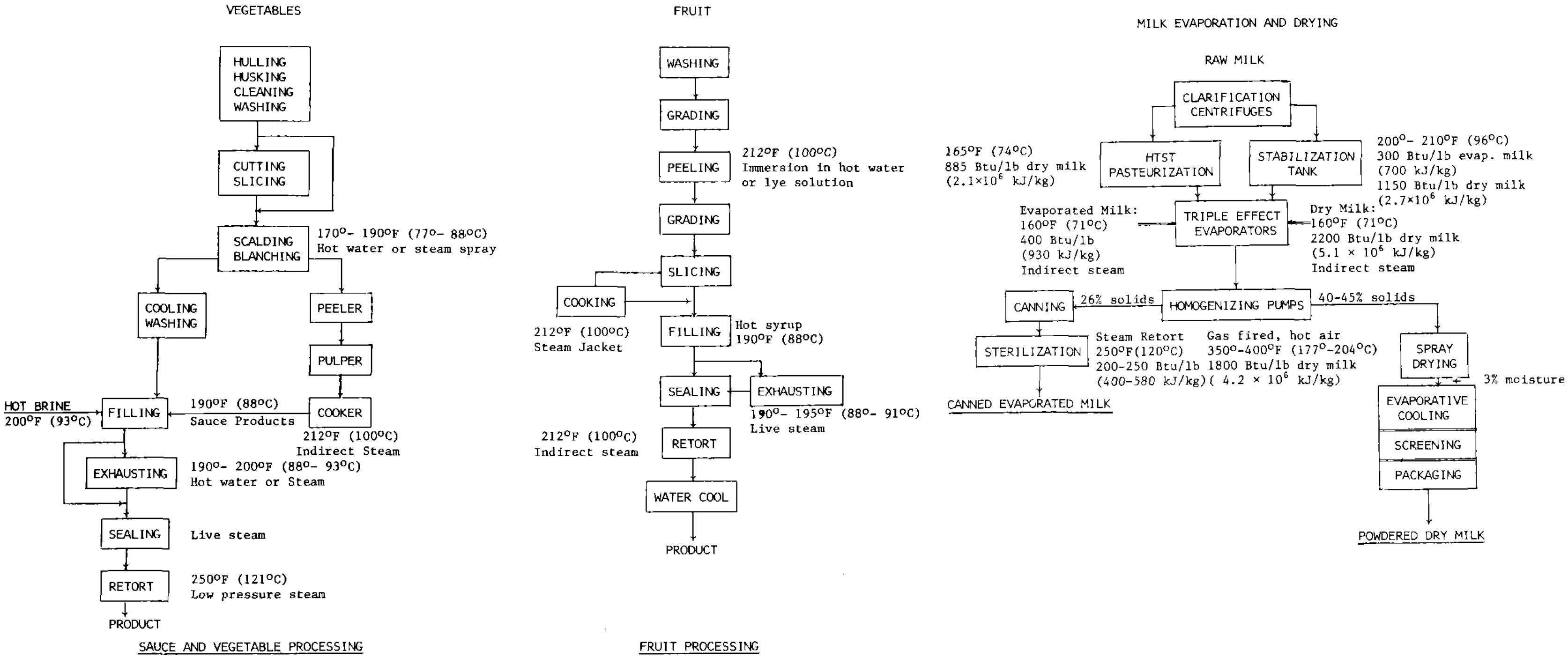

Fig. D-1 Process heat requirements - flow charts.

APPENDIX D.

TABLE D-I

THE POTENTIAL FOR SOLAR PROCESS HEAT IN THREE FOOD PROCESSING INDUSTRIES

200 DEGREES F.
INDIRECT PROCESS HEAT
CANNED FRUITS AND VEGETABLES
SIC - 2033
HOT BRINE ADDITION

Year	Solar Region	Total Process Heat Demand (10^9 Btu)	Oil		Gas		Total Solar Heat (10^9 Btu)
			Optimum % Solar	Solar Heat (10^9 Btu)	Optimum % Solar	Solar Heat (10^9 Btu)	
1976	I	90					
	II	428					
	III	44					
	IV	67					
	V	144					
	VI						
YEARLY TOTALS		765					
1985	I	102					
	II	479					
	III	50					
	IV	77	59	4			4
	V	164	69	4	67	105	109
	VI						
YEARLY TOTALS		872	—	7	—	105	112
2000	I	124	72	21	79	53	74
	II	579	82	86	82	287	373
	III	60	86	5	76	27	32
	IV	93	88	6	87	78	76
	V	199	90	6	89	169	175
	VI						
YEARLY TOTALS		1,055	—	124	—	686	730

200 DEGREES F.
INDIRECT PROCESS HEAT
CANNED FRUITS AND VEGETABLES
SIC - 2033
BLANCHING

Year	Solar Region	Total Process Heat Demand (10^9 Btu)	Oil		Gas		Total Solar Heat (10^9 Btu)
			Optimum % Solar	Solar Heat (10^9 Btu)	Optimum % Solar	Solar Heat (10^9 Btu)	
1976	I	179					
	II	840					
	III	87					
	IV	135					
	V	288					
	VI						
YEARLY TOTALS		1,529					
1985	I	205					
	II	958					
	III	99					
	IV	153	59	7			7
	V	328	69	7	67	210	218
	VI						
YEARLY TOTALS		1,743	—	15	—	210	225
2000	I	247	72	42	79	106	148
	II	1,159	82	172	82	574	746
	III	120	86	10	76	54	64
	IV	186	88	13	87	139	152
	V	397	90	12	89	338	349
	VI						
YEARLY TOTALS		2,118	—	249	—	1,211	1,460

400 DEGREES F.
INDIRECT PROCESS HEAT
CONDENSED AND EVAPORATED MILK
SIC - 2033
DRY MILK - SPRAY DRYING

Year	Solar Region	Total Process Heat Demand (10^9 Btu)	Oil		Gas		Total Solar Heat (10^9 Btu)
			Optimum % Solar	Solar Heat (10^9 Btu)	Optimum % Solar	Solar Heat (10^9 Btu)	
1976	I	261					
	II	245					
	III	192					
	IV	8					
	V	269					
	VI	-					
YEARLY TOTALS		1,975					
1985	I	261					
	II	245					
	III	192					
	IV	8	30				
	V	269	52	5	48	123	128
	VI	-					
YEARLY TOTALS		1,975	—	5	—	123	128
2000	I	261	59	36	72	102	138
	II	1,245	74	167	74	556	723
	III	192	77	15	66	75	90
	IV	8	82	1	80	6	6
	V	269	84	7	83	213	221
	VI	-	-	-	-	-	-
YEARLY TOTALS		1,975	—	226	—	953	1,178

SOURCE: Intertechnology Corporation, "Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat," InterTech Report No. 028-1. Prepared for the Energy Research and Development Administration (February 7, 1977), p. 424, 466, and 467.

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